Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 90's

Compiled by James S. Burton

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These proceedings are a product of the Water Information Coordination Program (WICP) of the Federal Government. Office of Management and Budget Memorandum No. 92-01 establishes guidelines for the WICP and designates the U.S. Department of the Interior, through the U.S. Geological Survey (USGS), as the lead agency for water-information coordination. The WICP is conducted through a partnership among Federal agencies and the non-Federal sector. An interdepartmental working group of the WICP selected the papers contained in these proceedings from abstracts. Contributing organizations provided the papers in camera-ready form, and the USGS complied the proceedings.

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FOREWORD

The Interagency Advisory Committee on Water Data is part of the governmentwide Water Information Coordination Program as required by the Office of Management and Budget Memorandum No. 92-01 (M-92-01, dated December 10, 1991). The purpose of M-92-01 is to ensure the availability of water information for effective decisionmaking for natural resources management and environmental protection at all levels of government and in the private sector. Memorandum No. 92-01 replaces OMB Circular A-67 that was signed in 1964 and that set forth the original guidance to Federal agencies about coordinating water information. The overall mission of the WICP is to establish and maintain active partnerships among all levels of government and the private sector to meet water information requirements nationwide effectively and economically. The scope of the WICP includes surface-water and ground-water quality and quantity, sediment, and precipitation information critical to water resources management. The WICP also addresses water use information. For the purposes of M-92-01, water resources include streams, lakes, reservoirs, ground water, estuaries, and other aquatic habitats influenced primarily by fresh water.

Participating Federal and non-Federal organizations of the WICP perform a variety of functions including the following: 1) evaluating the effectiveness of existing water-information programs and recommending improvements, 2) coordinating funding staffing and other capabilities to assure the best use of available resources, 3) developing voluntary consensus guidelines for water-resources information, and 4) facilitating information sharing and technology transfer. Thirty Federal bureaus, services, and other organizations that fund, collect, or use water information participate as members of the Interagency Committee. The Interagency Committee oversees the operation of about two dozen subcommittees, working groups, and tasks forces to fulfill the objectives of M-92-01. For more than 25 years, the Interagency Committee has provided leadership to meet water information requirements in the United States. Private sector interests are represented in the WICP through the Advisory Committee on Water Data for Public Use. Both the Interagency Committee and the Advisory Committee report to a subcabinet level, interdepartmental WICP Steering Committee chaired by the Assistant Secretary for Water and Science of the U.S. Department of the Interior. For additional information or to request copies of reports, please write or telephone the Office of Water Data Coordination, U.S. Geological Survey, 417 National Center, Reston, VA 22124. Telephone (703) 648-5023. Fax: (703) 648-6802.

(PAGE V FOLLOWS)

PREFACE

During the last 10 years, many technological advances have been made in computer hardware and software. At the same time, the use of satellite telemetry to collect hydrologic data has been increasingly popular, thus placing more emphasis on data automation. In addition, a nationwide advanced weather radar system is being installed and will be fully operational in 5 years. As a result, Federal agencies responsible for collecting hydrologic data, forecasting floods, and operating water resource projects have initiated new programs to modernize their operational systems. Federal agencies that are members of the Interagency Subcommittee on Hydrology expressed strong interest in the exchange of information pertaining to these modernization activities. In recognition of this need, the Subcommittees on Hydrology and Water Data and Information Exchange of the Interagency Advisory Committee on Water Data (IACWD) agreed to jointly sponsor a workshop in 1993 to discuss these emerging issues. A Work Group was subsequently formed to organize the workshop.

The primary purposes of the workshop were to promote interagency coordination and technology exchange in the area of surface-water hydrologic modeling. The workshop also provided opportunities for hydrologic modelers to share their existing models and exchange ideas to guide the future direction of model development. Major topics for the workshop included surface-water hydrologic modeling systems, data management and exchange, stochastic hydrology, model verification, and integration of geographic information systems (GIS) and hydrologic models. Particular emphasis was placed upon presentations of each agency's future hydrologic model development. Also, a demonstration and poster session was incorporated in the program. Participation in the workshop was by invitation, and the Working Group selected the papers presented at the workshop from abstracts offered by the participating organizations.

Ming T. Tseng
Chairman

(PAG VII FOLLOWS)

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(PAGE IX FOLLOWS)

CONTENTS-Continued

Page

SECTION 3. INTEGRATION OF GIS AND HYDROLOGIC MODELS-continued

Estimating Snow Water Equivalent Using a GIS
Ann McManamon, Gerald N. Day, and Thomas R. Carroll 3-18
Integrating Hydrologic Models, Geographic Information Systems, and Multiple Data Bases: A Data Centered Approach
Thomas P. Ryan and David Sieh 3-26

SECTION 4. HYDROLOGIC MODELING SYSTEMS

Expert System for Calibration and Application of Watershed Models
Alan M. Lumb and John L. Kittle, Jr. 4-1
A System Of Hydrologic Models
Jimmy R. Williams and Jeffrey G. Arnold 4-8
An Object-Oriented Approach to General-Purpose River-Basin Management
Jean M. Boyer 4-16
Object-Oriented Simulation Modeling of Watersheds
Robert E. Kort and E. Allan Cassell 4-24
ANN-AGNPS: A Continuous Simulation Watershed Model
Scott E. Needham and Robert A. Young 4-32
The Modular Hydrologic Modeling Systems-MHMS
George H. Leavesley, Pedro J. Restrepo, Linda G. Stannard, and Michael J. Dixon 4-40
Soil Water Hydrology and Chemical Budgets with the Enhanced SPAW Model
Dr. Keith E. Saxton 4-43
Surface Water and Groundwater Model Developments at the Waterways Experiment Station
Jeffrey P. Holland 4-52

SECTION 5. COMPUTER DEMONSTRATIONS AND POSTERS

COMPUTER DEMONSTRATIONS

RZWQM to Model Management Effects on Water Quality
R.W. Rojas, L.R. Ahuja, Q.L. Ma, D.G. DeCoursey, V. Ferreira, J.D. Hanson, and M.J. Shaffer 5-1
Water Erosion Prediction Project (WEPP) Hydrology Submodel
M.R. Savabi 5-8
Developing Hydrologic Parameters Using GIS
Billy E. Johnson 5-17
Snowmelt Runoff Forecasting
Timothy Pangborn, Joyce A. Nagle, and Robert E. Davis 5-20
Intergration and Use of the Nitrate Leaching and Economic Analysis Package (NLEAP) in the GIS Environment
M.J. Shaffer, M.K. Brodahl, and B.K. Wylie 5-28

CONTENTS

Page

Foreword iii
Preface v
Acknowledgments vii

SECTION 1. AGENCY OVERVIEW

Past, Present, and Future Hydrologic Modeling in ARS
Kenneth G. Renard 1-1
Hydrologic Models used by the U.S. Bureau of Mines
Allen O. Perry 1-16
Bureau of Reclamation Hydrologic Modeling Trends
R. Wayne Cheney 1-24
Recent HEC Modeling Activities
Arlen D. Feldman and Darryl W. Davis 1-30
The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations
Richard K. Farnsworth, Donna Page, Timothy Sweeney, Ann McManamon, George F. Smith, Donald P. Laurine, and Danny L. Fread 1-45
Past, Present and Future needs of SCS Water Quantity Modeling Efforts
Gerald D. Seinwill 1-61
U.S. Geological Survey Program to Meet the Hydrologic Modeling Demands for the 90'S
Alan M. Lumb 1-70

SECTION 2. DATA MANAGEMENT AND EXCHANGE

Remote Sensing for Hydrologic Models
Edwin T. Engman 2-1
Precipitation Processing with the WSR-88D
Robert C. Shedd, Richard A. Fulton, and Albert D. Peterlin 2-9
Use of an On-Line Information System and CD-ROMs for Dissemination of ARS Water Data
Jane L. Thurman and Ralph T. Roberts 2-15
Second Release of the U.S. Geological Survey's National Water Information System-II
Jeffrey D. Christman and Owen O. Williams 2-21
SNOTEL
David E. Johnson 2-30

SECTION 3. INTEGRATION OF GIS AND HYDROLOGIC MODELS

Visualization Techniques for Hydrologic Modeling
Lauren Hay and Loey Knapp 3-1
Object-Oriented Methods for Hydrologic Modeling and Remote Sensing
Harlan L. McKim, Perry J. LaPotin, E. Allen Cassell, and Andrew J. Bruzewicz 3-9

CONTENTS–Continued

Page

SECTION 7. STOCHASTIC HYDROLOGY–RISK AND UNCERTAINTY–continued

Upper Colorado River Simulation/Optimization Model
Leslie C. Stillwater 7-7
Using CLIGEN to Stochastically Generate Climate Data Inputs to WEPP and Other Water Resource Models
Arlin D. Nicks and Gene A. Gander 7-14
Muskingum Basin Reservoir Frequency Analysis
Dr. Surya Bhamidipaty and Jerry W. Webb 7-22
Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast
Donald P. Laurine and Larry E. Brazil 7-30

SECTION 8. MODEL VERIFICATION

Validation Strategies Based on Model Application Objectives
David C. Goodrich, Jeffry J. Stone, and Richard van der Zweep 8-1
Verification of Hydrologic Modeling Systems
Billy E. Johnson, Nolan K. Raphelt, and Joe C. Willis 8-9
A System Response Approach for Verifying Surface and Groundwater Models
Bernard H. Hsieh 8-21
Urban Runoff Model Calibration and Validation
R.S. Dinicola 8-29
Wetland Identification SCS, Missouri
Jerry P. Edwards 8-35
Determining Design Unit Hydrographs for Small Watersheds
Joseph M. Sheridan and William H. Merkel 8-42
TOPMODEL, A Topography-Based Watershed Model
David M. Wolock 8-50

FIGURES AND TABLES

SECTION 1. AGENCY OVERVIEW

Past, Present, and Future Hydrologic Modeling in ARS 1-1

Figure: 1. Model classification (Source: Woolhiser and Brakensiek, 1982) 1-3

Tables: 1. ARS hydrologic models, acronym, authors and date of publication 1-14
2. ARS hydrologic model details 1-15

Bureau of Reclamation Hydrologic Modeling Trends 1-24

Figures: 1. ADSS model tools 1-28
2. ADSS data handling tools 1-28

Recent HEC Modeling Activities 1-30

Figures: 1. HEC data storage system 1-36
2. Interior flood hydrology continuous simulation 1-37

CONTENTS-Continued

Page

SECTION 5. COMPUTER DEMONSTRATIONS AND POSTERS-continued

COMPUTER DEMONSTATIONS-continued

A Graphical User Interface for ARS Water Data on CD-ROM
Ralph T. Roberts and Jane L. Thurman 5-36

HYDROSS Simulation Support System
Mike S. Brewer 5-42

A Comprehensive System for Surface Water and Groundwater Modeling
H.C. Lin, J.D. Jorgeson, D.R. Richards, and W.D. Martin 5-47

Program for Daily Weather Simulation
C.L. Hanson, K.A. Cumming, D.A. Woolhiser, and C.W. Richardson 5-55

Interior Drainage Analysis, West Columbus, OH
Dr. Surya Bhamidipaty and Jerry W. Webb 5-62

POSTERS

A Disparity Detected in Hydrologic Soil Grouping
Geoffrey A. Cerrelli 5-70

Current Issues in River Ice Forecasting
Kathleen D. White, Jon E. Zufelt, and Steven F. Daly 5-74

Watershed Modeling—Spatial Partitioning Using GIS
Ann E. Jeton and J. LaRue Smith 5-81

TR-20 Proves Viable Flood Reduction Alternative
Laurel F. Mulvey 5-89

GIS Application for NWS Flash Flood Guidance Model
Timothy L. Sweeney, Danny L. Fread, and Konstantine P. Georgakakos 5-94

Adaption of TR-20, Project Formuation-Hydrology
John W. Chenoweth, PE 5-102

Multi-Dmensional Analysis of a Surface Coal Mine
Judith Schenk, Keith Kirk, and Alan Wilhelm 5-109

SECTION 6. HYDROLOGIC MODELING SYSTEMS

Modeling for Water Supply Forecasting in the West
David C. Garen 6-1

Computer Modeling of Alpine Stream Diversions
T.M. Brady, and L.A. Martin 6-9

Automating Detailed System Regulation Studies
Douglas D. Speers, Gary R. Flightner, and Peter F. Brooks 6-18

NEXGEN-HEC's Next Generation Software Development Project
Arthur F. Pabst 6-26

SECTION 7. STOCHASTIC HYDROLOGY-RISK AND UNCERTAINTY

Advances on the Last Stochastic Hydrology Package
Donald K. Frevert 7-1

Page

Estimating Snow Water Equivalent Using a GIS 3-18

Figures: 1. Example of a simulation used to define a relationship for the zone between the mean seasonal precipitation and the mean snow water equivalent for a particular date 3-22
2. April 1, 1980 interpolated snow water equivalent grid, Animas River at Durango, Colorado 3-23
3. Schematic of the updating component 3-24

Integrating Hydrologic Models, Geographic Information Systems, and Multiple Databases: A Data Centered Approach 3-26

Figures: 1. Data centered architecture 3-27
2. Implemented water resource management support system 3-29

SECTION 4. HYDROLOGIC MODELING SYSTEMS

Expert System for Calibration and Application of Watershed Models 4-1

Figure: 1. Detailed steps to calibrate HSPF with HSPEXP 4-5

A System of Hydrologic Models 4-8

Figure: 1. Integration of models, GIS, and databases 4-15

An Object-Oriented Approach to General-Purpose River-Basin Management 4-16

Figure: 1. Network schematic for the Lower Nile River Basin 4-19

Object Oriented Simulation Modeling of Watersheds 4-24

Figures: 1. STELLA® II screen showing a structural diagram of Compound Interest Model 4-26
2. Structural diagram for the Compound Interest Model 4-26
3. Illustration of the animation of the objects (note filling of Acct Balance and dial movement of Interest Income) and active creation of an output plot over the simulation period. The horizontal line is Mon Interest Rate and Acct Balance is the line having exponential form 4-28
4. STELLA® II structural diagram for portions of TR-55 4-29
5. STELLA® II structural diagrams for portions of HYMO 4-29
6. Runoff hydrograph for a watershed generated with HY5⁰. Qa, Qb, and Qc are flow rates for the corresponding HYMO hydrograph segments. Qhymo represents the summation of the flow rates of the three segments. All flows are in cfs 4-30
7. Sensitivity plot of peak discharge (Qp in cfs) vs. Curve Number (CN). CN was varied from 50 to 95 while all other parameters remained constant 4-31

ANN-AGNPS: A Continuous Simulation Watershed Model 4-32

Table: 1. Summary of observed and predicted watershed response 4-37

Soil Water hydrology and Chemical Budgets with the Enchanced SPAW Model 4-43

Figures: 1. A schematic of the SPAW control volume 4-44
2. Example simulated AET, soil moisture, and nitrate nitrogen for 6 and 12 layer soil profile representations over one year 4-50

FIGURES AND TABLES-Continued

Page

SECTION 1. AGENCY OVERVIEW-continued

Recent HEC Modeling Activities-continued

Figures: 3. Water control system 1-39
4. HEC continuous watershed simulation model 1-41

The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations 1-45

Figures: 1. NWSRFS Version 5 structure 1-51
2. Example of a workstation screen 1-54

Table: 1. NWSRFS hydrologic models 1-50

SECTION 2. DATA MANAGEMENT AND EXCHANGE

Remote Sensing for Hydrologic Models 2-1

Table: 1. Future satellite systems that will have important instruments for hydrologic modeling 2-8

Use of an On-Line Information System and CD-ROMs for Dissemination of ARS Water Data 2-15

Figures: 1. ARS experimental agricultural watersheds 2-16
2. Source of water data center data requests 2-18

Second Release of the U.S. Geological Survey's National Water Information System II 2-21

Figures: 1. Main menu of the National Water Information System II 2-24
2. Menu structure of the National Water Information System II 2-25
3. Sequence of operations in the processing of time-series hydrologic data 2-27

SECTION 3. INTEGRATION OF GIS AND HYDROLOGIC MODELS

Visualization Techniques for Hydrologic Modeling 3-1

Figure: 1. Conceptual view of the input-output relations between an orographic precipitation model (MODEL), a scientific visualization system (SVS), and a geographic information system (GIS) 3-3

Object-Oriented Methods for Hydrologic Modeling and Remote Sensing 3-9

Figures: 1. Mass flux into and out of an incremental volume ($\triangle$V) 3-11
2. Skeletal object representation for mass flux into and out of an incremental volume 3-12
3. Temperature and precipitation patterns 3-14
4. Snowmelt and runoff sources 3-14
5. Components of discharge 3-15
6. Simulated runoff versus actual runoff 3-15

Page

SECTION 5. COMPUTER DEMONSTRATIONS AND POSTERS-continued

COMPUTER DEMONSTRATIONS-continued

A Comprehensive System for Surface Water and Groundwater Modeling-continued

Figures: 7. Water surface elevation contour in gray scale for Cape Fear River, North Carolina 5-53
8. Sample of a 3-D finite element mesh 5-54

Program for Daily Weather Simulation 5-55

Table: 1. Historical and generated mean monthly climatic data for Boise, Idaho 5-59

Interior Drainage Analysis, West Columbus, OH 6-62

Plate: 1. Scioto River, Columbus, Ohio 5-69

Table: 1. Flood depths area subject to inundation 5-68

POSTERS

Watershed Modeling—Spatial Partitioning Using GIS 5-81

Figures: 1. Location of part of East Fork Carson River basin (above Markleeville, California) and North Fork American River basin (above North Fork Dam) 5-82
2. Schematic diagram of Precipitation-Runoff Modeling System (modified from Leavesley and others, 1983) 5-83
3. Flowchart for watershed characterization and hydrologic-response-unit (HRU) delineation 5-86
4. Hydrologic-response unit (HRU) overlay for East Fork Carson River basin 5-87

Tables: 1. Source data for geographic information system 5-84
2. Data layers for East Carson River basin geographic information system 5-85
3. Characteristics of combination permutation identification number 121 5-86

GIS Application for NWS Flash Flood Guidance Model 5-94

Figures: 1. Threshold runoff values for 1-hour rainfall duration based on 2-year return period discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.5 (darkest color) to 0.8 inches. Raccoon River in Iowa, CU 07100007 5-100
2. Threshold runoff values for 1-hour rainfall duration based on Manning's equation at bankful discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.2 (darkest color) to 1.2 inches. Raccoon RIver in Iowa, CU 07100007 5-101

Adaptation of TR-20, Project Formulation-Hydrology 5-102

Plates: 1. Kanakakee River Basin 5-108
2. Kanakakee River at Shelby, Ind 5-108

Page

SECTION 5. COMPUTER DEMONSTRATIONS AND POSTERS

COMPUTER DEMONSTRATIONS

RZWQM To Model Management Effects on Water Quality 5-1

Figures: 1. Measured and predicted runoff water and atrazine in 1973 5-3
2. Measured and predicted runoff atrazine and cyanazine in 1975 5-3
3. Measured and predicted soil water distributions in watershed P2, Watkinsville, G.A. 1974 and 1975 5-4
4. Measured and predicted atrazine persistence in watershed P2, Watkinsville, GA. 1973 and 1974 5-5
5. Measured and predicted atrazine distributions in the soil profile, P2, Watkinsville, G.A. 1973 5-5
6. Measured and predicted atrazine distributions in the soil profile, Watershed P2, Watkinsville, G.A. 1974 5-5
7. Measured and predicted atrazine and cyanazine distributions in the soil profile. Watershed P2, Watkinsville, G.A. 1975 5-5

Water Erosion Prediction Project (WEPP) Hydrology Submodel 5-8

Figures: 1. Schematic computational sequence of the WEPP hydrology component, Eu is potential evaporation, Esp is potential soil evaporation, L is leaf area index, Ep is potential plant transpiration, Es is potential soil evaporation for area covered by plant residue 5-11
2. Schematic representation of WEPP artifical subsurface drainage. ET is actual evapotranspiration 5-13

Integration and use of the Nitrate Leaching and Economic Analysis Package (NLEAP) in the GIS Environment 5-28

Figure: 1. Average Groundwater $N0_3$-N from 1989 to 1991 (la) and NLEAP $N0_3$-N Leached (NL) Index for Irrigated Areas near Greeley, Colorado (1b) 5-33

A Graphical User Interface for ARS Water Data on CD-ROM 5-36

Figures: 1. "Desktop" of GUI 5-38
2. Linked list query 5-39
3. Graphical query 5-40

Hydross Simulation Support System 5-42

Table: 1. Output reports available in HYDROSS 5-44

A Comprehensive System for Surface Water and Groundwater Modeling 5-47

Figures: 1. The scattered set of data points of Walnut Creek, Iowa 5-50
2. Delineated sub-basins for Walnut Creek, Iowa 5-50
3. Display of hydrograph at two selected points, Walnut Creek, Iowa 5-51
4. Finite element mesh for Cape Fear River, North Carolina 5-52
5. Bathymetry in gray scale for Cape Fear River, North Carolina 5-52
6. Velocity contour plot in gray scale for Cape Fear River, North Carolina 5-53

Page

SECTION 7. STOCHASTIC HYDROLOGY-RISK AND UNCERTAINTY-continued

Muskingum Basin Reservoir Frequency Analysis 7-22

Plate: 1. Project Map Muskingum River Reservoirs 7-29

Table: 1. A summary comparison of the frequency of filling curves resulting from previous studies and the current analysis 7-28

Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast 7-30

Figure: 1. WARFS Colorado demonstration project area 7-33

SECTION 8. MODEL VERIFICATION

Validation Strategies based on Model Application Objectives 8-1

Figures: 1. Lucky Hills Watersheds location map and maximum number of overland and channel elements used by KINEROS and WEPPWV 8-7
2. Scatter plots for KINEROS validation for runoff volume and peak discharge for LH-4 8-8
3. WEPPWV Validation efficiencies for runoff volume and peak discharge for LH-5 8-8

Tables: 1. Sequential validation steps for the WEPPWV 8-4
2. KINEROS calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge using optimum multipliers 8-4
3. WEPPWV calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge 8-5

Verification of Hydrologic Modeling Systems 8-9

Figures: 1. Goodwin Creek Watershed Site Map 8-14
2. Goodwin Creek Watershed-Event No. 1 8-15
3. Goodwin Creek Watershed-Event No. 2 8-16
4. Goodwin Creek Watershed-Event No. 3 8-17
5. Goodwin Creek Watershed-Event No. 4 8-18
6. Goodwin Creek Watershed-Event No. 5 8-19

A System Response Approach for Verifying Surface and Groundwater Models 8-21

Figures: 1. Moving response function with fixed input structure 8-22
2. Frequency response coefficients of the numerical model simulation for a nonlinear MISO system 8-24
3. Tidal current comparisons near bottom layer (33 ft depth) at Summit Bridge, C&D Canal 8-25
4. System simulated results versus field observations for a water well near Wichita, Kansas 8-27

Page

SECTION 5. COMPUTER DEMONSTRATIONS AND POSTERS-continued

POSTERS-continued

Adaptation of TR-20, Project Formulation-Hydrology-continued

Tables: 1. Annual floods 5-107
2. Shelby local cumulative rainfall (abbreviated) 5-107
3. Kankakee River peak comparison (cfs) 5-107

Multi-Dimensional Analysis of a Surface Coal Mine 5-109

Figures: 1. Mine area ground-water model grid and location of the sediment pond and ground-water seep 5-110
2. Simulated transient water levels in mined-out area 5-112
3. Multi-dimensional analysis of ground-water model results and overburden quality 5-113

SECTION 6. HYDROLOGIC MODELING SYSTEMS

Computer Modeling of Alpine Stream Diversions 6-9

Figures: 1. Stream blow-out caused by anchor icing 6-10
2. Proposed final diversion with vegetation 6-12
3. Wetland area for stream diversion 6-12
4. Plot of channel design characteristics 6-15

Table: 1. Manning's Equation (French, 1985, table 4.8) 6-14

Automating Detailed System Regulation Studies 6-18

Figure: 1. Schematic of the Columbia River System 6-21

NEXGEN HEC's Next Generation Software Project 6-26

Figures: 1. NexGen hydrologic modeling system 6-31
2. Hydrologic component-class hierarchy 6-32
3. Hydrologic modeling system-object relationships 6-33

SECTION 7. STOCHASTIC HYDROLOGY-RISK AND UNCERTAINTY

Upper Colorado River Simulation/Optimization Model 7-7

Figure: 1. Schematic of the Upper Colorado River System 7-8

Using Cligen to Stochastically Generate Climate Data Inputs to WEPP and Other Water Resource Models 7-14

Figures: 1. Precipitation and temperature stations selected for parameterization 7-19
2. Solar radiation and dew point temperature stations 7-19
3. Wind speed and direction stations 7-19
4. CLIGEN generated average annual rainfall erosion index 7-20

Page

SECTION 8. MODEL VERIFICATION-continued

A System Response Approach for Verifying Surface and Groundwater Models-continued

Table: 1. Frequency response coefficients of tidal current verification at the Summit Bridge, C&D Canal 8-26

Wetland Identification, SCS, Missouri 8-35

Figure: 1. Drainage Area vs. Discharge: 2-Year Frequency, 7- and 15-Day Duration 8-40

Plate: 1. Wetland identification by SCS in Missouri 8-41

Table: 1. Log-Pearson Type III duration frequency analysis Grand River near Sumner, Missouri, Drainage Area = 6,880 Square Miles 8-38

Determining Design Unit Hydrographs for Small Watershed

Table: 1. Selected regional watershed UH parameters 8-45

TOPMODEL, A Topography-Based Watershed Model 8-50

Figures: 1. Diagrams of streamflow-generation mechanisms during high-flow periods 8-51

2. Diagram of water fluxes in TOPMODEL 8-52
3. Plan view of grids of (a) elevation, (b) steepest downhill direction, (c) number of upslope nodes, (d) tanB values, and (e) In(a/tanB) values. The data shown are a subsection of a larger uniform 10x10 grid 8-55
4. Maps of (a) elevation, and (b) In(a/tanB) values for Sleepers River watershed in Vermont. Higher values are indicated by darker shades of gray 8-56

PAST, PRESENT, AND FUTURE HYDROLOGIC MODELING IN ARS

KENNETH G. RENARD[1]

ABSTRACT

Hydrologic modeling efforts in ARS have closely paralleled the developments in computer technology. Early efforts used experimental watershed data to evaluate curve number values in the Soil Conservation Service National Engineering Handbook. About this time, digital computers began to be available and there was an early emphasis on kinematic cascade models. The water quality emphasis of the 1970's led to hydrologic models such as CREAMS, a multidiscipline and multilocation effort. Resource inventory programs in USDA in the late 1970's resulted in ARS efforts to quantify the impact of soil erosion on soil productivity. The EPIC model resulted from this legislation. Conservation planning for the USDA's Food Security Act of 1985 led to emphasis to develop a new generation of models to address water and wind erosion using fundamental climate, hydrology and erosion simulation processes.

Future efforts using physically-based algorithms will need to address temporal and spatial variability in hydrologic processes currently addressed by lumping. Scale problems in hydrologic models remain a challenge requiring major emphasis. As answers for resource management vary from plots and fields, to small watersheds and larger river basins, the algorithms needed for natural resource management changes because of the process filtering involved.

INTRODUCTION

The quality of once good agricultural land in many parts of the U.S. began to deteriorate at increasing rates in the early 1900's. Soil erosion was rapidly becoming a national crisis. The first national recognition of this problem was the allocation of funds for erosion-control experiments in the Agricultural Appropriation Act of 1930.

Some references exist of early watershed and plot studies dating back into the early 1900's that were precursors to the Soil and Water Conservation Experiment Stations, which in turn set the pattern for investigations that has passed to the present. C. E. Ramser (Bureau of Agricultural Engineering) reported in 1927 the measurement of rainfall amounts and runoff rates from six agricultural watersheds (1.25 to 112 acres) near Jackson, Tenn. In Ramser's opinion "these investigations are the first of the kind that have been made to determine rates of runoff in open channels from purely agricultural areas where self-recording instruments were employed" (Ramser, 1927, p. 822). A 1937 report of the work of the Experiment Station at Clarinda, Iowa mentions the work of M. F. Miller at Missouri Agricultural Experiment Station in 1917; of A. B. Conner and R. C. Dickson at the Texas agricultural experiment substation beginning in 1926;

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and that of the Bureau of Public Roads at Raleigh, N. C., started in 1924, as patterns for hydrologic investigations. Also, the Bureau of Agricultural Engineering and the College of Engineering at the State University of Iowa cooperated in the collection of hydrologic data at the Ralston Creek Watershed between 1924 and 1935 (Mavis and Soucek, 1936).

The "New Deal" was implemented during F.D. Roosevelt's first term as President as a massive campaign against social and natural calamities buffeting the country. Heading the agricultural assault was Henry A. Wallace (Secretary of Agriculture) and H. H. Bennett, Director of the Soil Erosion Service (August 25, 1933). Several subsequent changes including a June 16, 1936 letter from President Roosevelt to Secretary of Agriculture, H. A. Wallace, enumerated: "The objective of upstream engineering is through forestry and land management, to keep water out of our streams, to control its action once in the stream, and generally to retard the journey of the raindrop to the sea. Thus the crests of down-stream floods are lowered." An Upstream Engineering Conference held in Washington, D.C. on September 22-23, 1936 defined the needs for the collection of hydrologic data as a continuing need. Shortly thereafter $100,000 was appropriated for initiating twenty experimental watersheds throughout the U.S. These watershed had a inauspicious beginning for many reasons including inadequate funds until D. B. Kringold presented plans for establishing the experimental watershed plans to a conference of Regional Conservators on September 25, 1936. The responsibility for the watersheds (in the Research division of the Soil Conservation Service) and directions on how to select them were issued in a memoranda from C. E. Ramser to field personnel. Data from these watershed locations subsequently become a key resource in the development of the curve number concept of the SCS National Engineering Handbook which is widely used even to the current time. ARS was created in 1954 as a mechanism to identify research activites in USDA.

Senate Document 59 (Browning et al., 1959) had a tremendous impact on the watershed engineering programs of ARS. As a result of the recommendations of this document, 6 regional watershed research centers (Boise, ID, Tucson, AZ, Columbia, MO, Durant, OK, State College, PA, and Tifton, GA), a national soil erosion research laboratory (W. Lafayette, IN), a national sedimentation research laboratory (Oxford, MS), and a national hydrology research laboratory (Beltsville, MD) were established in the early 1960's to support hydrology and erosion/sedimentation programs of USDA-SCS. In addition, a water data center was established in Beltsville, MD. The watersheds at these facilities range from small homogeneous areas a few hectares in size to large mixed land uses having drainage areas of 300 km^2 (Johnson et al., 1982). These facilities continue even today along with other soil and water conservation programs centers and laboratories, and form the essence of the ARS natural resource research programs.

The watershed data collection program mentioned above has led to, and made possible, the hydrologic models mentioned subsequently. Such models have been hypothesized, parameterized, and compared to such watershed data.

SECTION 1

AGENCY OVERVIEW

Page

Past, Present, and Future Hydrologic Modeling in ARS
Kenneth G. Renard 1-1
Hydrologic Models used by the U.S. Bureau of Mines
Allen O. Perry 1-16
Bureau of Reclamation Hydrologic Modeling Trends
R. Wayne Cheney 1-24
Recent HEC Modeling Activities
Arlen D. Feldman and Darryl W. Davis 1-30
The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations
Richard K. Farnsworth, Donna Page, Timothy Sweeney, Ann McManamon, George F. Smith, Donald P. Laurine, and Danny L. Fread 1-45
Past, Present and Future needs of SCS Water Quantity Modeling Efforts
Gerald D. Seinwill 1-61
U.S. Geological Survey Program to Meet the Hydrologic Modeling Demands for the 90'S
Alan M. Lumb 1-70

Figures and Tables

Past, Present, and Future Hydrologic Modeling in ARS 1-1

Figure: 1. Model classification (Source: Woolhiser and Brakensiek, 1982) 1-3

Tables: 1. ARS hydrologic models, acronym, authors and date of publication 1-14
2. ARS hydrologic model details 1-15

Bureau of Reclamation Hydrologic Modeling Trends 1-24

Figures: 1. ADSS model tools 1-28
2. ADSS data handling tools 1-28

Recent HEC modeling activities 1-30

Figures: 1. HEC data storage system 1-36
2. Interior flood hydrology continuous simulation 1-37
3. Water control system 1-39
4. HEC continuous watershed simulation model 1-41

The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations 1-45

Figures: 1. NWSRFS Version 5 structure 1-51
2. Example of a workstation screen 1-54

Table: 1. NWSRFS hydrologic models 1-50

Model Classification

Several different criteria have been proposed to classify models. In many cases, these criteria reflect the special interest or needs of a particular discipline. However, models used in any discipline can be categorized as either *formal* or *material*.

A *formal*, or intellectual, model is a symbolic, usually mathematical, representation of an idealized situation that has the important structural properties of the real system. A *material* model is a physical representation of a complex system that is assumed to be simpler than the prototype system and is also assumed to have properties similar to those of the prototype system.

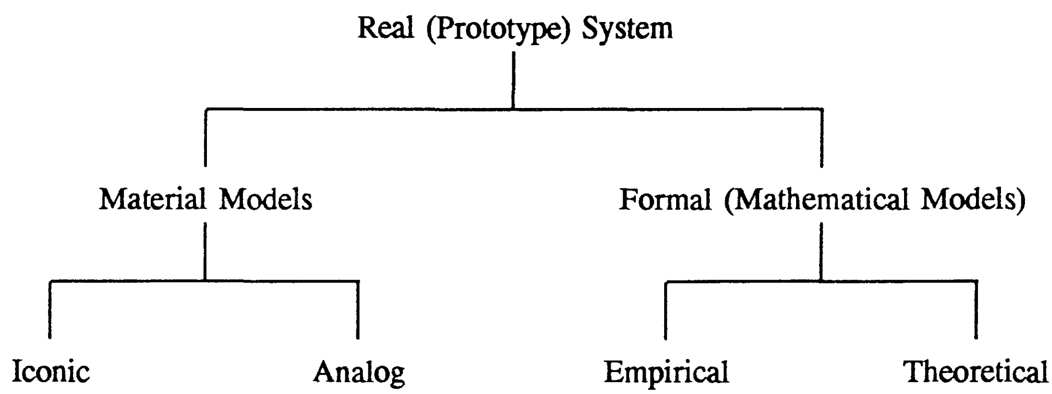

Figure 1. Model Classification (Source: Woolhiser and Brakensiek, 1982)

Figure 1 is a schematic classification of models taken from Woolhiser and Brakensiek (1982). They state (p. 7):

"Material models include iconic or 'look alike' models and analog models. An iconic model is a simplified version of the real-world system. It requires the same materials as the real state (i.e., the model of a fluid is also a fluid). Lysimeters, rainfall simulators, hydraulic flumes, and watershed experimental systems are all examples of iconic models. By measuring the volume of water draining from a lysimeter and weighing it periodically, we gain some insight into the relative rates of deep percolations and evapotranspiration from nearby, undisturbed areas with similar vegetation and soils. We are not interested in the model measurements in themselves, but we are interested in the insight they give us into processes occurring in the more complicated natural systems. Rainfall simulators, hydraulic flumes, and watershed experimental systems may help to determine the most significant factors that should be included in mathematical models of overland flow and erosion processes. To be useful, iconic models must be easier to work with than the real system and must provide some information that is not a direct consequence of known and accepted mathematical models. Changes of length or time scale (or both) are frequently required to make the model useful. Because of these scale changes and other necessary simplifications, iconic models often involve distortions, and the magnitude of these distortions must be careful considered and included in prediction equations.

"In an analog model the quantities measured in the model are different physical substances than in the real (prototype) system. For example, the flow of electrical current may represent the flow of water, or the deflection of a thin membrane might represent the drawdown of a water table. The validity of an analog model depends on the existence of identical mathematical relationships describing both the real system and its analog, and so depends on the other class of models, the formal model. In watershed hydrology all formal models are mathematical; hence, we will use the term 'mathematical model' or simply 'model' hereafter. In this monograph we will concentrate our attention on mathematical models.

"Mathematical models can be further subdivided into theoretical models and empirical models. A theoretical model includes both a set of general laws or theoretical principles and a set of statements of empirical circumstances. An empirical model omits the general laws and is in reality a representation of data. This distinction breaks down when we consider a model that includes some but not all of the necessary general laws. All theoretical models simplify the physical system and are, therefore, more or less incorrect. In addition, the so-called theoretical models often include obviously empirical components. All empirical relationships have some chance of be fortuitous; that is, by chance two variables may appear to be correlated when in fact they are not. In principle such relationships should not be applied outside the range of the data from which they were obtained. In modeling of small watersheds, examples of the simplification of theoretical models abound. The surface flow of water in a small watershed is generally described by the equation of conservation of mass and that of conservation of momentum, which contain an empirical hydraulic resistance term. Under certain conditions the momentum equation is greatly simplified to the so-called kinematic equation. Subsurface flow problems utilize the Darcy equation, an empirical equation. Modern infiltration modeling is based on the Green and Ampt equation, a gross simplification of the flow system. Theory and empiricism are generally so intermeshed that in actuality most all watershed hydrology models are hybrids that include both theoretical and empirical components."

Most modeling efforts in ARS and specifically hydrologic models fall in the formal (mathematical) classification. More specifically, they might be classified as theoretical with empirical relations embedded using data to parameterize the equations used (often regression relations).

EARLY MODELING EFFORTS

Most early modeling efforts in ARS involved treatment of site specific precipitation-runoff data. For example, Minshall (1960) developed a method that involved estimating storm runoff volume from the rainfall pattern and antecedent rainfall, and distributing the runoff through an adaption of the unit hydrograph principle. The work was significant because it demonstrated that the unit hydrograph was not independent of rainfall intensity and led to unit hydrograph equations involving the gamma distribution (DeCoursey, 1966) and the Pearson Type V empirical distribution with a square root transformation of the time scale (Brakensiek, 1967a). A detailed treatise on unit hydrographs is given by Dooge (1973).

McCuen et al. (1977) presented a detailed literature evaluation of flood flow frequency analysis techniques used for ungaged watersheds. They separated the procedures used into eight categories: 1) statistical estimation of Q_p, 2) statistical estimation of moments, 3) index flood estimation, 4) estimation by transfer of Q_p, 5) "empirical" equations, 6) single storm event: rain frequency is proportional to runoff frequency, 7) multiple discrete events, and 8) continuous record.

Developments in kinematic wave theory (Wooding, 1965) as approximations of the continuity equations of mass and momentum have had major impacts on ARS hydrologic modeling efforts. For example, the efforts of Brakensiek (1967b), Woolhiser and Liggett (1967), Brakensiek and Onstad (1968), Lane and Woolhiser (1977) have contributed to the feasibility of many of the models discussed subsequently.

Stochastic runoff simulation models have also received limited attention in ARS. For example, Diskin and Lane (1972) used a stochastic model for generation of synthetic data on watersheds of 150 km^2 or less in southeastern Arizona. Variables describing the intermittent and independent runoff events were start of runoff season, number of runoff events per season, time interval between events, beginning time of runoff event, volume of runoff, and peak discharge. Each of these variables is generated from its probability distribution. The means and standard deviations of the various distributions form the set of parameters that define the stochastic model. Some parameters are expressed as functions of drainage area; others are assumed constant for the range of basin areas used in the study. By describing the variation of the model parameters with basin area, a model for a specific basin was developed into a model of a general basin. This same model was used with a deterministic sediment transport relation for describing sediment yield in rangeland areas of southern Arizona (Renard and Laursen, 1975). Such a technique has not been used extensively because the model is site specific in that the parameter values must be determined from actual data and are thus not considered to be robust.

CURRENTLY AVAILABLE ARS HYDROLOGIC MODELS

Numerous ARS hydrologic models are currently available (Table 1 and 2). The models would all be described as formal (mathematic) models (Figure 1) with a mixture of empirical and theoretical components/relations. For example, several of them involve the kinematic approximations of the equations for continuity of mass and momentum. At the same time, they involve empirical relations for estimation of various parameters in the embedded algorithms.

The fact that there are many commonalities between several of the models is predicated on the intended model use dictating some differences to ensure model efficiency. For example, EPIC being intended for predicting long-term impacts of erosion on soil productivity and SWRRB being intended to assess land use and peak runoff results in some commonality of rainfall excess and evapotranspiration but differences in other model elements. In contrast SWRRB has detailed algorithms for water and sediment routing, flow through ponds and reservoirs with less specificity for what happens on a soil pedon such as EPIC emphasizes..

Most of the models described in Tables 1 and 2 include the hydrologic cycle calculation as an integral part of some other model objective. For example SPUR is intended as a tool to describe utilization of rangelands and is a quasi-complete ecological model. As such, the abiotic elements are one component of a more detailed model simulating plant productivity and animal utilization of the forage produced.

The following section provides a brief description of those hydrologic models developed by ARS personnel which are or have been used fairly extensively in the programs of various agencies both inside and outside the USA. Further details on some of these models will be presented elsewhere in this workshop.

BRIEF FUNCTIONAL MODEL DESCRIPTIONS

1. ACTMO (Agricultural Chemical Transport Model). For each storm in a series, the objective is to use the model to predict the concentration of a chemical in the runoff water, the total amount carried by the runoff water and sediment, and the location and concentration of the chemical remaining on the watershed. The hydrology part of the model uses a modification of USDAHL using hydrologic zones as a cascade of flow tubes flowing over zones and through soils layers. Evapotranspiration is calculated as a combination of techniques involving cardinal temperatures for specific crops. Hydrogeology is considered for base flow and downward seepage. Sediment yield is calculated by MUSLE (Williams, 1975). *Source: ARS, Watkinsville, GA.*

2. AGNPS (Agricultural Non-Point-Source Pollution Model). The computer simulation model was developed to analyze the water quality of runoff from Minnesota watersheds although it is not limited to there. The model predicts runoff volume and peak discharge (using a modification of SCS curve numbers), eroded and delivered sediment (using USLE and five sediment particle classes), and nitrogen, phosphorus, and chemical oxygen demand concentrations in runoff and the sediment for single storm events for all points in the watershed. The model works on a cell basis. The cells are uniform square areas that divide the watershed and permit detailed analysis of any area. Runoff and sediment transport is calculated for each cell with pollutant transport subdivided for soluble and sediment-attached pollutants. Large river basins can be simulated. *Source: ARS, Morris, MN.*

3. CREAMS (Chemicals, Runoff, Erosion, and Agricultural Management Systems: GLEAMS (Groundwater Loading Effects of Agricultural Management Systems). This model is a field scale model developed to predict potential pesticide leaching below the root zone, pesticide movement with surface runoff, and sediment losses from a field. Climate data (precipitation) on a storm basis must be input in addition to topographic, soil, and plant data. Using a climate simulator simplifies the input. Rainfall excess is calculated using a modification to the SCS curve number procedure. The model uses fundamental erosion concepts to describe erosion, deposition, and sediment transport for five particle size classes by overland flow, concentrated flow, and deposition in small ponds. *Source: ARS, Tifton, GA.*

4. EPIC (Erosion Productivity Impact Calculator). This model provides a detailed treatment of the management impacts of farming systems as they affect soil productivity from long-term erosion. Climate simulation simplifies the input of precipitation, temperature, and radiation (Nicks, 1974; Richardson, 1981). Runoff is simulated from daily rainfall using a modification of the SCS curve number procedure. Erosion is calculated using the Onstad and Foster (1975) modification of the Universal Soil Loss Equation (Wischmeier and Smith, 1978). The continuous simulation model uses the Ritchie (1972) relations for evapotranspiration between storm events. Crop simulation is based on a single model with constraints for water, temperature, and nutrient stress. Nitrogen and phosphorus are modeled in detail including immobilization, mineralization, denitrification, and leaching. *Source: ARS, Temple, TX.*

5. HYMO (HYdrologic MOdeling). The HYMO model is an event-oriented hydrograph and sediment yield model. Three options are available for computing rainfall excess, SCS curve numbers, the Green-Ampt infiltration equation, and Snyder's retention function. Hydrographs are computed from unit hydrograph principles. Routing is from individually designated small watersheds using a variable storage coefficient and can include reservoirs. Sediment yield is estimated with the Modified Universal Soil Loss Equation. HYMO is quite flexible and offers hydrologists the opportunity to add new commands or modify existing ones. HYMO has been found useful in the design and evaluation of flood control structures and flood forecasting. *Source: ARS, Temple, TX.*

6. KINEROS (KINematic runoff and EROSion). The kinematic runoff and erosion model, Kineros, is an event-oriented, physically-based model describing the processes of interception, infiltration, surface runoff, and erosion from small agricultural and urban watersheds. The watershed is represented by a cascade of planes and channels; and the partial differential equations describing overland flow, channel flow and erosion, and sediment transport are solved by finite difference techniques. Spatial variability of rainfall and infiltration (calculated by the Smith and Parlange (1978) model), runoff, and erosion parameters can be accommodated. KINEROS may be used to determine the effects of various artificial features such as urban developments, small detention reservoirs, or lined channels on flood hydrographs and sediment yield. *Source: ARS, Tucson, AZ.*

7. SRM (Snowmelt Runoff Model). The snowmelt runoff model has been used for simulation using a degree-day melt relation and snow cover depletion curves that are elevation dependent. The model has been successfully used on 57 basins in 67 countries for heterogeneous areas between 0.76 and 63,600 km^2 and wide elevation ranges. The model requires air temperature, precipitation, and snow-covered area. These variables can be either measured, predicted, or estimated. Runoff coefficients must be estimated based on similarities to other years and experience. Characteristic daily fluctuations of snowmelt runoff enable the time lag to be determined directly from past year hydrographs. *Source: ARS, Beltsville, MD.*

8. SPUR (Simulation of Production and Utilization of Rangelands). The SPUR model is a comprehensive rangeland simulation model developed to provide information for research and management. It is composed of five basic components: climate, hydrology, plant, animal, and economic. The model is driven by daily maximum and minimum air temperatures, precipitation, solar radiation, and wind run. SPUR simulates the daily growth of individual plant species or functional species groups and uses preference vectors based on forage palatability, location, and abundance to control plant utilization. Animal growth is simulated on a steer-equivalent basis, and net gain is used to calculate economic benefits. The hydrology component calculates upland surface runoff volumes, peak flow, snowmelt, streamflow, and upland and channel sediment yields. Climate can be either simulated or directly input. Runoff calculation is based on a modification of the SCS curve number technology. The snowmelt model is based on the Anderson (1973) model from the National Weather Service. Erosion is estimated from MUSLE (Williams, 1975). Channel routing of both water (including transmission losses and sediment

transport/deposition) is simulated for specified channel conditions. *Source: ARS, Boise, ID.*

9. SWRRB (Simulation of Water Resources from Rural Basins). SWRRB is a computer model used for resource assessment of hydrologic unit sized areas. Outputs related to nutrients, pesticides, and sediment are provided. The model tracks the fate of pesticides and phosphorus from land to deposition in water bodies. Water, sediment, and chemicals are routed from sub-basins to the basin outlet. Watershed and channel characteristics are user specified, as is land use which provides input to a modification of the SCS curve number approach for estimating precipitation excess in continuous simulation. Use of a climate simulator simplifies input generation. *Source: ARS, Temple, TX.*

10. USDAHL (USDA Hydrology Laboratory) The hydrologic model is an attempt to express watershed hydrology as a continuum designed to serve the purposes of agricultural watershed engineering. The model is organized on a multidisciplinary basis and includes meteorology and climate, soils and vegetation, hydraulic, hydrogeology, and watershed hydrologic systems. The continuous simulation model requires many inputs including a physical watershed description to accommodate surface, channel, and subsurface water routing. Also needed are temperature, percent grazing, tillage practices, percent land use by hydrologic zones, pan evaporation and temperature. *Source: ARS, Beltsville, MD*

11. WEPP (Water Erosion Prediction Project). The WEPP hillslope profile erosion model is a continuous simulation computer model which predicts soil loss and deposition on a hillslope. It includes a climate component which uses a stochastic generator to provide daily weather information, an infiltration component which is based on the Green-Ampt infiltration equation, a surface runoff component which is based on the Kinematic wave equations, a daily water balance component, a plant growth and residue decay component, and a rill-interrill erosion component. The profile erosion model computes spatial and temporal distributions of soil loss and deposition. It provides explicit estimates of when and where on the hillslope erosion is occurring so that conservation measures can be designed to most effectively control soil loss and sediment yield. The hillslope profile erosion model is based on the best available science for predicting soil erosion on hillslopes. The relationships in the model are based on sound scientific theory and the parameters in the model were derived from a broad base of experimental data. The model runs on standard computer hardware and is easily used, applicable to a broad range of conditions and robust. *Source: ARS, West Lafayette, IN)*

Reference to climate generators used in the aforementioned models requires further explanation. The three models cited carry the acronyms WGEN (Weather Generator) (Richardson, 1981; Richardson and Wright, 1984), CLIGEN (Climate Generator) (Nicks and Lane, 1989), and USCLIMAT.BAS (Woolhiser et al., 1988). The three models use Markov-chain wet-dry probabilities for generating daily precipitation. WGEN describes the precipitation depth using a gamma distribution; CLIGEN uses a skewed normal distribution; and USCLIMAT.BAS uses a mixed exponential distribution. All generate wind, radiation, and temperature. CLIGEN also generates terms for the infiltration component in WEPP, namely maximum precipitation intensity, storm amount and duration, and the time to peak intensity. CLIGEN is used in EPIC, SWRRB, and WEPP; WGEN is used in SPUR; and USCLIMAT.BAS is used in KINEROS.

Considerable research in any hydrologic model involves efforts to parameterize the algorithms used. for example, ARS and other hydrologic models often have problems with parameter robustness using data from limited geographic, climatic, and land use areas. Such problems will undoubtedly extend into the future. Users of hydrologic models need to be cautious as they use such models in areas different from those where the calibration data was collected.

There are other models developed in ARS for various programs and specific objectives but space does not permit their inclusion; thus, their absence is not intended to slight their importance. Rather they are generally intended for uses other than watershed engineering/hydrology modeling.

FUTURE HYDROLOGIC MODELING

The use of geographic information systems (GIS), and specifically digital elevation models (DEM), is advancing the utility of using the aforementioned models.

Brakensiek and Rawls (1989) presented an involved treatment of infiltration research needs in watershed hydrology. They point out that the infiltration component in practical use is often an empirical model or sometimes an approximate model. Most infiltration approaches handle spatial variability by subdividing watersheds into subareas or zones. Many of the models discussed in detail from Tables 1 and 2 use this concept. Field determination of model parameters or procedures for calculating model parameters from available data, although challenging, is feasible. Thus, the watershed subdividing practice will undoubtedly continue.

David Farrell (personal communication, 1993) recently stated, "The accuracy and reliability of the information that is available should be a primary consideration in the development of hydrologic procedures. Somewhat surprisingly, we seem to have convinced ourselves that if we get the processes right, or think we have, our information deficiencies will not matter. An example that comes readily to mind is the enormous effort that has been made to define in physical and mathematical terms the process of infiltration. In fact, several internationally acclaimed scientists have devoted entire careers to this process. Unfortunately, little serious attention has been given to the reality and reliability of the hydraulic properties of soils and the relationships that form the foundation of infiltration theory. For example, is there a unique relationship between the water content and water potential of soils? No, there is not. Uniqueness does not exist even for a single soil. The wetting and drying history, the temperature, the presence of certain contaminants, all have substantial effects on this relationship. The seasonal effects of biological activity, and the modifying effects of vegetation, though substantial, are largely unknown and ignored. The relationship between water content and hydraulic conductivity is also neither constant in time, nor invariant in space. Furthermore, as the size of the land area for which a hydrologic response is to be determine increases, the difficulties of characterizing it in a "real" sense are greatly compounded. Radical new thinking is needed. The much used and abused approach of building models of greater and greater complexity, and the overparameterization that results from this approach must be avoided. Admittedly, this will raise some concern. However, the false sense of confidence that these synthetically parameterized models give to less-informed scientists and users is decidedly more dangerous."

Decision support systems (DSS) are an exciting new topic that impact the need for hydrologic models. A "Decision Support System" is a set of computer programs which bring the most up-to-date databases together with computer simulation models (often hydrologic and erosion models) to help decision makers evaluate the environmental and economic consequences of such things as alternative farming practices. The objective might then be to develop the "Best Management Practice" which is environmentally and economically sustainable, or improve management, conservation, and protection of watershed resources. Using a decision support system, Yakowitz et al. (1992) evaluated the impact of farming practices on ground and surface water quality for a field near Treynor, Iowa. This exciting approach may well be the wave of the future. Such DSS results are strongly influenced by the hydrologic model included. Thus, the future need for carefully conceived and calibrated hydrologic models ensures future efforts that go beyond currently available hydrologic models.

CONCLUSIONS

Numerous hydrologic models have been developed within the past couple of decades. Most of the models were developed in connection with other primary objectives, e.g. to provide the driving mechanism for water quality. Many of the models were made easier to use by coupling a climate generator to provide needed input data. The 11 models cited and their brief descriptions should be helpful to potential users of the technology. Most of these models have had widespread use (including testing, verification, and validation).

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Table 1. ARS hydrologic models, acronym, authors and date of publication.

Model Acronym	Title	Source and Date of Publication
ACTMO	Agricultural Chemical Transport Model	Frere, Onstad, & Holtan, 1975
AGNPS	Agricultural Non-Point Source	Young et al., 1987
CREAMS/GLEAMS	Chemicals, Runoff, Erosion and Agricultural Management Systems; Groundwater Loading Effects of Agricultural Management Systems	Knisel (ed.), 1980; Leonard et al., 1987
EPIC	Erosion Productivity Impact Calculator	Williams and Renard, 1985; Wiiliams, Renard, and Dyke, 1983
HYMO	Hydrologic Modeling	Williams and Hann, 1972; Williams and Hann, 1973
KINEROS	Kinematic Runoff and Erosion Model	Woolhiser et al., 1990
SPUR	Simulation of Production and Utilization of Rangelands	Wight and Skiles (eds.), 1987
SRM	Snowmelt Runoff Model	Rango, 1988; Rango and van Katwijk, 1990
SWRRB	Simulator for Water Resources in Rural Basins	Williams and Berndt, 1977; Williams, Nicks, Arnold, 1985
USDAHL	USDA Hydrology Lab Model	Holtan et al. 1975; Holtan, 1965
WEPP	Water Erosion Prediction Project Model	Lane and Nearing (eds), 1989; Laflen, Lane, and Foster, 1991

Table 2. ARS hydrologic model details.

Model Acronym	Process Simulated	Simulation: Continuous	Simulation: Storm	Rainfall Excess Computation	Input Needs	Time Scale	Space Scale
ACTMO	watershed hydrology erosion and chemical transport	X	X	Holtan infiltration	watershed data and climate data	hourly	field zones
AGNPS	watershed hydrology, non-point source pollution		X	SCS curve numbers	cell and watershed characteristics	daily	cell basis for large & small watersheds
CREAMS/ GLEAMS	hydrology, erosion and chemical transport	X	X	modification of SCS curve number	watershed description and climate data	daily	homogeneous fields
EPIC	hydrology, erosion, soil productivity	X	X	modification of SCS curve numbers	climate and pedon data	daily	homogenous pedons
HYMO	watershed hydrology, flood hydrograph, sediment yield		X	options for curve numbers, Green-Ampt infiltration, or Snyder retention function	climate, channel travel times, watershed characteristics	hours	fields and watersheds
KINEROS	hydrology and erosion		X	Smith-Parlange infiltration	climate and watershed data	minutes	hillslope to watershed
SPUR	rangeland hydrology, plant simulation and sediment yield	X	X	modification of SCS curve numbers	climate and watershed data	minutes	fields and watersheds
SRM	snowmelt runoff	X		a family of snow cover depletion curves for each elevation zone	temperature, precipitation and snow cover	daily	small to large heterogenous watersheds
SWRRB	watershed hydrology, erosion and channel transport	X	X	modification of SCS curve numbers	climate and watershed/channel data	daily	small and large watersheds
USDAHL	watershed hydrology	X	X	Holtan (1965) infiltration: subsurface drainage	climate and watershed data	minutes	hillslope and watershed
WEPP	hillsope hydrology and erosion	X	X	Green-Ampt infiltration	simulated climate, land use, crop sequences	minutes	heterogeneous fields

HYDROLOGIC MODELS USED BY THE U.S. BUREAU OF MINES

ALLEN O. PERRY[1]

ABSTRACT

The Bureau of Mines conducts hydrologic studies in several areas with the overall goal of increasing productivity and environmental compatibility of the U.S. mining industry. Hydrologic models are used for mineral resources development and to determine the impacts of mining and mineral processing on the Nation's ground and surface waters. This research has focused upon specific challenges pertaining to the design of in-situ leaching operations, containment and control of mine wastes, and the protection of municipal and residential water supplies in mining regions. Hydrologic models are used extensively in these investigations to simulate both saturated and unsaturated flow conditions in porous media and fractured materials. Hydrochemical and hydromechanical models are used to evaluate coupled processes associated with in-situ leaching, mine drainage control, and subsidence prediction. The Bureau also uses models to describe the present flow and contaminant transport conditions at mine waste sites as part of the complete site characterization, and to help predict future contaminant migration. These models can help guide risk assessment and decisions regarding remediation. The Bureau has developed an analytical model called MINEFLO, which simulates many of the hydrologic features common to mining operations, including wells, pits, underground voids, ponds, and impoundments. This paper describes the hydrologic models presently being used, ones that will probably be used in the future, and some recommendations for future models based on perceived needs.

INTRODUCTION

The U.S. Bureau of Mines' overall mission is to help ensure that the United States has an adequate and dependable supply of minerals to meet its defense and economic needs at acceptable social, environmental, and economic costs. Surface and underground mining are by their very nature disruptive to the existing ground and surface water regimes, both with respect to flows, quality and quantity. Mining and mineral processing wastes which are the result of mineral extraction activities, differ from other industrial wastes in that they are relatively low in toxicity. Their large volume can pose a threat to the Nation's waters, primarily by the release of heavy metals. The diversity of these wastes makes it difficult to develop generic technological solutions to these problems. The approaches used by regulatory agencies of assessing hazards and possible toxicity with the development of generic safe decontamination and/or disposal technologies for industrial wastes are not realistically applicable to all mining wastes. Acid mine drainage from mined areas and leachates from mine wastes are caused by weathering processes when sulfide minerals are exposed to oxygen and water. Since most coal and metal mines contain sulfide minerals, water contamination usually results in those areas. Extensive studies are underway by the Bureau of Mines (BOM) to

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evaluate the impacts on the hydrologic regime of mining and mineral processing activities, and conversely, the impact of the hydrologic regime on mining operations. These studies many times involve the use of hydrologic models. Hydrologic models, which are based on an idealized system of flow through porous media, generally are not applicable to the fractured and highly disturbed strata resulting from mining. Furthermore, the empirical methods developed by the USGS for watershed or regional analyses do not address impacts in the immediate vicinity of mines.

HYDROLOGIC MODELS USED AND THEIR APPLICATIONS

Ground-Water Models and Codes

MODFLOW - There are numerous ground-water flow models presently being used in ground-water studies. The most widely used of these models is the finite-difference ground water flow model MODFLOW, developed by McDonald and Harbaugh of the U.S. Geological Survey. MODFLOW is capable of representing flow: 1) in one, two and three dimensions; 2) in confined and unconfined aquifers; and 3) under steady-state or short term conditions. MODFLOW simulates the ground-water flow within an aquifer or water bearing zone using a block-centered finite difference approach. Layers of water bearing zones can be simulated as confining zones, unconfining zones or a combination of both. Flow from external stresses, such as flow to wells, aereal recharge, evapotranspiration, flow to drains and flow through riverbeds can also be simulated utilizing MODFLOW. It is presently being used by the Bureau of Mines to simulate three-dimensional ground water flow by using multiple layers. A variety of modules allow simulation of wells, drains, ground water/surface water interactions, evapotranspiration, and areal recharge. The program MODPATH is used in conjunction with MODFLOW to compute ground water flow pathlines. Output from MODFLOW and MODPATH is input to various graphics software packages for presentation. MODFLOW is presently being used to verify hydrochemical modeling performed at a tailings impoundment in Washington State by accounting for sources of recharge to and paths of water flow through and around the impoundment. The output from these models will be used in conjunction with pore water chemical characterization to estimate contaminant flux from mine waste sites. This information in turn can be used to identify potential remediation schemes.

Geochemical and Transport Codes

BOM staff have not extensively used any of the existing finite element ground-water flow and transport codes to model contaminant transport, because they have focussed thus far on geochemical process that are not well-represented by the conventional transport codes such as MOC (USGS) and the Penn State finite element series LEMA, LEWASTE, and 3DLEWASTE. MOC is a two-dimensional contaminant transport model also developed by the USGS. Ground water flow is solved using the finite difference method and contaminant transport is solved using the method of characteristics. MOC computes changes in concentrations with time due to advection, dispersion, and mixing. MOC does not consider retardation of reactive constituents or changes in density, viscosity, and temperature. A related model that BOM has used, MOCDENSE, does consider the effect of density, however. The ground-water quality of the sites studied are typically dominated by the chemistry of sulfide oxidation. Therefore, BOM staff have thus far used USGS codes with redox capabilities in conjunction with ground-water flow models.

BOM staff uses the USGS geochemical computer code WATEQ4F (Ball et al., 1987), most recently updated by Nordstrom, et al. WATEQ4F (WATer EQuilibrium, version 4 in FORTRAN) is an inverse model which determines the phase distributions of dissolved mineral species from analyses of ground water and calculates the saturation indices of all minerals contained in the internal database that apply to the given water samples. For each input data set, the code computes an ion balance, ion species distributions, and the potential for mineral phases to dissolve or precipitate. The saturation index indicates whether a mineral is at chemical equilibrium in the solution, whether it is likely to dissolve, or whether it is likely to precipitate. This model has been used to interpret ground and surface water samples collected for several Mine Waste Management projects in northwestern U.S. The model outputs provide useful "fingerprints" to compare the water chemistry at various locations at a site. The model outputs can also be used as inputs to another USGS model called BALANCE, which evaluates the chemical changes in water quality from point A to point B along a flowpath.

BALANCE

BALANCE is a U.S.G.S. chemical mass balance computation code, which is used to determine what combination(s) of logical precipitating and/or dissolving phases successfully satisfy mass balance change between the two points. From this reduced list of active phases the chemical mechanisms are deduced which control contaminant concentrations and fate. Once these mechanisms are understood, it may be possible to develop contaminant control procedures which do not conflict with natural tendencies. The code is capable of maintaining electron balance and considering the effects of dilution by an additional water source.

Seepage Codes

The application of seepage codes by BOM has been primarily to predict the location of the phreatic surface of water impounding mine waste embankments. This information was subsequently used in slope stability analyses of these embankments. Both finite-element and finite difference methods were used.

The finite-element method accurately predicted the location of the phreatic surface in layered mine tailings embankments by Kealy and Busch (1971). Corp, Schuster, and McDonald (1975) used results from a finite-element seepage code to obtain pore pressures for input into a finite-element continuum code. The continuum code identified failure zones in the embankment and provided an additional approach to slope stability analysis (besides the method of slices or Swedish slip circle). The finite-element method was also used to obtain safety factors for saturated and unsaturated homogeneous tailings pond embankments. The factors of safety were mathematically related to embankment geometry and strength properties in the form of charts (Tesarik and McWilliams, 1981). The code used in the above publications was CFLOW, written by Taylor and Brown (1967).

Two- and three-dimensional finite-element codes were used to analyze the effect of horizontal drains on the phreatic surface in homogeneous embankments and a finite-difference code was written at the Bureau's Spokane Research Center to model horizontal drains in a laboratory-scale embankment impounding water (Tesarik and Kealy, 1984). This problem-specific code was written because results were within acceptable limits of the answer generated from a three-dimensional finite-element program, but the finite-difference code was faster.

U.S. Bureau of Mines' MINEFLO Model

Due to the limitations of the application of most existing ground-water models to mining operations, the Bureau of Mines has developed an analytic element program called MINEFLO, which operates on desktop microcomputers. This model is based on a new analytical element technique, and incorporates a CAD-based user interface in which individual flow features are represented as graphical objects. It is currently being used to assess hydrologic concerns of coal and copper mining operations. This program has been used for a variety of ground-water flow problems associated with mining including surface and underground mine dewatering, well head protection, waste impoundment hydrologic assessments, heap leach designs and in-situ leaching. MINEFLOW simulates hydrologic flow systems, and helps researchers and practicing engineers visualize how hydrologic components interact. It is based on a method of hydrologic analysis developed by O.D.L. Strack (Strack, 1989) of the University of Minnesota. MINEFLO's hydrologic components are the following: 1) point sources/sinks; 2) line sources/sinks; 3) area sources/sinks; 4) permeability zones; 5) cracks/fractures; 6) lens; and 7) uniform flow. It is interfaced with other graphics, statistical and data reduction software packages to generate an extensive hydrologic data base, and to isolate intervals of steady-state hydrologic conditions.

In-House Versus Off-the-Shelf Codes, and Bureau of Mines Modifications to Existing Models

Thus far, the ground-water flow codes have been used without modification. Only minor modifications have been made to the USGS geochemical codes in house, although the Bureau of Mines has had some input to USGS staff as they have upgraded the models. For instance we have requested modified versions of BALANCE from the authors at the USGS, which gave the model freedom to consider more phases simultaneously. The original version was dimensioned to handle major and minor ions only, and the BOM needed to also consider trace elements. Also the interpretation of the output from WATEQ4F is very tedious, and the BOM may add graphical routines to the program which would actually construct phase stability diagrams specific to the component concentrations in the sample. At present the BOM uses a "SWAG" method to select stable phases. The seepage codes were a combination of in-house and off-the-shelf codes with minor modifications as needed.

There are a few models which attempt to combine ground water flow, hydrochemistry, and biochemistry, but they tend to be very site specific, and BOM's use of them has been only marginally successful. FASTCHEM from EPRI combines hydrogeochemical equilibrium algorithms with hydrologic flow algorithms with reasonable success. Unfortunately, the database does not contain many trace elements of interest to the BOM, and the program requires a GE or IBM mainframe (EPRI will not release the source code to allow its modification). Perhaps the most advanced of all of these models is RATAP.BMT3 from the Canadian Government (CANMET/MEND). This forward model combines rudimentary microbial, kinetic, and hydrogeochemical algorithms with a mass transport module to predict environmental effects. The silicate mineral database, the source of most major ions, is very limited, however, and the sulfide mineral database is also inadequate from a BOM point of view. The program was designed to predict acid flux; trace metal content prediction was a secondary function.

ANTICIPATED FUTURE NEEDS AND RECOMMENDATIONS

BOM's future modeling needs will be in data input and processing of model output. The use of graphical preprocessors and geographical information systems would enhance model input. Greater graphics capabilities, especially for displaying three dimensional model output, would enhance the visualization of model output.

With respect to geochemical modeling, BOM staff plans to make an accessory module to the USGS codes to generate Eh/pH diagrams from the code output. This will facilitate improved decision making regarding the stability of probable mineral phases applicable to a given solution. Ultimately, we will be searching the literature for models that couple cold temperature geochemical thermodynamics, kinetics, adsorption and chemisorption with flow, or any combination thereof. The bottom line is that rudimentary codes which combines hydrogeochemistry and ground water flow are available, but before we can advance computer models much further we need a great deal of additional basic scientific research relative to kinetics, microbial activity, and chemical interferences not currently being considered.

Leaching and fixing of metals in fluvial or lacustrine sediments are affected by microbial processes. The interdependence of hydrogeochemical and microbial factors is recognized as critical to such processes as sulfide oxidation and chemical weathering. Successful bioremediation is dependent upon the links between such mechanisms. In the short term, scientists need to make an effort to pool our data bases and design multidisciplinary experiments to understand these processes. In the longer term, it may be feasible to develop computer models that link various biochemical and geochemical mechanisms. The scientific community will be well served when individuals with backgrounds in the areas of these two disciplines push forward on this frontier.

As of this time, BOM has not acquired or developing computer codes to simulate fracture flow systems. BOM expertise derived from field studies of fracture flow systems indicates that fracture-flow systems are usually too site specific to be simulated by a generalized computer model. When adequate information has been acquired for a realistic simulation, the simulation is often no longer unnecessary.

Several ground-water models have been developed which utilize theoretical data obtained from room-and-pillar mining operations. These models were designed to simulate and possibly predict mine dewatering needs and mine inflows associated with room-and-pillar mining activities. Although the above results provide useful information in relation to that type of mining, very few experimental studies have been conducted which provide the necessary hydrogeological information needed in determining the impact of high-extraction mining techniques, namely longwall mining, has on the ground-water system. In this regard the need is to address the problem of ground-water response to longwall mining and the relationship to the stress/strain relationships located within the overburden strata (water bearing strata), characteristic of the subsidence process. Although the ground-water models have not addressed the problem of deforming overburden strata, numerous rock-mechanics models have been developed to simulate and predict strains/stresses in the overburden strata. A communication between both types of models is needed in order to predict strains and stresses, changes in hydraulic properties, i.e. hydraulic conductivity changes due to these additional strains/stresses determined and the prediction of 3-D flow rates and leakages as a result of these predicted changes. The development and/or use of such a ground-water/rock mechanics model involves precise data collection, data preparation, history matching and prediction. The successful use or modifications of the above programs will not only improve or enhance the understanding of the ground-water system (both before and after mining), but would encourage prediction and analysis for future projects.

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BUREAU OF RECLAMATION HYDROLOGIC MODELING TRENDS

R. Wayne Cheney [1]

ABSTRACT

Recent advances in modeling capabilities in the U.S. Bureau of Reclamation have focused primarily on data centered approaches using object oriented programming. This presentation gives an overview of capabilities developed in the past several years using these approaches and some specific applications of these capabilities to water resources issues Reclamation has had to face.

INTRODUCTION

In the late 1980's, the Bureau of Reclamation embarked on a model development process which focused on data centered modeling capabilities - that is capabilities which were compatible not only with the agency's model needs, but also with the data which are readily available from within Reclamation other sources. Reclamation applied basin-specific hydrologic models in many cases and for many years. However, their use is generally limited to those applications where data has been developed specifically for that application. Similar data assembled and used by others could not be used by these models without considerable conversion efforts. This allows little opportunity for independent testing and validation, and more importantly, use by others who may have similar needs.

Initial development on some of these data centered modeling activities was conducted under an Advanced Decision Support System (ADSS) working agreement with the University of Colorado's Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) in Boulder, Colorado. This agreement began in 1988 and was concluded in 1992. Reclamation has been working to enhance these capabilities with its own staff both in the Denver Office and some of its regional offices.

The remainder of this presentation will focus on the theme of data centered modeling capabilities with emphasis on three case studies, two of which will be discussed in more detail in other presentations at this workshop.

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KEY CONCEPTS IN DATA CENTERED - OBJECT ORIENTED MODELING

Reclamation has approached the development of ADSS with a particular design philosophy and a specific programming technique.

Design Philosophy - Data Centered.
Data centered means that the focus of model development is directed toward the data. Data are required to completely understand the physical processes of the basin are identified. Priorities are established according to data that is readily available and affordable to assemble and maintain. If we can't afford to assemble and maintain the data, then we don't design a model to simulate that physical process. Data handling and analysis systems may be required and this is where they are identified. In summary, a great deal of data management design effort is warranted with this philosophy.

Programming Technique - Object Oriented.
Object oriented means that each type feature to be modeled (reservoir, power plant, diversion, aquifer, etc.) is treated as a separate object class. Each object class has distinct attributes (name, size, relationships such as head/discharge relationships, limits, etc.) that are activated by data. Therefore, once a reservoir object is constructed, no additional programming is needed to model multiple reservoirs. Objects are copied as many times as needed and their behavior is controlled by populating their attributes with the proper data. Using this technique, modules of code can be easily developed to simulate different physical processes.

If different modules need to communicate with each other, which is often likely, Data Management Interfaces (DMI) are constructed to allow the information to flow with little or no assistance by the user. Graphical User Interfaces (GUI) are also constructed so that the user experiences the same "look and feel" without regard to the particular module in use.

The data centered approach can involve the generalizing and enhancement of models already in use as well as the development of new object oriented procedures. Figure 1 illustrates both of these approaches with some typical examples.

Reclamation is currently involved in both types of activities and both will be explored in subsequent presentations at this workshop. These efforts are typically carried out with engineering work station hardware using UNIX operating system. The programming languages are restrict only to those available under UNIX. Reclamation is using FORTRAN, C, Objective-C, C++, and in some cases a combination of the above. Figure 2 illustrates some of the types of data bases typically involved both from an input as well as from a computational viewpoint.

When using proven models as a starting point, Reclamation has drawn primarily on its own models, particularly the Hydrologic River Operation Study System (HYDROSS) model developed by Reclamation's Great Plains Region and the Colorado River Simulation System (CRSS) model developed in an extensive joint effort between Reclamation's Upper and Lower Colorado Regions and Denver Office. Both of these models are the focus of ongoing efforts to broaden their capabilities and make better use of available data. The next section will provide a more detailed description of the effort to enhance and adapt HYDROSS to modeling needs and existing data bases on the Flathead River and the Upper Missouri River in Montana.

Analogous efforts are underway at Reclamation to enhance newer object oriented models which were initially developed as part of the cooperative agreement with CADSWES. These efforts are, in some respects, more direct because these models were originally developed with a data centered philosophy. An example of this type of effort will also be described in more detail later in this presentation focusing on the CALIDAD model. This model was originally developed for use on the Nile River in Egypt and was adapted to Reclamation water management problems in the Central Valley of California.

ENHANCEMENT OF THE HYDROSS MODEL FOR DATA CENTERED APPLICATION

The HYDROSS model, developed in 1977 by Reclamation's Upper Missouri (now Great Plains) Region, was originally written in FORTRAN IV and run on a CDC Cyber main frame computer. The model was subsequently converted to FORTRAN 77 and adapted to the personal computer.

HYDROSS is a demand driven water supply model which is used to simulate river basin and reservoir operations and related parameters. HYDROSS had been useful in modeling not only long range reservoir operation strategies, but also water delivery and water rights issues.

The potential for using HYDROSS as part of a data centered package to deal with water quantity and quality issues on the Flathead River arose in 1990. EPA's water quality model QUAL2E was chosen to be the primary water quality modeling tool for this effort. It was clear from the start that the necessary linkages and interfaces could best be accomplished in a workstation environment.

Graphical User Interfaces have been developed to facilitate the use of the two models in the work station environment. The present status of this project is described in Brewer (1993). It is presently anticipated that this data centered package will be available for production work in the summer of 1993.

ADAPTION OF THE DATA CENTERED CALIDAD MODEL TO RECLAMATION OPERATIONAL ISSUES

Unlike HYDROSS, the CALIDAD model was originally developed in Objective-C for use in a work station environment. This model typifies the object-oriented approach illustrated in Figure 1 where each type of feature to be modeled (reservoir, diversion, power plant, river reach or other feature) is treated as a separate object class. Within each object class (reservoirs in general, for example), specific features (particular reservoirs, for example) are treated as separate objects. Changes can easily be made to object classes or particular objects in this type of framework. It is also very easy to add new classes and objects.

CALIDAD was developed originally for use in monthly simulation of the lower reaches of the Nile River system of Egypt. Lake Nasser was the primary reservoir object in this original formulation. Although the bulk of the model was written in Objective-C, several routines written in other languages such as the FORTRAN Area-Capacity routine (ACAP85) were incorporated into the CALIDAD structure.

As the developmental effort on the Nile River system was being completed, a more complex modeling need for the Central Valley Project of California was identified. The new effort was also to be done in a monthly time frame, but would utilize a far more extensive data base and begin to focus on some water quality issues as well. Boyer (1993) provides a more detailed description of the CALIDAD model and its application to the Central Valley Project. The present phase of model development for the Central Valley Project should be complete in the summer of 1993.

FUTURE APPLICATIONS

Reclamation will continue to pursue the development of the generalized data centered modeling system started by CADSWES. This system is called River Simulation System (RSS) and is designed to assist planning, managing or decision making in complex systems where conflicts exist in water interests due to multiple jurisdictions and several tiers of legislative mandates. Further information and details about RSS can be explored in CADSWES (1992).

Future plans for CALIDAD include the development of daily modeling capabilities for use on the Pecos River of New Mexico. Daily management of the Pecos is under increased scrutiny as a result of the jeopardy opinion issued by the Fish and Wildlife Service on the Pecos Bluntnose Shiner. Ultimately, temperature and water quality modeling capabilities in CALIDAD will need to be enhanced as well.

Future applications for the enhanced version of HYDROSS will probably include reservoir management issues on the Upper Missouri basin. It is anticipated that the new version will be most useful for Reclamation in dealing with water rights issues and generally for prioritization of demands.

Ultimately, general purpose optimization capabilities and stochastic modeling techniques will be brought into the work station environment as well.

ADSS

MODEL TOOLS

PROVEN OR IMPROVED MODELS

HYDROSS	Hydraulic Routing
HEC-5	Habitat
CRSS	Wetlands
OPTIMIZATION	MODFLOW

OBJECT-ORIENTED PROGRAMMING ENVIRONMENT

RESERVOIR OBJECT

AQUIFER OBJECT

DIVERSION OBJECT

RIVER OBJECT

POWER\PUMPING OBJECT

Figure 1

ADSS

DATA HANDLING TOOLS

RELATIONAL DATA BASE MANAGEMENT

Observed Data

- Streamflow & Quality
- Climate
- Snowpack
- Diversions

Calculated Data

- Natural Flow
- Consumptive Uses
- Projections

GEOGRAPHIC INFORMATION SYSTEMS

- Mapping
- Spatially Distributed
- Network Searches

Figure 2

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RECENT HEC MODELING ACTIVITIES

ARLEN D. FELDMAN and DARRYL W. DAVIS*

ABSTRACT

The Hydrologic Engineering Center's (HEC) collection of software for water resource analysis and simulation has continued to grow over the years. From its beginnings in basic floodplain hydrology, the capabilities have now expanded to risk analysis for project design and reservoir system optimization. This paper summarizes recent additions to mainline flood hydrology software as well as new software packages for hydrologic analysis and water resource system analysis. A separate paper in these proceedings describes HEC'S efforts to develop a new generation of hydrologic engineering software.

Software rarely remains fixed over time; there are new technical methods to add and improved computer resources to use. Several improvements were made to HEC's watershed runoff, flood frequency, and reservoir system operation software in recent years. HEC's data storage and graphics system, developed in the early 1980's, is a major asset in linking various software together to perform the overall analysis. Many other software packages were updated as well.

Several new software packages were also developed. An interior flood hydrology package was developed to analyze the difficult urban runoff problem of local runoff ponding/flooding behind a levee. A continuous watershed and river basin runoff simulation model was begun to investigate watershed yields. A flood forecasting version of HEC-1 was developed. A prescriptive reservoir model was developed to determine the optimal release schedule for a system of reservoirs.

New areas being considered for development in the 1990's are: a next generation software development project; a continuous watershed simulation model; water balance modeling; risk-based project evaluations; and GIS support for water resource analyses.

INTRODUCTION

Background

As the Corps national center for hydrologic engineering and analytical planning methods, HEC's work is motivated by the needs of the Corps district and division offices. The main responsibilities of those field offices have been flood control, hydropower, and navigation; and HEC developed simulation models to meet those needs. The majority of

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the models address the hydrologic engineering aspects of the Corps flood control studies. Most software is for physical-process simulation. Corps offices are also becoming involved in longer-term water supply studies. The impact of Corps projects on groundwater is also receiving more attention, as is the impact of groundwater on Corps projects. Current software development is placing major emphasis on the systematic design, development, and implementation of software. We are now in a next generation software development project for hydrologic, hydraulic, reservoir operation, and flood damage computations. The various computer programs and reports referenced in this paper may be found in HEC's Publications Catalog, 1992.

Modeling Philosophy

HEC has developed and supported a full range of simulation models for understanding how water resources systems function. It is assumed that experienced professionals can deduce the appropriate solution to a problem given the insight provided by selective execution of the simulation models. This deduction process has historically been the dominant methodology for planning and operational decisions in the water resources community, and it continues. We have used hydrologic simulation methods in a variety of situations with notable success. Some optimization models are now being used to evaluate reservoir system operation.

A Suite of Hydrologic Engineering Software

This paper primarily addresses the hydrologic software activities of HEC, including flood frequency calculation and reservoir system operation. Not included in the paper is information about HEC's river hydraulics, flood damage, and water quality models. River hydraulics modeling receives a major emphasis like hydrology. In recent years, many improvements have been made to: HEC-2, the steady state water surface profile model; HEC-6, the sediment scour and deposition model; and UNET, the unsteady flow model. In the area of flood damage analysis, a Flood Damage Analysis Package provides a comprehensive set of tools to evaluate flood damage reduction, and a new program accounts for project benefits during flood event operations. HEC also maintains a set of non-point source, river, and reservoir water quality simulation models. The reservoir operation for water quality model, HEC-5Q, is briefly discussed in the reservoir simulation model portion of this paper.

SOFTWARE ENGINEERING

A Proven Software Development Strategy

Computer hardware advances in the last 25 years have been notable. Equally notable are the advances in software. The software development philosophy of one engineer programmer-maintainer has given way to modern software engineering procedures. A method for successfully accomplishing software development, implementation, and servicing is as follows: a) need for new methods and procedures surface through solving real world problems and maintaining contacts with the user community; b) research and development work is performed to solve specific problems; c) solutions are generalized so that they may service other problems; d) high quality documentation is developed and software is prepared for long-term service and maintenance; e) training courses are held and consultation projects performed that gradually, but systematically, move the software into everyday work of users; and f) continuing development, servicing and maintenance are performed to assure aid to users and guarantee up-to-date capabilities are incorporated.

Observations for Applications Package Developers

Several "truisms" have emerged that are applicable to the development and implementation of engineering applications packages. Theses observations are directed to a unit in an institution (public or private) that is developing new applications software and provides service and support to in-house and other users.

1) Large-scale, complex, comprehensive computer programs are dynamic entities that require continuous nurturing and support in order to remain viable and useful. Such computer software needs a permanent home; an institution that is philosophically committed to the improvement in procedures, morally committed to servicing an improving the programs, competently staffed to perform that task, and available "on call" to users.

2) Professionally developed computer program code and its management is vital for software to be effectively maintained and be portable among hardware platforms. Use of special purpose languages that are proprietary or are not generally within platform and software industry standards should be avoided. Adherence to "standards" such as American National Standards Institute (ANSI) language standards is important and use of modern programming practice is needed to minimize difficulties in computer source code maintenance.

3) Successful implementation of advanced application packages requires both that useful technology be available in appropriate form and that users are interested and eager to take advantage of the opportunities. It is important in early stages to encourage applications that are manageable and have potential for success. A commitment to a service attitude, and a genuine interest in solving user community specific problems are basic.

IMPROVEMENTS TO EXISTING MODELS

HEC-1 Flood Hydrograph Package

The HEC-1, Flood Hydrograph Package, computer program was originally developed in 1967 by Leo R. Beard and other members of the HEC staff. The first version of the HEC-1 program package was published in October 1968. It was expanded and revised and published again in 1969 and 1970. To simplify input requirements and to make the program output more meaningful and readable, the 1970 version underwent a major revision in 1973. In 1981 the computational capabilities of the dam-break, project optimization, and kinematic wave special versions were combined into a single easy to use package. In late 1984 a microcomputer version (PC version) was developed. A menu capability was added to facilitate user interaction with the model; an interactive input developer, a data editor, and output display features were also added.

The latest version, Version 4.0 (September 1990), represents improvements and expansions to the hydrologic simulation capabilities together with interfaces to the HEC Data Storage System (HEC-DSS). The DSS connection allows HEC-1 to interact with the I/O of many HEC and other models. New hydrologic capabilities in HEC-1 include Green and Ampt infiltration, Muskingum-Cunge flood routing, reservoir releases input, and improved numerical solution of kinematic wave equations. The Muskingum-Cunge routing may also be used for the collector and main channels in a kinematic wave land-surface runoff calculation. This new release also automatically performs numerical analysis stability checks for the kinematic wave and Muskingum-Cunge routings. The numerical stability check was added because many users did not check the validity of the time and distance steps used in the model.

In September 1991, version 4.0.1E HEC-1 was released for use on extended memory PC's. A hydrograph-array size of 2,000 ordinates is now available in this version. The increased array size reduces limitations encountered when simulating long storms using short time intervals. For example, simulation of the fixed-length (96-hour) standard project storm at 15-minute intervals requires 384 ordinates just for the storm; more time intervals would be required to simulate the full runoff hydrograph and route it through a river basin. The large-array version also allows greater flexibility in checking for numerical stability of simulation processes (e.g., kinematic runoff and routing computations). The large-array version uses an extended or virtual memory operating system available on 386 and 486 machines.

Flood Frequency Analysis, HEC-FFA

The name of HEC's flood frequency analysis program, formerly called HECWRC, was changed to HEC-FFA, with a new release in January 1993. The new name is more in keeping with other HEC computer program names, and goes back to something closer to its original name. The new program follows the same procedures as HECWRC, but many of the routines were rewritten in a top-down, structured-program style. This was done to ease further improvements and maintenance. Some new capabilities were also added to the program as noted below.

A change in the high-outlier specification in FFA differs from HECWRC in that all peaks above a specified threshold will be adjusted via historic weighing. If a historic peak is less than the specified threshold, then that peak will not be used to estimate the frequency curve except for determining the historic period. If the threshold is not specified, then FFA chooses the threshold as the minimum historic peak as in HECWRC. Changes in the low-outlier specification allow the option of specifying a low-threshold base; this value will override the bases determined by 17B procedures.

For plotting positions, FFA compares the first historic peak with the first systematic peak, if the historic peak has an earlier date, all the historic peaks are placed before the systematic records in the plotting positions table. Otherwise all historic peaks are put at end of the systematic record. This affects only output display; it does not affect the computed frequency curve or the plotting positions.

For clarity of output in the event of zero-flow years, the preliminary frequency curve now is calculated using preliminary statistics and is printed. The conditional probability adjustment is then made on that curve, then printed out. Thus, the frequency curve always corresponds to the statistics below it. FFA now allows the user to input frequency-curve statistics, either with or without flow data, and compute the frequency curve ordinates.

Other improvements were to the user interface and include: printer output format using an extended character set to build the output tables; output to HEC-DSS of the computed frequency curves, confidence limits, and plotting positions; and output to a HP laser jet by writing the Hewlett Packard printer codes to a file. The HEC menu operation capability was added to FFA. The Microsoft FGRAPH utility was included to plot the final frequency curve to the screen without needing special drivers. CD-ROM data from Earth Info's HYDRODATA CD-ROM package can now be read into FFA.

HEC-5, Simulation of Flood Control and Conservation Systems

The HEC-5 computer program development began in 1972 by Bill S. Eichert. The first version of the program released in May 1973 was as a single event, flood control only, reservoir system model. HEC-5 capabilities were considerably expanded with the 1974 release which included simulation capability for hydropower and water supply. In 1979, development of the HEC-5 water quality analysis capability (termed HEC-5Q) was initiated. In 1981, HEC-5 input was simplified and the program was adapted to utilize the HEC-DSS data storage system for time-series data. In 1986 a PC version of the program was developed. The PC release included a menu system with input preparation and data checking utilities.

The current version of HEC-5, Version 7.2 (March 1991) can simulate the essential features and operational goals and constraints of simple or complex reservoir systems. Simulation intervals can range from minutes to one month depending on the study needs. Single-event flood analysis and period-of-record conservation analysis may be accomplished with the model. Flood control analysis includes balanced system operation for downstream damage centers with consideration of forecasted local flows and hydrologic routing. In addition, induced surcharge operation based on spillway gate regulation schedules can be simulated.

Hydropower analysis may include run-of-river, peaking, and pumped-storage plants as well as system power operation. Water supply simulation can include reservoir and downstream flow requirements in addition to diversions and return flows. Water quality analysis can include simulation of temperature, dissolved oxygen, up to three conservative and up to three non-conservative constituents. Recent improvements to HEC-5Q, which were incorporated for simulation of the Columbia River system, include simulation of pH, dissolved organic chemicals, heavy metals, dioxins, and organic and inorganic particulates. Also, the reservoir storage in HEC-5Q may now be segmented horizontally or vertically.

Three DOS-based PC configurations of the March 1991 release version are available: (1) an overlaid edition suitable for XTs with 640kb memory, math coprocessor, and a hard disk; (2) an extended-memory edition suitable for a 386 PC with math coprocessor, hard disk and 2-4 Mb of memory; and (3) an extended-memory version of HEC-5Q suitable for a 386 PC with math coprocessor, hard disk and 2-8 Mb of memory. All three include a menu system with input and output utilities and HEC-DSS programs.

HEC-DSS, Data Storage System

HEC-DSS was the outgrowth of a need that emerged in the mid 1970's. During that time most studies were performed in a step-wise fashion, passing data from one analysis program to another in a manual mode. While this was functional, it was not very productive. Programs that used the same type of data, or were sequentially related, did not use a common data format. Also this required that each program have it own set of graphics routines, or other such functions, to aid in the program's use.

HEC-DSS was developed to manage data storage and retrieval needs for water resource studies. The system enables efficient storage and retrieval of hydrologic and meteorologic time-series data. The HEC-DSS consists of a library of subroutines that can be readily used with virtually any applications programs to enable retrieval and storage of information. At present approximately 20 applications programs have been adapted in this fashion. HEC-DSS has been used to connect EPA's Storm Water Management Model (SWMM) to HEC software.

Approximately 17 DSS utility programs have been developed. A number of these programs are for data entry from such files as the USGS' WATSTORE data base or from the NWS precipitation data files. Other utility programs include a powerful graphics program, a general editor, and a program for performing mathematical transformations, DSSMATH. Macros, selection screens, and other user interface features combine with DSS products to provide a set of tools whose application is limited only by the ingenuity of the user. HEC-DSS is depicted in Fig. 1.

A new MS-DOS version, 6-G, of the HEC-DSS was released in April 1991. This version has an improved catalog sorting capability which can sort the catalogs of larger DSS files (about 2,000 records depending on the length of the pathnames), and sort more rapidly than previous versions. A "record locking" capability allows a DSS file to be accessed by several users on a network at the same time (for MS-DOS). The DSS file may be on a DOS, OS/2 or UNIX node. As many users as desired can access the same file at the same time, all reading or writing data to the DSS file. Enhancements have also been made to improve the interaction with large database file (greater than 10,000 records).

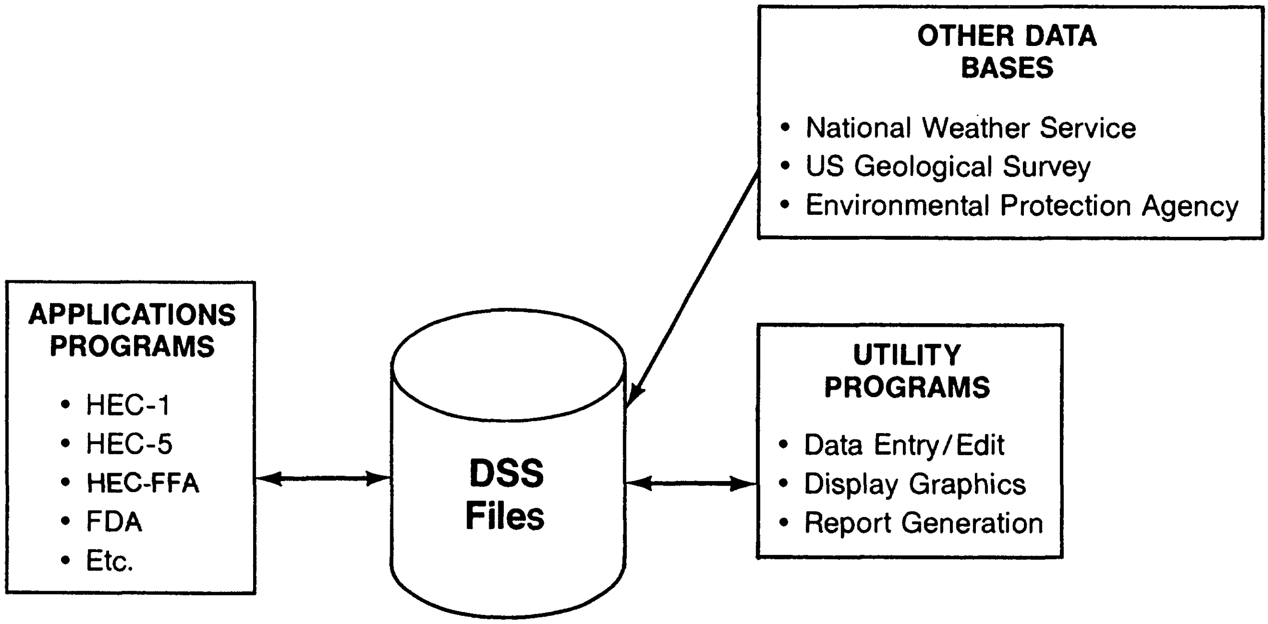

Figure 1. HEC Data Storage System

Version 6-G has been tested with DSS files with more than 150,000 records (150 megabytes) on MS-DOS computers. There is little degradation in performance when accessing data from such large files, although it becomes impractical to use the catalog file.

A new version of DSSUTL, which exports and imports time-series data for exchange between DSS and MS-DOS spreadsheet and database programs (such as LOTUS 1-2-3 and dBase) is now being beta tested. When exporting data from DSS, the data are written to an ASCII (text) file in a user-defined format. DSSUTL is exited, then the user runs the PC program and imports that ASCII file. Importing data to DSS essentially follows the reverse procedure. This capability can also serve as a "user-defined" tabulation format.

NEW MODELS

HEC-IFH, Interior Flood Hydrology

Projects that include flood damage reduction measures such as levees and floodwalls usually involve special problems associated with isolated interior areas. Storm runoff patterns are altered and remedial measures are often required to prevent increased or residual flooding in the interior due to natural flow blockage. Hydrologic analyses are needed to characterize the interior area flood hazard and to evaluate the performance of the potential flood damage reduction measures and plans. The HEC-IFH program services this need.

HEC-IFH is a comprehensive, interactive program that is operational on 386 class personal computers with 3 MB of extended memory (4 MB total). It is particularly powerful for performing long, historical-period simulations and makes extensive use of a menu-driven user interface, statistical and graphical data representations, and data summaries. Annual or partial series interior elevation-frequency relationships can be derived directly for various alternative configurations of interior features such as gravity outlets, pumps, and diversions. An engineer may use either a continuous simulation or hypothetical event approach depending on the type of study.

Continuous simulation analysis (also called a period-of-record analysis) uses continuous historical precipitation and stream flow records, see Fig. 2. HEC-IFH is designed to accommodate complete continuous simulations for at least 50 years of hourly records. However, these are not the absolute limits of the program's capabilities. For example, total periods of up to 100 years and time increments as small as 5 minutes may be used, although significant increases in data storage requirements are computation time will result.

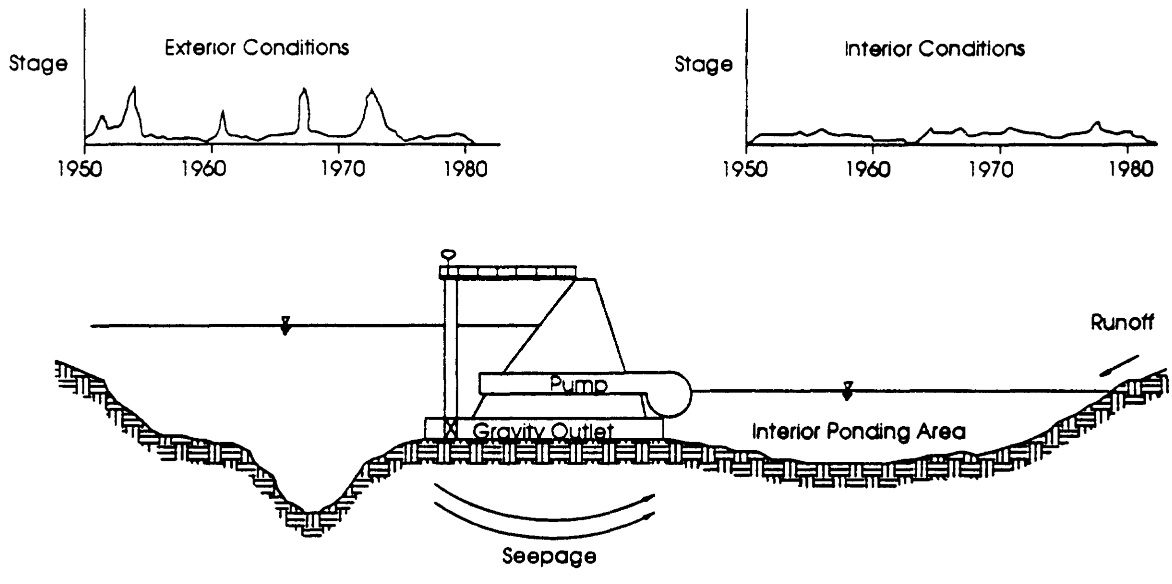

Figure 2. Interior Flood Hydrology Continuous Simulation

Hypothetical-event analysis is generally applicable when interior and exterior flood events are dependent. The analysis can be conducted so that the same series of synthetic storm events occur over both the interior and exterior areas. This analysis method can also be applied using a constant exterior stage, or for any "blocked" or "unblocked" gravity outlet condition.

<u>HEC-PRM, Prescriptive Reservoir Model</u>

A new reservoir systems analysis model uses network programming algorithms to improve regulation plans for multiple-use, multiple-reservoir systems. A project to help analyze the Missouri River main stem reservoir system operation was recently undertaken by HEC. The system of six reservoirs and seven downstream control points was formulated as a minimum-cost, network-flow problem. Penalty functions (costs) are used to force the operation of the reservoirs system to meet desired goals and flow and storage constraints. Penalty functions were developed for flood damage, water supply, recreation, hydropower, navigation, and environmental interests. The environmental penalty (fish and wildlife protection) is not as directly based on real costs as the other penalties, but it serves to input explicitly a value on that resource. The sensitivity of the reservoir system performance to changes in water values for different purposes can be readily evaluated.

The Missouri River is being analyzed for 92 years of monthly flows. Approximately 750,000 network equations are necessary to describe the objective function, continuity equations, and boundary constraints for that time period. For such a large system, the network solver becomes critical to timely completion of the computations. An interface for exporting the network matrices to a powerful commercial solver was developed for those large systems.

The initial, successful application of network systems analysis on the Missouri River system has given new insight to Corps water control managers. One problem that HEC is currently addressing is how to translate the optimal releases and storages, and penalties, into practical rules for real-time reservoir operation. An application of HEC-PRM to the Columbia River system is currently being completed; more applications are envisioned for several other Corps reservoir systems.

HEC-1F, Real-Time Flood Forecasting

Computer program HEC-1F is an adaptation of computer program HEC-1. The basic HEC-1 capabilities for calculating runoff with a unit hydrograph approach from a multi-subbasin watershed, and for parameter optimization, are retained in HEC-1F. However, HEC-1F contains additional capabilities that facilitate the task of runoff forecasting. Aspects of application of HEC-1F for forecasting are discussed below.

Forecasting with HEC-1F is intended to involve a "hands-on" process by which the analyst can readily compare simulated hydrographs with observed hydrographs (up to the time-of-forecast) and adjust loss rates, or perhaps other parameters, to improve results. Forecasting is performed in two separate executions of HEC-1F. In the first, unit hydrograph, loss rate and base flow parameters are optimized for gaged headwater subbasins. The optimization process has built-in constraints that prevent physically unreasonable values for the parameters being optimized. The analyst reviews optimization results and parameter estimates as an aid to setting regional values of loss rate and base flow parameters for the remainder of the basin.

The second application of HEC-1F performs runoff computations, and routing and combining operations throughout the basin. At each location for which an observed hydrograph is available, "blending" can be performed. Forecasts developed with HEC-

1F take into account precipitation and reservoir releases up to the time of forecast. The software system provides the capacity to specify future precipitation and future reservoir releases so that "what if" conditions can be readily evaluated.

A new snowfall/snowmelt simulation program, SNOSIM, for midwest snow conditions was added to HEC-1F. The program simulates snow accumulation, ripening, and melt processes to determine snowmelt contributions to runoff, and computes rainfall attenuation and lag caused by snow on the ground. SNOSIM was designed to simulate shallow snowpacks at relatively short computational time intervals. Most snowmelt models have been developed for relatively deep snowpack in mountainous locations. The procedures embodied in the SNOSIM program are those used by the Pittsburgh District, Corps of Engineers; the procedures are most applicable to that snowfall and melt regime.

HEC-1F is a major element of HEC's water control software system, see Fig. 3. A key component is the Data Storage System (HEC-DSS). The data acquisition software is composed of a set of programs which capture, decode and store data from a variety of sources such as GOES downlinks, Corps gages, and NWS-AFOS lines. The software has been designed to run on a UNIX-based operating system and has been implemented on the CD-4330 workstation and 386/486 Intel chip-based PC's running SCO Unix.

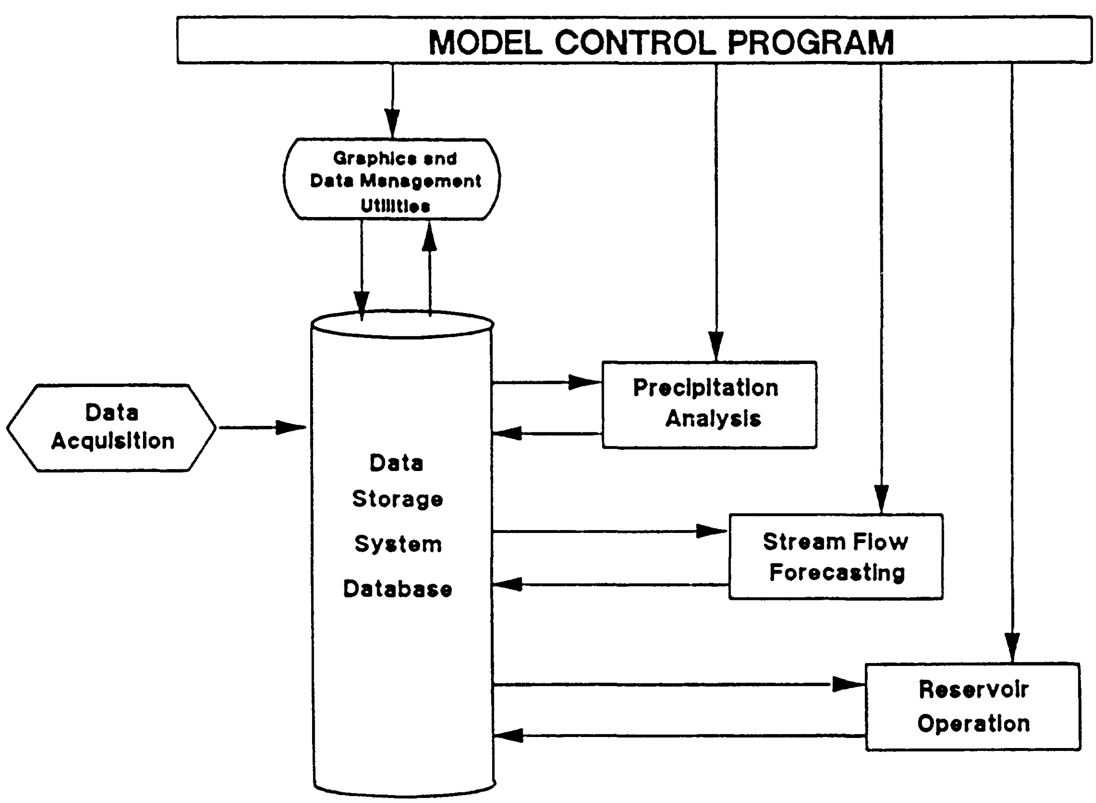

Figure 3. Water Control System

FUTURE MODELS

Next Generation Software Development Project

In 1990, HEC embarked on a project to develop the next generation of its simulation models. The objectives of the new modeling capabilities were to provide the user with better means to visualize and understand the process being simulated, and to build more engineering expertise into the models themselves. With the recent advances in computer hardware, it was no longer necessary to have the computer programming constrained by the limitations of old machines. It was quite evident that the old batch processing format would not suffice and that interactive processing was necessary. The capabilities of modern workstations and PC's using the NT and UNIX operating systems offers a new level of processing power that could meet these next-generation software needs.

The intent of this next generation of models (called NexGen) is to put the users inside the model and give them the tools to easily work with the data, simulation processes, and results. The user will enter data into a data base that is constructed in a logical engineering-analysis format, not a format for some computer input device. Output will also be stored in the data base for ready analysis. A graphical user interface will let the user view the data, computations, and results for maximum understanding and analysis of the data and the physical processes.

Four technical areas are being addressed in the current NexGen effort: river hydraulics, watershed runoff, reservoir system, and flood damage analysis. The new models will have most of the capabilities of the existing HEC models in those areas plus new algorithms where appropriate. For example, current river hydraulics modeling capabilities require reformatting the river geometry differently for each analysis - steady state, unsteady, and multi-dimensional. The new river analysis system of software will use consistent geometric representation of the river and floodplain for all applications. The simulation results will also be shown on the same geometric representations.

The ultimate goal is to have smarter models that automatically evaluate numerical stability (time and distance steps) and physical constraints of the process being simulated. The user will be advised of process-simulation problems, and alternative methods and analyses will be recommended where possible. Thus, more engineering expertise will be built into the models to enhance their application and interaction with the user. The NexGen project is a five-year effort, and interim products will be made available as the work progresses. More detailed information about the NexGen hydrologic modeling project is provided in these proceedings by Art Pabst.

Continuous Watershed Simulation Model

A continuous watershed model is being developed to study the potential for increasing water yields from the Salt/Verde River Basin in Arizona. The state is considering weather modification and vegetation management to increase the yield at Phoenix. The net increase in water yield will depend on the extent to which the snow pack will be increased due to weather modification and decreased due to evaporative and channel losses. The new model, depicted in Fig. 4, is being developed in the likeness of HEC-1.

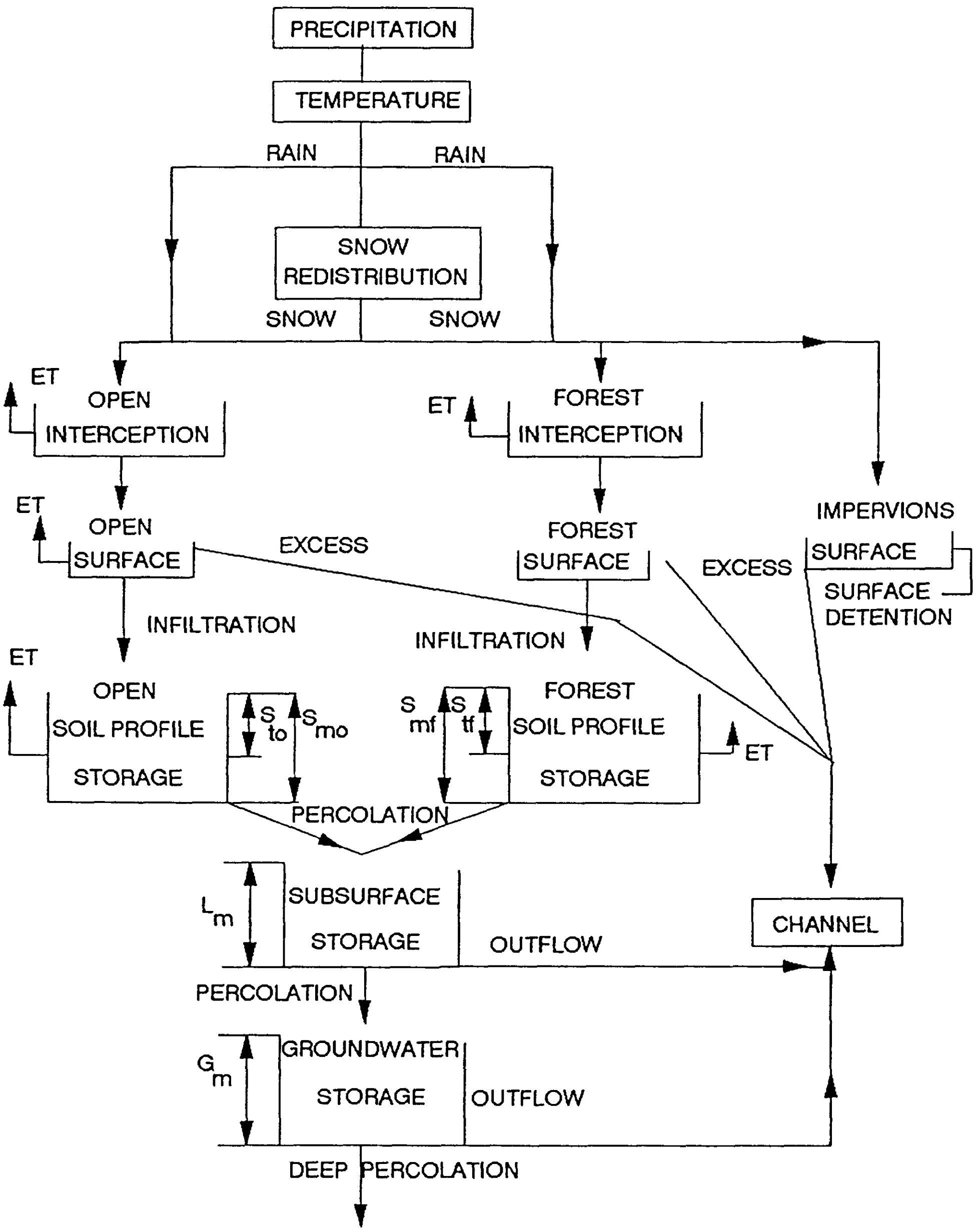

Figure 4. HEC Continuous Watershed Simulation Model

The goal of the model development and application is to provide a tool to accurately represent the water balance in the sub-alpine catchments of the Salt/Verde Watersheds. Critical to the accurate modeling of the water balance is the appropriate representation of the distribution of evaporation and transpiration (ET) among competing sources. The sources of ET are primarily evaporation from interception in the forest canopy and surface litter, transpiration from the root zone, and sublimation from the snowpack. The modeling study will attempt to identify the appropriate snowpack ET loss rates by employing the following strategy: constrain model parameters to the most physically reasonable values; calibrate the model to observed runoff by adjusting parameters within the constraints; and assess whether or not the resulting distribution of ET among the competing sources is physically reasonable.

The model development has been essentially completed. The model soil moisture accounting algorithm can simulate a number of elevation zones and land uses within a subbasin, making the model useful for both small and large watershed applications. A new simulation methodology using variable computation-time intervals is employed. This capability adapts the computations to the dynamics of the precipitation-runoff process being simulated.

Basin and Regional Water Balance Analysis

The overall water balance of a river reach, basin, or region is an important consideration in analyzing water resource systems. This is especially true for water supply systems. The water balance analysis gives a much broader perspective to the potential water problems than one can ascertain through detailed simulation. A new model, Water Evaluation and Planning System (WEAP), is being adapted for use by the Corps. The model was developed by consultants for evaluating alternative water development policy options in complex systems such as the Aral Sea region in the Soviet Union. The WEAP model employs a scenario approach to analyze integrated water demand-supply systems.

Risk-Based Project Studies

The risk-based approach is similar to present practice in that the basic data are the same, except that uncertainty is now explicitly quantified. Best estimates are made of discharge frequency, water surface profile, and stage-damage relationships. Project alternatives are formulated and evaluated, and the selected project is that which reasonably maximizes net economic benefits subject to acceptable performance. The difference is that uncertainty in technical data is quantified and explicitly included in evaluating project performance and benefits. The uncertainty analysis is accomplished through Monte Carlo simulation to compute a derived damage-frequency distribution. The @Risk spreadsheet program is currently being used for these simulations, other Monte Carlo simulators are being investigated. Because of the risk-based approach, performance can now be stated in terms of reliability of achieving stated goals. Also, adjustments/additions of features to accommodate uncertainty, such as adding freeboard for levee/flood walls, are not used.

The procedures recommended in Bulletin 17B (Guidelines for Determining Flood Flow Frequency) can be used to quantify discharge-frequency uncertainty as needed for risk-based analysis. For locations and conditions without a valid gage record, uncertainty is quantified by associating an equivalent record length with the adopted frequency curve and proceeding with the analysis as if there were a gaged record. HEC is researching ways of determining such equivalent record lengths.

Uncertainty in water surface profiles (stage-flow ratings) can be described by associating a distribution of error about the rating curve. A standard deviation of stage errors taken as normally as distributed, for example, may adequately characterizes uncertainty in many instances. At a gaged location, field measurements are available for quantifying the uncertainty. The more common circumstance is that there is no gage at a site, except for possibly some high water marks. The Corps Waterways Experiment Station is researching representation of stage uncertainty. Uncertainty in flood damage is the province of the economist but is approached in a manner similar to the engineering approach for uncertainty in stage-flow rating. The Corps Institute for Water Resources is researching representation of flood damage uncertainty.

GIS Hydrology

Some of HEC's earliest work in GIS hydrology involved development of a systematic methodology for automating the data preparation process. The raster-based organization chosen by HEC was called a grid cell data bank. Techniques for use of satellite data, for conversion of polygon data to grid format, and for use of commercially available software to manipulate and convert the data were developed. Parameters for HEC-1 and other hydrologic models were computed by a program called HYDPAR which accessed the grid cell data. The grid cell data bank approach was formalized in the HEC Spatial Analysis Methodology (HEC-SAM). Remotely sensed land use and other hydrologic parameters were also incorporated in the SAM methodology. Later, HEC explored the use of triangular irregular elements, TINs, for representation of watershed characteristics. A program linking HEC-1 with the TIN was developed. Because of various hardware, software, and study-management problems associated with the GIS approach, HEC has been less active for the past decade.

Recent HEC efforts have included a review of GIS applications in hydrologic modeling, and research into a method for combining the spatial GIS data with lineal hydrologic networks. A report by HEC's contractor, David Maidment, says: "A hybrid grid-network procedure for adapting these existing GIS capabilities for hydrologic modeling is possible in which two-dimensional spatially distributed processes are represented on a grid and one-dimensional flow and transport occurs through an associated network. There is a duality between a grid and a network in that once the direction of flow on each grid cell is defined to a single neighboring grid cell, an implied flow network is created. At an intermediate level of division, the stream network defined from the grid could be divided into modeling segments using dynamic segmentation. The drainage areas for each segment could be determined from the grid, or by other means, and their attributes determined from the grid. When the velocity field is spatially varying but time-invariant, rainfall-runoff hydrographs from subwatersheds can be computed directly from the grid and used as input to flow routing on the stream network. Cross-sections could be attached as attributes to the stream segmentation and used with known discharges to define the water surface elevation profile on the network, which could then be mapped back onto the grid to determine the areal extent of flooding." These ideas are being further investigated in HEC's NexGen project.

CONCLUSION

Several existing and emerging software packages for hydrologic modeling and analysis have been presented. More detailed information on any of the capabilities can be obtained from HEC. The purpose of HEC software is to help solve hydrologic analysis problems faced by Corps field offices. We follow a very applications-oriented approach to software development and problem solving. The following statement about software development in today's rapidly changing computer environment was given by HEC's Director at a recent conference.

"Successful development of the right engineering applications software packages requires adopting a strategy that determines user needs, and accomplishes development in a develop, test, user feedback process. Application package development should be performed by organizations that have: experience in solving engineering problems in the field; experience in developing, deploying, maintaining and supporting applications software; and are committed to a services approach to users. The development team should be comprised of a technical specialist in the applications area, and a complement of computer scientists and programmers. The engineering desktop platforms for the next few years includes high-end Intel-chip personal computers and RISC-based workstations. Use of modern software architecture concepts (including OOP, application of standard programming languages, and adherence to published software standards where they exist and de-facto industry standards) is essential to ensure successful applications package development."

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The National Weather Service's Transition to Hydrologic Modeling on Scientific Work Stations

by Richard K. Farnsworth[1], Donna Page[2], Timothy Sweeney[2], Ann McManamon[2], George F. Smith[2], Donald P. Laurine[3], and Danny L. Fread[4]

ABSTRACT

The National Oceanic and Atmospheric Administration's (NOAA) National Weather Service (NWS) is currently undergoing significant evolution. Under the program for Modernization and Associated Restructuring (MAR), NWS is establishing observing systems that increase the temporal and spatial resolution of observed data, enhancing the communication systems, and distributing the processing of the data to generate forecasts to be used for issuing watches and warnings. The new level of data observation, communication, and processing is bringing about improved procedures for making forecasts. This report will concentrate on those related to hydrologic forecasts. Specific topics include (1) the processing of rainfall data and display of rainfall fields from independent sources of varying resolution allowing the user some flexibility in adjusting these fields, (2) modularization of forecast software to make forecast programs more interactive with graphical user interfaces (GUI) to assist the forecasters in making appropriate choices, (3) the use of new graphical products to enhance model understanding (4) advancements in river routing procedures, (5) the capability of using digital elevation data bases to derive basin boundaries and geomorphologically model ungaged basins, and (6) new procedures using Geographic Information Systems (GIS) to estimate water content in snowpacks.

INTRODUCTION

The NWS has been given the responsibility to forecast watches and warnings of dangerous flood conditions on rivers. They also have the task of issuing forecast for water supplies. A third task is to provide warnings of flooding on basins that respond too quickly to gather and process precipitation to provide quantitative stage forecasts. This third service involves the preparation of flash flood guidance values which serve as the basis for issuing advisories for areas with a strong probability of flooding in a very short time (flash floods).

Over a decade ago, approximately 20,000 locations were identified as being at risk to flood damage. Even with those operations that are currently in place, the NWS is working near the

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limit of its operational capability to issue stage forecasts for about 3,000 forecast points. One of the major limitations is the size of the remaining watersheds. Many of them are small and respond too quickly to obtain the necessary input data, process a forecast, and issue the forecast to the public in sufficient time to control damage. In these situations, advisories are issued to alert the public; but the extent of the threat can not be expressed in terms that allow significant damage reduction activities. With the improved hardware and software currently under development, the NWS hopes to extend its capability to meet the public needs.

The accomplishment of this assignment requires that (1) precipitation be accurately observed with high temporal and spatial resolution, (2) that air temperature be observed and used to (a) model the separation of precipitation into rainfall which immediately infiltrates the soil or runs into channels, or snow which remains where it falls until it melts (or drifts to a new location) and (b) model the melting of the snow pack in a realistic manner, (3) that the land surface of the basin be modeled with appropriate state variables to indicate the (a) amount of the rainfall that flows to river channels, (b) the timing of runoff discharge past the forecast point (unit hydrograph), (c) the rate of ground water release to form the base flow, (d) the amount of moisture transpired from the soil, and (e) the moisture that the soil holds in storage, (4) that the flow through segments of basins be routed by an accurate modeling process to forecast points further down stream, and (5) that climatic variabilities be properly considered for making forecasts involving precipitation that has not yet been observed.

Almost all of these topics have been impacted by the NWS modernization. This impact will be described further in subsequent paragraphs. However, as this is an overview of the evolution of operational procedures by our agency, the details of several of these topics will be treated in a somewhat cursory manner.

The technical evolution in our procedures to accomplish the specific tasks listed above are strongly influenced by the following considerations: (1) the Modernization and Associated Restructuring (MAR) program of the NWS; (2) advances in the technology required to observe, record, and report precipitation and other hydrometeorological data; (3) advances in communications, data processing, and display technology; and (4) advances in the science of hydrometeorological models.

Because NWS is highly focused on its forecasting mission, our research and development is concentrated on operational models and applications. Essentially all models considered for research and development are designed to fit directly into our National Weather Service River Forecast System (NWSRFS).

The modernization and restructuring of the NWS has occurred in large part from the need to replace aging weather observation radars, slow and saturated communications systems, and limited observation networks. The implementation of the WSR-88D radars (also known as NEXRAD) brings about a system that will cover, within a very short time, 98 percent of the country under an umbrella of radars that makes hourly observations of rainfall fields with resolution sufficient to map them into a grid 4 km on a side. These radars will be generally collocated with the primary NWS weather and river forecast offices for the area of radar coverage.

Station surface observations are beginning to be reported hourly from a system that ultimately will consist of well over 1000 automatic stations through the implementation of the Automation of Surface Observations Program (ASOS). These automated stations will include all of the first order weather stations and over 500 locations required by the Federal Aviation Administration.

The added data collected from the radars and the ASOS stations will be communicated, stored, and processed at the Weather Forecast Offices (WFO) and River Forecast Centers (RFC) by the Advanced Weather Interactive Processing System (AWIPS). The contract for the initial phase of this system was awarded in late December of last year. This system will provide significantly increased capacity for data transmission and it will focus on local processing of river forecasts on scientific workstations, thus replacing to a significant degree, the centralized processing on mainframe computers.

The introduction of workstations will allow significantly more flexibility in operational procedures. Currently most RFCs run batch programs which model their entire area of responsibility in a single computer run. The new interactive software on the workstations will be able to identify and process individual forecast basins where flood or drought threats are greatest. The workstations facilitate the use of graphics and graphical user interfaces (GUI) for assisting forecasters in assessing, analyzing, and processing data; developing their forecasts; monitoring precipitation to issue flash flood watches and warnings; calibrating basins; and generating water resource forecasts.

This report discusses improvements that have been made in the NWS in (1) data processing, (2) hydrologic modeling, (3) the use of GIS, (4) water supply forecasting systems, (5) and model verifications. Hydrologic modeling and model verification will be discussed in some detail in this paper. Other papers by NWS staff members will cover items 2,3, and 4 in more detail.

DATA PROCESSING AND MATHEMATICAL MODELING

In accordance with its mandated mission of issuing river flood and water supply forecasts, the NWS develops models for real-time simulation and forecasting.

Precipitation is the primary process that drives our forecast models. Innovations in observing and recording precipitation are being worked on in NWS by two different teams. One team is looking at producing a hydrologically meaningful quantitative precipitation forecast (QPF). The second is working to merge data from the WSR-88D radar, rain gages, and satellites to produce a real-time, high-resolution assessment of hourly precipitation on a 4 km grid.

Quantitative Precipitation Forecasts

The Ohio River RFC (OHRFC) located in Cincinnati, Ohio has been leading the team to produce QPFs and convert them to a grid and/or to assign QPF values to the basins being forecast by the RFC. The team includes the OHRFC, forecasters at the NWS National Meteorological Center (NMC) in Camp Springs, Maryland and at the NWS Techniques Development Laboratory (TDL) located at NWS headquarters in Silver Spring, Maryland, and meteorologists at Weather Service Forecast Offices (WSFO) within the OHRFC area of forecast responsibility. Interactive software to carry out this task has been written to operate on an IBM RISC 6000 scientific workstation.

The major problem associated with QPFs is the large areas where potentially intense rain may fall. If the total area within which relatively small, intense rainfall concentrations might occur were used (with the maximum intensities predicted) to generate a flood forecast, floods of record would occur. It is therefore important that probabilities be associated with the forecast intensities in such a way that a map of the forecast intensities can provide reasonable assessments of river runoff that might occur. Certain simplifying assumptions are being made in the initial modeling of this process. We expect that as experience is gained with the initial models and as the overall system evolves, these models will include objectively computed probabilities of occurrence of heavy rainfall intensities resulting in improved accuracies of the QPFs. This improvement will increase their value for use in forecasting floods.

Precipitation Processing

The monitoring of precipitation in real time is taking a great leap forward with the installation of the WSR-88Ds. There are only a handful of these radars that have been fully accepted at this time (February 1, 1993). However, several have been installed and are being actively tested. By January 1996 95 percent of the continental U.S. will be covered.

As of this time, WSR-88D systems produce hourly maps of gridded rainfall on a 4 km grid. The radars themselves can provide higher resolution than this. A graphical product is currently being produced on a 2 km grid. Many forecasters are pressing for digital conversion of this product for flash flood detection.

The processing of precipitation data from the radar is covered in more detail in these proceedings in the report "Precipitation Processing with the WSR-88D" by Robert C. Shedd, et al. In general terms, however, the system involves three stages. The first stage (1) detects a reflected return from the radar signal, quantifies it to a set of intensity rates which are averaged over the hour and converted to rainfall volumes; (2) compares the areal average of these rainfall volumes with an average volume derived from readily reporting rain gages and adjusts for bias in the data (the ratio of the two averages); (3) makes preliminary quality control corrections for ground clutter, anomalous propagation (AP), and range effects; and (4) maps the data from the polar coordinate system in which it is initially observed into the polarstereographic projection coordinate system. This processing takes place in the WSR-88D computer system.

The second stage (1) adjusts the rainfall field to conform to readings from additional rain gages, (2) makes further quality control checks by comparing thermal infrared data from satellites with areas indicated as rainfall by the radar to reduce the effects of AP occurring under cloud free skies, and (3) sets up information for further interactive quality control activities to be carried out in the succeeding step. This processing can occur on a mainframe or a scientific workstation.

The third stage performs two major functions. It creates mosaics of the mapped rainfall, i.e. merges data from several radars, resolving differences in the estimates in areas that are overlapped by more than one radar. This stage also generates graphic displays of the rainfall fields resulting from (1) the rain gages, (2) the radar, and (3) the combined field. By alternating between these views, trained hydrometeorologists can spot problems arising in the radar measurement and filter erroneous data. Stage III is run on scientific workstations at the RFC.

FORECASTING SOFTWARE

NWS River Forecast System

Once the observed and forecast precipitation are estimated, the other aspects of the hydrologic cycle that are required to develop forecasts, are modeled. All of these computations are carried out in the software system known at the NWS River Forecast System (NWSRFS). The NWSRFS has been developed over the past 20 years and is now in its fifth major revision (Version 5.0). The functional requirements which guided the design of NWSRFS Version 5 were to:

1. allow for a variety of models and procedures,
2. let the user control selection of models and sequence of use,
3. easily add new models and procedures to keep up with technological changes,
4. efficiently process large amounts of data to produce forecasts at hundreds of locations for each RFC, and
5. allow the user to flexibly control real-time processing.

Version 5 was designed to be modular, so that components could be developed by a number of individuals and then combined into a total system. References in the program code to system specific routines were isolated so that the entire NWSRFS could be ported from one hardware/ operating system platform to another with minimum effort. Routines which performed scientific algorithms were separated from input/output routines so that the science could be run on any computer without needing changes in the reading or writing of information from the computer system. Scientific algorithms were organized into modular functions so that the functions could be shared, unchanged, among major components of the NWSRFS.

The functions representing one scientific algorithm, such as functions that model snow accumulation and ablation, or soil moisture accounting, or river routing, are called an operation. In general, an operation in the NWSRFS is a set of functions that performs actions on a time series. Typically an operation describes the equations of motion governing the flow of water through a portion of the hydrologic cycle. There are also operations to display results, or to perform utility functions such as adding two time series. Table 1 provides a list of some of the currently available operations in the NWSRFS.

Table 1. NWSRFS Hydrologic Models

Snow

HYDRO-17 Snow Model

Soil

Sacramento Soil Moisture Accounting
Ohio RFC API Rainfall-Runoff Model
Middle Atlantic RFC API Rainfall-Runoff Model
Central Region RFC API Rainfall-Runoff Model
Colorado Basin RFC API Rainfall-Runoff Model
Xinanjiang Soil Moisture Accounting
Continuous API Model
Middle Atlantic RFC API Rainfall-Runoff Model #2

Channel

Channel Loss
Dynamic Wave Routing
Lag and K Routing
Layered Coefficient Routing
Muskingum Routing
Tatum Routing
Stage-Discharge Conversion
Single Reservoir Simulation Model
Unit Hydrograph

The operations that model the flow of water through the hydrologic cycle fall generally into the categories of (1) snow accumulation and melting, (2) water flow on or below the ground surface, or (3) water movement from one location to another on a river. Operations form the scientific heart of the NWSRFS and are shown in Figure 1 to be shared by the major sub-systems which comprise the NWSRFS Version 5. These subsystems are: 1) the calibration system for estimating model parameters based on historical data, 2) the Operational Forecast System (OFS) for producing river forecasts for a few days in the future, and 3) the Extended Streamflow Prediction System (ESP) for producing longer range forecasts (a few weeks to months) for water supply information.

Because of the modular nature of the functions which make up any operation, functions can be shared **with no change whatsoever** among the programs which form the NWSRFS. This also allows new scientific techniques to be developed in the structure specified for an operation, and once tested to be immediately available for use in forecasting with the NWSRFS.

Hydrologic operations in NWSRFS are organized into an "operations table" to specify the physics of water movement for any subbasin. Operations can be selected from the list shown in

Table 1. The order in which they are computed depends on the hydrometeorologic conditions of the subbasin being modelled. RFC forecasters can use their hydrologic expertise to determine the best sequence of scientific algorithms (operations) to model each subbasin. In this way, NWSRFS provides a generalized river forecasting system which can be used to model basins in any hydroclimatic regime.

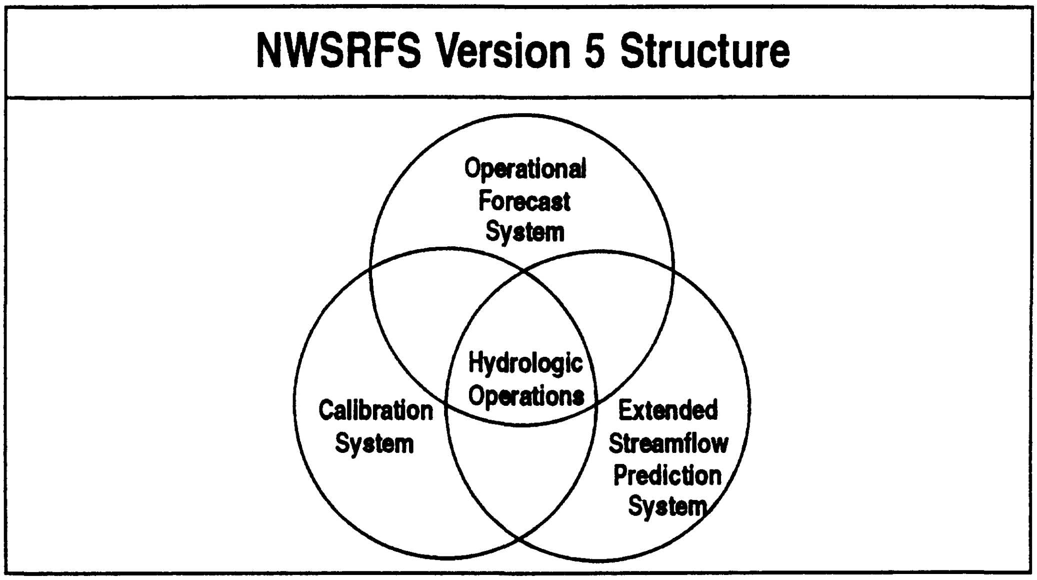

Figure 1.

A typical operations table might include: 1) the Snow operation to account for snow accumulation and ablation, 2) the Sacramento Soil Moisture Accounting operation to determine the rainfall excess, 3) the Unit Hydrograph operation to time distribute the rainfall excess, 4) the Dynamic Wave channel routing operation to route upstream flows through the forecast point, and 5) a utility operation to graphically display the resulting hydrographs.

Initial NWSRFS Version 5 development occurred from 1979 through 1984. Since 1985, NWSRFS Version 5 has been installed in RFCs and has been used daily to produce operational forecasts at thousands of locations along rivers throughout the U.S. New subbasins are continuously being calibrated and added as operational forecast locations by RFC hydrologists. Many new scientific algorithms and enhancements to existing operations have been added to improve the hydrologic modelling capabilities of the NWSRFS.

The initial NWSRFS design and development was on a mainframe computer [NAS9000s-(IBM look alikes)] at the NOAA Central Computer Facility (CCF). As minicomputers became powerful enough to support the system requirements of the NWSRFS, the Operational Forecast System (OFS), a sub system of NWSRFS, was ported to PR1ME minicomputers, located at NWS headquarters and at several RFCs. With the explosive growth in computational capabilities for scientific workstations, the NWS's Office of Hydrology (OH) initiated a project in the late

1980's to prepare for the anticipated modernization of the entire NWS by moving the OFS, the forecasting component of NWSRFS including hydrologic operations, onto IBM RISC System 6000 workstations.

When the NWSRFS is run from the NOAA CCF mainframe, command input is sent on Remote Job Entry (RJE) lines from RFCs to the CCF. Line printer results are sent back to the RFC for display on standard printers or to on-site data storage files for display on personal computers or terminal monitors.

Beginning in 1989, graphical display and user interface capabilities were developed for the NWSRFS. The result is the NWSRFS Interactive Forecast Program (IFP) which is discussed below.

NWSRFS Interactive Forecast Program (IFP)

As the practice of river forecasting has developed, it has evolved from being totally based on memory and experience, allowing a significant amount of subjectivity on the part of forecasters, toward a more object procedure where consistently observed input data is mathematically applied to physical models.

The evolutionary progress is occurring at an accelerated rate and, while machines are executing more and more of the procedures in an objective fashion, hydrologic forecasting still requires human-machine interaction because:

1. the equations with which we represent the physics of the hydrologic cycle do not perfectly model the actual movement of water,

2. the models that we use to approximate the physics of the hydrologic cycle require parameters to fit specific basin characteristics. The calibrations processes do not produce perfect results, and

3. we still have uncertainty and error in our observations and estimations of rainfall and streamflow which are the inputs to our models.

With the new computer capabilities, this required human interaction may occur more frequently and effectively in the forecast process. To properly forecast a hydrologically connected series of subbasins, a forecaster must make decisions for each location along the river where observed river conditions are available. If values simulated by NWSRFS do not agree with observations, the forecaster must decide on the most likely source(s) of error, and make adjustments. When a river system is forecast with NWSRFS on the mainframe or minicomputer, large groups of subbasins are processed in a single batch run. Errors in upstream subbasins propagate into downstream basins, making forecasts for those basins less reliable. The problem can be reduced by making appropriate adjustments to reduce or if possible remove the error in a subbasin before processing downstream subbasins. The IFP provides this capability to the forecaster. The IFP together with the workstations also provide the capability for high resolution color graphics to communicate products more clearly and effectively than the mainframe line printers.

The NWSRFS with the IFP offers:

1. an operationally proven set of hydrologic models,
2. a system configuration which uses the UNIX operating system with X Windows graphical display protocol and Open Software Foundation (OSF) Motif,
3. adherence to OSF standards to be computer hardware platform independent,
4. a GUI that provides easy, powerful user interactions,
5. scientific applications that are isolated from the operating system specific functions calls and input/output, and
6. the use of both C and FORTRAN programming languages; C for user interface and graphical display routines, FORTRAN for physical process modeling.

Currently, the NWSRFS requires input data from existing NWS data sources. With the advent of AWIPS, these data sources will be passed through the AWIPS communication system to the AWIPS workstation where the forecasting will be done.

The new interactive forecast software now being tested at two RFCs, provides the forecaster with several new capabilities. First, in beginning a forecast assignment, forecasters can review on the workstation screen the hydrologic situation for basins where they have assigned responsibility. The IFP allows them to select the assigned group of river basins and display on the screen both a schematic and a geographic map of the basins. The potential for flooding is indicated in color for each individual basin. Streams already above floodstage are marked in red, those with some possibility for flooding in yellow, and those with little or no likelihood are in green. By moving the cursor on the screen with a mouse, the forecaster can zoom in on individual basins. They can call for a window to appear on the screen listing basic basin parameters including flood stage. An example of a workstation screen is shown in Figure 2.

When the IFP begins, the hydrologic models for the most upstream basin are run on the workstation and the resulting hydrographs are displayed. The IFP then allows the forecaster, using the mouse, to point and click to make modifications to time series values or to other model inputs. A few examples of the modifications that can be made include correcting errors in observed stage data, adding QPF values, adjusting the baseflow for the Sacramento Soil Moisture Accounting operation, or temporarily adjusting the unit hydrograph for the basin.

After the forecaster is done making modifications, the hydrologic models for the basin are rerun and, within seconds, the results are displayed. When the forecaster is satisfied with the results for that basin they can move on to the next downstream basin and repeat the analysis until they are done with the chosen set of forecast points.

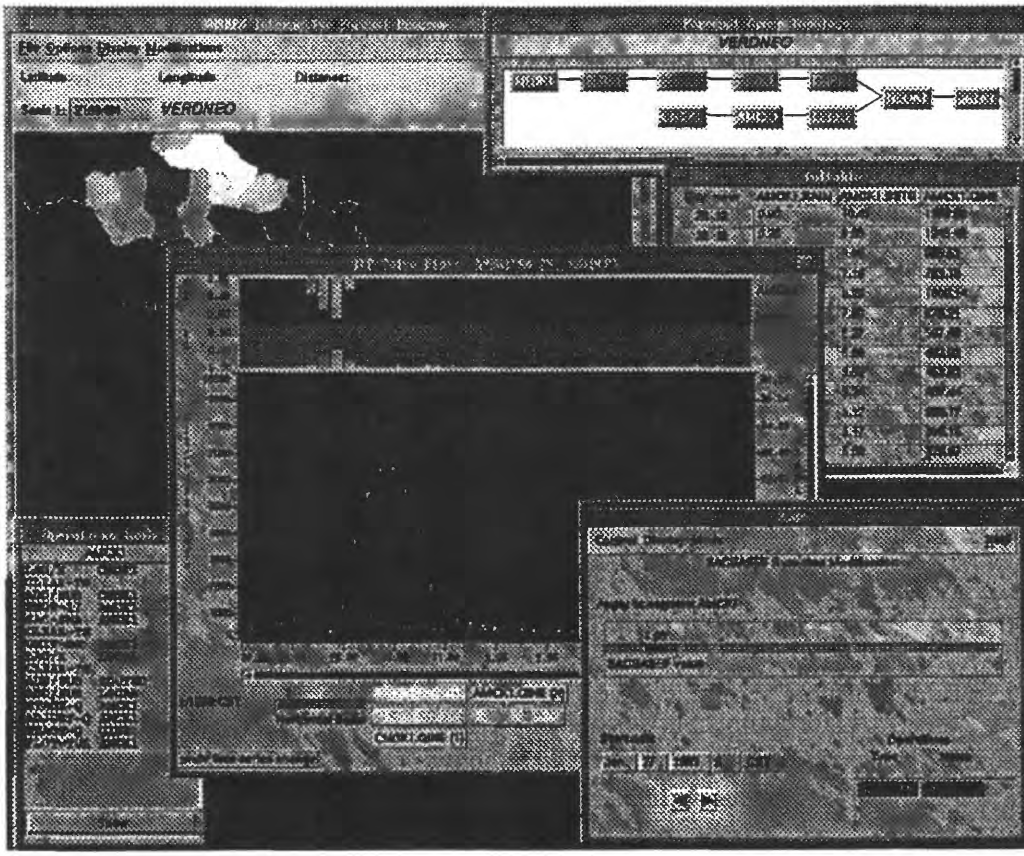

Figure 2.

With the new interactive software for the AWIPS era, forecasters will have both the Stage III precipitation processing program for interactive processing with the improved data from the WSR-88D and raingage network, and the IFP for interactive streamflow estimates on the same workstations. In a potential scenario, a forecaster looking at the Stage III display might observe heavy localized rainfall near the outlet of a basin. With this knowledge, using the IFP, the forecaster could then modify basin unit hydrograph to route the runoff to the outlet of that basin more quickly for that storm.

In summary, the new interactive forecast software will enable greater flexibility in adjusting model parameters, take less time to incorporate these modifications, and improve the accuracy of the forecast.

River Mechanics

Following, in a conceptual sense, the path of the water after it enters into the stream channel, the next computation involves routing the discharge downstream to lower basins. As noted in the previous section, NWSRFS has several channel models available for routing flows. Many of these models are empirical and while they correctly simulate many conditions, there are many remaining situations where the routing models do not correctly describe the process. For this reason research continues in HRL.

The dynamic wave channel routing operation model is the most physically based of our routing models. It is continuously being improved to account for a wider range of hydraulic situations.

Routing models generally have several vital steps. The primary requirement is to have an accurate stage-discharge relationship. Our models generally route volumes of water downstream. Maintaining this relationship is difficult in areas where significant changes occur in the river bed or where the river slopes are very flat. Stage-discharge in these shallow slope areas are significantly influenced by changes in bedform roughness due to scouring or filling of the channel or to the change in the water surface slope with the passage of storm crests.

Studies are being conducted in our laboratory on sediment transport in order to simulate processes that influence stage-discharge relations and thereby improve our accuracy in routing flows.

In addition to forecasting downstream flows based on continuous modeling, NWS has a responsibility for forecasting damaging flows that might occur as a result of the failure of any of over 70,000 dams in the country.

To do this we have assembled catalogs and on-line data bases identifying each reservoir, its location, the river that it is on, the first downstream point of interest (community, school, power plant, hospital, etc.), general travel times of flood waves from the dam to that point of interest, and given standard conditions, the flood crest (maximum stage of the flood waters) that might be expected in the vicinity of that point. Since conditions are continually changing, to compute the flood data, a program known as the "Simplified Dam Break Model" (SMPDBK) was used. This model makes many basic assumptions and requires very little input data. This software is designed to run on the smallest of computers and give "first guess" category results. With such a large number of reservoirs, each changing continuously with inflows and outflows, it would be very difficult to maintain much greater detail than this. When conditions arise making the failure of a reservoir probable, this SMPDBK can be run with improved estimates of the relatively few input parameters or variables involved. The output from this processing can provide an improved estimate of the downstream flood crest.

The full scale dam break model can be run when time allows and when significant data such as downstream channel cross sections can be obtained.

These models are continuously being updated and improved. With the introduction of more powerful PCs and scientific workstations, many more graphics and graphical user interfaces are being introduced. Thus the software is being updated to make it more user friendly both in ease of input and in understanding the meaning of the output values.

The routing of the flows downstream can be done to many different levels of accuracy based on the extent and accuracy of the input data. When rivers or streams pass through reservoirs, the outflow becomes much more a function of the operating principals of the reservoir. During times when the outflow is most critical for making flood forecasts is when there is the least time for communication between forecasters and dam operators. There are other conditions when the operations of the reservoir are not readily available to a forecaster or hydrologic modeler that will be discussed under the section on water supply forecasting.

For these reasons, we have a suit of algorithms which seek to simulate what we think reservoir operators will do under various conditions. This model application is also evolving as we gain experience with its use.

Flash Flood Guidance

A significant fraction of the lives lost to flood events are those related to very intense storms over small but rapidly responding stream basins. We currently identify 12 hours as the minimum response time for which we can collect data and process and disseminate a forecast with enough warning lead time to be effective. For smaller basins with shorter lead times we issue "flash flood advisories."

In the past, these advisories have been developed by independent procedures in either the office issuing them or by the NWS region governing the offices that issue the forecast.

All of the procedures were based at least in part on the soil moisture conditions in each area for which the advisories were issued. The soil moisture conditions were provide by the RFCs. The different RFCs had different methods and formats for providing these data. A significant problem occurred where the soil moisture data for a single forecast office was provided by as many as three RFCs. Because their procedures differed, discontinuation would exist in the guidance values at the RFC boundries.

With new communication and processing capabilities, the Office of Hydrology plans to support a single standard procedure. The standard system would reduce discontinuation at RFC boundries. In this procedure, threshold runoff values will be determined for 1-, 3-, and 6- hour rainfall durations. Threshold runoff is defined as the runoff from a rain of specified duration that causes the streams located within a local geographical area to slightly exceed bankfull.

Since bankfull is not constant along a length of stream, these threshold values must relate to particular points in the basin. Further, since the small streams for which these advisories are issued are rarely gaged, and since there are a very large number of them, physical observations can not be made for each basin. For that reason, the procedures are developed using digital elevation data bases (DEDB) and GIS. Details of this development work are included in the paper "GIS Application in the NWS Flash Flood Guidance Model" by Timothy L. Sweeney, Danny L. Fread, and Konstantine Georgakakos, included in this publication and reported through a poster paper.

Water supply from surface water sources generally requires projections which extend several months into the future. Deterministic forecasts of precipitation have usable skill only a few days into the future. Climatological forecast for months or seasons are based on observable conditions such as those associated with the El Nino-Southern Oscillation but the accuracy of those forecast is quite limited.

Extended Streamflow Prediction (ESP) System

Long term flow forecasts based on averages of river flows also suffer a loss in accuracy caused by changes in the basin over the period of record. Channels are modified, basin surface areas are urbanized, agriculture and/or forestry practices are changed, etc.. All of these changes can be observed to one degree or another but their effect is difficult to model and use in making predictions of future runoff. The NWS long term forecast component of NWSRFS known as ESP uses the same hydrologic models used for standard river forecasts instead of a model based on long term averages of flow. The forecasts of flows or flow volumes up to a year into the future use current conditions for the model states and historical rainfall and temperature time series as inputs to the models.

First, however, these data are checked and corrected for internal consistency over the period of record. Each year of historical data is processed as if it were occurring in the current year. In this way, a set of streamflow traces are developed for each year of data. Considering each trace as an equally likely occurrence, a probability density function (PDF) is constructed indicating the probability of a given flow for the coming year. With this PDF, probabilities can be estimated for a range of flow levels.

When regulated rivers are forecast some distance into the future, then the rules for regulation, i.e. reservoir operating instructions, etc., must be extrapolated or "modeled" into the future. Thus the study of reservoir simulations that were briefly described in the section on river mechanics is vital for extended forecasting of streamflows.

The NWS also is interested in modeling snow pack conditions for large portions of the country. In the western United States up to 75 percent of the water used for irrigation comes from snow melt. Accurate estimates of water equivalent of snow packs are important observations for use by NWS.

Just as the NWS must depend on other government agencies for observing precipitation, the water contained in the snow pack is frequently observed by others, notably the Soil Conservation Service (SCS). Such observations include over 40 years of observations from over 1500 snow courses. The SCS has also been collecting snow-water related data at approximately 650 sites which it identifies by the name SNOTEL. These have been in operation for about 10 years.

Based on data from snow observations, regression models have been used for over 70 years to estimate seasonal runoff from regions with significant snowpack. The regression models provide estimates with the greatest accuracy for mean values. Confidence can drop significantly during the occurrence of extreme conditions, when runoff estimates are usually the greatest concern. Regression equations are developed to include coefficients relating the independent variables to that being predicted. These coefficients are defined only for the condition that values are present for all of the independent variables used in the development of the equation. A basic assumption made in developing the regression equation is that correlations between snow at various index points and the flow at the mouth of the stream remain constant year after year. In fact there are many changes occurring in basins that influence changes in that relationship. Because of these limitations, the NWS uses a physically based snow accumulation and ablation model (Anderson, 1978). This model also requires an adequate level of input data but can compensate more readily for missing data.

In addition to the data from the SCS, the NWS uses data generated by the National Operational Hydrologic Remote Sensing Center (NOHRSC) that is collocated with the North Central RFC in Minneapolis, Minnesota. The NOHRSC, with interagency support, directs the monitoring of snow pack conditions with low altitude aircraft flights that record the natural gamma radiation of the soil. The sources of this radiation exist naturally in the soil. The radiation essentially occurs at a constant rate but is attenuated by moisture in the soil and the overlying snowpack. By measuring the difference in radiation during the no snow condition to that observed with snow present, the mean value of the water equivalent can be determined in transects 80 meters wide and several kilometers long. Over time these transects can be indexed to the effective average of water held in the snowpack for a given area.

Also at the NOHRSC, the areal extent of snow cover is routinely mapped. These data can be used to determine areal depletion curves as a further index to the amount of water in the snow in a basin.

Snow Estimation and Updating System

Even with all of these data, there are difficulties in estimating basin averages of water equivalent in the snow pack. A method for interpolating between observed points and thereby estimating areal values is being developed. This system, known as SEUS for the Snow Estimation and Updating System, also dynamically models the changes in the snow pack with the passage of time.

The software algorithm which computes snow melt contributions to runoff in NWSRFS is the conceptual snow model. It relies on estimates of mean areal precipitation and mean areal temperature to compute estimates of current snow cover conditions. These mean areal estimates of precipitation and temperature are developed from point observations. As indicated earlier, because of the difficulties in accurately estimating precipitation in the mountains, it is essential that all possible snow water equivalent observations be used to update model simulated snow cover conditions. SEUS is used to interpolate observations of snow water equivalent to produce gridded estimates of snow water equivalent. These grids are summed to develop estimates of the areal snow cover conditions needed by the NWSRFS conceptual snow model. These estimates are weighted with the model simulated conditions based on their relative uncertainties to compute updated snow conditions.

A paper describing this snow melt updating procedure in detail is included in these proceedings. The paper is entitled "Estimating Snow Water Equivalent Using a GIS" by Ann McManamon of NWS, Gerald N. Day (RTi) and Thomas R. Carroll (NWS).

The conceptual modeling of the physical basin where the snow accumulation and ablation will occur, is made in terms of geophysical factors which include slope, aspect, vegetative cover, elevation, etc.. This work is done most effectively using a Geographical Information System (GIS). The GIS used in our development work is the Geographic Resources Analysis Support System (GRASS) developed by the U.S. Army Corps of Engineers at their Army Construction Engineering Research Laboratory (USACERL). Based on this work, melt relationships are determined for the various combinations of geophysical classifications in the basin. With these factors, melting of the snow pack in the basin is modeled dynamically in the NWSRFS snow model as a function of air temperature and seasonal factors relating to the length of the day.

Briefly described, the SEUS has three components, one for calibration, one for real-time operations, and one for updating. The calibration component analyzes historical observations and develops the model parameters required to estimate a gridded map of snow water equivalent. It further processes the data to obtain areal or basin averages. The operational component uses real-time observations to develop gridded and areal estimates of snow water equivalent. The updating component uses information developed in the calibration phase to remove model bias and update snow conditions based on subsequent data, weighting such data according to the reliability that the input data has demonstrated as an effective index to the snow estimate.

Water Supply Forecasting Services Pilot Project

The economic effects of effective water supply forecasts which include probabilities for forecast realization have been described in conceptual terms for several years. As a quick example, the benefit from the dynamic operation of multiple use reservoirs using long-range probabilistic forecasts is rather easily recognizable. When large inflow volumes of water are expected into a reservoir that has been designed for both water supply and flood control, the long-range forecast provides the opportunity to water managers to lower the storage pool gradually several weeks in advance of any anticipated large inflows, thereby increasing the flood control capacity of the dam. They can do this knowing in advance the probability that a sufficient volume of water to restore the reservoir to the same capacity will occur as during the inflow period. Using the long-range forecast, excess water would not need to be spilled in an emergency manner potentially causing flooding in downstream areas. For these dams equipped with power-generating turbines, the systematically spilled water could be beneficially used to generate power following a set schedule. The competing uses can be taken into consideration and strategies can be developed to optimize dam operation for all uses.

To demonstrate this service in a practical manner, the NWS, with the cooperation of the Bureau of Reclamation has joined with the Denver Colorado Water Department, Riverside Technologies inc, and the Colorado State University to execute a pilot project. This project is described in more detail in these proceedings in a paper entitled "Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast." by Donald Laurine and Dr. Larry Brazil.

The project is applied to water management systems operated by the Denver Water Department which bring water from the Colorado Basin to the Denver Metropolitan area. The referenced paper details the economic value of operating these systems using long range forecasts to optimize the operation strategy to comply with water rights, serve the water needs of the City of Denver, while increasing sales of hydroelectric power and reducing other costs.

The use of scientific workstations to accomplish these water supply forecasts allows the complex factors involved in decision making and the graphics required to understand possible options to be simultaneously available to the forecaster.

SUMMARY

The introduction of scientific workstations and improved communications capabilities that are becoming available to NWS under MAR programs are allowing many opportunities to improve forecasts through improved higher spatial and temporal data observations, faster and more uniform data transmission, interactive processing involving more computer support in terms of graphics and GUIs and GISs, and to implement technologies related to QPFs and flash flood guidance values. These systems are being developed and managed so that as the technology increases, hydrologic innovations can also be applied at an accelerated rate. These systems also enhance the ability of the NWS to communicate its products more rapidly to the public and to exchange vital water related data with other sister agencies of the Federal Government.
The NWS is now on a faster track to better warn the public at risk to flooding and drought and better execute its assigned mission.

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PAST, PRESENT AND FUTURE NEEDS OF SCS WATER QUANTITY MODELING EFFORTS

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ABSTRACT

The Soil Conservation Service (SCS) has been using water quantity models since the early 1960. These models start with a single model peak flow model for watersheds. Tools developed from many runs of the watershed model have been automated. Continuous simulation water quantity models have been used. SCS uses watershed and field size computer models to estimated the on- and off-site effect of management practices on water quality and quantity. SCS is developing watershed water quantity model and forecast tools where snowmelt is a major contributor to the annual runoff. SCS is testing the use of geographic information systems to develop input data and to display output data.

PAST

TR-20 Model

The first major hydrologic modeling effort in the SCS was development of Computer Program for Project Formulation - Hydrology (TR-20). This effort began in the early 1960's after passage of the Watershed Protection and Flood Prevention Act, Public Law 83-566, (PL-556) in August 1954. PL-566 assigned to SCS primary responsibility for US Department of Agriculture's cooperation with local organizations in small watersheds throughout the Nation. It provided for prevention of erosion, floodwater, and sediment damages in the watersheds of the rivers and streams of the United States.

To satisfy requirements of PL-566, SCS needed a watershed model that would simulate present and future land use and structural effects on floodwaters. Early in 1960, SCS contracted with CEIR, a consulting firm with the capabilities to develop FORTRAN computer programs for the available mainframe computers, to develop such a model. The first version of the model was available for use in 1964. The program was written using the logic of normal manual computations. It was one of the first computer program that stressed the user logic rather than making the user understand computer logic.

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The first uses of TR-20 were on the IBM 1130 computer in the SCS regional Engineering and Watershed Planning Units. Later it was put on mainframe computers at Washington and Kansas City computer centers. The initial version of TR-20 used the batch mode of operation.

TR-20 is a single event computer model. The TR-20 computer program estimates volumes of direct runoff and peak rates of runoff, and routes hydrographs through structures and stream reaches. TR-20 can be used to add hydrographs and to divert flow from subarea hydrographs. It can handle up to 9 rainfall events with natural or design rainfall temporal distributions for 600 subareas, 99 structures and 200 stream reaches.

After CEIR completed the TR-20 computer program, later modifications and updates were made by SCS engineers. With the proliferation of personal computers in the late 1970's, TR-20 was converted to operate on a PC. The PC version of the TR-20 became available in 1984. The present version of the TR-20 computer program is batch mode. Input data is developed using the TR-20 input data computer program. A TR-20 check program provides editing of input files for data outside certain ranges and missing data. The check program describes possible data errors.

The present version of TR-20 computer program has an output file that can be used with graphic programs, but does not have graphic capabilities. The TR-20 computer program operates in the DOS environment.

The TR-20 computer program has been used in watershed evaluation studies and floodplain management and flood insurance studies. Several of the papers at this session will describe how the TR-20 computer program is currently being used on a production basis.

TR-55

In the early 1970's there was a need for SCS District offices to provide assistance in rural and urban areas in evaluating the impact of urbanization on peak rates of runoff. The Northeast National Technical Center (NTC) started developing a hydrology manual with short cut procedures. These procedures were based on TR-20 computer program runs for a wide range of time of concentration, with a 24-hour rainfall distribution.

This effort was continued with National Headquarters Staff and in January 1975, Urban Hydrology for Small Watersheds, TR-55 was distributed. The TR-55 manual contains shortcut procedures in the form of charts and graphs. These charts and graphs were developed from TR-20 computer program runs for a wide range of Tc's and 4 standard SCS 24 hour rainfall distributions. The charts and graphs in TR-55 are used to estimate peak rates of runoff and volumes of direct runoff. TR-55 can be used to estimate the floodwater storage needed to reduce the postproject peak flow to preproject conditions. TR-55 has become one of the most popular and widely used documents, both within and outside SCS. Over 100,000 copies of the manual have been distributed.

Revisions and updates were made using an user analysis process. Users asked that the material in TR-55 be automated for personal computers. Agricultural Research Service (ARS) provided assistance in coding the BASIC TR-55 computer program. The first version of the TR-55 computer program is dated June 1986. The TR-55 computer program automated the charts and graphs. Version 2 of the TR-55 computer program was distributed in September 1992.

The TR-55 computer program is the first SCS program that uses input screens designed by the user. The screens were arranged to ask for needed input data in a logical sequence. Data checking is part of each input screen, and check is based on missing data or data outside an expected range. The TR-55 computer program does not have graphic capabilities. The TR-55 computer program operates in the DOS environment.

EFH2

In the 1980's, it was realized that the District office staffs needed an automated procedure to estimate the peak rates of runoff for small agricultural watersheds under 2000 acres. The short cut procedures are used to estimate peak rates of runoff for the design of grass waterways, terraces, culverts, and other low hazard structures. The computation of time of concentration is embedded in the procedure and is not provided by the user.

The charts in Chapter 2 of Engineering Field Handbook (EFH2) were developed from many runs of TR-20 for standard rainfall distributions. Early in the 1980's, these peak rates of runoff charts were automated for PC computer program using BASIC computer language by SCS engineers in the National Headquarters. The program is a simple version of the TR-55 computer program. The EMF2 computer program uses input screens. Data is checked for expected ranges as it is entered. The EFM2 computer program does not have graphic capabilities and operates in the DOS environment.

The EFM2 computer program has been used to compute peak rate of runoff for other computer programs, such as Ephemeral Gully Erosion Model (EGEM) which estimates erosion rate in ephemeral gullies.

Basin Simulation Model

The Soil Conservation Service in 1967 began using a parametric, deterministic continuous simulation computer model to inventory average and monthly runoff for ungaged watersheds in the west. The Basin Simulation model was developed by the Desert Research Institute in Nevada. The original model was a modification of the Stanford Watershed Model IV. The Basin Simulation model was modified to operate on the IBM 1130 in 1972. It has since been modified to operate on a PC in the DOS environment.

The Basin Simulation Model was used in four states to inventory the annual water budget of 23 watersheds. These studies were made as part of the Type IV River Basin studies. All four states asked SCS to estimate average annual water yield, annual flow frequencies, monthly distribution, and the effect of land treatment and other planned structural measures.

One of the most important uses of the model was to determine the depletions of the annual runoff by subarea within a watershed. The model has been used as a forecast tool with very limited success. The internal structure of the program limited its use as a forecast tool. The program as written only uses historic precipitation data and could not handle forecasted precipitation data. The basin simulation computer program has not been used for about 10 years because of a change in the direction of river basin studies.

PRESENT

With the arrival of water quality and erosion concerns, modelling efforts in the SCS are being directed to continuous simulation models for use on PC's. Continuous simulation models posed a problem in the past because of the high volume of data handled. This has become less of a problem with the availability of 386 and 486 computers with math co-processors.

Water Supply Forecasts

Presently, SCS uses regression equations to forecast expected seasonal runoff volumes. Seasonal runoff volume forecasts depend on the present snowpack and expected precipitation. The normal regression forecast equations provide volume estimates for a fixed time period.

The Water Supply Forecast Staff in the West NTC is working on development of a snowmelt forecast model. This model uses standard snowmelt equations to keep track of snow pack in high elevation watersheds of the West. The model will allow the user to forecast seasonal runoff volumes for river basins. A computer model will allow the user to update forecasts at any time and allow for the forecast to be made on nontraditional time periods.

The computer program is a continuous simulation model that will accumulate snow pack and then melt the pack during the spring. One of the papers at this session will describe the details of this model.

Precipitation data for this model will partially come from the Snow Telemetry (SNOTEL) sampling sites maintained by SCS. The SNOTEL sampling sites collect precipitation and temperature data at high elevations and estimate water content of the snow pack.

Data is collected at remote sites and transmitted to a central location using meteor burst technology. One paper at this session will describe the SNOTEL data base and its operation.

Water Erosion Prediction Project

The SCS, ARS, Bureau of Land Management, and Forest Service are involved in a joint venture to develop a physical process based erosion model to replace the Universal Soil Loss Equation (USLE). This effort has spawned the Water Erosion Prediction Project (WEPP). ARS is developing the technology, and SCS is responsible for the input data interfaces. This continuous simulation water model uses the Green and Ampt technology to develop volumes of runoff. Kinematic wave theory is used to generate overland flow hydrographs.

The model will use data screens based on user defined requirements and needs. The computer program is designed to access common data files at District offices. These files include producer information, soils, climate, plant and equipment data. These files will be developed once for each location and the program user will not be required to develop the needed data every time the program is run.

This model is still in the development phase and should be available for field use in 1996. The program will have graphic output capabilities. The WEPP computer program will eventually operate in the UNIX environment; however, the present Beta Test version operates in the DOS environment.

Field Office Engineering Software

SCS's Technology Information System Division (TISD) is developing a hydrology computer program that will operate in the UNIX environment and on a standard platform. The Field Office Engineering Software computer program provides estimates of peak rates of runoff and runoff volume using existing SCS technology. The program is designed to access common data files such as producer information and soils and climate information normally available in each District office.

Structured design concepts were used to design the computer program. The data screens and data flows were developed by the user. The program has graphic capabilities. The programming is being done by contractors at the in Fort Collins. The Beta version of the Field Office Engineering Software will be released shortly.

Water Budget

TISD is developing a water budget model that can be used to provide estimates of water leaving a site, in the soil profile, and leaving the profile. The model will be able to handle rainfall and irrigation. This type of model will be the backbone of various quality model needs. SCS users determined the model requirements and then looked at various existing ARS models that would meet the requirements. It has been decided for the first version of the water budget model to adapt the ARS Soil Plant Air and Water (SPAW) model to satisfy our needs. The primary reason for selecting this model was that the soil component used Darcian concepts to keep track of the water in the soil profile and the model was operational.

SCS is designing the input screens and coding the input/output routines. The program will operate in UNIX on the standard District office platform. The program will have some graphic output options.

This effort is a good example of ARS and SCS partnering. ARS has developed the technology and SCS is adapting the technology to meet our operating environments. The program will be modular so that as new or improved technology becomes available, it can be inserted into the program. Output from this program will become the input for other modules under the FOES umbrella. Each component of the hydrologic cycle will be a separate module, e.g., infiltration, evapotranspiration, and soil moisture.

Water Quality

The SCS is currently involved in water quality efforts that will require our District offices to determine on- and off-site effects of various management practices. The needs will also involve determining the amount of water leaving the root zone or contributing to local ground water.

SCS is looking to ARS to provide the technology to meet our water quality program needs. Initially, SCS will modify the input/output portions of existing programs that satisfy our District office needs. ARS will provide the technology and SCS will provide the user requirements and needs and the coding to meet our hardware and platform requirements.

SCS is involved in a two phase effort to implement a 5-year Water Quality Plan. The first effort is evaluation of the technology in existing ARS computer programs. The technology must allow us to evaluate on- and off-site impacts of all management practices. The current programs being evaluated are AGNPS, SWRRB-WQ, GLEAMS, and EPIC.

To have these programs effectively used at a District office, Geographic Information System (GIS) will be needed. GIS can be used to develop spatial data and attribute for watershed or field scale models and to display graphically the output data. Thus, the second phase of the current water quality modelling effort is to develop a prototype GIS data interface that can be used to run the models and to continue the evaluation of the models. The evaluation of the models consists of understanding the technology and being sure the technology satisfies our needs. This effort is know as the HUA or hydrologic unit area effort.

SCS is using GRASS as the GIS computer program, because it operates in UNIX and is public domain software. This is causing some problems because the current versions of the water quality programs operate in DOS. The programming for the GRASS interfaces for the prototype is being done by the TISD staff in Fort Collins using C programing language that can be compiled to operate in the UNIX environment.

The prototype software was scheduled for a Beta test in April using GIS data from 6 states. It is interesting to note that one of the major problems has been how to develop the needed data from various data layers that are available. The lack of commonality between the data requirements of the various programs has also caused problems. GIS interfaces are being designed to limit the amount of data the user is required to collect. The interface will develop the needed data from various data layers. It is hoped that this HUA effort will become the vanguard for future GIS interface model efforts for the SCS.

SCS is currently using AGNPS and SWRRB-WQ on a conditional basis after certain changes are made. None of the existing HUA or watershed programs will meet all the user defined technology needs. The HUA size will be limited to about 250,000 acres. One by product of this effort, is the identification of additional research needs and the short comings in existing physical models.

SWAT

Resources Conservation Act (RCA) of 1980 required that SCS inventory the water resources on a regular basis. In the past this type of analysis was done manually and the techniques used varied between inventories.

SCS is currently involved in an effort with Texas Agricultural Experiment Station (TAES) to develop a river basin size hydrologic model to provide information on the surface and subsurface water resources of major rivers basins. The model will be able to estimate the impact of management practices on water resources of each basin.

TAES with the assistance of ARS is modifying SWRRB to inventory develop the water resources of the river basins. ARS has developed a computer program that will combine outflow from subbasins and route the flow downstream. Stream gage data will be used to adjust or proportion the flow from the subbasins.

GRASS will be used to develop the needed data from the various data layers and to display the output. The present version of Soil Water Analysis Tool (SWAT) operates in DOS on a mainframe computer because of the large volumes of data used in the computations. The Lower Colorado River Basin in Texas is being used as the test case for the model development.

FUTURE

While the future direction of SCS and its programs is being decided at this time, it is assumed that SCS will be required to become more involved in evaluating the impact of management practices on water quantity and quality. The days of saying no till is the answer or terrace are the answer is gone. Congress is requiring agencies to provide quantified answers.

SCS will need computer models that will provide on- and off-site answers to the water quality questions. This model will need to be physically- based and numerically correct, and address a wide range of water quality questions. The models will need to evaluate both point and nonpoint sources of pollution.

The models will need to simulate the hydrologic cycle on a continuous basis on a daily basis. The models will have to include irrigation water requirements. The plant module will need to simulate both root and canopy development over the growing season for a wide range of crops and native vegetation. The plant module will provide estimates of the water requirements.

The program will be modular in concept. There are some thoughts that each phase of the hydrologic cycle will need to be a separate module and have various levels of complexity. There will be a tool box of these modules and depending on the application the umbrella program will call the appropriate module. The umbrella program will make the necessary computations, call the required databases and display the correct input data screens. There will be soils, plant, equipment, and climate data bases at each District office. The umbrella program will obtain the needed information from appropriate data base and make needed adjustments to the data. For example the umbrella program would use GIS to compute a curve number from information on the soils, land use, and hydrologic conditions data layers. GIS would then be used to display the curve number for the spatial area or cell.

The user will not know what modules or techniques are being used. However the user must be assured that the best and most appropriate technology was used. The computer program must provide the answers consistent with the users need.

For example, if a producer wants to know if a certain chemical can be used on a sandy soil on his land, a screening tool may be used. If a producer wants to know if use of a certain chemical on his soils will cause increased pollution of a lake at the lower end of the watershed, a continuous HUA simulation model analysis would be required.

To get these concepts into District office computing environment will require partnering of many agencies. For example, ARS and Environmental Protection Agency will provide the technology, National Weather Service and US Geological Survey will provide the basic data for input data and model calibration, and SCS will provide the resources to modify the technology to satisfy our needs. This type of partnering will increase the delivery rate of the technology to the District office and reduce the cost of delivering the technology.

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U.S. GEOLOGICAL SURVEY PROGRAM TO MEET

THE HYDROLOGIC MODELING DEMANDS FOR THE 90's

ALAN M. LUMB[1]

INTRODUCTION

This paper provides an overview of the activities of the U.S. Geological Survey (USGS) in river basin and watershed modeling and addresses the role of the USGS and the range of activities taking place. The USGS does not manage our Nation's water resources but rather collects and disseminates information on water-resources data and conducts and reports results of scientific investigations needed for the management of the water resources by all levels of government and the private sector. Current activities in watershed modeling investigations are described as they set the stage for meeting the river basin modeling demands of the 90's.

GOAL OF MODELING

The USGS's river basin modeling activities focus on the assessment of change. What are the changes to the magnitude, timing, and distribution of water and the quality of that water as a result of man's activities and of catastrophic natural phenomena? The categories of man's activities that have been addressed in river basin models include:

urban development and mitigation measures,
timber harvesting and forest fires,
animal grazing and feedlots,
agricultural acreages and practices,
surface mining,
reservoir operating rules,
water allocations,
wetland creation, removal and management, and
solid- and toxic-waste disposal.

Categories of natural phenomena include:

volcanic activity,
climate change,
mud slides, debris flows, and major floods, and
forest fires.

WATERSHED MODELS

River basin (watershed) models are commonly used to estimate the timing and distribution of water before and after a planned activity of man or as a result of a natural phenomenon. River basin models used in the USGS are generally categorized as distributed-parameter, continuous-simulation, physically-based watershed models. Three such models are fully supported and used in the USGS: Distributed Rainfall Runoff Routing (DR3M) (Alley and Smith, 1982), Hydrological Simulation Program Fortran (HSPF) (Johanson and others, 1984) (jointly supported with the U.S. Environmental Protection Agency), and the Precipitation Runoff Modeling System (PRMS) (Leavesley and others, 1983).

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These distributed-parameter models take into consideration the variation in slope, soils, vegetal cover, and land use found in the study areas. In most cases a lumped-parameter model cannot appropriately reflect physical changes in the study area. The three models are continuous simulation models to more fully assess the effects of natural and constantly changing wet and dry periods. Also, with a long simulated time series of flow or storage of water at a location in the river basin, the probabilities of various levels of flow or storage can be computed directly without the assumptions required by event-based simulations to combine the probability of a watershed condition with the probability of a meteorologic event. The three models are physically based so there is reasonable assurance that the modeled response to a land use or other change is a reasonable representation of the actual response that would be observed in the study area. The size of study areas are usually a few square miles to several thousand square miles; so that detailed, micro-scale representations of the physics of the processes must be replaced with a physically-reasoned macro-scale representation. Such macro-scale representations of the physical system include concepts of variable-source area, even within the smallest land segment simulated with a unique parameter set.

WATERSHED MODELING RESEARCH

Numerous research projects in the USGS address the various phases of water movement from precipitation on the vegetation and land surface to the outflow in the channel system. Such topics as the effect of frozen ground on infiltration, watershed response to acid rain, effect of climate change, and the origin, fate, and transport of organic compounds have been addressed. It is not the intent of this paper to provide a summary of USGS research, which is documented by Nichols and Friedman (1991).

SOFTWARE DEVELOPMENT FOR WATERSHED MODELING

Several projects in the USGS have the objective to decrease the cost and improve the efficiency of using watershed models. Software shells are being created to help the modeler create the input necessary to simulate hydrologic processes in a river basin, edit the input to the model, and produce graphic visualizations of the model output. These shells are also being developed for different users; the researcher that wants to investigate different process algorithms, the scientist or engineer that wants to calibrate and validate the model for a river basin or region, and the manager that wants to use a calibrated and validated model to assess the effects of change. Two such shells or systems--HSPEXP and MHMS--are described by Lumb and Kittle (1993) and Leavesley and others (1993), respectively.

GEOGRAPHICAL INFORMATION SYSTEMS (GIS) AND WATERSHED MODELING

GIS provides an important tool in watershed modeling through the development of input for watershed models. Such tools are useful in automating the disaggregation of the river basin into land-surface units that have a similar hydrologic response to meteorologic inputs and in linking those units to the drainage system of tributaries and main channels. The automation becomes most effective when numerous land-use and disaggregation conditions are being investigated. GIS can also be useful for graphic visualization of the results of simulations, but it is most powerful for development of input for the models. Presentations by Hay and Knapp (1993) and Jeton and Smith (1993) illustrate the type of work being done in the USGS with respect to GIS and watershed modeling.

The appropriate level of integration of GIS software with watershed modeling software is uncertain. With current widely accessible computer technologies, full integration into one software package must simplify the model processes and length of simulation period or simplify the GIS capabilities. An appropriate level to initially interface complex modeling and complex GIS could be the development of a data model and format for data to be exchanged between GIS and a river basin model. In that way, any one of several GIS systems could be used for any one of several watershed models.

WATERSHED MODEL CALIBRATION/VALIDATION

Although input parameters for some watershed models can be estimated from characteristics of the drainage basin, the ability of a watershed model to more accurately simulate streamflow in a basin can be improved significantly by calibration. However, calibration requires additional data and more resources. For a single-purpose, single-site investigation, the costs of calibration commonly exceed the benefits. However, the USGS has begun several investigations in Washington, Oregon, Illinois, and Maryland where the watershed model applications will be numerous in a region or river basin of similar climate and topography. In such applications, a watershed model can be calibrated by associating the model parameters with measurable characteristics of watersheds, such as vegetation, soils, land use, and basin slope. The observed data for some of the watersheds are used for calibration and some are used for validation; the calibration process develops the associations or parameter sets for the major categories of land use and soils, and the validation process checks the associations of watershed characteristics with model parameters for the validation watersheds. The errors resulting from simulations for the validation watersheds provide an estimate of the errors that can be expected when the model is applied to ungaged watersheds in the region. An example of such an effort in the state of Washington is presented in the paper by Dinicola (1993).

A TOOL FOR MANAGERS

How will the hydrologic models and modeling methods that evolved in the 80's and early 90's be synthesized to meet the hydrologic modeling demands of the 90's? A vision shared by many in the USGS, as well as those in other agencies, universities, and the private sector, is to provide the water manager software to display maps and schematics of the river basin to easily and graphically identify alternatives, to execute the simulations, and to provide meaningful graphs and tables of the effects of the selected alternatives. The vision is being realized with modeling software that is categorized as decision support systems.

To produce effective decision support systems, greater communication and cooperation is needed between the managers, practicing hydrologists and engineers, research scientists, software engineers, and geographic information system specialists. The technologies of each are quite complex and difficult to learn but need to be combined to meet the hydrologic modeling demands of the 90's. Successes are emerging, but much remains to be done.

Within the USGS, the process has begun. First, an assessment objective for a change is identified for a river basin or region. Data availability is evaluated and additional data networks are established as needed. The model parameters are defined in part by use of GIS. The regional calibration and validation of models are completed using modeling shells. Then the data files and model are placed within an application shell for managers. This application shell displays maps of the area and provides facilities to describe interactively the change to be evaluated and to identify locations where hydrologic information is required. The evaluation requirements provided by the manager are then translated by the shell to detailed changes to model inputs. The model is executed by the shell and the required information is displayed or tabulated in a form directly usable by the manager.

To realize this vision, researchers need to improve the algorithms used in the models; the software developers need to design, code, test, support, and maintain the shells and models they use; the geographers need to refine the GIS tools, procedures, and GIS data layers; the scientists and engineers need to design data networks and calibrate and validate the models; and finally the managers of the Nation's water resources need to use the new tools to more fully assess the effects of planned changes.

SUMMARY

USGS program activities to meet the demands for hydrologic modeling for the 90's include development of hydrologic modeling systems for use by water-resource managers to more fully assess the effects of (1) the acreage and location of timber harvesting, (2) shopping center development, (3) implementation of agricultural best management practices, and (4) changes from the reallocation of irrigation water to municipal water supply on the magnitude, timing, and distribution of water and the quality of that water. These demands are being addressed by the use and integration of process model research, principles of software engineering, application of geographical information systems, and greater communication between the research scientist, practicing hydrologist and engineer, geographer, computer scientist, and the water-resource manager.

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SECTION 2

DATA MANAGEMENT AND EXCHANGE

Page

Remote Sensing for Hydrologic Models
Edwin T. Engman 2-1

Precipitation Processing with the WSR-88D
Robert C. Shedd, Richard A. Fulton, and Albert D. Peterlin 2-9

Use of an On-Line Information System and CD-ROMs for Dissemination of ARS Water Data
Jane L. Thurman and Ralph T. Roberts 2-15

Second Release of the U.S. Geological Survey's National Water Information System-II
Jeffrey D. Christman and Owen O. Williams 2-21

SNOTEL
David E. Johnson 2-30

Figures and Tables

Remote Sensing for Hydrologic Models 2-1

Table: 1. Future satellite systems that will have important instruments for hydrologic modeling 2-8

Use of an On-Line Information System and CD-ROMs for Dissemination of ARS Water Data 2-15

Figures: 1. ARS experimental agricultural watersheds 2-16
2. Source of water data center data requests 2-18

Second Release of the U.S. Geological Survey's National Water Information System II 2-21

Figures: 1. Main menu of the National Water Information System II 2-24
2. Menu structure of the National Water Information System II 2-25
3. Sequence of operations in the processing of time-series hydrologic data 2-27

REMOTE SENSING FOR HYDROLOGIC MODELS

Edwin T. Engman

One of the hydrologic modeling demands for the 90's is to develop and validate models that can be used to estimate the effects of climate change on water resources. These models will have to be physically based (as opposed to empirical or calibrated) so that they can react to changes in inputs brought about by climate change or variability. In addition they will have to be able to use the data type being collected to monitor the climate change on a global basis. Not only will remote sensing play a major role in the monitoring of global change but it will also play an equally important role in supplying data for hydrologic and water resource models.

This paper addresses the type of questions that need to be addressed with hydrologic models. These deal with the obvious scale discrepancies but also the conceptual differences between models developed from point measurements and remote sensing data which are spatial. This paper also identifies areas and strategies for research that are needed to couple hydrologic and atmospheric models and to use remote sensing as the principal data for running the models.

INTRODUCTION

Historically hydrology has developed as an engineering discipline to solve water resources problems such as flood protection and water supply. Evidence of the success of engineering hydrology can be found throughout well developed societies by their relatively high standards of living. Although there are still many water related problems to be solved worldwide, the realizations that water problems are no longer constrained to local drainage basins and the recent concern about climate change have asked completely new questions about hydrology; questions that traditional engineering hydrology is not equipped to answer.

Evaluating the impact of climate change on hydrology and water resources will require models to be much more universal in their structure and applicable to diverse regions of the globe. Furthermore, within the global change scenario hydrologic models will have to be driven by atmospheric models (GCM's and mesoscale) and be coupled to the models in such a way as to provide realistic feedback. In as much as many of the data used to monitor climate change and its effects on the land surface will

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be remote sensing data from satellite systems, these data will also play a major role in developing and validating appropriate hydrologic models. Remote sensing data are the only type of data that can provide global coverage and a consistent long term record. To accomplish this, the new hydrologic models will have to be designed to use remote sensing data as a primary input.

SCIENTIFIC HYDROLOGY

According to Chahine (1992), the hydrologic cycle within the framework of climate change encompasses much more than the classical surface hydrologic framework (precipitation, evaporation, runoff, etc.). In addition to these land surface processes, scientific hydrology must focus on the interactive processes of clouds and radiation, precipitation, oceans, and atmospheric moisture. This conception of the hydrologic cycle not only addresses the transport and storage of water in the global system, but also the energy needed and released through the phase changes.

If we attempted to phrase these new concerns in the form of a single statement it would most likely be: "The major problem facing scientific hydrology is the tremendous spatial and temporal variability of hydrologic processes across the globe" (National Research Council, 1991). Thus it is primarily a scale effect that separates engineering hydrology from today's needs in scientific hydrology. However it is more than just a scale effect. We are now being asked more detailed questions about the intermediate stages of the hydrologic cycle in contrast to the engineering questions that have been frequently answered empirically. Thus in scientific hydrology we literally are asked where each drop of water resides and for how long and how this drop moves through the Earth's system. That is, we need to quantify fluxes and storages of both water and energy.

Although the global hydrologic questions are provocative, we need to narrow our focus to land processes, not only because it is the subject of this workshop but also it narrows our focus to something doable. From this we can identify some of the key science issues that need to be addressed to answer climate change questions. These include at least two of the major unsolved problems that exist in the hydrological sciences (National Research Council, 1991).

> *How do we aggregate the dynamic behavior of hydrologic processes at various space and time scales in the presence of great natural heterogeneity?"*
>
> *What are the feedback sensitivities of atmospheric dynamics and climate to changes in land surface hydrology, and how do these vary with season and geography?*

These issues can only be addressed with a physically based hydrologic model that is tightly coupled to an atmospheric model.

HYDROLOGIC MODELS

Hydrologic modeling provides a structure for analyzing the hydrologic processes individually and as a balanced system. Hydrologic modeling provides a useful framework for interpreting key biological processes and ecosystem dynamics. Hydrologic modeling allows one to study the scaling properties of processes in drainage basins and how their time and space scales are connected. Hydrologic modeling is necessary for linking land surface processes to the atmospheric processes. It is important to realize that the terrestrial models and atmospheric models exist in different time and space domains and that there is no bridge between them. However, this is the domain of physically based hydrologic models and an area that must be addressed scientifically if there is to be synergism between the terrestrial and the atmospheric sciences. This is not the historical role for these models but it is a role that must be accepted if we are going to be able to evaluate the impact of climate change on water resources.

Although hydrologic models have not generally been designed to use remote sensing data, applications of remote sensing data are becoming more common. To date, most remote sensing applications have consisted of fairly direct extensions of photogrammetry, determining land use for the SCS curve number model for example. However, other than in snow hydrology, very few other applications exist because in general the structure of most hydrologic models is not amenable to incorporating remote sensing data. Peck et al.; (1981) conducted a detailed study on the suitability of seven hydrologic forecasting and simulation models to use remote sensing data. In general, they concluded that remote sensing has limited usefulness for these models in their present form. Their study identified model variables in addition to land use and snow cover area that could be provided by remote sensing. These include soil moisture, frozen ground, and snow water equivalent. These three characteristics are currently not used as input data to any of the models studied. However, because of their importance in determining hydrologic storages and fluxes, it appears that demonstrable improvements in modeling accuracy may be achieved if these quantities could be measured for input data.

Improved simulations depend upon two major factors: more physically realistic models to simulate the hydrologic process and adequate data available to drive the models. The development of new models must proceed with the knowledge of what data will be available. These models must also progress from the simple input (rainfall) and output (runoff) to models that use more complex inputs from coupled atmospheric models, account for systems states that are measurable (such as soil moisture and snow water content), and produce more complex outputs that feed-back energy and moisture fluxes to the atmospheric models as well as develop spatially distributed runoff and storages.

The scale of hydrology to be addressed in the climate change questions is generally larger than typically faced by engineers solving water resources problems. In general, the surface hydrology models will need to interact with atmospheric models, especially those operating at the GCM grid scale. However, there is also the need to have models developed that are driven by measured data and system states with a minimal reliance upon calibration. This is necessary, if these models are to simulate the hydrology for conditions different from a set of calibration data, that is conditions resulting from climate change.

Hydrologic model development should progress at two scales; one at the GCM scale or macroscale in which the scaling down questions become dominant. The second is at the mesoscale in which scaling up from point processes guides the modeling effort (World Climate Research Program, 1991). Each approach is discussed in more detail below.

Macroscale Hydrologic Models

The development and validation of macroscale hydrologic models will be essential for any hydrologic analysis of climate change. These models, which will operate at the grid scale of atmospheric models (approximately 100 km square regions) must integrate surface runoff and groundwater processes on the basin scale, account for all storages and be with fully interactive with the land-atmosphere system. A major weakness in the current capability of global climate models remains " the adequate parameterization of variables representing the terrestrial phase of the hydrologic cycle....., which is principally the result of totally inadequate information concerning the high degree of spatial variability of precipitation, evapotranspiration, and other components of hydrology" (Committee on Earth Sciences, 1989). This report goes so far as to say that "the lack of such regional-scale measurements introduces a severe shortcoming in the testing of GCM output" (Committee on Earth Sciences, 1989).

Most GCMs use parameterization schemes to represent the effects of such small-scale processes such as cumulus convection and precipitation processes, turbulent surface and boundary layer transport and cloud-radiative interaction processes. This approach is inadequate for addressing the effects of climate change on water resources. Any model used in this context must represent the physical processes as much as possible. Thus, there is a clear need for a better understanding of land surface processes and storages at a scale defined by the GCM grid. This is where the need for physically based macroscale hydrologic models becomes evident and new models must be developed to meet this need.

Macroscale hydrologic models must meet two rather strict but, to date, disparate needs:

(1) To represent the land processes as an interface to the GCMs,
(2) To accurately simulate the water balance for areas of different scale such that climate changes impact on water resources can be accurately simulated.

A pure parameterization approach that may satisfy the GCM needs will not be satisfactory; nor will a model that simulates runoff accurately without being able to accurately represent the spatial and temporal distribution of the storages and fluxes within the basin.

Mesoscale Hydrologic Models

Mesoscale modeling will involve the coupling of hydrology and atmospheric models into a single model at about a 10 km resolution. This research will provide the opportunity to investigate the scaling and process parameterization issues facing both the hydrologist and the atmospheric scientist. The hydrologist will develop and test scaling methods to a grid of about 10 km. Using this understanding and the hydrology/atmospheric interface knowledge gained from these studies, the next stop would be to scale up to about 100 km to join the GCM and macroscale modelers.

There is a need to understand at what scale and which parameters need to be used to better represent the land-surface processes in GCM's. An approach must be taken, concurrently with the development of the macroscale modeling, to better understand the various processes and interactions. The only way that this can be done is to couple a hydrologic model with a mesoscale atmospheric model. This means, in effect, that the hydrologic processes will have to be scaled up to the mesoscale atmospheric model. In this case the mesoscale would be "forced" by its boundary conditions, which are the land surface and the synoptic scale atmospheric conditions. Thus, these boundary conditions must be provided, for a real case with assimilation of real data or from a GCM model outputs.

The mesoscale model could be used to understand the relation between the surface hydrology and the dynamics of the atmosphere: how landscape heterogeneity would affect sensible heat flux and latent heat flux in the atmosphere and how that would affect the development of mesoscale circulations and clouds. The information that will be collected will be used to parameterize these processes at the scale of the GCM (next generation of GCM will probably have a grid resolution of 100 km).

Mesoscale modeling would not be applied at 10 km resolution over entire GCM grid cells but selected regions (on the order of 100 km resolution) of representative topography, land cover and differing hydrologies. At the grid scale of the mesoscale model (say 10 km) there would be a great deal of heterogeneity which would need to be parameterized or lumped. Furthermore, the hydrologic model would produce sensible and latent heat fluxes, as feed back to the atmospheric model.

USE OF REMOTE SENSING

Implicit in the development of macroscale and mesoscale hydrologic modeling for evaluating the effects of climate change will be the use of remote sensing data. Remote sensing data planned for the EOS era are designed to monitor aspects of climate change. Only remote sensing data will be able to provide the large scale (continent to global) coverage for extended periods. With respect to hydrologic model development, these models should be developed to use as much remote sensing data as possible. This is necessary if the models are to be used in areas with limited surface data availability. It is also necessary if there is to be a direct connection between measured indices of climate change (via satellite) and modeled effects of climate change. Surface temperatures, NVDI, snow cover and soil moisture are examples of remote sensing derived parameters that could be used as indicators of climate change and model inputs or system states.

When considering how remote sensing data may be used in models, it is necessary to consider the type of data and the structure of the model. There are four broad areas of applications of remote sensing data to hydrologic models, each of these is discussed below:

(1) Measuring System States: Use of electromagnetic radiation outside of the visible range such as thermal infrared and microwave for their unique responses to properties important to hydrology.

(2) Area versus Point Data: The use of data representing an area in which the spatial variability of specific parameters of the area have been integrated.

(3) Temporal Data: The potential for frequent measurement to develop time series of changes in given parameters and to monitor the dynamic properties in hydrology.

(4) New Data Forms: The merging of several data sets of different wavelengths, polarizations, look angles, etc. to provide specific measurements of hydrologic parameters or entirely new hydrologic parameters that are developed from the unique characteristics of remote sensing.

Each of these presents a unique opportunity for hydrologists to apply remote sensing in ways other than simple extensions of photogrammetry. Remote sensing can produce an integrated measurement that is simultaneously observing several factors. It is also giving us a view that is uncommon to our past thinking in that it looks at a relatively large area and somehow integrates information from the entire scene. To use these data effectively we must develop new concepts and change our historical way of conceptualizing hydrologic processes.

FUTURE REMOTE SENSING DATA

Historically most hydrologic data have been collected to answer engineering rather than scientific questions. In addition, these data, for the most part, have been point measurements. However, to address the global change possibilities, hydrologic data are needed to measure fluxes and reservoirs in the hydrologic cycle and to monitor hydrologic change over a wide range of spatial and temporal scales.

Fortunately, the EOS (Earth Observing System) era will have a number of new instruments on satellites that will be extremely important for hydrologic modeling. Perhaps the most important of these will be some of the proposed microwave instruments that may be used for soil moisture, snow properties, and other moisture related system states. Table 1 lists some of the future satellite systems and sensors that should have a major impact on hydrologic modeling. Current satellite systems are dominated by visible and reflected infrared sensors. These provide useful, but limited data for use in hydrologic modeling. It can be expected that the future satellite systems, with more sensors in the thermal IR and microwave regions of the spectrum will provide much more useful data for the development and operations of hydrologic models.

SUMMARY

It is apparent that some improvement in hydrologic modeling can be made by modifying existing models to use remote sensing data. However, it follows that even greater gains can be achieved with new models designed to use remote sensing as well as conventional data. Such models would resemble existing comprehensive models but would be able to account for the spatial variability inherent in a natural system and measured by remote sensing. In addition those new models should emphasize the use of thermal IR and microwave data for defining system states as well as the frequency of observation possible from satellite systems.

It is also important to recognize that the same satellite sensors that will be used to monitor climate change can also be used for model input data and accounting for storages in the form of snow and soil moisture. Thus, through the satellites, there will be a direct link between the measures of climate change and water resource model outputs.

Table 1. Future satellite systems that will have important instruments for hydrologic modeling.

Satellite	Instruments	Principal Hydrologic Variables
RADARSAT	SAR C-band VV	snow
	VNIR	soil moisture
EOS-AM	ASTER	radiation
	CERES	vegetation
	MISR	land cover
	MODIS-N	
EPOP-1	MERIS	vegetation
	AVHRR	soil moisture
	SAR C-band	snow
	MIMR	
	AMSV	
EOS-PM	AIRS	land cover
	AMSU	radiation
	CERES	soil moisture
	MIMR	snow
	MODIS-N	vegetation
TRMM	AVHRR	rainfall
	Radar	
	Microwave radiometer	
JPOP-1	AMSR	soil moisture
	AVNIR	land cover
	SAR	

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PRECIPITATION PROCESSING WITH THE WSR-88D

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ABSTRACT

The National Weather Service (NWS) has been deploying the new WSR-88D weather radars since late 1991. A significant portion of the WSR-88D algorithm set is in support of precipitation processing. The integrated system of the WSR-88D with high resolution radar data along with significant computing capabilities will allow the use of radar for wide scale generation of quantitative precipitation estimates from radar for the first time. Precipitation processing will be performed in three stages to support both the flood and flash-flood forecasting requirements of NWS. The three stage processing will also take advantage of other supporting information -- rain gage and satellite infrared imagery -- in order to improve and quality control the radar precipitation estimates. The final stage of processing is an interactive process to perform final quality control of the precipitation field while mosaicking data from multiple radars over NWS River Forecast Center areas of responsibility. The radar estimated precipitation will then be used as input to the hydrologic models run by the River Forecast Center. It is anticipated by 1996, when the complete network of WSR-88Ds is deployed, that approximately 98% of the continental United States will be provided with radar coverage.

INTRODUCTION

Since 1979, a significant amount of work has taken place within the NEXRAD (Next Generation Weather Radar) program in the development of the WSR-88D (Weather Surveillance Radar - 1988, Doppler). NEXRAD is a joint program of the Departments of Commerce, Defense and Transportation for the development, deployment, and operation of a new nationwide network of weather radars. The first commissioning of a WSR-88D system is scheduled to take place in 1993.

A major portion of the WSR-88D software is in support of precipitation processing. In addition to the processing within the WSR-88D, the NWS Office of Hydrology has developed a three stage process for developing high quality quantitative estimates of precipitation for use as input into existing hydrologic models. These radar derived precipitation products will have a number of uses both in NWS forecasting and other water management applications.

Availability to the data stream will be provided through a variety of mechanisms for both real-time and non-real-time products. The appropriate path for a given organization depends on whether or not they are a NEXRAD program agency, the time requirements of their data needs, and the resolution of the data required.

THE WSR-88D SYSTEM

The new WSR-88D radar system has two major components: state-of-the-art microwave radar, computer, and communication hardware and high performance

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software which combine to produce a system which is second to none in the world in terms of performance, versatility, and information processing. The network of over 100 radars, each of which will operate 24 hours per day in an automatic scanning mode, will serve as a replacement and upgrade to the aging WSR-57 and WSR-74 radar systems currently in operational use by the NWS.

Never before has the U.S. had the capability to produce quantitative radar-derived rainfall estimates over the U.S., much less rainfall estimates at the fine spatial (2 km) and temporal scales (6 min) possible with the WSR-88D. This is possible because of digital data processing of the backscattered radar signals by computers (unlike the current radar system) and the generation of a diverse array of value-added products, both rainfall products as well as Doppler velocity-derived products to aid the forecasters in identifying adverse weather situations which may develop rapidly and to serve as numerical input into existing computer models which forecast rainfall and streamflow.

In order to accomplish this task, the WSR-88D system has been designed around four major pieces of hardware: 1) the pedestal and antenna which transmit and receive microwave signals with a high resolution 0.95 degree beamwidth, 2) the Radar Data Acquisition (RDA) unit which generates the transmitted microwave signal and converts the raw returned signal into reflectivity, radial velocity, and spectrum width data, 3) the Radar Product Generator (RPG) computer which runs quality control and scientific algorithms to generate a myriad of derived meteorological and hydrological products from these three measurements, and 4) the Principal User Processor (PUP) which allows the forecaster to visualize the products and aid him in the automatic identification of potentially hazardous weather situations (Klazura et al, 1992). Within about five years the PUP will be replaced by the Advanced Weather Interactive Processing System, a workstation which will allow WSR-88D products to be combined with other data sources such as satellite and automated surface weather observations.

The reflectivity data which is collected by the radar is used to generate a number of value-added products. The Precipitation Processing System (PPS), to be described in more detail in the next section, produces rainfall accumulations over various time periods and is the focus of this paper. In addition to these hydrologic applications, the reflectivity data are also used for meteorological applications. Storm track algorithms keep track of storm motions and forecast future positions. The vertical reflectivity structure is used to determine the likelihood of hail production. Also the probability of severe weather is computed using reflectivity tops and the vertically integrated liquid water content (OFCM, 1991).

Radial velocity data are used to produce a variety of products used to automatically detect severe-weather-producing mesocyclones. Vertical wind profiles are computed, and wind shear and turbulence are produced for aviation applications. Despite the computer automation of the radar scanning and product generation, the human forecaster remains a key element in the hydrological and meteorological interpretation of the products and the issuance of watches and warnings based on the output.

THREE STAGES OF PRECIPITATION PROCESSING

The NWS has defined three stages of precipitation processing for operational use. These different stages are designed to meet the various needs of the hydrometeorologist, ranging from flash-flood warnings, to river stage forecasting, and water management activities. The overall objective is to provide the best quantitative estimates of precipitation possible given the various time constraints imposed on the operational forecaster.

The first stage of processing is performed in the WSR-88D RPG. It will perform a high level of automated quality control, incorporating radar reflectivity data from the four lowest elevation angles of the WSR-88D volume scan, along with a limited sample of precipitation gage data in order to generate precipitation accumulations. The quality control attempts to minimize the impacts resulting from isolated reflectivity points, excessively high reflectivity values, anomalous propagation, abrupt time rates of change of precipitation volume, and range effects resulting from a height varying vertical profile of reflectivity. Precipitation products are updated every 5-10 minutes. Graphical products are produced on a 2-km rectilinear grid with 16 data levels. These products depict 1-hour, 3-hour, and storm total accumulations. The timeliness and spatial resolution of these products are designed to meet the needs of the flash-flood warning program. (Ahnert et al. 1983)

Stage II processing is performed on an hourly time step and produces products on a polar stereographic grid projection, approximately 4-km on a side. Since the time constraints on Stage II are not as great as for Stage I, a more comprehensive set of precipitation gage data is available in order to compute a mean bias of the precipitation field as well as performing local adjustments of the radar estimated precipitation. Satellite and surface temperature data are also incorporated into Stage II processing in order to detect anomalous radar echoes occurring in clear air. Stage II creates a gage-only field which uses radar information to locate areas of precipitation; however, quantitatively, this field is based strictly upon gage data. This gage-only field is then merged with the radar field to produce a multi-sensor field. The merging is an objective analysis based on the nearness of any gages and the uniformity of the precipitation field.

In order to produce river flow forecasts, precipitation estimates must be available over the entire river basin in question. In some cases for the NWS, this requires incorporating data from up to 25 radars within a single office in order to generate a precipitation time series. Stage III processing runs at the River Forecast Center to incorporate data from each radar in the RFC area of responsibility. Stage III has been designed as an interactive process to allow the forecaster some control over the precipitation estimates being input to the hydrologic models. In order to accomplish this task, each RFC will be staffed with three hydrometeorologists whose responsibility it will be to ensure that the highest quality data is input to the models and that appropriate coordination with various Weather Forecast Offices is achieved. Stage III operates with the same spatial and temporal resolution as defined by Stage II. Stage III allows the forecaster the capability to assess the quality of both the radar estimated precipitation as well as the precipitation gage data and to make modifications to the data as appropriate. (Shedd and Smith, 1991).

The output of Stage III processing will be used as precipitation input to the hydrologic models running at the RFC. Currently, these models rely almost completely upon data from precipitation gages to generate the necessary precipitation input for the streamflow and stage forecasts. The increased time and space resolution available from the radar estimated precipitation should allow for consideration of decreasing the areas for which the models are currently applied, and eventually allow for the possibility of more distributed approach to NWS hydrologic modelling.

DATA DISTRIBUTION

Stage I WSR-88D data output is available at several levels, which we will appropriately call Level I, Level II and Level III. Level I data consists of analog WSR-88D echo signals obtained directly from the receiver on the Radar Data Acquisition (RDA) portion of the 88D. This signal is digitized within the RDA before it is sent to the Radar Product Generator (RPG) portion of the WSR-88D for immediate, real-time generation of base and derived products. Level I signal can be archived (called Archive Level I) for use by technical staff doing maintenance or during training. There are now no developed plans to collect, archive, or distribute Level I data.

Level II data consists of digitized base data (reflectivity, radial velocity and spectrum width) from the RDA prior to further processing. Level II data is then ported to the hydrometeorological algorithms resident in the RPG for development of the 39 types of derived products. Access to real-time Level II data will generally be restricted to the three WSR-88D member agencies. It is anticipated that some selected university access to real-time Level II data may be needed, and it is likely it will be limited to universities having specific contractual agreements for WSR-88D algorithm analysis, evaluation or development through an on-going formal Memorandum of Agreement with the member agencies. Level II data will be archived (Archive Level II) on a significant number of WSR-88D sites. Archive Level II data will be used in support of non-realtime operations, maintenance, and development of WSR-88D products within the NWS. It will also be useful for a wide range of radar hydrology and radar meteorology research and development activities. Archive Level II data will be stored and distributed to the governmental agencies, universities, private corporations, individuals and the public by the National Climatic Data Center at Asheville, North Carolina.

Level III data consists of the processed base products and the output of the hydrometeorological algorithms. Level III data will be available to the three member agencies and to many additional users (called external users) via a wide range of delivery options, several to be highlighted.

The NEXRAD Information Dissemination Service (NIDS) has been established to allow real-time dissemination of selected WSR-88D base and derived products to external users, in fact, anyone entering into contractual arrangements with one of the NIDS providers. Four private sector data providers selected by the NWS will access each WSR-88D in the United States and make them available to subscribers. The basic set of eleven WSR-88D base and derived products will be available in real-time from each NIDS vendor. These vendors may also provide value added products derived from the base unaltered products. The contractual agreement between the NIDS vendors and the NWS specifies that all real-time access to the WSR-88D products available to the NIDS vendors will be through a NIDS vendor. (Baer, 1991) The NIDS contract pertains only to the Stage I products.

As a means of insuring low cost access to NIDS output by selected agencies (governmental, public and private), a Special Subscriber program has been developed by the NWS. State Emergency Management Agencies and other agencies with established, shared and contractual arrangements with the NWS will be eligible to become NIDS Special Subscribers. The Special Subscriber program will be limited to 100 participants when the full WSR-88D network is in place. Approval of all Special Subscriber applications rests jointly with the Office of Hydrology and the Office of Meteorology. The University Corporation of Atmospheric Research (UCAR) has been encouraged to negotiate a contract with one or more of the NIDS providers. If this type of contract arrangement can be accomplished to serve university interests, there may be no need to consider university requests within the Special Subscriber context.

Level III data will also be available in non-realtime through several archival mechanisms. The first of these is referred to as archive Level III data, and is prescribed within the Federal Meteorological Handbook Number 11 (FMH-11). Archive Level III will be routinely collected at all NWS sites. The mandated set of WSR-88D base and derived products will be archived at each site and then delivered to the National Climatic Data Center at Asheville, North Carolina for distribution to the nation for non-operational and non-real-time use. Selected Level III data will also be archive at NWS operational sites for use in internal post analysis, training, and development activities on the site. This selected data archive is referred to as Archive Level IV.

While the RFCs have not fully developed plans to archive or distribute the value added Stage II or regional Stage III precipitation products, the NWS has every intention of continuing to share it's data with those water agencies with which it has ongoing relationships of mutual cooperation. The actual means and methods for sharing this data with water resource agencies is now being studied, and within the next several months, a formal mechanism should be developed within the NWS to insure water agencies across the country that access to the Stage II and Stage III precipitation products will be available to them.

It is also anticipated that one answer to national water resource and climatological resource data needs for a national real-time or near real-time precipitation product (called Stage IV precipitation) could be a product developed by collecting and mosaicking the basin wide mosaicked product prepared at each of the 12 RFCs in the conterminous United States. In the future, invitations will be extended to a wide range of water resource interests to meet and help map out requirements for collection, compilation, archiving, and disseminating this product.

STATUS AND EXPERIENCE

As of January 1993, approximately 15 radars have been deployed across the United States. When the full network across the United States of 135 radars is completely available, approximately 98% of the area of the country will be provided with radar estimated precipitation estimates. Although some problems with both hardware and software have been discovered over the past year, overall the experience with the new radars has been extremely positive. In the past, many or most flash-flood warnings have been issued after the onset of the flood event. In regions where the WSR-88D has been deployed, there have been a number of cases with a significant lead time on the issuance of the flash-flood warnings. Similar improvements in the area of severe weather prediction have also been noted.

Although precipitation estimates from the WSR-88D have not yet been directly and routinely input to the RFC hydrologic models, in a number of cases, the radar estimated precipitation has been manually input by the forecaster to update the model on a more timely basis than had they had to wait for precipitation gage reports.

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USE OF AN ON-LINE INFORMATION SYSTEM AND CD-ROMS
FOR DISSEMINATION OF ARS WATER DATA

Jane L. Thurman and Ralph T. Roberts[1]

ABSTRACT

The Water Data Center (WDC) is a unit within the Agricultural Research Service (ARS) of the U.S. Department of Agriculture responsible for the storage, dissemination, and archival of water data collected by the agency. In an effort to make data readily available to the public and to the research community the WDC have developed two complementary methods of distribution. The WDC now provides an on-line information management system using public phone lines and will soon offer a CD-ROM to distribute the data base to researchers. The ARS Water Data Base consists primarily of rainfall and runoff data from experimental agricultural watersheds located in the United States.
KEYWORDS: data base, water, precipitation, runoff, streamflow, hydrology, CD-ROM

INTRODUCTION

Research into the hydrologic processes which affect water and land resources in this country has often been restricted by the quantity and quality of the measured data available to verify theories and to evaluate alternative practices. The Agricultural Research Service (ARS) has recognized the need to compile hydrologic data which will help scientists and engineers to determine practices and methodologies to conserve our national resources. In support of this mission, the ARS maintains a series of experimental watersheds operated by 14 Research Centers some of which have been operational for over 50 years. The continuous data collection activities of the ARS have resulted in an enormous data base of water-related information useful for the validation of physically-based models for energy and water transfer in agricultural and rangeland systems, for studying the effects of various land management practices and for predicting the effects of future climate changes on agricultural and rangeland ecosystems.

The Water Data Center (WDC) is a group within the ARS responsible for organizing and distributing water data that has been collected by the agency. WDC programs include maintaining the ARS Water Data Base, acting as a liaison for ARS with other water information sources, and providing technical support for water resource projects within ARS. The WDC has supported the ARS mission to conserve natural resources by continually improving the accessibility of water data collected by the agency. During the first half of this decade these activities are concentrated around two targets. They are the development of an on-line information system which can be accessed through most microcomputer systems using asynchrounous communication software and a CD-ROM which can be used to provide the entire data base to the immediate use of the research scientist or engineer.

HISTORY OF THE ARS WATER DATA BASE

The watershed research program for ARS was originally developed to conduct research on the effects of alternative agricultural practices on the hydrology

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of small watersheds. All the ARS experimental watersheds are heavily instrumented. Generally the watersheds consist of nested or paired study areas where alternative practices, land use, and climatic variability can be studied in a closely monitored environment. The rainfall/runoff data are unique in that they have been collected with a high degree of detail not often available from agencies known for their data collection activities (e.g., Showen, 1985; Davidson and Guttman, 1986). ARS data include variable time-intensity readings known as breakpoint data. These data are sufficient to recreate storm hydrographs and rainfall hyetographs.

Rainfall and runoff data in the ARS Water Data Base are organized by station year. 'Station year' is used here to signify a calendar year of data for one recording station. A station year of data may vary from 400-10,000 readings per year. There are, as of January 1, 1993, almost 14,000 such datasets, approximately 8,500 and 5,300 station years of precipitation and runoff data, respectively. These data represent information from 333 different study areas varying in size from .2 ha to 637 km^2. The study areas are located in the continental United States as shown in Figure 1. Rain gage networks have from 1 to more than 200 recording stations per watershed.

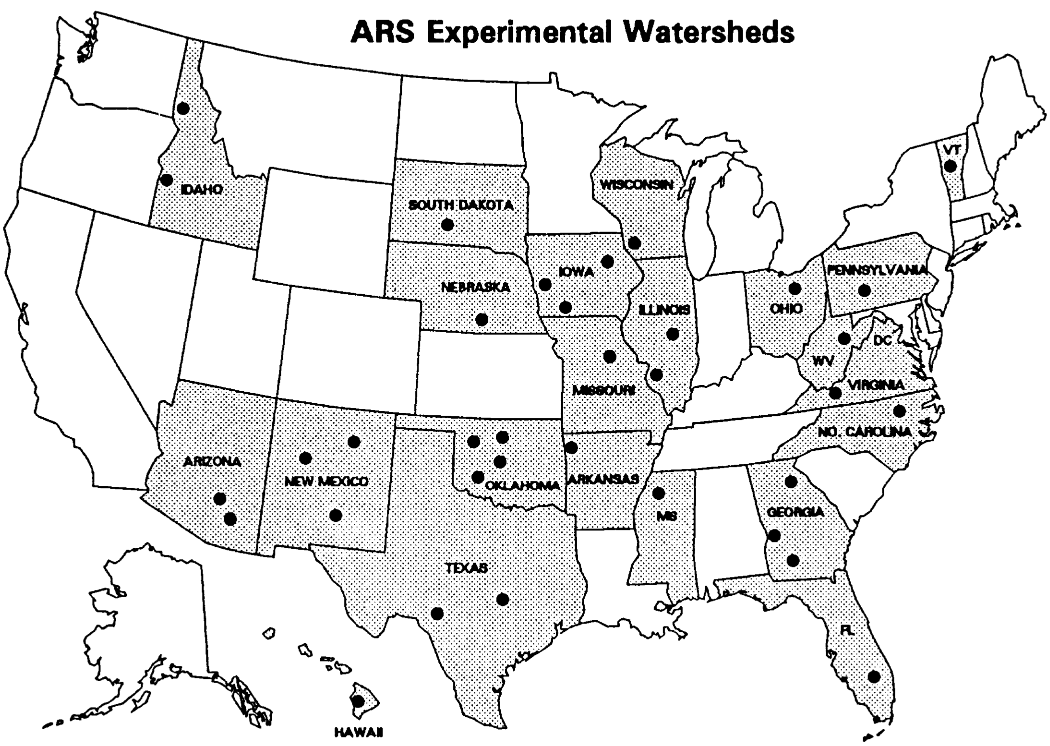

Figure 1: ARS Experimental Agricultural Watersheds

In the late 1950's ARS attempted to provide public access to it's water data by publishing summaries of data collected by the Watershed Research Centers. The WDC was established to compile data publications summarizing the rainfall/runoff data. The result was a series of USDA Miscellaneous Publications now numbering 22 volumes (Thurman and Roberts, 1989).

Compiling datasets for the validation of models or for use in the understanding of natural processes can be a time-consuming and labor-intensive activity. As a central repository for ARS water data the WDC evolved as the distribution point for that data. In keeping with the general goal of making the information readily available to the public and easy to manage, the first activity of the WDC was to standardize data formats. This allowed the WDC to develop generalized programs for updating files, retrieving subsets of data, and summarizing data for publications. Standardizing data formats for the ARS Water Data Base also made processing easier for the research scientist using the data by letting him use the same procedures or programs to input data from diverse locations into his research models.

For many years the ARS Water Data Base was maintained on a USDA regional mainframe computer with the files stored on magnetic tapes. An interactive computer system, known as REPHLEX (Thurman, et al, 1983), was developed to allow individuals to access the data base from their own computer terminals.

DEVELOPMENT OF THE REPHLEX II SYSTEM

Several developments prompted the WDC to move the ARS Water Data Base to a microcomputer based system located in the Hydrology Laboratory offices. The foremost reason for moving the data base was to improve the responsiveness of the system. Using a USDA mainframe computer precluded non-governmental organizations from using the system. Even governmental organizations had to set up reimbursable agreements to pay for on-line computer costs. Other considerations included the ongoing need to reduce WDC computer costs and to further improve the 'friendliness' of the system. The development of the 386 class of microcomputers and mass storage capabilities such as optical disk storage made the microcomputer environment viable for the needs of the WDC.

As the microcomputer environment evolved, the WDC developed criteria for a system that would meet its' needs. These requirements include the following goals:

1) Multi-user dial-up access using standard communications software.
2) On-line storage capabilities for the ARS Water Data Base.
3) User-friendly dialogues with the customer.
4) Retrieval strategies equivalent to those in the mainframe environment.
5) Electronic file transfer capabilities.

The WDC developed a system in the microcomputer environment with the ability to support multiple dial-up sessions from computer systems using standard asynchronous communications software. The user is able to access the ARS Water Data Base with the same system that he uses for mainframe access, for Bulletin Board System (BBS) access, for electronic mail access or for access to information systems such as CompuServe, Prodigy, etc. Today's computer user is well-versed in the dynamics of calling into a remote system, negotiating screen menu systems and retrieving information. The WDC, like other organizations, intends to capitalize on this expertise. For instance, the Environmental Protection Agency's Center for Exposure Assessment Modeling has found that 18% of their models have been transferred electronically since the implementation of a single-line BBS in 1988 (Turk, 1990).

The current REPHLEX II system consists of an IBM PS/2 Model 80 computer system with three optical disk drives. Two of the write-once, read-many (WORM) optical disks are capable of storing 200 MB of data on each cartridge. The third drive supports a cartridge capable of holding 1.2 GB of information. Life expectancy for data on these cartridges is approximately 25 years. Under the current configuration the entire data base is on-line and is available through the REPHLEX II system.

The WDC implemented a host information system known as InfoHost/2A from A-Comm Electronics, Inc. to handle the communications and data management portion of the REPHLEX II system. This is a full-function version of the software from A-Comm supporting two ports. The system runs in a standard DOS environment, allows for customized menus, and handles all file-handling, message processing, and logging functions. The system uses Novell's Btrieve file handler software to manage the data base. The InfoHost system manages the log-in procedure, capturing name and address information on new users, and assigns log-in ids and passwords. A logging feature maintains a detailed audit trail of users and their activity. The system can handle different access or security levels for both users and data files. Menu screens are customized for the particular application. The menu tree structure can handle up to 15 selection items at each level and up to 20 menu levels (a total of 15^{20} selectable items). Each menu selection item can point to a file giving the system almost unlimited retrieval capabilities.

Access to the ARS Water Data Base can be made using a microcomputer equipped with a modem and almost any asynchronous communications software. The phone number for the REPHLEX II system is 301-504-9300. Modem settings for the user's system should be set to 8 bits per word, 1 stop bit, and no parity. Some systems will need to turn local echo off. Modem speeds of 300, 1200, and 2400 BPS are handled automatically by the REPHLEX II system. No on-line charges are made for using the REPHLEX II system. The only costs associated with the system are the user's phone charges.

DEVELOPMENT OF A CD-ROM

With the development of the REPHLEX II system thoroughly established, the WDC began looking for ways to improve the distribution of data to research activities which need large amounts of data such as that involved in modelling processes for climate change, comparing alternative practices and forecasting. Many of the users of the ARS Water Data Base need more data than could ever be sent over phone lines. Often studies will need to compare measurements from diverse locations spanning many years of data. Also, the development of CD-ROMs by various federal agencies and private organizations made the hardware more often available to the researcher. As Figure 1 demonstrates, the majority of data requests to the WDC are from universities, ARS and other federal agencies. These institutions now frequently have CD-ROM readers.

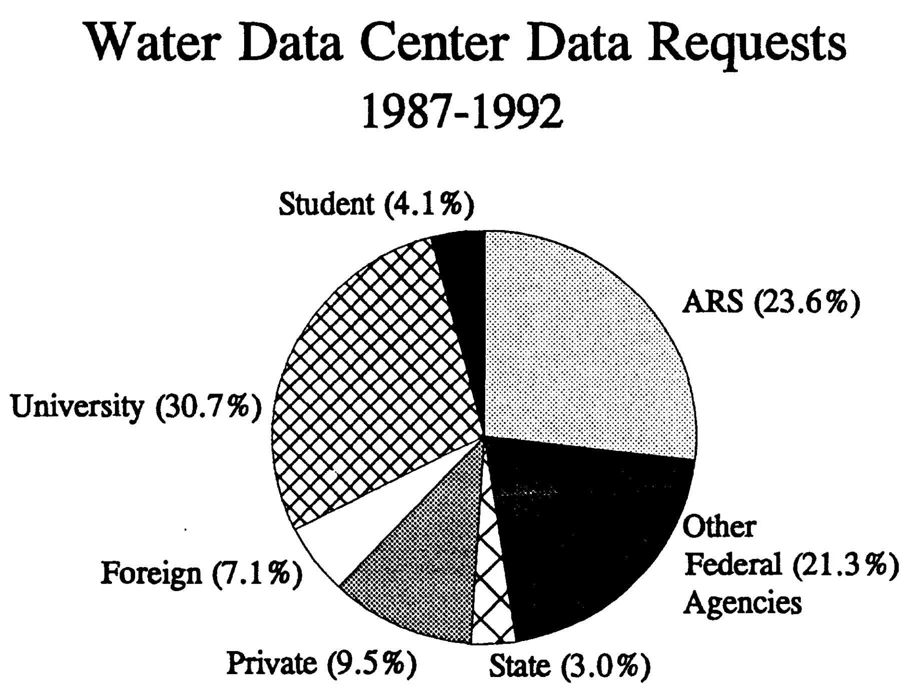

Figure 2: Source of Water Data Center Data Requests.

The ARS Water Data Base is particularly well-suited to distribution by CD-ROM since it is basically an archival data base. Data are added to the data base in minimum increments of a year. Typically several years of data are added at various intervals for a specific location. Rarely is data for an already existing dataset modified. Updates to distributed CD-ROMs are expected to be necessary only about once every 5 years.

The storage needs of the ARS Water Data Base also work well with CD-ROMs. Typical storage for a CD-ROM is approximately 600 MB. The ARS Water Data Base with all redundant information deleted from the data can be reduced to about 400 MB leaving substantial space for auxiliary information and retrieval accessories such as map and land use information.

As the CD-ROM technology evolves, the WDC goals for this distribution method are:

1) On-line storage capabilities for the ARS Water Data Base at the user's location.
2) User-friendly dialogues with the customer.
3) Extensive use of map-oriented extractions.
4) Incorporation of WDC analytic and graphics software.

RETRIEVAL PROGRAM FOR THE CD-ROM

A CD-ROM is considered to be a successful tool or just a storage media depending upon the quality of the retrieval program or interface. The WDC therefore is using the expertise garnered from previous interfaces along with the innovations available in the microcomputer environment to develop a Graphical User Interface (GUI) which will be both user-friendly, efficient and expandable.

The GUI being developed for accessing the ARS Water Data Base was originally conceived and developed to facilitate in-house access in REPHLEX II. It is a logical progression from the interactive REPHLEX system used on the mainframe system and the general capabilities of the microcomputer environment. It's extension to the use of a CD-ROM were enhanced by the availability of in-house mastering systems, CD-ROM recording standards and the availability of extensive code already developed by the WDC.

The basic design concepts of the GUI are taken from several successful commercial window managers, primarily Microsoft Windows and OSF/Motif for X Window. The program is written in Microsoft Professional Development System Basic 7.0, extended with several assembly language routines provided from Crescent Software's Graphics Workshop, allowing the program to run completely in graphics mode. The GUI features the use of menu bars, pop-up menus, and dialogue boxes. All of these tools are or can be controlled through the use of a computer drawing device such as a mouse. Help screens are context-sensitive and callable by function keys or mouse clicks.

There are seven primary functions represented by menu bar choices (Roberts, 1993). Input/output functions are grouped under "FILES". An "OPTIONS" function allows the user to customize his system by setting environmental variables such as colors and path names. The "QUERY" function allows the user to select one or more years of data and to copy it from the CD-ROM. Many different methodologies will be available to the user for specifying selection criteria for queries. The "PLOT" component groups several user routines to analyze and to visually inspect data from the CD-ROM. One of the most innovative of these will be the use of computer-generated map images which will allow the user to select, via the computer mouse, icons representing the data files associated with that location. For instance, a map of a small watershed depicting several rain gages will allow the user to click the mouse on a particular rain gage. A pop-up menu will then indicate the available years of data for that gage and give the user several options for reviewing, copying or summarizing the data. A "REPORTS" component generates various summaries or WDC standard reports. The GUI will also include the ability to link in an individual's local programs.

CONCLUSION

The ARS Water Data Base is a collection of rainfall and runoff data collected by ARS with some stations operational continuously for over 50 years. Over 300 watersheds are represented in the data base with a total of almost 14,000 station years of data. The WDC is currently using a two-pronged strategy to make this data available for public use. The REPHLEX II system combines the advantages of a BBS interface using tree-structured menus, message handling functions, security levels, and rudimentary search capabilities with a strong data management system to provide an on-line information system for the ARS Water Data Base available through dial-up phone lines. The WDC is also in the process of developing a CD-ROM to distribute the data with a GUI which features map-oriented retrieval mechanisms, plotting routines, extraction capabilities and summarization facilities. For many users of the ARS Water Data Base this will mean the availability of data on-line at their own location.

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SECOND RELEASE OF THE U.S. GEOLOGICAL SURVEY'S NATIONAL WATER INFORMATION SYSTEM II

JEFFREY D. CHRISTMAN AND OWEN O. WILLIAMS[1]

INTRODUCTION

The U.S. Geological Survey's Water Resources Division (WRD) is developing an integrated, hydrologic data management system called the National Water Information System II (NWIS-II), which will replace the functions of WRD's current systems and include expanded capability for the management of surface-water, ground-water, water-quality, biological, sediment, water-use, and spatial data. The current systems, developed between 1971 and 1986, comprise more than 14 major data bases that exist as separate files. Each file is structured differently with its own input and output applications. Each system contains the same site location and descriptive information as well as outdated and excessive code that is difficult to manage. NWIS-II, a single, integrated data base with structured, compact code will remove the need for redundant information and be more manageable than the separate current systems. In addition, the processing and retrieving of data for multi-discipline studies will be facilitated by removing the need for numerous input and output applications. NWIS-II will be distributed across the Nation on 32-bit microcomputers and will include a polling capability for retrieving data from multiple nodes of the network. The goal of the NWIS-II effort is to develop and implement a highly flexible hydrologic data management and processing system that can be easily changed and expanded in a rapidly changing technological environment. Most of the functionality of NWIS-II will be implemented in the first two releases. This paper describes the system requirements and the functionality of the second release.

DEVELOPMENT PROCESS

The development of NWIS-II is being done in phases: initiation, requirements definition, analysis, design, acceptance, installation, and implementation. The initiation phase began in 1988 when the Strategic Planning Group (SPG) was formed. The SPG consists of most of the senior managers of WRD, including the five Assistant Chief Hydrologists and the four Regional Hydrologists. The purposes of the SPG are to (1) establish the framework within which the NWIS-II is developed, (2) establish policy and guidelines for the NWIS-II development, (3) provide ongoing direction to the development effort, and (4) provide the necessary personnel and financial resources to complete the development.

The SPG appointed 50 WRD personnel to eight discipline-specific User Groups in January 1989, marking the beginning of the Requirements Definition Phase. The eight User Groups represent the disciplines of surface water, ground water, quality of water, sediment, biology, water use, spatial, and a National Water Data Exchange Group to represent the non-USGS users of the current systems. The purpose of the User Groups is to describe the user needs, including specific capabilities of inputting, computing, storing, and retrieving all forms of hydrologic data and ancillary data.

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The Analysis Phase began with the formation of the design team in Reston, Virginia. The initial tasks of the design team were to integrate the eight user documents produced by the User Groups, decompose the requirements to major functions, and diagram the high-level entity relationships. The Analysis Phase continued through 1991 with the review and publication of the System Requirements Specifications (Mathey, 1991).

We are currently, 1993, in the Design Phase using the Rapid Application Development (RAD) method to develop the NWIS-II. Groups have been formed within the design team to model subsets of the system and demonstrate them to the User Group Chairs for acceptability prior to evolving to the next level of development. Much of the coding for NWIS-II is done by two code teams located within the USGS District Offices in Tucson, Arizona and Little Rock, Arkansas.

All products produced by the design team are reviewed by the Review Team formed by the SPG. The products reviewed include the System Requirements Specification, the logical data model, the data dictionary, the data-flow diagrams, and the integrated design. This team will do the system acceptance testing, which determines when the system is ready for release.

The installation and implementation of NWIS-II will be accomplished through a series of releases. The first release is planned for April 1993 and will contain the subsystems for processing and storing discrete data, i.e., data collected less frequently than daily. The first release will provide for entering, editing, verifying, retrieving, and displaying discrete ground-water, water-quality, biological, and sediment data. It also will provide for establishing new sites and updating existing site-descriptive information. The second release is planned for October 1993 and will provide for processing and storing water-use data, time-series data, and discrete surface-water data, such as peak flows.

NWIS-II SYSTEM REQUIREMENTS

Software Requirements

The NWIS-II data base has been designed and modeled using an INGRES[2] relational data-base management system interfaced with UNIX files for the storage of time-series data. The applications for entering, editing, verifying, retrieving, and displaying data are being modeled and developed using INGRES Windows/4GL, which is a fourth-generation language producing a graphical user interface. Pop-up and pull-down menus, scroll bars, and multi-form processing will be available to the user for entering and retrieving data. Publication-ready tables will be generated using FrameMaker, a reports processing system that will be interfaced with the INGRES software. A main menu has been developed that consists of buttons by which the user may select a function using a mouse.

Hardware Requirements

NWIS-II will be distributed across the Nation on 32-bit microcomputers utilizing local-area network and wide-area network technology. Each USGS District Office will be a node on the network. The hardware requirements of each office vary with the size of the office, but basically consist of a dual processor server with 128 megabytes of memory and 8 to 12 gigabytes of storage

2. The use of trade or firm names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

for the NWIS-II data base and INGRES software. Each user of the system should have a workstation with 20 to 28 megabytes of memory and a 322-megabyte hard disk. Field offices required to remotely access the district data base may require at a minimum one workstation with the INGRES and NWIS-II software loaded on a 622-megabyte hard disk and 28 to 32 megabytes of memory.

Security

Data stored in the data base will go through an aging process using flags to indicate the status of the data. The data-aging statuses are "original," "working," "in-review," "approved," and "published." Upon entry, WRD time-series data will be flagged as "working," whereas data collected by other organizations and individuals will be flagged as "accepted as reported." The authority for changing the status of the data and the type of access a user will have are determined by the user's role in a project and the status of the data. The local system administrator has all rights to the data regardless of the status. The project manager has all access rights to the data collected in his project area and stored in the data base with his project identifier. The project manager also has the authority to assign a user role to other people for access rights to the data associated with his or her project. The user roles that may be assigned by the project chief include project worker, data reviewer, and project viewer. A public viewer will have "view" access rights only for approved and published data.

Mandatory and Required Data

The site must be established in the data base prior to entering data into the data base. To establish a site in the data base, seven mandatory items must be entered. The mandatory items are listed below:

1. Feature Type --A feature is defined as a physical, conceptual, political, or other object that may be sampled or measured, or be a subject of any other activity. Some example feature types are streams, springs, wells, estuaries, lakes, project areas. water treatment facilities, states, counties, and hydrologic units.
2. Feature Name -- A name used to distinguish a particular feature from other features of the same type. An example is "Ohio River."
3. Source Organization --The organization that has fiscal responsibility for the maintenance of the site and/or the collection and management of the data. No point data, statistical data, or aggregated data describing features, stations, or water-use facilities can be entered without the source organization being entered or already existing in the system.
4. Station Identification Number -- A 1- to 15-alphanumeric character that identifies the site established by the source organization. This is entered for all data except those that characterize a complete feature. Even though a well is considered a feature, a station identification number is mandatory. In the case of non-USGS data where no station number has been assigned, a number will have to be assigned before it can be established in the data base.
5. Project Number -- The project number is the officially recognized and funded WRD task that is the basis for activities. This is required for performing security functions of the data at a project level.
6. Time Zone -- This is the time zone in which the site is located. An example is "EST" for Eastern Standard Time.

7. Daylight Saving Time Flag - This flag indicates that daylight saving time is used at the site when activities take place.

Another category of data elements for the system is required data, the items that must be entered before the data can be flagged as approved or published. These items include state, county, hydrologic unit, latitude and longitude, and altitude to define the location of the data collection. Also included are the accuracy of the latitude and longitude; accuracy of the altitude; accuracy of the data collected; accuracy of the time of collection; and the method of measurement, sampling, or analysis.

SECOND-RELEASE FUNCTIONS

The main menu of the NWIS-II, shown in Figure 1, has five buttons labeled: Establish Sites, Conduct Activities, Process Data, Output Results, and Help.

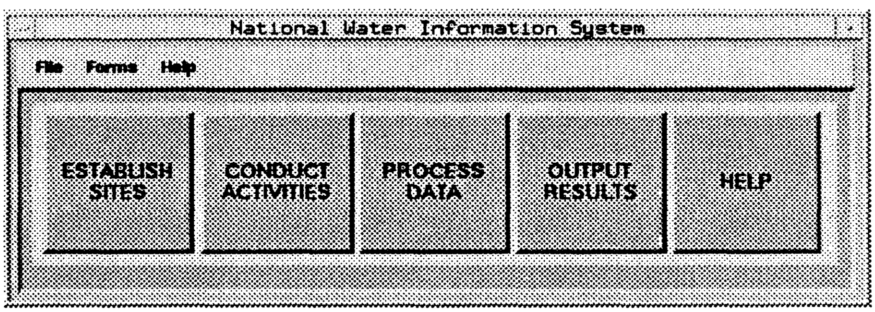

Figure 1. -- Main menu of the National Water Information System II

Selecting one of the buttons with the mouse will bring up a main form for performing related functions that may require additional forms selected from the main menu. Figure 2 depicts the menu structure and functions performed by selecting the appropriate main menu button. All second-release functions will use the main menu to display the forms required and navigate through the system. The second-release NWIS-II capabilities are described below.

Establish Sites

Most of the functionality of Establish Sites will be provided by the first release of the NWIS-II. This functionality will include station, location, and event-point input forms. The second release will provide additional forms to enter additional site information needed for the processing of time-series data and to describe water-use facilities.

Conduct Activities

Conduct Activities contains the electronic input forms that the user fills in to enter information about hydrologic activities. These activities usually take place in the field but are not limited to field activities. The input includes activity and quality-assurance information, such as persons engaged in the activities, dates and times of the activity, purpose of activity, equipment used, calibration of equipment, and environmental conditions during the activity. The second-release input forms for hydrologic activities will include stream-discharge measurements, crest-stage

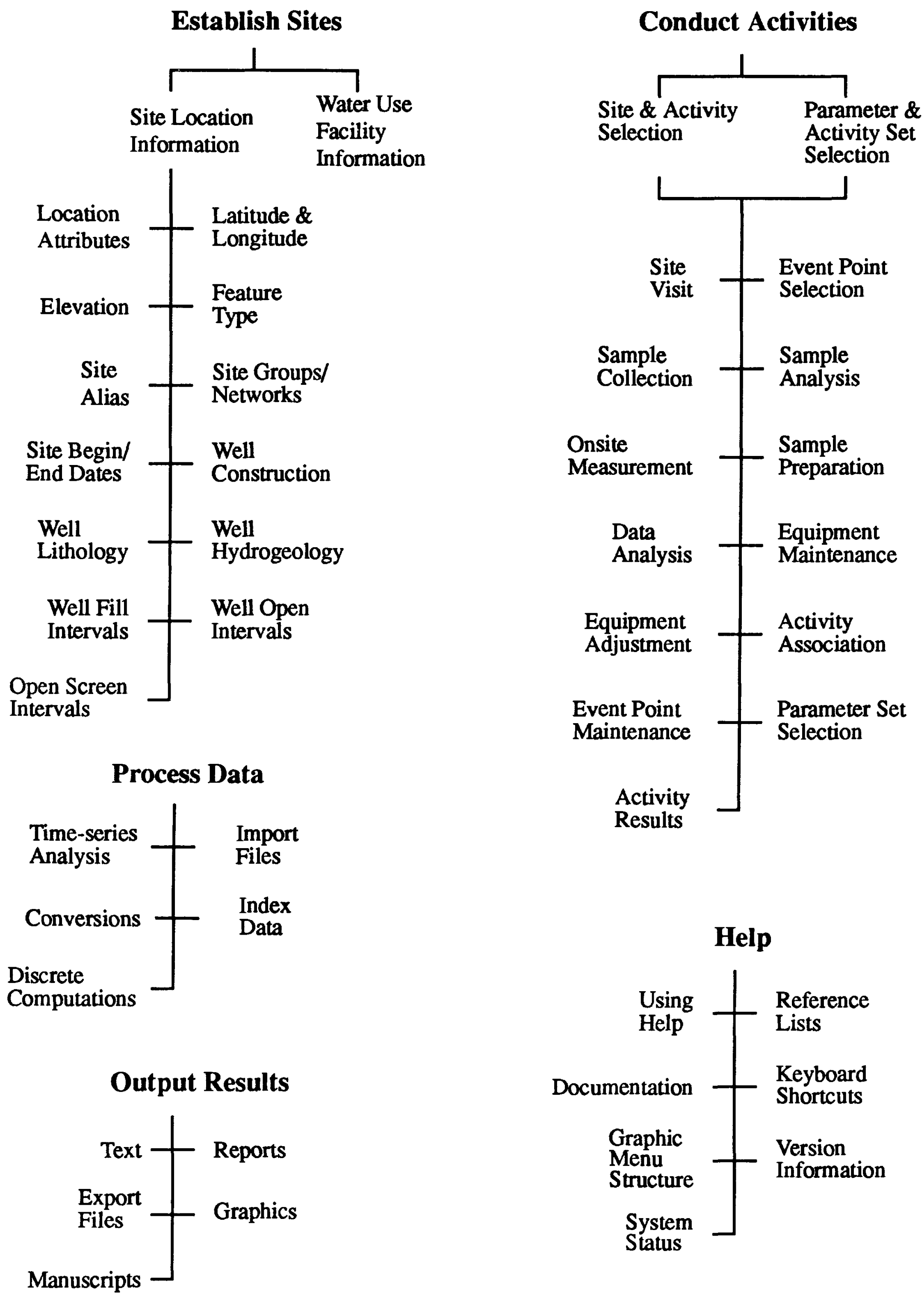

Figure 2. -- Menu Structure of the National Water Information System II

measurements, water-quality monitor inspections, determination of peak flows, and basin characteristics. The discharge-measurement form will include information on the method and equipment of measurement, hydrologic and meteorologic conditions, the rated quality of the measurement, and the measured discharge, width, and velocity of the stream section. The crest-stage-measurement form will include field data from the measurement of the peak stage by use of a crest-stage-measurement pipe. The water-quality-monitor inspection form will include field-visit calibration information for a water-quality monitor, remarks, and time checks for the recorder. The input forms for water-use data also will include water-use facility, site-specific, and aggregate information. The determination of peak flows will be an application that scans the unit values of the discharge, displays the peaks of storm events, and permits the user to select the representative peaks for storage in the data base. The basin characteristics input form will permit the user to enter any number of characteristics of a hydrologic basin, the method of determination, and the accuracy of the value.

Process Data

Process Data will consist mainly of the analysis of time-series data and the development of rating tables and equations. Time-series data are data collected once a day or more frequently, and are termed unit values or daily values. Unit values are collected more frequently than once a day by an analog-to-digital recorder (ADR), an electronic digital logger (EDL), a strip-chart analog recorder (SCR), or a data-collection platform (DCP) that relays the data through a Geostationary Operational Environmental Satellite (GOES) to a local receive site. A daily value, a single statistical value for each day, is determined from the unit values collected. A daily-value record may consist of daily means, daily maximums, daily minimums, or other statistical values for each day of the record. In fiscal year 1991, WRD operated 7,346 time-series surface-water-discharge stations. During the same period, WRD collected time-series stage-only data at 1,394 stations, water-quality data at 653 sites, and ground-water-level data at 2,376 sites.

Before the processing of time-series data can take place, the rating table or equation must be developed. The rating is used to determine one parameter from another parameter, such as determining stream discharge from stage. This rating is either a value "look-up" table or an equation that mathematically describes the relation between the two parameters. NWIS-II will allow the development and entry of either a linear rating table, a logarithmic rating table, or a rating equation.

Time-series data are processed by completing several operations (fig. 3) that permit the user to enter, edit, compute, and review the data. All types of time-series data generally follow the same processing steps. The user is led through this processing by a display screen that identifies the site, the parameter, and the time period to be processed; shows the completion status of each operation; and presents the next operation to the user. The basic philosophy followed in the processing of time-series data is that a copy of the results of each operation are kept in the data base so users can, at any time, back up and start over at any previous operation of the processing. If this happens, the user is led through each critical stage from that operation forward.

The processing of time-series data starts with the input of field-recorded unit-values data from ADR's. EDL's, and SCR's. The unit-values data entered are passed to an application called DECODES, which translates the format of the data from the recorder to a WRD standard format. These WRD standard-formatted data are saved as original data, are part of the permanent record, and are not changed thereafter. From this point, the user can edit the unit values to correct for recorder malfunctions and to apply time- and value-prorated data corrections to the unit values to

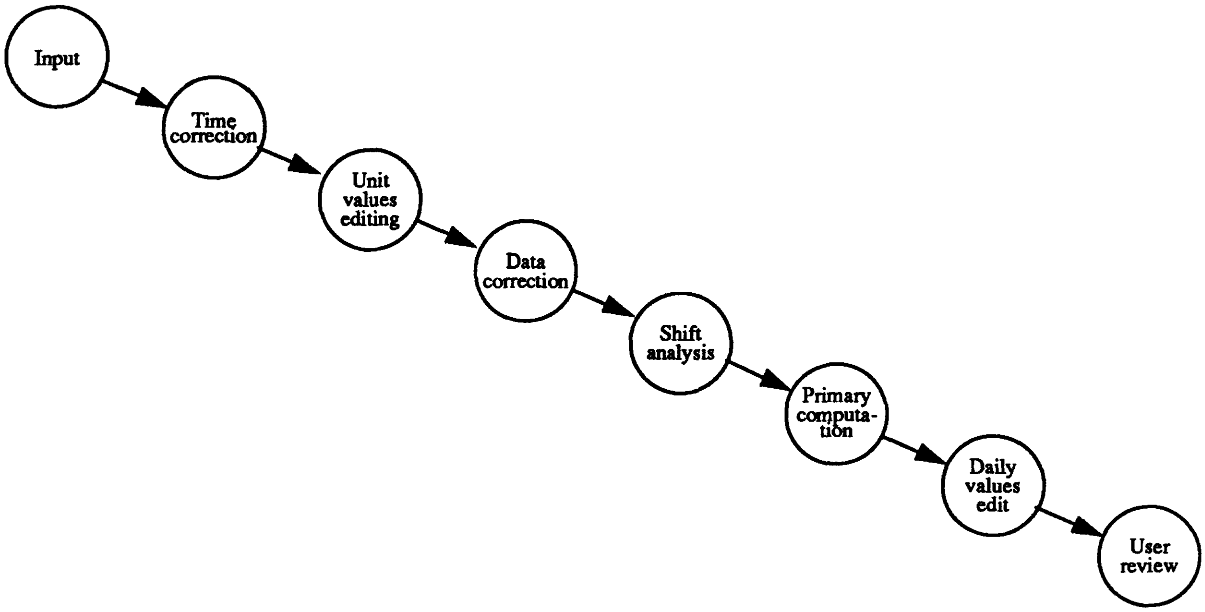

Figure 3. -- Sequence of operations in the processing of time-series hydrologic data

adjust unit values for such items as water-quality monitor calibrations and instrument datum errors. These corrected unit values are considered the official unit values of the input parameter and become part of the permanent record. If the unit values are gage heights used to compute unit values of discharge, the user can analyze the hydrologic conditions as they apply to the stage-discharge rating and define shifts caused by changes in stage added to the official gage-height values, and effectively shift the unit values to the rating curve, adjusting for changes to the control section of the stream. The shifted unit values of gage height are used only to compute stream discharge.

When all of these operations are completed, the primary computation can be executed. The primary computation takes the results of the previous operations and, using existing computation instructions and ratings, computes unit and daily values for the selected station, the computed parameter, and the time period. The primary computation performs several different types of unit-values computations, such as stage-discharge, slope-discharge, velocity index-discharge, discharge through a dam, sediment load, water-quality load, reservoir content and level, rainfall, and miscellaneous rating. The daily values computed will include maximum, minimum, mean, total, and tidal-statistics. The user can then review the results of processing the time-series data by displaying or printing primary sheets, unit-values tables, daily-values tables, corrections or shifts, comments made during the processing, or error logs. The user can return, if necessary, to any step of the process and re-start the processing at that point, modifying what has been done previously. If the user is fully satisfied with the processing done, the status of the time-series data is changed from "working" to "in-review," which means the time-series data cannot be changed (unless its status is changed back to "working" by the project chief or reviewer). When the data are approved by the project data reviewer, the results are open to public viewing.

The time-series processing of sediment data in NWIS-II will also be included. Sediment data are collected in the field either manually or by water-quality samplers automatically. These samples are analyzed in a laboratory to produce discrete values of sediment concentrations. To compute sediment discharges, these concentrations are used to produce a set of unit values of concentration. These unit-value concentrations are combined in the primary computations with unit values of stream discharge to produce unit values of sediment discharge. The daily load of sediment discharge is computed from the unit values of sediment discharge. This type of computation can be used on any water-quality parameter of concentration to produce a water-quality parameter discharge.

One other type of data input is the automatic processing of data collected and transmitted by Data Collection Platforms (DCP's) through the GOES and other types of automatically transmitted data. The process is accomplished by two applications: (1) an application called SATIN, which receives data from DCP's, translates the format into the WRD standard format, and distributes it across the DIS-II network to local WRD offices; and (2) an application called SENTRY, which receives the WRD standard-formatted data, enters the data into the data base, and does the primary computations on the data, making these data available to users 24 hours a day. These data will then later be retrieved and manually processed by users as described previously for ADR, EDL, and SCR.

Output Results

The principal function of NWIS-II is to disseminate the hydrologic data to the users who request the data. Therefore, one of the most-used functions of the NWIS-II will be the applications that retrieve the data from the data base and output the data in a useful format. This function is accessed by selecting Output Results from the main menu. A form to select a type of report and to iteratively select the data needed is then displayed on the screen. Because there is a wide diversity of hydrologic data in the data base, the user is led through one or more forms that help define the data needed, on the basis of the type of report selected. The forms permit the user to specify the time period, station(s), and constituent(s). The user can narrow the scope of the data by starting with a wide retrieval and iteratively specifying more detailed retrieval instructions. The application contains all of the report formats specified as needed by the User Groups that defined the requirements of the NWIS-II. The time-series reports include several different formats of unit- and daily-values tables, primary computation sheets, and publication-ready manuscripts for the WRD annual data report. Water-use reports for facility, site-specific, and aggregate data also will be included in the second release.

SUMMARY

NWIS-II is an integrated, hydrologic data-management and processing system that will be distributed across the nation on 32-bit microcomputers and will include an efficient polling capability for retrieving data from multiple nodes of the network. The first release of NWIS-II will contain the functions for processing and managing discrete ground-water, water-quality, biological, and sediment data. The second release of NWIS-II will contain all the functions required for processing and managing time-series data collected by ADR, EDL, SCR or DCP and will include the water-use functions of input, edit, and tabling of data.

NWIS-II will have the capability to store the original time-series data, make time corrections, insert missing values, change or delete incorrect values, add a remark code to the data, apply time- and value-prorated corrections, perform a shift analysis of stage, apply a rating, compute unit values, and compute daily values, The daily values computed include maximum, minimum, mean, total, and tidal-statistics. Computations performed include stage-discharge, slope-discharge, velocity index-discharge, reservoir content and level, sediment load, water-quality load, rainfall, and discharge through a dam.

The time-series and water-use data will be retrievable by specifying the type of report required and then narrowing down the amount of data retrieved by specifying the time period, station(s), and constituent(s). The reports available will include several formats of unit-values and daily-values tables, primary computation sheets, publication-ready manuscripts for the WRD annual data report, and water-use reports.

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SNOTEL

DAVID E. JOHNSON [1]

ABSTRACT

Conceptual hydrologic modeling is being investigated by the USDA/Soil Conservation Service (SCS) to improve decision making by Western water resource managers. These models are data intensive and generally intolerant of problems with data availability, quality, or format. The SCS data collection and management systems have the characteristics and proven reliability to support conceptual hydrologic modeling.

INTRODUCTION

Water supply forecasting is particularly important in the generally arid Western states where mountain snowpack is the source of most streamflow. Since the mid-1930s the SCS has been the principal agency collecting snowpack data to support water supply forecasting by SCS and other agencies.

In the post World War II decades, development and heightened attention to environmental concerns in the West have produced increasing demands on water resources. There have been associated demands to improve the reliability and timeliness of water supply forecasts.

The response to these demands by SCS has been improved regression-based streamflow volume forecasting (Garen 1992a) and, for some key forecast points, forecast modeling (Garen 1992b). Improvements in the SCS systems for collecting and managing snowpack and related hydrometeorological data provide necessary support for these improved forecasting procedures. Data from the automated SNOwpack TELemetry (SNOTEL) system and the data management capabilities of the Centralized Forecasting System (CFS) play a vital role in conceptual modeling for water supply forecasting.

THE SNOTEL SYSTEM

By the late 1950s the cooperative federal-state-private snow survey program that SCS directs included almost 2000 manual snow courses. These courses, located in high mountain meadows, were the point measurements used as the basis for water supply forecasting. Measurements were made monthly beginning usually on January 1 and continuing through May or June 1. In some cases one or more mid-month measurements were also made. The desire for more frequent information and the hazards associated with the labor intensive manual measurements led to the development of automatic sensors to measure accumulated precipitation and temperature as well as the weight of the snowpack (snow pillows).

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In the mid-1960s several line-of-sight radio networks were installed to monitor remote data collection sites automatically. These networks required mountaintop repeaters, and they were relatively expensive to install and maintain. In addition, some repeater locations were being challenged for removal as a result of the wilderness legislation.

Studies were initiated by SCS to find a new communications system for the entire Western U.S. that could provide the required snowpack and related hydrometeorological data in a near real-time mode. Functional requirements for the new system were specified in part by the forecasting hydrologists with the intent of eventually supporting conceptual modeling. The studies investigated several data systems. The emerging meteorburst technology was selected as the most cost effective system meeting the functional requirements. Meteorburst communications uses the billions of sand and gravel sized particles that daily enter the zone 50 to 75 miles above the Earth's surface. The ionized gas trails produced as the particles enter the zone reflect or reradiate the VHF signals used for data transactions between the master stations and the remote sites (Crook and Johnson 1987). Signals can be received at a master station from remote sites up to 1200 miles away.

Congressional approval came in 1974 and funds were appropriated to implement SNOTEL. Implementation began in 1977, and by 1980, 465 remote sites had been installed.

SNOTEL is operated by SCS and, except for the early installation period, SCS performs all maintenance and system enhancements. By the early 1980s SNOTEL performance exceeded design levels and system capabilities were expanding. In 1985 a system upgrade was initiated to modernize all components. The upgrade will be completed in 1993 for the nearly 600 SNOTEL sites in the system, as well as the two master stations and the central computer in Portland.

THE CENTRALIZED FORECASTING SYSTEM

A data collection system, to be effective and efficient, must include facilities for quality control, data storage, format modification and easy access to the data. SCS developed the Centralized Forecasting System (CFS) to handle the information related to water supply forecasting (Shafer and Huddleston 1986). It includes streamflow, precipitation, snow water equivalent and reservoir data. These data are available for the current water year (October 1 through September 30) and for historical water years. CFS also includes numerous routines and interactive programs as utilities for manipulating water supply data.

CFS is on-line 24 hours a day, 365 days a year. It is a menu driven system designed for easy, rapid access. Most computer systems can access the data and products available in CFS. Automatic data exchanges with the National Weather Service (NWS) and other agencies ensure the availability of required data.

Forecast development and generation are performed on CFS by SCS hydrologists, and reports are created that are downloaded in SCS offices for local distribution. Various site-specific or period-specific reports can be developed. CFS supports natural resource management and conservation planning activities. In addition, CFS contains various utility programs for SCS use in quality control of measured data and forecasts.

SNOTEL AND CFS FOR SUPPORT OF CONCEPTUAL HYDROLOGIC MODELING

The goals that SCS has in using conceptual hydrologic models in water supply forecasting deal with improved forecast accuracy, shorter forecast periods, related forecast products, "what-if" scenarios, and improved reservoir operation and water resource management (Garen 1993). The realization of these goals will enhance water resource management in the West for agriculture and other purposes.

Modeling imposes some rigorous demands for data and for the data collection system. The amounts of data required for frequent model-based forecasts greatly exceed the requirement for monthly regression-based forecasts, and the time frame for supplying data is much shorter. Generally, tolerances for data errors or missing data are minimal, and precise format requirements are the rule. Three characteristics of the SNOTEL network and CFS make them an excellent system for supporting conceptual modeling: system reliability, easy access to the data, and adjustable data formats. These characteristics are discussed below.

System Reliability

SNOTEL is designed to operate in severe environments unattended for at least one year. Extra battery and solar power as well as dual sensors are often provided for the most critical or most difficult to reach sites. Eight performance characteristics are reported daily to provide advance warning of any site problems that may be developing. System performance averages above 98 percent.

SNOTEL includes two on-line master stations (in Boise, Idaho, and Ogden, Utah) that can each run the system independently with only minor degradation in performance. Similar redundancy is included in the Central Computer Facility (CCF) in Portland, Oregon. Five data Collection offices located in the major Western river basins monitor site performance as well as data quality.

Easy Access

The SNOTEL CCF can be accessed directly for agencies requiring immediate data. Generally access is through CFS after the data have been validated and transferred from CCF to CFS (about 6:20a.m. PT). Data are also posted daily to the NWS Gateway system. CFS supports 18 telephone lines and accommodates most computers.

Adjustable Formats

Data are retrieved in a format that lends itself to computerized data exchange in the Standard Hydrologic Exchange Format (SHEF). This is a machine readable format that supports model input. Utility programs in CFS allow certain data reformatting to meet specific model requirements.

DATA CHARACTERISTICS TO SUPPORT CONCEPTUAL MODELING

In addition to having a data collection and data management system that supports conceptual modeling, the data must possess certain essential characteristics. Three characteristics of the data from SNOTEL are particularly important: data site distribution, data time steps, and data to validate and update simulated values. These characteristics are discussed below.

Data Site Distribution

SNOTEL sites were located by hydrologists specifically to collect representative snowpack and related hydrometeorological data. Many were colocated with manual snow courses that have been measured since the 1930s or earlier, thus reducing the need for manual measurements. The 570 SNOTEL sites are distributed throughout the major snowpack areas at critical elevations. Meteorburst communications allows optimization of site locations for hydrologic response without concern for the data communications paths. SNOTEL data make it possible to estimate basin precipitation and temperature much more accurately than previously.

Data Time Steps

SNOTEL is polled daily which generally satisfies forecast modeling requirements. More frequent system polls or specific site polls can be initiated when needed. After the SNOTEL upgrade is completed, the timesteps for most individual sensor measurements can be adjusted remotely from the CCF using the meteorburst link.

Validation Data

Modeling generally simulates the snowpack from temperature and precipitation data. SNOTEL provides a distinct advantage with a snow pillow included in the standard sensor package. The pillow reports daily values of the snow water equivalent (SWE) at each site. An annual manual ground truth measurement confirms the accuracy of the SNOTEL pillow value. This SWE value allows for validation of the model's simulated snowpack and daily updating.

FUTURE DEVELOPMENT OF SNOTEL - CFS

Several enhancements are planned for future system modifications. SNOTEL will include remote selection for on-site data processing as well as all sensor operations. Event activated reporting will be available, and a subtelemetry (line-of-sight) system will be an option at each site. The data rate will increase from 4,000 to 8,000 bits per second allowing utilization of shorter duration meteor trails and resulting in average wait times reduced from 6 to 3 minutes.

CFS will be transfered to a new computer platform in 1994 allowing reduced transaction time. High speed data communications will be supported. An Internet connection is being initiated to facilitate data communications with other agencies, particularly universities, and additional dial-up phone lines are planned. To improve data quality, algorithms for real-time data screening and estimation of missing values are being developed.

CONCLUSION

As SCS moves to adopt conceptual hydrologic modeling for a portion of its water supply forecasting responsibilities, SNOTEL and CFS are providing the required data. Recent system enhancements were designed specifically to support conceptual modeling and the resulting improved water resource management. Planned future modifications of the system will provide additional capabilities. SNOTEL and CFS are playing a major part in supporting the wise management of Western water resources.

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SECTION 3

INTEGRATION OF GIS AND HYDROLOGIC MODELS

Page

Visualization Techniques for Hydrologic Modeling
Lauren Hay and Loey Knapp 3-1

Object-Oriented Methods for Hydrologic Modeling and Remote Sensing
Harlan L. McKim, Perry J. LaPotin, E. Allen Cassell, and
Andrew J. Bruzewicz 3-9

Estimating Snow Water Equivalent Using a GIS
Ann McManamon, Gerald N. Day, and Thomas R. Carroll 3-18

Integrating Hydrologic Models, Geographic Information Systems, and Multiple
Data Bases: A Data Centered Approach
Thomas P. Ryan and David Sieh 3-26

Figures and Tables

Visualization Techniques for Hydrologic Modeling 3-1

Figure: 1. Conceptual view of the input-output relations between an orographic precipitation model (MODEL), a scientific visualization system (SVS), and a geographic information system (GIS) 3-3

Object-Oriented Methods for Hydrologic Modeling and Remote Sensing 3-9

Figures: 1. Mass flux into and out of an incremental volume ($\triangle$V) 3-11
2. Skeletal object representation for mass flux into and out of an incremental volume 3-12
3. Temperature and precipitation patterns 3-14
4. Snowmelt and runoff sources 3-14
5. Components of discharge 3-15
6. Simulated runoff versus actual runoff 3-15

Estimating Snow Water Equivalent Using a GIS 3-18

Figures: 1. Example of a simulation used to define a relationship for the zone between the mean seasonal precipitation and the mean snow water equivalent for a particular date 3-22
2. April 1, 1980 interpolated snow water equivalent grid, Animas River at Durango, Colorado 3-23
3. Schematic of the updating component 3-24

Integrating Hydrologic Models, Geographic Information Systems, and Multiple Databases: A Data Centered Approach 3-26

Figures: 1. Data centered architecture 3-27
2. Implemented water resource management support system 3-29

VISUALIZATION TECHNIQUES FOR HYDROLOGIC MODELING

LAUREN HAY[1] AND LOEY KNAPP[2]

ABSTRACT

As part of the U. S. Geological Survey's Gunnison River Basin Climate Study, climatic and hydrologic processes are modeled to assess the effects of climate change on water resources. Overlapping data requirements for modeling applications, in combination with the massive amounts of one- to four-dimensional data, multiple scales, and multiple data formats, require the use of scientific visualization system (SVS) and geographic information system (GIS) technology for spatial data management and manipulation, model parameterization, visual interpretation, and model verification.

INTRODUCTION

Complex hydro-climatic modeling problems commonly involve overlapping data requirements, as well as massive amounts of one- to four-dimensional data at multiple scales and formats. Scientific visualization systems (SVS) and geographic information systems (GIS) are powerful tools useful in the development and analysis of complex hydro-climatic models. In this paper, an orographic precipitation modeling application from the Gunnison River Basin Climate Study is used to demonstrate a three component system that utilizes an orographic precipitation model, a GIS, and a SVS.

Background

SVS and GIS can be distinguished from one another on the basis of their analytical and visualization capabilities. SVS are used exclusively for display of complex images and have limited analytical capabilities; whereas GIS have advanced analytical capabilities with limited display capabilities. According to McCormick (1987), SVS techniques aid in both complex image generation and visual interpretation; creating an environment for the scientific exploration of massive data sets. SVS facilitate the sequencing of images through time, which can aid in the analysis of data through the use of faster visual operators. For example, groupings based on similar color or texture can speed the interpretation process and reduce the search time.

The ease of data access and the ability to develop flexible methods for the quantification of spatial variables over discrete

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areas makes GIS an integral tool to modelers (Hay et al., 1992; 1993a; 1993b). GIS have become popular for environmental analysis, party because of their display capabilities, but these display capabilities generally are limited to the creation of static, fixed-color maps (Knapp, 1993). The analytical capabilities of GIS facilitate spatial data creation and management, providing a link between data, researchers, and models. In this paper, an example of the flow of data and model output between SVS and GIS is demonstrated using an orographic precipitation modeling application.

Gunnison River Basin Climate Study

The objectives of the Gunnison River Basin Climate Study are to identify the sensitivity of water resources in the basin to reasonable scenarios of climate change, and to develop techniques useful in assessing the sensitivity of water resources to changes in climate. One of the techniques being developed is the use of GIS and SVS as tools in spatial data management and manipulation, model parameterization, visual data interpretation, and model verification.

The Gunnison River basin, located in southwestern Colorado, has a drainage area of 20,530 square kilometers, and elevations that range from 1,410 to 4,400 meters. The basin is geologically and hydrologically diverse and provides a challenge in defining the spatial distribution of various components of the water balance (e.g. precipitation, temperature, and evaporation). Simulating the spatial and temporal distributions of precipitation is a critical component of this effort (Kuhn and Parker, 1992). The spatial distribution of precipitation in the Gunnison River basin is variable and complex because of orographic effects and most of the available precipitation data are from lower elevations near population centers. Snow is the principal source of available water in the basin, with seasonal accumulation and storage being located above 2,800 meters. However, no long-term precipitation station exists above this elevation. Evaluation of hydrologic response to climate variability and change depends on accurate estimates of winter snowpack at these higher elevations. An orographic precipitation model is used to estimate the spatial and temporal distribution of winter precipitation within the Gunnison River basin.

In this study, computer programs are written within a GIS that expedites the transfer of information between the GIS, the orographic precipitation model, and the SVS. Model input and output are used in a SVS for visual interpretation in one- to four-dimensions. The development of true interfaces between models, GIS, and SVS is programming intensive and is deemed beyond the scope of work for the Gunnison River Basin Climate Study, although work is currently being done to develop true interfaces to certain models

(Leavesley and Stannard, 1990; J. Bromberg, IBM Corporation, personal communication, 1992).

THE SYSTEM

The system described in this paper consists of three components: (1) a model (an orographic precipitation model); (2) a GIS (ESRI's ARC/INFO[3]); and (3) a SVS (IBM's Data Explorer[3]). A conceptual view of this system is shown in Figure 1. The following sections describe the role of each component within the system, the connections between the components, and how each component is applied in the case example.

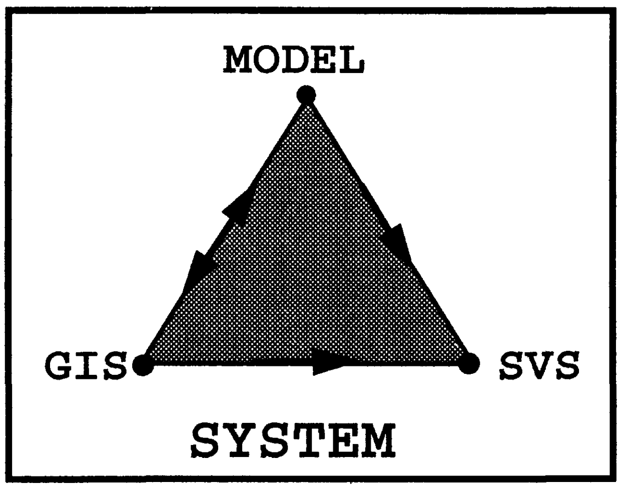

Figure 1.--Conceptual view of the input-output relations between an orographic precipitation model (MODEL), a scientific visualization system (SVS), and a geographic information system (GIS).

Orographic Precipitation Model

The Gunnison River Basin Climate Study is using an orographic precipitation model, the Rhea-Colorado State University (RHEA-CSU) model, to estimate precipitation on a daily basis and at a variety of scales (see Hay et al, 1993b). The RHEA-CSU model is also used within a larger modeling framework in which general circulation and mesoscale general circulation models are linked to the RHEA-CSU model and a watershed model to produce possible scenarios of climate change (Leavesley et al., 1992; Hay et al., 1992; Kuhn and Parker, 1992).

The RHEA-CSU model was developed in the late 1970's (Rhea, 1977). The model is steady-state, multi-layer, and 2-dimensional; one dimension is along the prevailing 700 millibar wind direction and the other is vertical. The model simulates the interaction of air

3. The use of trade or product names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

layers with the underlying topography by allowing vertical displacement of the air column while keeping track of resulting condensate or evaporation. The model requires as input (1) twice daily soundings from nearby or surrounding upper-air stations and (2) gridded elevation data. Nine elevation grids are generated using digital elevation model (DEM) point values, one for each ten degrees of rotation from 0-80 degrees; grids at complementary and supplementary angles are derived from these nine. Precipitation estimates are calculated at each point of the selected rotated grid and interpolated to a non-rotated inner grid. The inner grid is used for the model output and covers an area common to all of the rotated grids. As indicated in Figure 1, model input is derived from a GIS and model output is analyzed and interpreted using a GIS and a SVS.

Geographic Information System

The Gunnison River Basin Climate Study is using a GIS to: (1) establish a common data base for individuals working on different aspects of the project, (2) develop methods for acquiring, generating, managing, and displaying spatial data required for modeling efforts, (3) provide a means for verifying model results, (4) provide a means to investigate the effects of scale on model results, and (5) enhance the flow of information and ideas between project personnel with different specialties (Hay et al., 1993a). As indicated in Figure 1, the GIS provides input to the orographic precipitation model and to the SVS. Output from the RHEA-CSU model also is analyzed by the GIS. Specific examples of these applications are described below.

RHEA-CSU Model Input

The RHEA-CSU model was linked with a GIS that was used to automate the development of elevation grids from DEM point values, making it possible to simulate precipitation over a range of spatial scales and enabling the user to choose the method of topography characterization (e.g. mean, maximum, or minium elevation) (Hay, et al, 1992; 1993a; 1993b; and Battaglin et al., 1993). This modification eliminates what was the most labor intensive step involved in applying the model to a new area (M.D. Branson, Colorado State University, Department of Atmospheric Science, personal communication, 1991).

The RHEA-CSU model uses the inverse distance-squared from the four closest rotated grid cells when interpolating to the inner grid or when interpolating to an observation station for comparison of predicted versus measured precipitation at a point. The analytic capabilities of a GIS are used to calculate the input parameters used in the model's interpolation scheme.

RHEA-CSU Model Output

The GIS's visualization and arithmetic features were used to compare RHEA-CSU model output using 10-, 5-, and 2.5-km mean-elevation grids to assess the effects of a change in grid-cell size on model results (Hay et al.,1993b). GIS technology facilitated the comparison between RHEA-CSU model output from the three spatial resolutions by allowing the modeler to create static, fixed color maps of the results from the model runs. Arithmetic features of the GIS were used to compare the output at the three spatial resolutions using grid subtraction and accumulation. Visualizations of output using a GIS helps the modeler gain insight into model results at the three spatial resolutions, verify that the model is functioning correctly, and communicate model results to other scientists and non-scientists. It was expected that changes in precipitation would be consistent when there were no changes in any of the physical process parameters, i.e. if 10-km grids produce the least precipitation, then 2.5-km grids would produce the most precipitation. Results from this study showed the 2.5-km mean-elevation grids produced more precipitation over the entire inner grid area than that produced using the 10- or 5-km grids, but 10-km grids produced more precipitation than the 5-km grids, which was contrary to what was expected (Hay et al., 1993b).

Scientific Visualization System

A SVS facilitates the display and interpretation of one or more images through space and time. In this study, a GIS is used to view winter cumulative precipitation from the RHEA-CSU model spatially, but could not easily be used to view cumulative precipitation images. SVS can be used to animate sequences of images that display model results over space and time. In addition, SVS allows the user to interact with the data in a more flexible manner such as changing the opacity, value, and hue in real-time, determining the number of parameters to be displayed, and providing multiple views of the data (e.g. statistical as well as spatial). As indicated in Figure 1, the SVS is used to display output from the RHEA-CSU model and the GIS. The ability of SVS to effectively display data through space and time fills a gap in GIS visualization capabilities. Specific examples of SVS applications are described below.

GIS Output

SVS have limited analytic capabilities; therefore, data manipulation is conducted within a GIS and output from the GIS is channeled through to the SVS. For example, arithmetic features of the GIS were used to compare the RHEA-CSU model output at three spatial resolutions using grid subtraction and accumulation. The GIS could be used easily only to visualize differences in annual cumulative precipitation. In contrast, when results from the RHEA-CSU model are channeled into the SVS, displays of cumulative precipitation at the three spatial resolutions can be sequenced to display significant changes through space and time at the three resolutions.

RHEA-CSU Model Output

The SVS was used predominately for model verification by sequencing through time and space images of: (1) measured precipitation data and RHEA-CSU model output; (2) differences between measured and simulated precipitation; and (3) measured and simulated precipitation in cross-section and planar view.

The measured precipitation data are scattered point observations, whereas RHEA-CSU model output are gridded. The data and model output can be viewed, concurrently, draped over the topography, using symbols and color changes. For example, cumulative precipitation at each station and at each grid, can be viewed concurrently through time. Precipitation measurement station symbols can be programmed to become larger and a more intense color as precipitation accumulates. RHEA-CSU model grid cell color intensities change at the same time step and with the same color intensities as the measurement stations.

The SVS can also be used to examine residuals patterns through space and time. Residuals are calculated within the SVS by subtracting either the RHEA-CSU model grid-cell precipitation or the interpolated station precipitation from the station precipitation. Residuals are normalized to remove biases such as elevation effects on precipitation. Residuals at station locations can be viewed through time: symbols enlarge as the absolute values of a residual increases, and color and color intensities are opposite for negative and positive residuals.

Hay et al. (1992; 1993a; 1993b) identified errors in the RHEA-CSU model's interpolation of grid cell precipitation to a station location, and attributed these to be most likely the result of failure to include elevation in the interpolation scheme. The sequencing of RHEA-CSU model output images through time, in combination with two cross-sectional plots of precipitation and elevation, provides a visual aid that identifies this problem and allows for interpretation based on elevation differences between grid cell and station locations. The cross-section is defined on the RHEA-CSU model output image interactively within the SVS and two x-y plots appear along side the RHEA-CSU precipitation image. The first x-y plot depicts elevation along the cross-section as a line and station locations and elevations that fall along the cross-section as symbols. The second x-y plot shows the corresponding simulated cumulative precipitation as a line and cumulative precipitation from stations that fall along the cross-section as symbols. These images and cross-sectional plots are sequenced concurrently through time, displaying information on the spatial distribution of simulated precipitation, station elevation versus grid cell elevation, and measured versus simulated precipitation.

DISCUSSION AND CONCLUSIONS

A hydrologic modeling application from the Gunnison River Basin Climate Study was used to demonstrate the analytical and visualization capabilities of a GIS in combination with the added capabilities of SVS visualization. The application consisted of a three component system that utilizes an orographic precipitation model, a GIS, and a SVS. The GIS was shown to be an integral part of the system, facilitating the automation of input data generation for the orographic precipitation model application and the comparison and verification of model output at three spatial resolutions. SVS visualization capabilities were shown to provide the additional benefits of displaying images through time and space and allow more flexibility and breadth of display. Precipitation model output was either transferred directly to the SVS or channeled through the GIS for manipulation and then transferred to the SVS for visualization. In all cases, the GIS display capabilities described in this paper were used for visualization in the static mode. SVS has limited analytic capabilities, therefore all data manipulation is done within the GIS and channeled into the SVS for visualization through space and time. This work demonstrates the need for a system that more thoroughly integrates the display capabilities of SVS and analytic functions of GIS.

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Object-Oriented Methods for Hydrologic Modeling
and Remote Sensing

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Abstract

Operational satellites provide reliable, periodic coverage for all areas of the Earth. Data from these satellites are obtained in a digital format that provides enhanced flexibility for hydrologic modeling. Considerable advances in acquiring hydrologic data from airborne and in situ sensors also have been achieved. Additionally, data from non traditional remote sensing sources such as weather radar (from which spatial and temporal rainfall rates may be estimated) are widely available. New data acquisition capabilities have been paralleled by equal advancements in digital array processing and geographic information systems, which allow for effective extraction of both temporal and spatial information. This paper examines the use of object-oriented programming techniques as a method to create dynamic hydrologic models, and explores the potential application of object models to receive real and near real-time data from remote sensing sources. In this context, the Streamflow Synthesis and Reservoir Regulation Model (SSARR) is used to illustrate the conversion of an established hydrologic model to the object oriented framework as a method to improve hydrologic forecasting.

Introduction

Spatial and temporal data are required as initial and boundary conditions for both lumped system and distributed hydrologic models. Additional real-time data is also required for models that manage complex physical processes with unsteady flow conditions (Miers and Huebner [1985]). The modeling of hydrologic systems is enhanced by using object-oriented methods to symbolize differential and integral relationships (Cassell and Pangburn [1991]). These modeling techniques, known as object-oriented programming (OOP), include a simple yet robust set of procedures to manage and simulate the wide array of complex problems encountered in water resource management. Using OOP techniques, simple graphical interfaces are applied to differential, integral, and auxiliary equations as a method to examine complex systems in real time. The graphical interfaces provide a dialog with the user that manages the numerical method, sensitivity analysis, graphical analysis, and the corresponding generation of the differential equations. As a result, the object-oriented method greatly simplifies the simulation modeling of complex physical phenomena. In this paper, the basis for the state-space method of object-oriented programming is discussed and applied to the SSARR hydrologic model. Additionally the input of near real-time weather radar data into the model is discussed.

Object-Oriented Simulation Modeling

Object-oriented programming is a recent development designed to make computer code easier to write, understand and maintain (Baase [1988]). Software written using OOP tends to be more flexible (easier to customize), and often demonstrates superior information exchange capabilities. In comparison to traditional programming environments, programming within OOP is easier, and the final model is generally easier to understand

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and use (Rich [1983], Quinn and Narsingh [1984]). Both pure and hybrid object-oriented programming languages are available to create interfaces and applications. For example, OOP was instrumental in providing the user interface for Silicon Graphics and Macintosh computers.

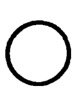
An object is the basic building block for OOP and usually encapsulates procedures and techniques for operating on the information. In graphical programming environments, an object appears on the screen in symbolic form such as a geometric form (square, triangle, rectangle) or as a miscellaneous symbol (icon, region, picture). Whenever a message is sent or passed to the object, the object carries out its predefined processing method. Objects can be grouped into user-defined classes, where each object within a given class reacts in the same way to a message, while objects in different classes react differently to the same message. New object classes can be created as a descendant, or sub-class, of a previously defined class. In this process the new object class inherits everything from the original class and the programmer then adds new information and/or redefines the processing methods.

Object oriented simulation modeling (OOSM) contains and uses the new tools provided by OOP to enhance the ease with which models are created, understood, and used. In OOSM the model is created by placing objects that represent the important elements of the system on the computer screen and then connecting the objects to allow messages (and control instructions) to be routed among the objects. In this manner, both linear and non linear systems can be modeled, and complicated feedback behavior can be simulated. Using the OOSM notation of Forrester [1968] and Richmond et al. [1987], the following symbols are used to construct each simulation model:

(1)  represent *Sources or Sinks.* If an arrow points into the cloud it must be a sink. Conversely, an arrow pointing away from a cloud implies that the cloud must be a source.

(2)  represent *Levels (integral equations).* Levels accumulate or deplete depending on the X-valves that are connected to them (i.e. they are assigned an initial condition, and then allowed to integrate the differential equations symbolized by the rates). The rectangles are referred to as the "State Variables" for the system since they have the capacity to change *states* through time and space. The term "steady-state" is used to describe a state variable invariant in time (and/or space).

(3)  represent *Rates (differentials).* The object is meant to symbolize a "plumber's" valve that opens or closes depending on physical conditions.

(4)  are referred to as "converters" and function to convert inputs into outputs. The inputs may be equations/logical statements etc. (open circles) or numerical relationships (circles containing tildes). Converters do not accumulate but change instantaneously over the simulation run.

(5) ⟹ are referred to as pipelines, and are represented as double-lined arrows. They function to allow physical flow into or out of levels and sources or sinks. The attached rates (differentials) are the flow regulators through the pipeline. Pipelines have no numerical value.

(6) ⟶ are referred to as "connectors" or information flows, and function to depict the causal linkages among the objects (variables) in the model. Connectors have no numerical value.

To illustrate how the specific objects are applied to simulation modeling, two examples are presented. In the first example, a continuity model is provided to illustrate the "one-to-one" correspondence between the object representation and the notation of control volumes and differential equations. In the second example, the Streamflow Synthesis and Reservoir Regulation Model (SSARR) is presented in the object notation of Richmond [1987], and the major equations governing the model are introduced.

Example Objects and Continuity Equations

Under mass conservation conditions, an equation of continuity may be derived for the generalized conditions of compressible fluid motion in three directions. In Cartesian coordinates, a control volume is useful to derive an expression for the conservation of mass. In Figure (1), the control volume ΔV is composed of three axes whose product

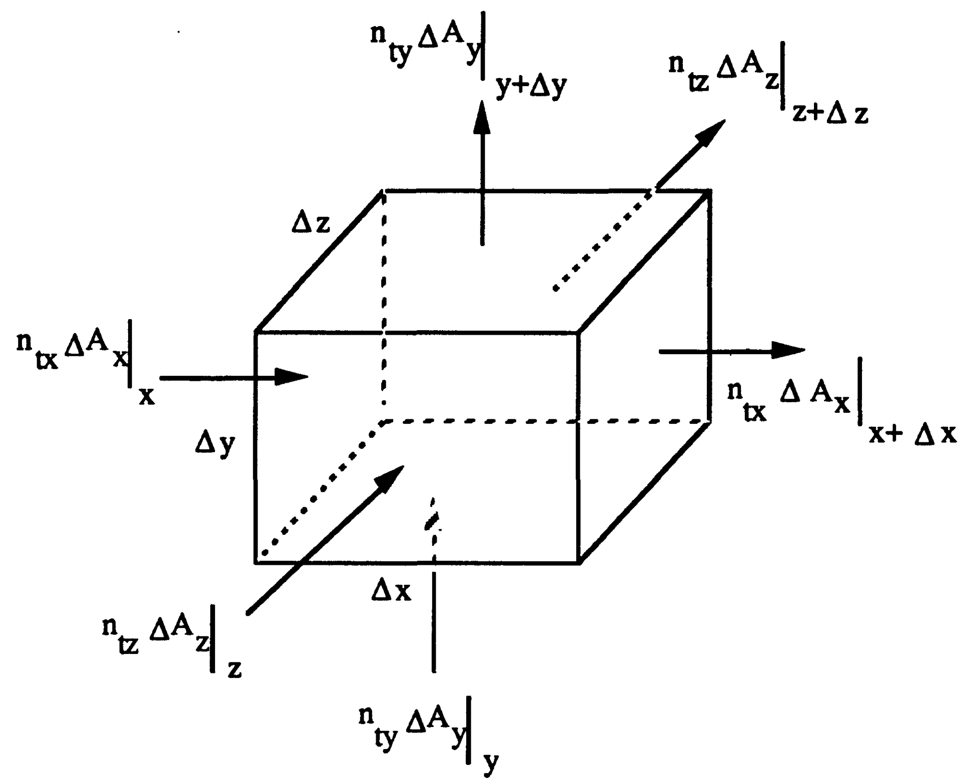


Figure (1) : Mass flux into and out of an incremental volume (ΔV).

defines the size of the differential volume or cube (i.e. $\Delta V = \Delta x \Delta y \Delta z$). The total mass flux ($n_{tx}$) across the x face of the cube is the product of the bulk density of the fluid (ρ) and the velocity of flow in that direction (v_x). For all six faces of the control volume, the mass balance becomes:

$$\Delta_x(n_{tx}\Delta A_x) + \Delta_y(n_{ty}\Delta A_y) + \Delta_z(n_{tz}\Delta A_z) - \Delta(\rho \Delta V)/\Delta t = 0 \qquad (1)$$

where
n_{ti} = total mass flux of the fluid in the ith direction (i = x,y,z),
ρ = fluid density,
Δt = time increment,
$\Delta A_x = \Delta z \Delta y$, $\Delta A_y = \Delta z \Delta x$, $\Delta A_z = \Delta x \Delta y$,

$\Delta_i(n_{ti}\Delta A_i) = (n_{ti}\Delta A_i)|_{i+\Delta i} - (n_{ti}\Delta A_i)|_i$ = net mass flow of the fluid through the incremental area ΔA_i, and $\Delta(\rho\Delta V)/\Delta t$ = bulk accumulation term

Dividing Equation (1) by ΔV, realizing that fluid is incompressible under ambient conditions ($\Delta(\rho\Delta V)/\Delta t \rightarrow 0$), and taking the limits as $\Delta x \rightarrow 0$, $\Delta y \rightarrow 0$, $\Delta z \rightarrow 0$ yields:

$$\partial n_{tx}/\partial x + \partial n_{ty}/\partial y + \partial n_{tz}/\partial z - \partial \rho/\partial t = 0. \qquad (2)$$

Letting n_{ti}, the total mass flux, equal the product of the fluid density (ρ) and the fluid velocity in the ith flow direction (v_i):

$$n_{ti} = \rho v_i \, . \qquad (3)$$

and Equation (2) becomes:

$$\rho\,(\partial v_x/\partial x + \partial v_y/\partial y + \partial v_z/\partial z) - \partial\rho/\partial t = 0 \quad \text{or}$$

$$\nabla \cdot \rho v - \partial\rho/\partial t = 0, \qquad (4)$$

where $v = v(x,y,z)$.

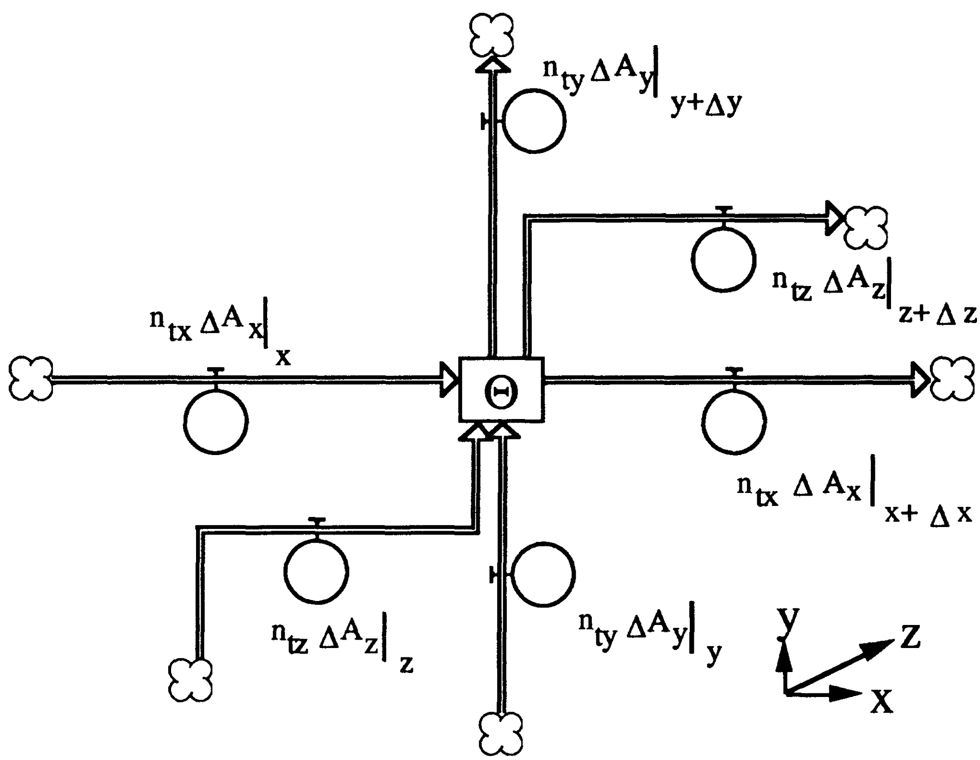


Figure (2) : Skeletal object representation for mass flux into and out of an incremental volume.

For the special case of constant fluid density through time, $\partial\rho/\partial t \rightarrow 0$, Equation (4) simplifies to:

$$\partial v_x/\partial x + \partial v_y/\partial y + \partial v_z/\partial z = 0 \quad \text{or}$$

$$\nabla \cdot v = 0 \qquad (5)$$

Equations (4) and (5) represent the equations of continuity for the simple control volume of Figure (1) under the generalized conditions of incompressible flow. An equivalent symbolic notation (object representation) for this continuity is provided in Figure (2). In this representation, the symbol Θ is used to indicate the accumulation of the fluid at time t within the simulation. The mass rate of flow into and out of the control volume is as shown in Equation (1).

The Object SSARR Model

The SSARR (Streamflow Synthesis and Reservoir Regulation) model is a generalized watershed model for computing runoff from rainfall and/or snowmelt events. The Corps developed SSARR to simulate watershed systems for the "planning, design, and operation of water control works" in a manner to achieve "a balance between hydrologic theory and practical considerations related to daily operational use" (Corp of Engineers, [1972]). SSARR synthesizes the runoff from snowmelt, rain, and/or their combination from a specific climatological event within hydrologic units that are assumed to be relatively homogeneous. The runoff can be routed downstream through channels and reservoirs that may define a complex watershed system. The impacts of reservoir regulation operational strategies also can be simulated.

The object SSARR model includes two major modules: (1) Snow Cover Depletion, and (2) Runoff Analysis. The Snow Cover Depletion Module separates input precipitation into rain or snow, accumulates snow when appropriate, and determines if any of the accumulated snowpack melts. The snowpack is assumed to be evenly distributed over the watershed above some initially defined elevation. At air temperatures higher than a base value, precipitation falls as rain and there is active snowmelt; otherwise the precipitation is snow and there is no snowmelt. An assumed temperature lapse rate is used to determine a critical elevation level above which it snows and there is no snowmelt and below which it rains and there is snowmelt. As the snowpack melts, the elevation above which snowcover remains increases, until, at the end of the melt season, the watershed is free from accumulated snow. This module tracks changes in precipitation and air temperatures and simulates rainfall and snowmelt (whether occurring simultaneously, separately, or not at all). The "temperature index method" functioning within the "single watershed snowcover depletion technique" is used (USACE 1972). The final output from this module is the total of the rainfall and snowmelt and is used as input into other objects within the object SSARR model.

The Runoff Analysis Module is patterned after the USACE "rainfall-runoff relationships" (USACE [1972][1986]). The input to this module is the output from the Snow Cover Depletion Module. This input is partitioned among: (a) the water that enters soil moisture storage for eventual consumption by evapotranspiration, (b) the water that becomes base flow (deep ground water), (c) the water that becomes quick flow (shallow sub-surface flow), and (d) the water which flows off as surface or overland flow. Each flow component moves through the watershed at a different rate; the surface flow component emerging from the watershed soonest after an input event, while the base flow component is last to emerge. The time for each flow component to move through the watershed is determined by a "routing routine" where each flow component moves through one or more simulated linear "reservoirs". Each reservoir has a theoretical volume that, when divided by the flow component, yields a routing constant that corresponds to values determined by analysis of historical flow records. The output or runoff leaving the watershed is the sum of the base flow, quick flow, and surface flow components. The object oriented SSARR model, unlike the original SSARR representation, adjusts for temperature effect on viscosity and surface tension. During periods of snow cover, the object SSARR allows for decreases in evapotranspiration. However, evaporation from the snow surface is not included within the object SSARR model.

The object oriented SSARR model is calibrated using 15 individual climatological events for the W3 sub-watershed in the Sleepers River Research Watershed located in northeastern Vermont (Anderson et al. [1977]). The W3 sub-watershed is a small (3.25 sq. mi.) area having elevations ranging from 1135 to 2280 feet above m.s.l. The watershed is about 60% forested and 40% cropland and pastureland. The watershed receives about 48 inches of precipitation each year with about 120 inches of snow each winter and is subject to rapid weather changes. In Figure (3), the output from an object oriented SSARR simulation is shown as a time-series plot for Precipitation, Air Temperature, and Percent Area in Rain. The event comprises both precipitation and snowmelt over the W3 sub-watershed when it was initially 100% covered with snow. The precipitation event occurred between hours 35 and 45 (Curve 2, Figure 3). The air

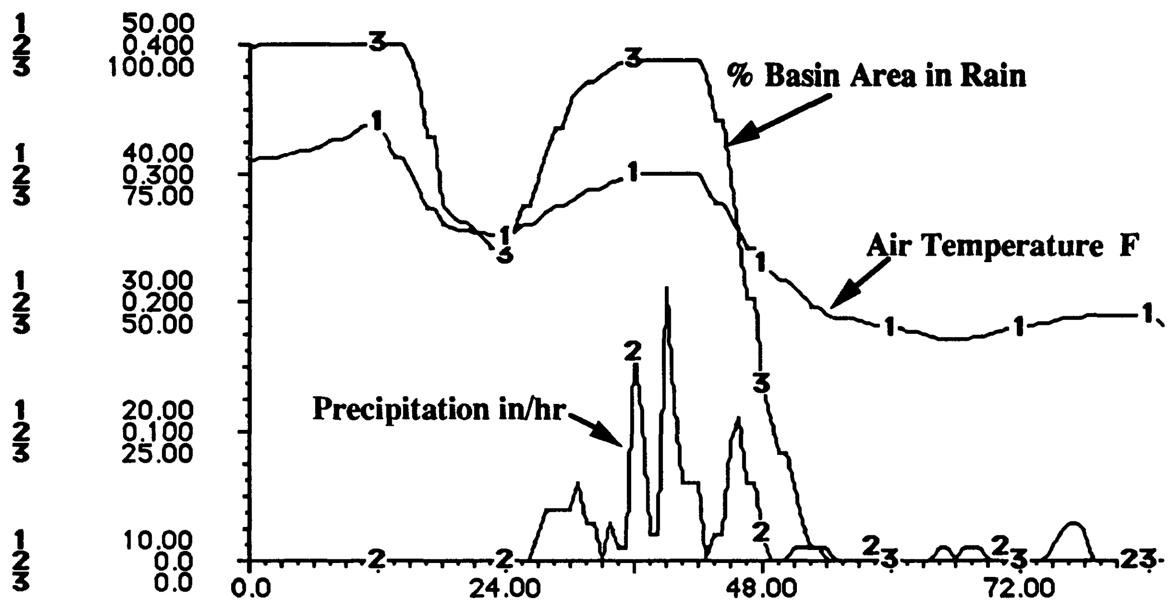


Figure (3): Temperature and Precipitation Patterns

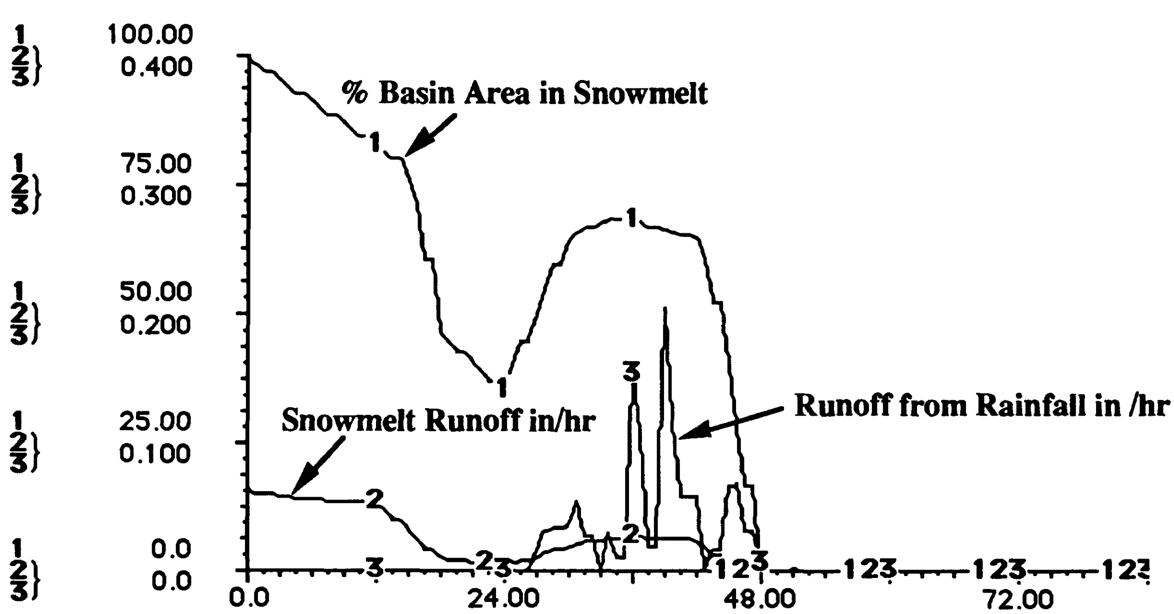


Figure (4): Snowmelt and Runoff Sources

temperature exceeded freezing until roughly 54 hours (Curve 1, Figure 3) with the result that until hour 54 the precipitation fell as rain over nearly all the watershed area (Curve 3, Figure 3). Similarly, until the temperature fell below freezing (at about 54 hours) most of

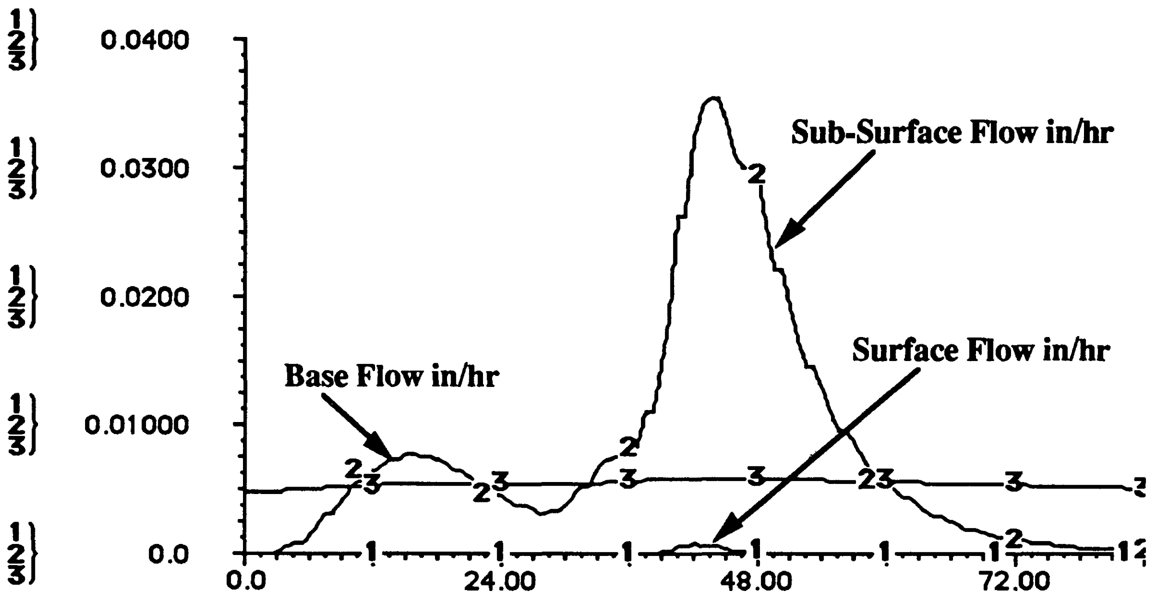


Figure (5): Components of Discharge

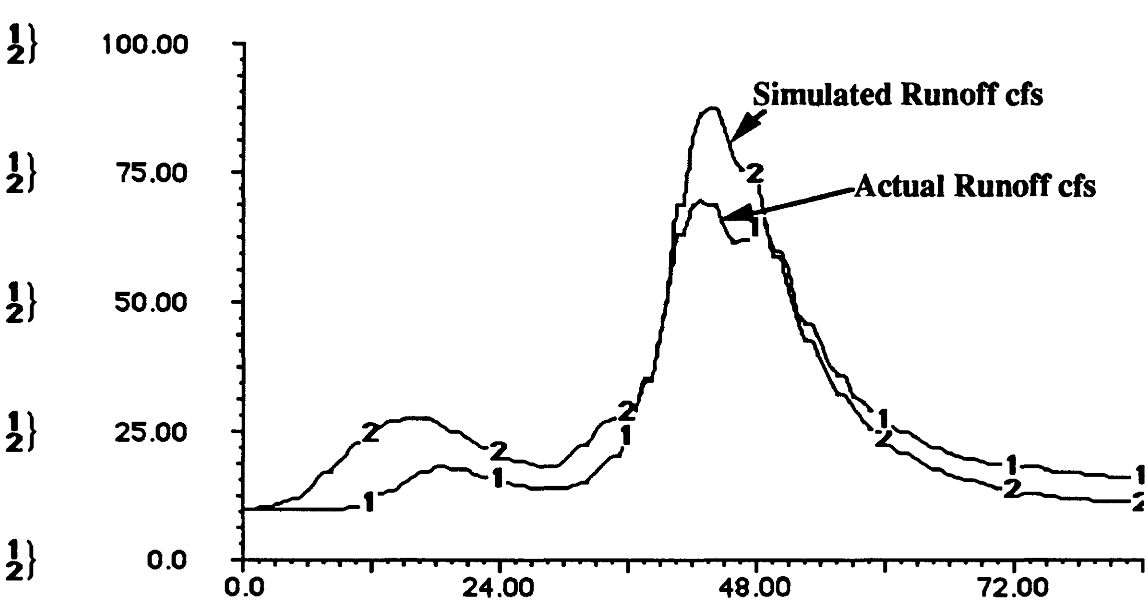


Figure (6): Simulated Runoff Versus Actual Runoff

the basin that remained snow-covered was undergoing active snowmelt (Curve 1, figure 4). The runoff resulting from snowmelt and rainfall is shown as Curves 2 and 3 respectively on Figure (4). Most of the runoff resulted from direct rainfall runoff.

Figure (5) shows the various runoff flow components accounted for within SSARR. The surface runoff is negligible throughout the simulation (Curve 1). The base flow component remained nearly constant during the event (Curve 3). Curve 2 shows that the sub-surface flow component exceeded other flow components except early and late in the event. The runoff from this event appears to be predominantly subsurface flow. Curve 1 on figure 6 is the simulated total runoff from the watershed and is, in fact, the summation of the simulated base, surface and sub-surface flow components. The actual measured runoff that resulted from the climatological event is shown as Curve 2 on Figure (6). Comparison of the simulated and actual runoffs do not show perfect agreement. The output suggests that the simulation overestimates the amount of runoff that results from snowmelt. By evaluating these outputs, it is possible to further debug the model and locate objects that do not behave as they should during the simulation period. The highly interactive programming environment provides a fast method to quickly identify sensitive parameters, and also provides an efficient method to modify all equations and parameters within the object SSARR model.

Discussion and Conclusions

In this paper, object-oriented notation is used to present two separate physical models. In the first model, a standard control volume is shown with its associated notation using objects to symbolize the flow of mass into and out of the faces of the unit cube. In the second model, a widely applied hydrologic model is adapted to the object format for fast simulation of streamflow and general watershed hydrology. Using the object notation, the hydrologic data underlying the model is modified to accept real-time information for improved hydrologic forecasting. Using both near real-time, and real-time telimetered data, critical model components such as snowmelt, rainfall, infiltration, runoff generation and channel flow can be modified within the OOP framework. Of these components, real-time hydrologic forecast models appear most sensitive to the spatial and temporal distribution and amount of snowmelt and rainfall (Barrett [1985], Stokely [1980]). Any improvement in rainfall/snowmelt measurement and its spatial distribution can significantly improve flood forecasts in real time (Feldman [1987]). Ideally, the capability for accurately forecasting precipitation would make an even more significant contribution. The application of telemetered rain gauge data for the periodic calibration of sub-watershed rainfalls and the comparison of weather radar data to these calibration values on a frequent basis (e.g. hourly or so) allows spatially variable near real-time precipitation data to be generated (Engdahl [1988, 1989]). Techniques for the input of these data into object models for water resource management are being developed (McKim et. al. [1992]).

Automated in-situ sensors to measure snow water equivalency, soil moisture, and precipitation are available as inputs into object models. There are also operational satellite systems whose data can be used to obtain the spatial distribution of the snowpack in the passive portion of the electromagnetic spectrum. All these data sources are characterized by frequent updating and are useful in near real-time forecasting (Engdahl [1989], Merry et al. [1987]). Full integration of radar-rainfall and snowmelt information into the hydrologic modeling process will require data storage systems that depict not only the spatial characteristics of the river basin but also the spatial distributions of each storm event. Static and near-static parameters of a river basin, such as elevation, soils, vegetative cover, land use, channel geometry and drainage network, are obtained from conventional maps and remotely sensed imagery. Geographic information and image processing systems can then be used to analyze and display significant hydrologic parameters. In addition, weather radar data can be used to portray the dynamic movement of storm events for a basin in real time (Wilson et. al [1979]), and the integration of these data over time and space can produce a real-time rainfall hyetograph for each area subdivision within a river basin.

Currently there are few real-time hydrologic models that are designed to accept frequent data updates from a variety of remote sensors. The object SSARR model is presented as one case where an existing static model may be adapted to dynamic real-time data using the object-oriented programming method. Additional models are being developed for water resource applications and hydrologic modeling.

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Estimating Snow Water Equivalent Using a GIS

Ann McManamon[1], Gerald N. Day[2] and Thomas R. Carroll[3]

ABSTRACT

In the Western United States approximately 75 percent of the annual runoff results from snowmelt. Observations of the snow cover provide an important source of information for forecasting seasonal water supply months in advance. Regression models have been used for over 70 years with snow water equivalent as one of the independent variables. More recently, conceptual hydrologic models have been used to forecast water supply using the Extended Streamflow Prediction (ESP) technique, which is the long-range forecasting component of the National Weather Service River Forecast System (NWSRFS). The conceptual models rely on estimates of mean areal precipitation and mean areal temperature to compute estimates of current snow cover conditions. Because of the difficulty in accurately estimating precipitation in the mountains, it is essential that snow water equivalent observations be used to update model simulated snow cover conditions to ensure that ESP forecasts are accurate.

This paper describes a software system that interpolates observations of snow water equivalent to produce gridded estimates of snow water equivalent. The system uses the GRASS Geographical Information System (GIS) to store, analyze, and display point, line and gridded data. The GIS permits the analysis of multiple data layers such as elevation, forest cover, seasonal precipitation, and their derived data layers, e.g. slope, aspect, and melt factor classification. The snow cover estimation system includes a calibration component which assists the user in estimating parametric information, and an operational component which performs the interpolation in real-time. The outputs of the system include gridded estimates of snow water equivalent, as well as estimates of the areal snow cover conditions needed by the snow accumulation and ablation model that is part of NWSRFS. These estimates are weighted with the model simulated conditions based on their relative uncertainties to compute updated snow conditions. Updating the simulated snow conditions has been demonstrated to provide significant improvements in streamflow forecasting in areas with significant snow cover.

INTRODUCTION

Because so much of the west's water supply is influenced by snow and snow melt, it is extremely important to accurately estimate the water equivalent contained in the snowpack. Knowledge of snow cover conditions is essential to producing seasonal water supply forecasts, which are needed for estimating hydropower generation, planning reservoir releases and determining water

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allocations. Regression equations are often used to forecast water supply with snowpack snow water equivalent as one of the independent variables. Regression techniques work well in average years, however in extreme years they sometimes do not provide as accurate an estimate as might be desired. It is often these extreme conditions (flooding and drought) that concern water managers the most.

More recently, conceptual models have also been used to forecast water supply. The Extended Streamflow Prediction (ESP) technique is the long-term forecasting component of the National Weather Service. It uses present day streamflow, soil moisture and snowpack conditions along with historical time series of precipitation and temperature to estimate streamflow weeks or months into the future. The streamflow hydrographs can be analyzed based on the likelihood of the precipitation and temperature time series to produce probabilistic forecasts of streamflow peaks, volumes, etc. Because of the difficulties in estimating precipitation in the mountains, the estimates of the initial conditions provided by the models are often inaccurate.

The Soil Conservation Service (SCS) and others have been collecting snow water equivalent information. Snow course data is available at over 1500 sites and in some places the period of record exceeds 40 years. More recently, they have begun collecting data at SNOTEL sites (approximately 650 locations). The NWS has developed a methodology to use snow data to improve the estimates of the snowpack conditions. (Day, 1990). The analysis of these snow data and its incorporation into the model should result in more reliable estimates of seasonal water supply volumes.

SNOW ESTIMATION AND UPDATING SYSTEM (SEUS)

The National Operational Hydrologic Remote Sensing Center (NOHRSC) will ingest available SNOTEL and snow course data on a weekly basis between January and June of each year. After some preliminary error checking, the SEUS will be used to develop gridded estimates of snow water equivalent. This gridded information will be provided to end users. In addition, NWS River Forecast Centers will be able to either use these estimates or recalculate the gridded estimates with perhaps improved error checking and additional data. The RFC's will compute areal estimates of snow water equivalent over basin subareas and use this information to update the snow states of the conceptual snow model.

The SEUS consists of three components, a calibration component, an operational component and an updating component. The calibration component analyzes historical snow observation data and develops the parameters needed to estimate gridded snow water equivalent. The operational component accesses real-time data and takes advantage of the parameters developed in the calibration phase to determine gridded snow water equivalent operationally. The updating component updates the existing snow water equivalent in the conceptual model based on the relative uncertainties of the simulated model snow states and estimates of the snow states developed using the snow observations. Much of the methodology involves managing and analyzing point, line, and gridded data.

SEUS uses the Geographic Resources Analysis Support System (GRASS) GIS to perform these tasks. GRASS is a raster based public domain GIS developed for UNIX platforms by the U.S.

Army Construction Engineering Research Lab (USACERL). Part of the appeal of using GRASS to develop the SEUS was its compartmentability and the availability of the source code, so that additions and modifications could easily be made to its existing capabilities. GRASS has many low-level commands which when combined with one another, provide the user with the capability to tailor the GIS to the function which needs to be performed. In order to isolate the user from as many of the details of the GIS as possible, all the GRASS commands for a particular function are packaged together in scripts. In addition, a graphical user interface has been developed to further simplify the system for the user.

Calibration Component

The methodology developed involves the interpolation of point snow water equivalent data into gridded estimates of snow water equivalent. The interpolation technique chosen requires that the data are second-order stationary and isotropic. This assumption asserts that each point has the same mean and variance and that the correlation between two points is a function only of distance. To meet these requirements, the point snow water equivalent data is transformed into standardized deviates (z) using the following equation.

$$z = \frac{x - \bar{x}}{\sigma}$$

where z = standardized deviate
x = observation
$\bar{x}$ = mean, for the station
σ = standard deviation for the station

This transformation requires the knowledge of each station's mean and standard deviation for specific dates when the interpolation is performed. Snow course and SNOTEL data were analyzed to estimate long term means and standard deviations for the first of each month from January to June. Weekly station means and standard deviations were estimated using the variation of the snow cover in the vicinity of the observation during the month.

The interpolation method also requires an estimate of the spatial correlation function of the standardized data. A correlation function was developed for each basin using the historical station data and expressing the correlation between each station pair as a function of distance. An equation of the form:

$$\rho = ce^{-dx}$$

where ρ = correlation coefficient
x = distance between points in km
c,d = regression coefficients

was fit to the data. Given a correlation function and a station mean and variance the point snow water equivalent can be transformed and interpolated at each grid point to produce a gridded field of standardized deviates.

What is really desired, however, is a gridded field of snow water equivalent. To transform the standardized deviate values back into snow water equivalent, an estimate of the mean and variance of the snow water equivalent at each grid point is needed. Estimates of the mean snow water equivalent are developed using a modeling approach which is discussed in the next section. The historical station data were analyzed to develop a relationship between the mean snow water equivalent at a point and its standard deviations for the first of each month during the snow season. The form of this relationship was assumed to be:

$$\sigma = a\bar{x}^{b}.$$

where σ = standard deviation
$\bar{x}$ = mean
a & b = regression coefficients

Given an estimate of the mean snow water equivalent at a grid point, this function can be used to transform the grid point deviate into an estimate of the actual snow water equivalent.

Mean Weekly Snow Water Equivalent

The approach taken in estimating the mean snow water equivalent at a particular grid point is to model the snow accumulation and ablation taking into account the precipitation and site characteristics of the grid point. The GIS is used to store, analyze and display spatial information to assist in the estimation of gridded mean snow water equivalent on a weekly basis throughout the snow melt season.

In the adopted approach, the mean snow water equivalent at each grid point is estimated using the conceptual snow model calibrated for the basin in which the grid point is located. It would be extremely computationally intensive to model snow water equivalent at individual grid points, so grid points are lumped into zones based on snow melt characteristics. The first step is to form melt factor classes which are a function of aspect, slope, and forest cover. Aspect and slope are computed from digital elevation data using the GIS, and then combined to form a new surface which represents an index to the available solar radiation. Since east and west-facing slopes receive the same amount of solar radiation over a day as a horizontal surface, the available solar radiation can be represented by three classes: north, south, and horizontal. The GIS is also used to classify vegetation data into forest and open area classifications. The three solar radiation classes and the two vegetation classes are combined to produce six melt factor classes. Given the average melt factors from a model calibration for the basin and the distribution of melt factor classes throughout the basin, melt factors are estimated for the six different melt factor classes.

The melt which occurs at a grid point is a function of temperature, as well as melt factor. Since temperature is well correlated with elevation, the elevation data are reclassed and combined with the melt factor classes to form snow melt zone classes. It is expected that all the grid points in a particular snow melt zone will exhibit similar snow melt characteristics, however, grid points in the same zone may experience significant differences in the amount of precipitation which they receive. The mean areal temperature (MAT) and mean areal precipitation (MAP) time series for the basin are used to simulate the snow cover for each zone. The melt factors for the zone are used in place of the average basin melt factors and the MAT time series is lapsed from the mean basin elevation to the elevation of the zone. In order to account for the different amounts of precipitation which can occur at grid points within the zone, the zone snow cover is simulated for different percentages of the basin's MAP time series. The resulting simulations are used to define a relationship for the zone between the mean seasonal precipitation and the mean snow water equivalent for a particular date, e.g. April 1. An example of one of these relationships is shown in Figure 1.

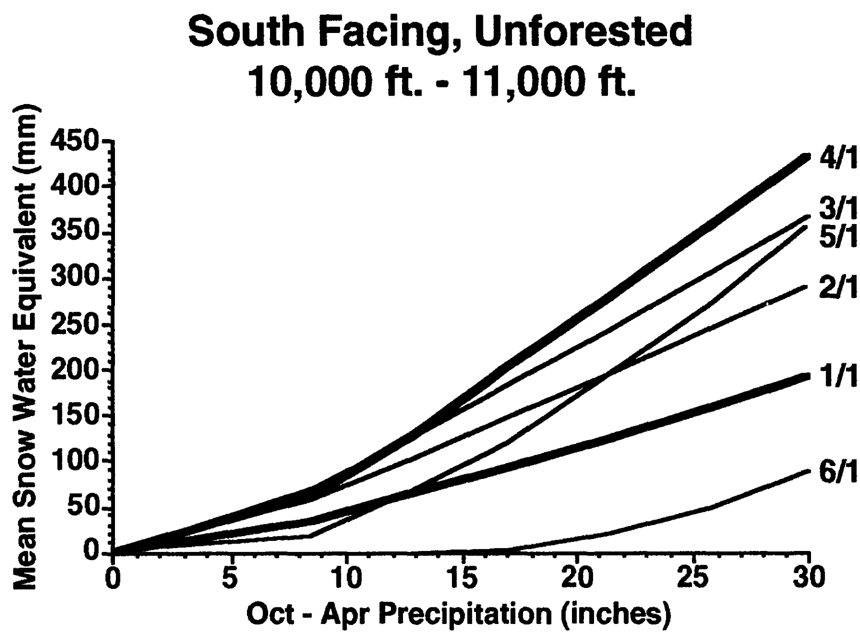

Figure 1.

The GIS is used to derive weekly mean snow water equivalent surfaces from the snow melt zone surface, a surface of the long-term mean October through April precipitation, and the relationships between seasonal precipitation and snow water equivalent. The mean April 1 snow water equivalent surface for a portion of the headwaters of the San Juan Basin in southern Colorado is shown in Figure 2.

Pseudo-Observed Snow Water Equivalent

All of the information needed to estimate snow water equivalent is now available, however, the snow water equivalent estimated using the interpolation procedure may not be consistent with the snow water equivalent states in the conceptual snow model. Historical estimates of the snow water equivalent needed by the model are generated by computing the model states which would have been necessary on a specific date (e.g. April 1, 1960) in order for the model to simulate the seasonal runoff (e.g. April through July, 1960), that was actually observed. These estimates are called pseudo-observed snow water equivalent, and they represent our best estimate of the optimal snow water equivalent model states.

In order to account for biases between the pseudo-observed values and the estimates of snow water equivalent from the interpolation procedure, regression relationships are developed from

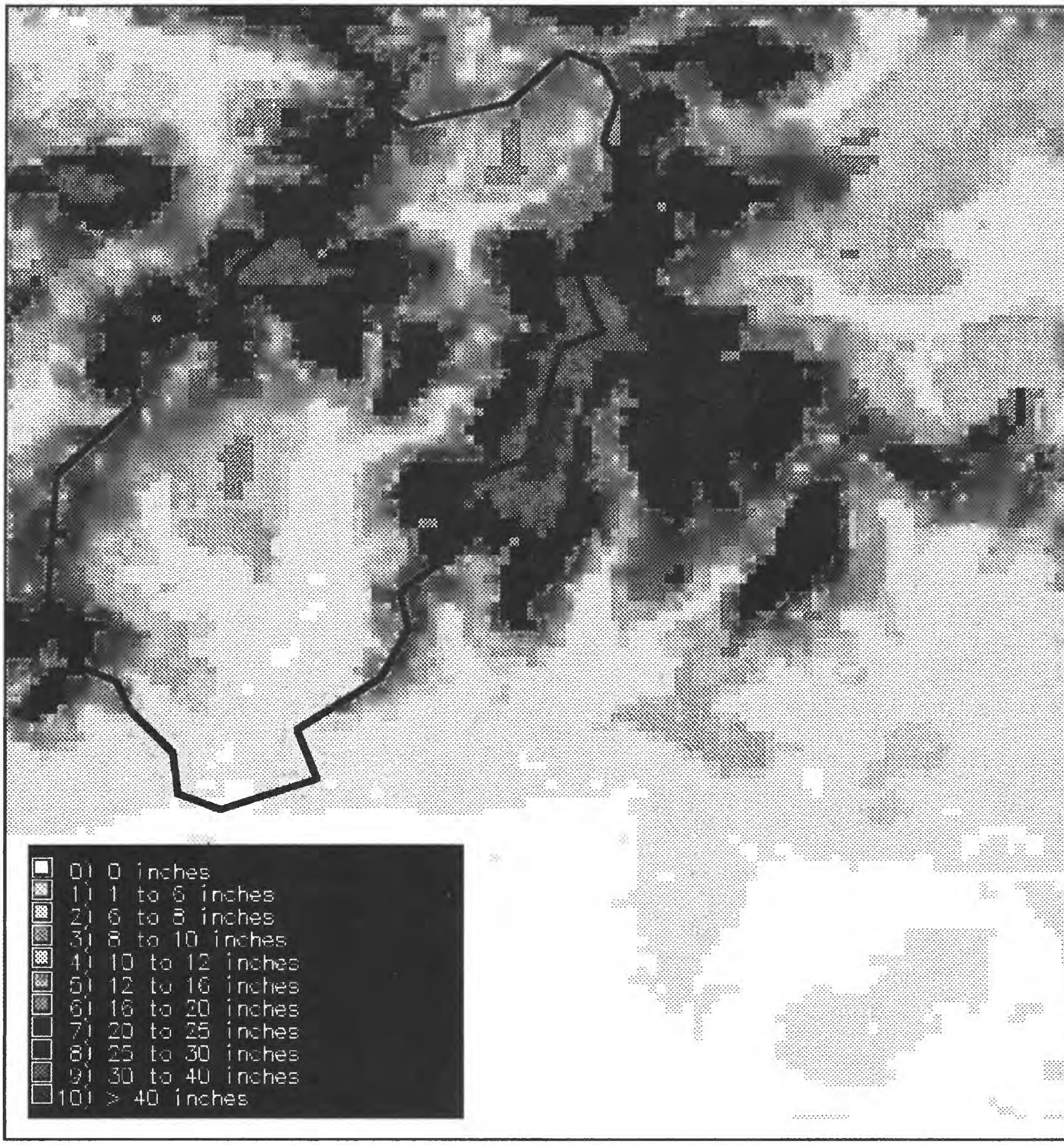

Figure 2. April 1, 1980 Interpolated Snow Water Equivalent Grid, Animas River @ Durango, Colorado

the historical data. Pseudo-observed values are estimated for the first of each month for the entire historical record. Similarly, the interpolation procedure is performed for the first of each month throughout the historical record. The GIS is used to compute basin averages from the gridded estimates of snow water equivalent. Regression relationships, which predict pseudo-observed values from basin average snow water equivalent, are developed for the first of each month. These relationships are used in the operational system to compute estimates of the model snow water equivalent states that can be used for updating.

Operational Component

The Operational Component uses the parametric information defined with the Calibration Component to estimate real-time snow water equivalent each week from January through June. As in the Calibration Component, the GIS is used to store, analyze, and display spatial information. The user interacts with the Operational Component through a GUI, that is structured like the one used for the Calibration Component. Real-time station observations are transformed to standardized deviates, and interpolated using the correlation function estimated for the basin in the calibration step. The GIS is used to transform the standardized deviates developed to estimates of the actual snow water equivalent on a grid point basis.

Updating Component

The GIS was also used to develop basin boundary outlines and to store masks representing the area within each watershed. The estimated snow water equivalent within a basin boundary is summed to determine an areal estimate of snow water equivalent. This basin average snow water equivalent is used with the regression relationships to estimate basin pseudo-observed snow water equivalent. The Updating Component of the methodology combines the pseudo-observed estimates with the current model simulated snow water equivalent states in NWSRFS. The two estimates are weighted based on the relative uncertainty of the estimates, to compute the updated model snow water equivalent states. These updated snow model states are then reflected in any streamflow forecast for the basin. A schematic of the updating step is shown in Figure 3.

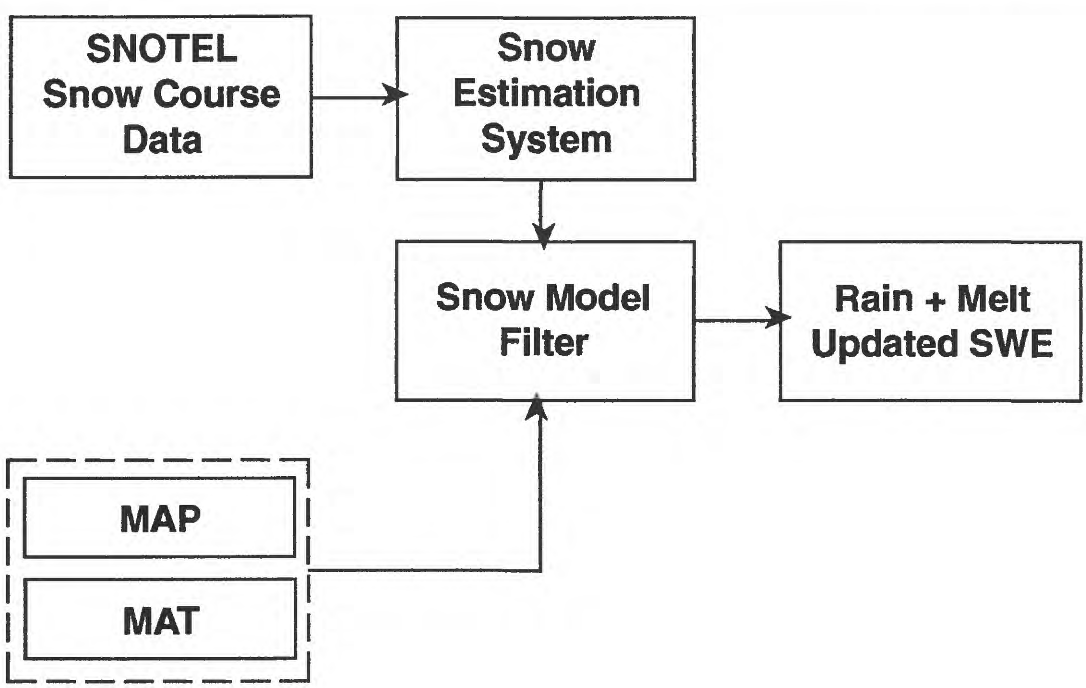

Figure 3.

SUMMARY

The National Weather Service is implementing a snow estimation system which interpolates point snow observations to produce gridded estimates of snow water equivalent. The system uses a GIS to store, analyze, and display point, line and gridded data. The SEUS consists of three components, a calibration component which is used to estimate parametric information and develop derived data planes, an operational component which performs the interpolation of the snow observations in real-time and an updating component which combines the estimated snow water equivalent developed using the system with the model simulated snow water equivalent. Results from several basins have indicated that the updating process improves streamflow forecasting.

This is the first year that the system has been implemented operationally. The baseline system focuses on the Colorado River above Lake Powell. Snow water equivalent grids have been estimated weekly over this area at the NOHRSC. The gridded information was provided to the Colorado Basin River Forecast Center, where it was used to determine areal estimates of snow water equivalent over selected basins within the upper Colorado River drainage basin. The areal estimates were used to update the model computed estimates of snow water equivalent for these selected basins. Additional basins will be included in the updating step in subsequent years.

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INTEGRATING HYDROLOGIC MODELS, GEOGRAPHIC INFORMATION SYSTEMS, AND MULTIPLE DATABASES: A DATA CENTERED APPROACH

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ABSTRACT

Data centered architectures offer a superior structure for water resource management support systems. Hydrologic models, geographic information systems, databases, and analysis software can be most effectively integrated using a data centered approach. Such a data centered system has been implemented by the Bureau of Reclamation for water system operation, planning, and management in the Upper Colorado River Basin.

INTRODUCTION

Effective and efficient water resource management necessitates the ability to obtain a satisfactory balance between a number of conflicting demands and interests. Water resource systems are now operated not only for traditional uses such as water supply, power generation, flood control, and recreation, but to satisfy an entire new array of competing demands. The protection of endangered species, maintenance of acceptable water quality standards, the protection of sensitive riparian zones, the preservation of game fisheries, among other considerations, have become major forces in the operating criteria of water resource systems.

To keep pace with this new set of demands and operating constraints, water resource managers are in need of decision support systems for water management. Such systems are composed of computer systems that: (1) collect, assimilate, and process data; (2) simulate (model) hydrologic and operational processes; and (3) display and analyze both raw and synthesized data. Components in such a support system must be integrated and must also be able to take advantage of the wealth of hydrologic and climatic data that are currently collected by numerous agencies. Presented herein is a discussion of the "Data Centered Architecture", a framework for the development of a decision support system for water resource management. This architecture provides a structure suitable for the integration of hydrologic models, geographic information systems (GIS) and multiple databases. Such a system is being implemented by the Bureau of Reclamation (Reclamation) in the Upper Colorado River Basin to facilitate optimal water resource management.

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THE DATA CENTERED APPROACH

Data centered architectures are based on the premise of a core database supporting multiple applications. Figure 1 illustrates the structure of a data centered architecture. At the heart of the architecture is a database management system (DMS). Surrounding the DMS are component applications that perform various tasks. The component applications can be grouped into four different categories: (1) modeling applications for the simulation of hydrologic and operational processes, (2) GIS applications for display and analysis of spatial data and information, (3) time series analysis applications such as statistical programs, plotting programs, spreadsheets etc., and (4) applications that supply data to the DMS or disseminate data from the DMS.

Data flow between the component applications and the DMS in a data centered architecture. Modeling applications obtain input data from the DMS and then store output data into the DMS. Such data are then available for use by other modeling applications, GIS applications or time series analysis applications.

Linkages between component applications and the DMS are made through data management interfaces (DMI). DMI's are software modules that are responsible for moving data back and forth between an application and the database. Whenever an application is added to the system, a DMI must be prepared.

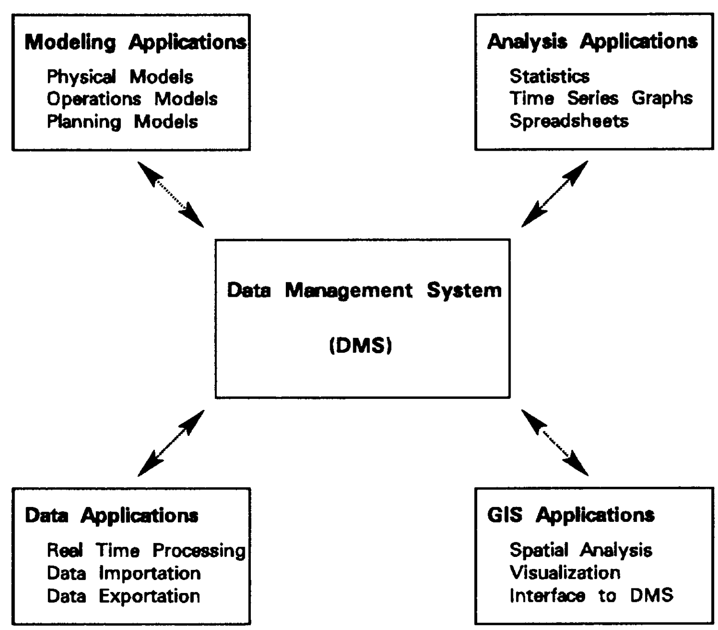

Figure 1. Data Centered Architecture

It should be noted that the modeling and time series applications in a data centered architecture are designed and coded to run independently from the DMS. Applications are not "hard coded" to communicate with a particular DMS. This ensures flexibility when models are transferred to other platforms or used by other agencies having different data management systems. The application once transferred can be run stand alone or a new DMI can be created linking the application to an appropriate DMS.

Data centered architectures are becoming increasingly feasible in federal water management agencies for the following reasons:

1. Maturation of Data Management. Development and field use of third party data management systems have led to the evolution of reasonably stable data management products. These products are capable of managing a variety of types of data encountered in water resources operations, management, and planning (i.e. time series, spatial, physical parameters, documents, images, etc...). These capabilities are most commonly found in third party relational database management systems and geographic information systems.

2. Industry Database Standards. Over the past decade, standard database languages have evolved. Most third party relational database management systems have implemented structured query language (SQL). SQL can be used to query a database interactively or it can be embedded in third generation programming languages like C or FORTRAN. Embedded SQL programs can obtain data from and store data to a relational database, as they run. Embedded SQL programs are highly useful for creating DMI's for application programs in a data centered system.

3. Industry Recognition of Need for Open Systems. There is an industry trend to produce software that has hooks into other software packages and/or provides third generation language bindings so that programmers can develop applications based on libraries provided by the software package. This trend makes development of data centered architectures significantly more feasible.

A DATA CENTERED ARCHITECTURE FOR WATER SYSTEM OPERATION, PLANNING, AND MANAGEMENT IN THE UPPER COLORADO RIVER BASIN

Reclamation has partnered with the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) to develop a decision support system using a data centered approach for water resource management in the Upper Colorado River Basin. The system supports data collection, data and information dissemination, spatial display of data using a GIS, daily rainfall-runoff modeling, long range planning studies, and project specific studies. Each of the applications in the system utilize data stored in a DMS. The system has been implemented on three networked UNIX workstations.

Figure 2 depicts the data centered support system that is being implemented at Reclamation's Water Operations Office in Salt Lake City. The DMS is composed of a relational database (INGRES) and a GIS (ARC/INFO). A database, the Colorado River Database (CRDB) has been designed and implemented using the INGRES software. Stored in the CRDB are current and historic flows, synthesized virgin flows, current and historic reservoir data, hydropower data, snotel data, data describing facilities and gages, along with a variety of other pertinent hydrologic data. Spatial/coordinate data describing the river network, water bodies, drainage boundaries, and facilities/structures along the river network (dams, powerplants, diversions, gages, etc.) are managed in the GIS. A number of other thematic map layers are also stored and managed in the GIS.

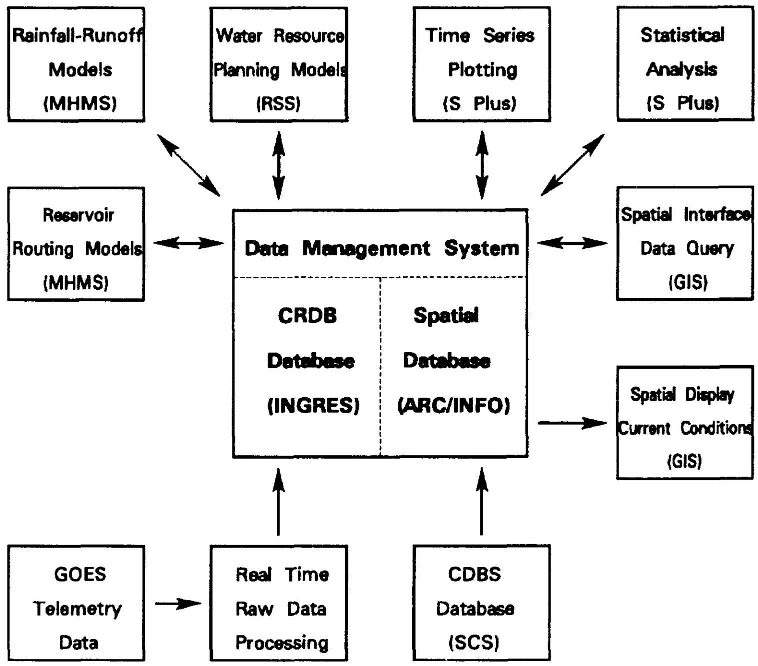

Figure 2. Implemented Water Resource Management Support System

One modeling component in the data centered system is the Modular Hydrologic Modeling System (MHMS). MHMS has been developed cooperatively by the United States Geological Survey, CADSWES, and Reclamation. MHMS is a modeling environment that provides utilities that allow users to customize simulation models from a library of predefined program modules. Individual program modules can be linked together by the user to create customized models to perform specific tasks. MHMS runs in an X Window environment and has utilities to assist the user parameterize and calibrate models, as well as analyze output data. These utilities include run time plots of model variables, graphical forms and spreadsheets for parameter and run control input, statistical summaries, sensitivity analysis, parameter optimization, and Extended Streamflow Prediction (ESP) capability.

While MHMS has many utilities that are self contained in the program, input data preparation is left to the user. To simplify input data preparation, a DMI has been developed that communicates with the CRDB to generates MHMS input files. This DMI checks the database for missing or possible erroneous input data (outliers), and provides methods by which missing input data can be synthesized from other information available in the CRDB.

MHMS is being utilized for daily time step rainfall-runoff modeling and for fill and spill operations of small reservoirs throughout the Upper Colorado Region. Rainfall-runoff modeling uses the Precipitation Runoff Modeling System (PRMS), the code for which has been modularized for use in MHMS. Two separate modules have been developed for MHMS by Reclamation: a channel routing module, and a reservoir module. The channel routing module can be linked to PRMS to create a customized model that routes streamflow output from the PRMS modules through nodes in a drainage network. Such customized models are useful as research tools to assess the effects of changing climates on basin hydrology, and as operations tool to assess the effects of short term climate scenarios on reservoir inflows. Using the ESP capability within MHMS, probabilistic flow distributions can be generated for the nodes in the network, assisting in the operation and risk of spill assessment of basin reservoirs. Linking the reservoir module creates a model that stores, evaporates, releases water in reservoirs as well. This provides a complete simulation of both the natural and developed water resource system. The reservoir module can also be run stand alone for basins where rainfall-runoff models have not yet been developed.

The River Simulation System (RSS) is another modeling component in the data centered system. RSS has been developed by CADSWES under the direction of Reclamation. RSS is an object oriented simulator based on stimulus response theory. It is used to perform long range monthly river basin planning studies. RSS is unique in that it is based on a picture programming paradigm. The model is written in C and C++ and runs in an X window environment. The model separates the physical system of a water resource system from the policies by which the system is operated. RSS has a built in rulebase where river basin operating criteria (policies) are entered, giving the model the intelligence to properly simulate a water resource system. RSS communicates with the CRDB through a customized DMI integrated directly into the application source code. This DMI pulls model input data from the CRDB and stores output data back into the CRDB.

RSS is being utilized to address the effects of long term operating criteria on endangered fishes in the Colorado River system. The flexibility of RSS to alter the operating policy makes RSS and excellent modeling tool for this task. It is expected that the complete operating criteria for the Colorado River will be written into the RSS rulebase and that RSS will ultimately replace the Colorado River Simulation Model as Reclamations simulation system for the Colorado River.

Several component applications that import and process data are in place in the data centered system.

One such component is a real time data acquisition system. Currently, telemetry data from over 200 remote sites is being processed in Reclamation's Water Operations Office in Salt Lake City. This data originates from Data Collection Platforms (DCP's) which collect and transmit hydrometerological data over the Geostationary Orbiting Environmental Satellite (GOES) telemetry network. Telemetry data is processed and stored using DSM III software, developed by the Sutron Corporation, which runs on a VAX computer. The DSM III software decodes raw data streams into hourly data values. Hourly data and summarized daily values are subsequently stored in indexed sequential files on the VAX.

An application has been developed to port telemetry data stored on the indexed sequential files to the CRDB. The application is composed of embedded SQL programs written in C. These programs open sequential files on the VAX and transfer user specified data to the CRDB on the UNIX workstations. These programs run automatically at 5 a.m. each morning using the UNIX cron utility. There is a daily flux of current hydrologic data (via the telemetry network) flowing into the CRDB. This data are available for use by the modeling applications, the GIS applications, and the analysis applications. This telemetry data is particularly useful for rainfall-runoff models in MHMS where such current data can be used to run these models in a "near real time" environment.

Another data importation component is an application to import Soil Conservation Service (SCS) snotel data into the CRDB. At weekly intervals, Reclamation logs into the SCS computer system in Portland, Or. A query of all snotel sites in the Upper Colorado Drainage is made. An embedded SQL program then loads this data into the CRDB. Once in the database, this data is available for use by other application programs in the system.

The development of a fully automated data link between the SCS and the CRDB is planned for the spring of 1993. The SCS is currently preparing to get on the internet to which Reclamation is already connected. The internet supports remote logins, using TELNET, and remote file transfers, using File Transfer Protocol (FTP). These tools will facilitate the development of an automated data link through which appropriate data can be transferred daily from the SCS database to the CRDB in Salt Lake City.

The development of a similar automated data link with the USGS is also envisioned. The USGS is currently migrating to a UNIX based environment for the National Water Information System (NWIS II). Once NWIS II is operational an automated data link will be developed to port surface water data pertinent to the Colorado River Drainage to the CRDB.

Statistical data analysis, time series plotting and visualization of data is accomplished in S-Plus. AT&T originally developed S. S is now supported and enhanced by Statistical Sciences Inc. S-Plus communicates with the CRDB through a specialized DMI that is dynamically loaded into the S-Plus application at run time. SQL statements (i.e. queries) can be issued at the S-Plus command line. The results of the queries (i.e. data) are brought directly into the S-Plus application.

Another key component to the system is the GIS. An menu driven spatial interface to the INGRES database has been developed using ARC/INFO software. Environmental Systems Research Institute (ESRI), developers of ARC/INFO, have incorporated links to relational databases (i.e. DMI) into the latest releases of the software. Through this interface the data in the CRDB database is brought into the GIS environment as attribute data to spatial features (lines, points, and polygons).

The GIS interface has multiple functionality. Raw and model generated data can be displayed draped over user selected thematic map layers. Using menus, the user can zoom to selected sub drainage basins in the Upper Colorado. Different sets of water objects (reservoirs, power plants, diversions, gages, etc) may be displayed as icons on the display overlaid on top of users specified thematic layers (i.e. hydrography, political boundaries, land use, canals, aqueducts, etc.). The application generates snow distribution maps in the Upper Colorado Basin, depicts reservoir content conditions by highlighting different level of capacities with different symbology, and displays the most current available data for selected water objects. Postscript files can also be generated from the program to create hard copy output.

The GIS program also serves as a data query interface. As not all persons wishing to access the CRDB will be familiar with SQL, such an interface is highly desirable. The user of the application can select a site for data query by clicking on an icon on the display. Available data parameters for that site are then displayed on a menu. The users then selects a parameter from the menu. If the parameter is a time series the user is prompted for a time or time range for the query on a graphical form. The data can be displayed on the screen or sent to a file at the users option.

IMPROVED WATER MANAGEMENT

The data centered system for the Upper Colorado River Basin has enhanced Reclamation's ability to manage water resources in the Upper Colorado Region. Reclamation's ability to disseminate water resource information (current conditions, projected conditions, special releases, delivery shortages, deviation from target flows, etc.) to decision and policy makers within the organization has been significantly improved. Such information is also more easily disseminated to other federal agencies, states, private companies, environmental groups, the general public, or any group with an interest in Colorado River water resources.

The GIS interface is an effective tool for monitoring the current conditions of the system. Reclamation often makes commitments to provide flow regimes for the purpose of research, endangered species recovery, construction, etc. The GIS display provides an easy method to quickly display current telemetry at gage sites in a selected subbasin. The GIS also assist in communicating the "big picture", so that the many variables (reservoir contents, reservoir inflows, snow conditions, basin precipitation, etc.) that affect water resource management can be effectively assimilated.

The integration of the CRDB with the RSS and MHMS modeling applications simplifies the preparation of model input data for simulations. The integrated plotting programs and statistical functionality in MHMS and the connection to S Plus in RSS simplify post processing and analysis of model output as well. The result is that Engineers and Hydrologists are more productive, capable of running more simulations, and providing more information than was previously possible.

CONCLUSION

Data Centered Architectures for water resource management offer a framework whereby models, GIS, analysis tools and multiple databases can be effectively integrated. While the design and development of a data management system is not a trivial task, and requires significant investment of resources, the advantages of data centered system offset the investment. Todays water resource issues are often multidisciplinary, encompassing many physical science and engineering disciplines. Such multidisciplinary assessments necessitate the ability to integrate multiple data sets, couple models, analyze output and display the results in a method that can be understood by all interested parties (i.e. GIS displays). A data centered approach provides a methodology through which such a formidable task can be accomplished.

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SECTION 4

HYDROLOGIC MODELING SYSTEMS

Page

Expert System for Calibration and Application of Watershed Models
Alan M. Lumb and John L. Kittle, Jr. 4-1
A System Of Hydrologic Models
Jimmy R. Williams and Jeffrey G. Arnold 4-8
An Object-Oriented Approach to General-Purpose River-Basin Management
Jean M. Boyer 4-16
Object-Oriented Simulation Modeling of Watersheds
Robert E. Kort and E. Allan Cassell 4-24
ANN-AGNPS: A Continuous Simulation Watershed Model
Scott E. Needham and Robert A. Young 4-32
The Modular Hydrologic Modeling Systems-MHMS
George H. Leavesley, Pedro J. Restrepo, Linda G. Stannard, and
Michael J. Dixon 4-40
Soil Water Hydrology and Chemical Budgets with the Enhanced SPAW Model
Dr. Keith E. Saxton 4-43
Surface Water and Groundwater Model Developments at the Waterways
Experiment Station
Jeffrey P. Holland 4-52

Figures and Tables

Expert System for Calibration and Application of Watershed Models 4-1

Figure: 1. Detailed steps to calibrate HSPF with HSPEXP 4-5

A System of Hydrologic Models 4-8

Figure: 1. Integration of models, GIS, and databases 4-15

An Object-Oriented Approach to General-Purpose River-Basin Management 4-16

Figure: 1. Network schematic for the Lower Nile River Basin 4-19

Object Oriented Simulation Modeling of Watersheds 4-24

Figures: 1. STELLA® II screen showing a structural diagram of Compound Interest Model 4-26
2. Structural diagram for the Compound Interest Model 4-26
3. Illustration of the animation of the objects (note filling of Acct Balance and dial movement of Interest Income) and active creation of an output plot over the simulation period. The horizontal line is Mon Interest Rate and Acct Balance is the line having exponential form 4-28
4. STELLA® II structural diagram for portions of TR-55 4-29
5. STELLA® II structural diagrams for portions of HYMO 4-29
6. Runoff hydrograph for a watershed generated with HY5[0]. Qa, Qb, and Qc are flow rates for the corresponding HYMO hydrograph segments. Qhymo represents the summation of the flow rates of the three segments. All flows are in cfs 4-30

EXPERT SYSTEM FOR CALIBRATION AND APPLICATION OF WATERSHED MODELS

ALAN M. LUMB[1] and JOHN L. KITTLE[2], Jr.

INTRODUCTION

Watershed models have been used for over two decades for the continuous simulation of river basin response to meteorologic variables of precipitation and potential evapotranspiration for flood forecasting, environmental impact assessments, and the design and operation of water-control facilities. Various parameters in the watershed models are used to adapt the models to specific river basins. Some of the parameters can be determined from measured properties of the river basins, but others must be determined by mathematical optimization or manual calibration. Optimization techniques used over the past two decades have not been totally satisfactory. Such techniques reduce the interaction between the model user and the modeling process, and, thus do not improve user understanding of the processes as simulated by the model and the actual processes in the watershed. Even though objective functions can be minimized by optimization, the physical meaning of such optimized model parameters is left, for the most part, unexplained. Manual calibration also has not been totally satisfactory, because it requires experienced watershed modelers and there are more potential users of watershed models than there are experienced modelers. With that in mind, an effort was begun to use the expertise of the experienced watershed modeler within the context of an expert system so that the less-experienced modelers can "manually" calibrate the model and improve their understanding of the link between the simulated processes and the actual processes. This paper describes such an expert system.

PROCEDURES FOR MANUAL CALIBRATION

The Hydrological Simulation Program - Fortran (HSPF) was selected as the basis for testing the feasibility of developing an expert system for parameter calibration (Johanson and others, 1984). In an earlier effort, an expert system was developed to estimate initial parameters for HSPF (Gaschnig and others, 1981).

In the present effort, two surface-water modeling experts, the first author and Norman H. Crawford (Hydrocomp, Inc.), and a knowledge engineer, Richard B. McCammon (U.S. Geological Survey), documented procedures used to manually calibrate the rainfall-runoff module of HSPF. These calibration procedures are divided into four major phases: (1) water balance, (2) low flow, (3) storm flow, and (4) seasonal adjustments. A fifth phase, to identify any bias within the model, was also identified. During each of the four major phases, a different set of calibration parameters were analyzed by comparing simulated streamflow with observed streamflow. In a decade of experience over a wide range of climates and topographies, experienced modelers have learned which parameters can be meaningfully adjusted in order to reduce the error of estimation. Although the adjustments in parameter values during calibration produce an error of estimation not significantly different than mathematical optimization routines, the parameters developed can be more meaningful and useful for regional applications of the model to ungaged watersheds. Mathematical optimization tends to treat the model as a "black box" and usually considers minimization of only one criterion, which is typically the sum of the square of the difference between simulated and observed flows.

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INITIAL PROTOTYPE

A set of conditions was developed for each of the major phases, in which the end user would be prompted for the general observations of the differences between simulated and measured flows. For example, the user would be asked if simulated storm flows are too high in the summer, if the total volume of simulated flow is too low, and so forth. Given the user's responses, the initial prototype of the expert system identified the parameter to be changed, direction of that change, and the reason for the change.

ADDITION OF COMPUTED ERRORS

Although parameter adjustment (advice) from the initial prototype of the expert system was useful, there was a major burden on the user to identify the errors and communicate them to the expert system. To ease that burden, seven error terms are computed by the system from the simulated and observed streamflow time series:

(1) total flow volume error,
(2) error in low-flow recession based on a portion of the ratios of flow today divided by the flow yesterday,
(3) error in the lowest 50% daily mean flows,
(4) error in the highest 10% daily mean flows,
(5) error in flow volumes for selected storms,
(6) seasonal volume error, considering the June-August and December-February periods, and
(7) error in flow volume for selected summer storms.

Two other computations were made that are needed by the expert system:

(1) ratio of simulated surface runoff and interflow volumes, and
(2) the difference between the simulated evapotranspiration and the potential evapotranspiration.

With these computed values, the expert system could now provide advice without the subjective input from the end users. Several of the rules, however, contain optional conditions that the user can supply. Examples are the type of vegetation, the water-holding capacity of the soil, the soil depth, and whether there is substantial recharge to a deep aquifer.

DESCRIPTION OF HYDRO-II PROTOTYPE

The expert system designated HYDRO-II (Lumb and McCammon, 1991) is made up of a set of rules that are based on statistical measures and subjective judgments that reflect the role of the parameters in the rainfall-runoff module of HSPF. The statistical measures are calculated after each HSPF run. The subjective judgments are asked of the user by the system when such judgments, in combination with the rules, affect the advice offered by the program. In its simplest form, a rule can be expressed by the following:

$$\text{IF condition}_1\ \text{condition}_2\ \text{condition}_3 \quad \text{THEN action} \,,$$

where the conditions are tested from left to right. Each of the previously specified conditions represents a Boolean expression. The respective action will be taken if any of the previously specified conditions are true. The action in these situations is to advise the user about whether to increase or decrease the value of a particular parameter. To take one rule as an example:

> IF (the simulated total runoff is E1 % higher than measured
> AND the ET difference is less than the flow difference)
> (the simulated total runoff is E1 % higher than measured
> AND there could be recharge to deeper aquifers)
> THEN the advice is to increase DEEPFR,

where the error level E1 is set by the user, the simulated and measured runoff and the ET and flow differences are calculated from the output for the run, and the judgment about whether there could be recharge to deeper aquifers is elicited from the user if necessary. In this case, if the simulated total runoff is not E1 % higher than measured, there is no need to pursue this rule further and no need to ask the user about whether there could be recharge to deeper aquifers. Furthermore, if the first condition is true, the advice is to increase DEEPFR. There is no need to ask the user about possible deeper recharge. Only if the simulated total runoff is E1 % higher than measured, and the ET difference is greater or equal to the flow difference is there a need to ask the user whether there could be recharge to deeper aquifers. Such a strategy minimizes the subjective judgments required by the user.

In addition to the advice offered by the system, the user can request an explanation. In the case of the above rule, for example, the explanation given is:

> Water losses from watersheds include surface-water flow at the outlet, actual evapotranspiration, and subsurface losses. Because observed precipitation and total runoff are fixed, and the potential evapotranspiration provides a ceiling for evapotranspiration, the only way to reduce total runoff is to increase subsurface losses. DEEPFR is the only parameter used to roughly estimate those losses and should be based on results of a groundwater study of the area.

Such information has the greatest value to inexperienced hydrologists and to hydrologists unfamiliar with the HSPF program. Such an explanation affords an excellent training mechanism. As the knowledge of the user increases over time, however, explanations become less important.

Within HYDRO-II, there are currently 37 rules that involve 84 conditions of the type described above. The rules apply to the 13 major, process-related HSPF parameters. For many of the these parameters, there is more than one rule that contains advice about whether or not the value of the parameter should be increased or decreased. To avoid the potential conflict in the advice offered by the system, the rules are divided into the four phases previously defined, each phase determining the order in which the rules will be applied. Although there are several rules within each phase, there is only one rule that will advise whether a particular parameter should be increased or decreased. All rules within a phase are tested before moving on to the rules in the next phase. If any action is indicated after testing the rules within a phase, that advice is given and no further testing of the rules is performed. Such a strategy eliminates the possibility of conflicting advice being offered by the system.

HYDRO-II is written in Envos[1] LOOPS (Lisp Object-Oriented Programming System). LOOPS adds access, object, and rule-oriented programming to the procedure-oriented programming of Common Lisp and Interlisp-D. The result has been to make it possible to create an extended environment for the development of HYDRO-II.

TESTING

HYDRO-II has been used in the analyses of watersheds in Maryland and Washington. In each case the advice was verified by the experienced modeler, and in each case the advice resulted in a reduction of the error. Quantitative evaluations of the effectiveness of the system have not yet been conducted; however, the subjective response of users has been very positive.

DESCRIPTION OF THE PRODUCTION VERSION (HSPEXP)

To enable distribution and provide additional testing of HYDRO-II, the program has been converted to ANSI standard languages using public-domain software tools for the user interface, data management, and graphics. The production version, HSPEXP, is written in Fortran with a subroutine for each rule. The graphics utilities use the ANSI and FIPS Graphical Kernel System (GKS) library, which is commercially available for almost any computer. The user interface uses the ANNIE Interactive Development Environment (AIDE) tool developed by the U.S. Environmental Protection Agency and the U.S. Geological Survey (Kittle and others, 1989), and a Watershed Data Management (WDM) file is used for time-series data management.

HSPEXP is an interactive program that uses a set of menus and forms for the selection of options and the modification of specifications and parameters. The major menu options include: select basin files; simulate; compute and display statistics; produce graphics; get calibration advice; modify parameter values; and set error criteria.

The steps and procedures to calibrate HSPF with HSPEXP are shown in Figure 1. These steps are described below.

Step 1 is to create the user control input (UCI) file for HSPF, as described in the HSPF users manual (Johanson and others, 1984). A WDM file is used for the time series input to HSPF and can be created with the program ANNIE (Lumb and others, 1990). The expert system will require some specific records on the UCI file. The purpose of those records are to store output time series for 10 computed variables on the same WDM file as the input time series. HSPEXP uses the input and output time series to compute statistics needed to generate the expert advice. The 10 time series are:

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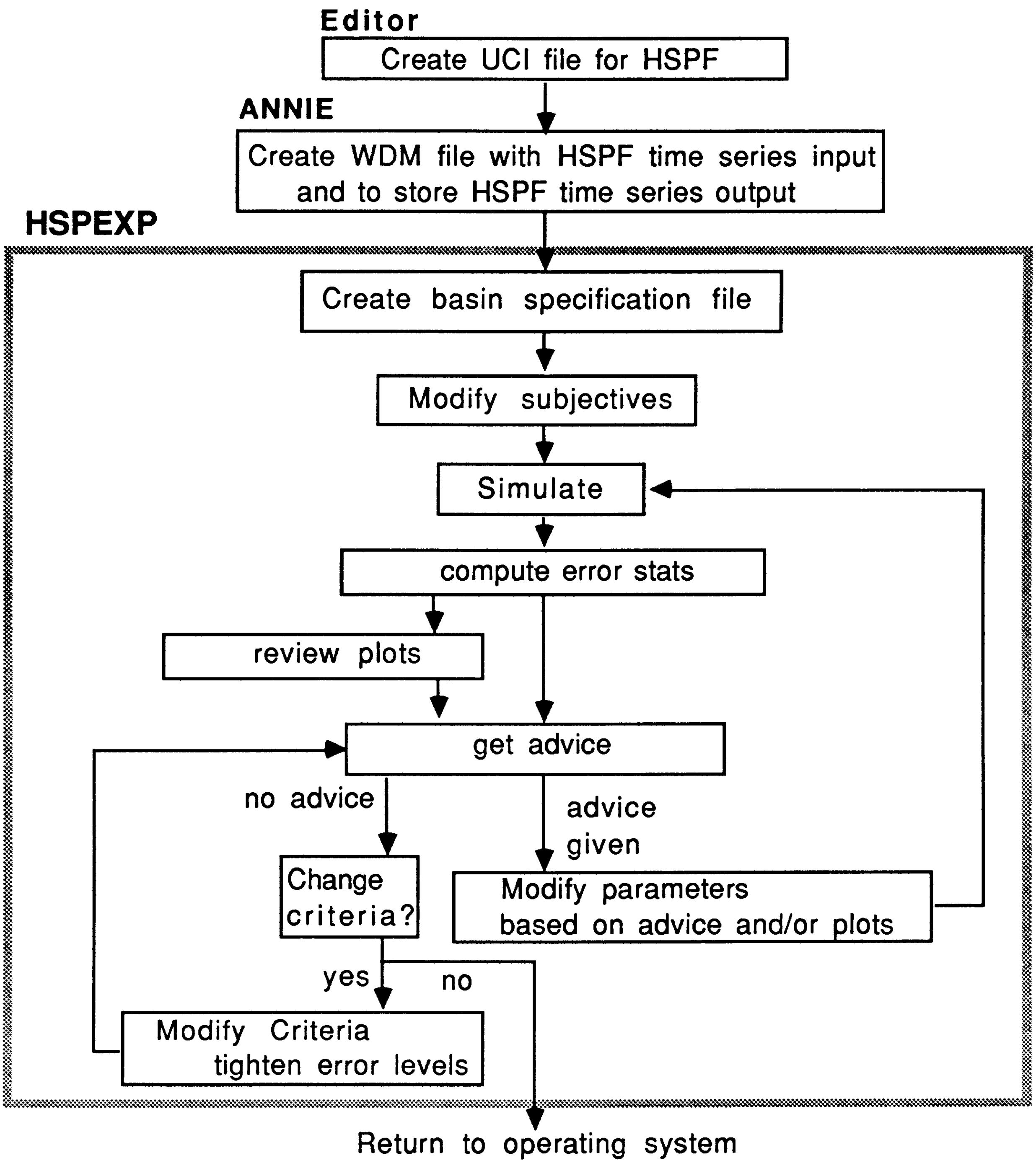
[1] Use of brand, trade, or firm names in this paper is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.




```
EXPLANATION: UCI - User Control Input
             HSPF - Hydrological Simulation Program Fortran
             WDM - Watershed Data Management
             HSPEXP - expert system to use HSPF
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Figure 1. Detailed Steps to Calibrate HSPF with HSPEXP

(1) simulated total runoff (inches),
(2) observed total runoff (inches),
(3) simulated surface runoff (inches),
(4) simulated interflow (inches),
(5) simulated base flow (inches),
(6) precipitation (inches),
(7) potential evapotranspiration (inches),
(8) actual evapotranspiration (inches),
(9) upper-zone storage (inches), and
(10) lower-zone storage (inches).

In order for the expert system to remember the error criteria and WDM data-set numbers for the time series, an ASCII file is used. The dates of storm periods to be used in error computations also are included on the file. HSPEXP can be used to create and modify the basin specifications file.

There are 23 subjective items, such as category of vegetal cover, that can be provided to the expert system by using an HSPEXP menu option. The default for each item is "unknown" unless modified with HSPEXP. It is useful to answer as many of these questions as possible. The responses are stored on the basin specification file.

At any time, plots can be generated to get a picture of the success of the calibrations. Ten different plots can be generated. For UNIX workstations, 1 to 4 of those plots can be shown on the monitor at one time. The most useful are the daily and monthly flow hydrographs and the flow-duration plots. The plots showing error against upper-zone storage, lower-zone storage, observed flow, and time are useful at later stages of the calibration to check for various types of biases. The evapotranspiration plots are useful to identify periods where evapotranspiration is limited by the potential or available moisture. A menu option under the graph option can be used to modify the plotting specifications. When leaving the graph option, a file is written with the plotting specifications and used in subsequent applications of HSPEXP.

The advise menu option in HSPEXP can be selected anytime after a simulation has been completed. The expert system advice will identify a parameter to change and the direction of the change. The user must assume an amount of change for the parameter and make that change under the HSPEXP modify menu option. This will change the parameters for the next simulation. For a permanent change to the UCI file, the menu option to save the file is selected.

Initially, the default values of the error terms should be appropriate. Upon several iterations of simulation, expert advice, and parameter changes, a point will be reached where no more advice is given. At that point (1) calibration can end, (2) the modeler can make further adjustments by trial-and-error, or (3) the error terms can be "tightened". To change (tighten or loosen) the error terms, the criteria menu option is selected.

SUMMARY

HSPEXP has been developed as an expert system for calibrating watershed models for drainage basins. HSPEXP represents an effort to make the knowledge of experienced modelers available to general model users. The knowledge consists of the statistical representation of the observed hydrograph in terms of the system parameters that drive the precipitation-runoff process. The particular model used to test HSPEXP was the Hydrologic Simulation Program Fortran (HSPF). The estimation procedure consists of a set of hierarchical rules designed to guide the calibration of the model through a systematic evaluation of the model parameters.

To date, the system has been tested on watersheds in Washington and Maryland, and the results are most encouraging. In each instance, the system correctly identified the model parameters to be adjusted and the adjustments led to an improved calibration. It is anticipated that HSPEXP will serve as a major component in the calibration of watershed models.

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A SYSTEM OF HYDROLOGIC MODELS

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INTRODUCTION

The hydrologic modeling system under development at Temple, TX contains several models for use in solving a variety of soil and water resource problems. The models range in temporal and spatial scales, applicability, and in required component detail. Models currently contained in the system include the Erosion Productivity Impact Calculator the Groundwater Loading Effects on Agricultural Management Systems (GLEAMS) (Leonard et al., 1987); the Simulator for Water Resources in Rural Basins (SWRRB)(Arnold et al., 1990; Williams et al., 1985); the HYdrologic MOdel (HYMO)(Williams and Hann, 1973); the Routing Outputs to the Outlet (ROTO)(Arnold, 1990). EPIC and GLEAMS are field scale models; SWRRB and HYMO were designed to operate on watersheds up to 2500 Km^2; and ROTO is a routing model that interfaces with EPIC, GLEAMS, and SWRRB to provide river basin scale capabilities. Recently, the ROTO/SWRRB interface was further developed to form a new model called SWAT. All of the models feature continuous simulation on a daily time step except HYMO which is a single event flood routing model.

Since each model was developed for solving a particular set of problems, each one offers unique strengths. EPIC provides strength in crop growth, nutrient cycling, and agricultural management. GLEAMS provides unique strengths in pesticide fate and landscape erosion simulation. SWRRB features on expanded spatial scale accomplished by subdivision, pond and reservoir simulation, and sediment routing capabilities.

The ROTO model was recently developed to estimate water and sediment yields from basins. ROTO accepts subarea inputs from EPIC, GLEAMS, or SWRRB and also point source inputs. The HYMO command structure is used to route through streams, valleys, and reservoirs, thus allowing almost total flexibility in subwatershed configurations.

Geographic Information Systems (GIS) are being utilized to automate input development and display spatially varying outputs. Model input data relating to soils, land use, elevation, and climate are spatially referenced in the GIS and directly written to the model input files. Maps of model outputs can also be displayed and the user can utilize the GIS as a spatial reference to access input and output files.

SWAT is a continuous time water and sediment routing model that operates on a daily time step. The objective in model development was to predict water and sediment movement in large ungaged basins, several thousand square miles, by accepting daily measured or simulated subarea inputs and routing them through channel reaches and reservoirs. To satisfy the objective, the model (a) is physically based (calibration is not possible on ungaged basins); (b) uses readily available inputs (detailed channel cross-section data is generally not available for large basins); (c) in computationally efficient to operate on large basins in a reasonable time, and (d) is continuous time and capable of simulating long periods for computing the effects of measurement changes.

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The System of Models

SWAT

SWAT was developed to predict the effect of alternative management decisions on water, sediment, and chemical yields with reasonable accuracy for ungaged rural basins. The model was developed by modifying the SWRRB model for application to large, complex rural basins. Major changes involved (a) expanding the model to allow simultaneous computations on several hundred subwatersheds and (b) adding components to simulate lateral flow, ground water flow, reach routing transmission, reach routing transmission losses, and sediment and chemical movement through ponds, reservoirs, streams and valleys. SWAT operates on a daily time step and is capable of simulating 100 years or more. Major components of the model include hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, ground water and lateral flow, and agricultural management.

The SWAT model boasts significant advantages over the combined SWRRB/ROTO (Arnold, 1990) model. SWAT offers distributed parameter and continuous time simulation, flexible watershed configuration, irrigation and water transfer, lateral flow, ground water, and detailed lake water quality components. The distributed parameter, continuous time feature was achieved by adding a new routing structure to the SWRRB/ROTO model. The input data structures (Arnold et al., 1993) have been changed for the SWAT model. In SWRRB, channels are routed directly from the subbasin outlets to the basin outlet, while the SWAT reach routing structure routes and adds flow down through the basin reaches and reservoirs, allowing flexible basin configuration. In general, the basin is divided into subbasins by natural flow paths, boundaries, and channels required for realistic routing of water, sediment and chemicals, thus preserving watershed configuration. However, SWAT can simulate a basin that is divided into grid cells and can also simulate flow along a hillslope. Due to its flexible basin and subbasin configuration and routing structures, the SWAT model can read in measured stream flow and can be used to model areas where input data collection is impossible.

Distributed parameter, continuous time models require significant amounts of input data for each basin. To assemble input data from maps and manually manipulated enter the data into required format would be extremely time consuming. Thus, GIS tools have been developed to automate model inputs from digital maps and spatially display model outputs. Figure 1 shows the link between the models, GIS, and databases.

Currently, SWAT accepts subarea inputs EPIC. Input can easily be accepted from any continuous daily water and sediment yield model such as WEPP (Lane and Nearing, 1989) or CREAMS (Knisel, 1980). SWAT output can also be used as input to another SWAT run making the model capable of handling unlimited drainage area. Computer storage requirements can be drastically reduced by deleting subarea output files within a SWAT run and working through a basin by linking SWAT runs. If measured data is available at certain nodes it can be read into SWAT. Also, hydrologic procedures can easily be replaced or added since each procedure is a subroutine. Besides providing river basin simulation capabilities, SWAT will also serve as shell to link the other Temple models.

The SWAT-GIS Input Interface Tool

The GIS (Geographic Information System) tool chosen was GRASS (U.S. Army, 1987) a public domain raster GIS designed and developed by the Environmental Division of the U.S. Army Construction Engineering Research Laboratory (USA-CERL), in Champaign, Illinois. GRASS is a general purpose, raster graphic modeling and analysis package and it is highly interactive and graphically oriented (both 2-D and 3-D), providing tools for developing analyzing, and displaying spatial information. GRASS is being used by numerous groups including the USDA SCS (Soil Conservation Service). This not only helps to ensure the availability of compatible databases, but confirms that the model will be of use to agencies and researchers associated with hydrology and erosion.

A toolbox rational was utilized in providing a collection of GIS programs to assist with the data development and analysis requirements of the SWAT model. The SWAT-GRASS input interface programs and other tools are written in C language and are integrated with the GRASS libraries. The SWAT model is written in FORTRAN 77 language and both the interface and model run under the UNIX environment. The input-interface tools assist with preparation and extraction of data from the GIS database for use in the SWAT model. The input interface (Srinivasan and Arnold, 1993) consists of three major divisions 1) project manage, 2) extract and aggregate inputs for the model; and 3) view, edit and check the input for the model. The function of the project manager is to interact with the user to collect, prepare, edit and store basin and subbasin information to be formatted into a SWAT input file.

The extract and aggregate step uses a variety of hydrologic tools (Srinivasan and Arnold, 1993). The GIS layers that are required at this step include: subbasin, soils, elevation, landuse, pesticide application, and weather network. In addition the reservoirs, inflow, pond and lake data can be collected directly from the user. In the third step the user can either view, edit or check the data extracted from the previous phase by using a subbasin number as input. There are about 15 different data forms that can be modified by the user. The developed interface is believed to reduce the data collection and manipulation time (Rosenthal et al., 1993) by several orders. The interface allows rapid modification of the various management practices and prepares the data for subsequent model runs. The interface can also be used to examine the model or to perform sensitivity analysis by modifying the GIS data layers and/or choosing different aggregation methods for various input data. Once the SWAT input file has been built by the input tools, the model is run.

SWAT-Output Analytical Tool

After the SWAT model is run, the output analytical tool extracts the distributed parameter output data from the ASCII output file and allows the user to visualize and analyze the outputs from the model graphically. The capabilities of the output analytical tool include statistical methods such as: scatter plots, line graphics, pie charts, and bar graphs. A user can select to view or analyze a subbasin, between subbasins, or the outlet of basin. The outputs include drainage area, monthly potential evapotranspiration, daily rainfall, runoff, sediment yield, and soluble and sorbed nutrient and pesticide yields for each day flow occurs and for each subbasin. The user is also given the option to query the water, sediment, and chemical balances within the channel of each subbasin. Using the statistics option in the output analytical tool, validation of observed versus simulated data can be easily performed and the regression curve can be displayed graphically. Another major advantage of this tool is to obtain a customized hard copy output for reports. The data can be analyzed for each month or for the entire simulation period.

Field Scale Model

EPIC

The Erosion-Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990) model was developed to assess the effect of soil erosion on soil productivity. It was used for that purpose as part of the 1985 RCA (1977 Soil and Water Resources Conservation Act) analysis. After the RCA analysis, model refinement and development continued and EPIC has been applied to a number of small watershed management problems. EPIC components are: hydrology, weather, erosion, nutrients and pesticides, soil temperature, plant growth, tillage, plant environment control, and economics. The hydrology component simulates (1) Surface runoff (Runoff volume is estimated with a modification of the SCS curve number method. Peak runoff rate predictions are based on a modification of the Rational Formula.) (2) Percolation (Uses a storage routing technique to predict flow through each soil layer in the root zone. Downward flow occurs when field capacity of a soil layer is exceeded if the layer below is not saturated.) (3) Lateral subsurface flow (Calculated simultaneously with percolation. A nonlinear function of lateral flow travel time is used to simulate the horizontal component of subsurface flow.) (4) Evapotranspiration (The model offers four options for estimating potential evaporation and computes soil and plant evaporation separately.) (5) Snow Melt (Snow is melted on days when the maximum temperature exceeds 0 degree C, using a linear function of temperature.)

The weather component accepts measured inputs or simulates (1) Precipitation (Given the wet-dry state, the model determines stochastically if precipitation occurs or not. When a precipitation event occurs, the amount is determined by generating from a skewed normal daily precipitation distribution.) (2) Daily maximum and minimum temperature (Generated from a multivariate normal distribution). (3) Solar radiation (Generated from a multivariate normal distribution). (4) Wind (Generates average daily wind velocity and direction). (5) Relative humidity (Simulates daily average relative humidity from the monthly average using a triangular distribution).

The EPIC water erosion model simulates erosion caused by rainfall and runoff and by irrigation (sprinkler and furrow). To simulate rainfall/runoff erosion, EPIC contains three equations--the USLE, the MUSLE, and the Onstad-Foster modification of the USLE. The Manhattan, Kansas, wind erosion equation was modified for use in the EPIC model. The original equation computes average annual wind erosion as a function of soil erodibility, a climatic factor, soil ridge roughness, field length along the prevailing wind direction, and vegetative cover. The main modification of the model was converting from annual to daily predictions to interface with EPIC.

The nutrient component considers N and P. Amounts of NO3-N contained in runoff, lateral flow, and percolation are estimated as the products of the volume of water and the average concentration. A loading function is used to estimate organic N loss. Denitrification, one of the microbial processes, is a function of temperature and water content. Denitrification is only allowed to occur when the soil water content is 90% of saturation or greater. The N mineralization model is a modification of the PAPRAN mineralization model. The model considers two sources of mineralization: fresh organic N associated with crop residue and microbial biomass and the stable organic N associated with the soil humus pool. The mineralization rate for fresh organic N is governed by C:N and C:P ratios, soil water, temperature, and the stage of residue decomposition. Crop use of N is estimated using a supply and demand approach. The daily crop N demand is estimated as the product of biomass growth and optimal N concentration in the plant. Optimal crop N concentration is a function of growth stage of the crop. Soil supply of N is limited by mass flow of NO3-N to the roots. Daily N fixation is estimated as a fraction of daily plant N uptake. The fraction is a function of soil NO3 and water content and plant growth stage. To estimate the N contribution from rainfall, EPIC uses an average rainfall N concentration at a location for all storms. The EPIC approach to estimating soluble P loss in surface runoff is based on the concept of partitioning pesticides into the solution and sediment phases. Sediment transport of P is simulated with a loading function as described in organic N transport. The P mineralization model is similar in structure to the N mineralization model. Mineral P is transferred among three pools: labile, active mineral, and stable mineral. Crop use of P is estimated with the supply and demand approach described in the N model.

The GLEAMS pesticide component is used in EPIC to simulate pesticide transport by runoff, percolate, soil evaporation, and sediment. Each pesticide has a unique set of parameters including solubility, half life in soil and on foliage, wash off fraction, organic carbon adsorption, and cost.

Daily average soil temperature is simulated at the center of each soil layer for use in nutrient cycling and hydrology. The temperature of the soil surface is estimated using daily maximum and minimum air temperature and snow, plant, and residue cover for the day of interest plus the four days immediately preceding. Soil temperature is simulated for each layer using a function of damping depth, surface temperature, and mean annual air temperature. Damping depth is dependent upon bulk density and soil water.

A single model is used in EPIC for simulating plant growth for about 25 crops. Of course, each crop has unique values for the model parameters. Energy interception is estimated as a function of solar radiation and the crop's leaf area index. Crop yield is estimated using the harvest index concept. The potential biomass is adjusted daily using the minimum plant stress factor (water, N, P, temperature, aeration). Roots are allowed to compensate for water deficits in certain layers by using more water in layers with adequate supplies. Compensation is governed by the minimum root growth stress factor (soil texture and bulk density, temperature, and aluminum toxicity).

The EPIC tillage component was designed to mix nutrients and crop residue within the plow depth, simulate the change in bulk density, and convert standing residue to flat residue. Other functions of the tillage component include simulating ridge height and surface roughness. The plant environment or management component consists of drainage, irrigation, fertilization, liming, and pesticide application. The economic component accounts for costs of farm operations and materials applied and for income from crop sales.

Example EPIC applications include: (1) 1985 RCA analysis; (2) 1988 drought assessment; (3) soil loss tolerance tool; (4) Australian sugarcane model (AUSCANE); (5) pine tree growth simulator; (6) global climate change analysis (effect of CO2, temperature, and precipitation change on runoff and crop yield); (7) farm level planning; (8) five-nation EEC assessment of environmental/agricultural policy alternatives; (9) Argentine assessment of erosion/productivity; (10) USDA-Water Quality Demonstration Project Evaluation; (11) N leaching index national analysis.

Watershed Scale Model

SWRRB

Simulator for Water Resources in Rural Basins (SWRRB) was developed to predict the effect of alternative management decisions on water and sediment yields with reasonable accuracy for ungaged, rural basins (Arnold et al., 1990; Williams et al., 1985). Recently, components have been added to simulate nutrient and pesticide movement. The model was developed by modifying the CREAMS daily rainfall model (Knisel, 1980) for application to large, complex, rural basins. The major changes involved were a) the model was expanded to all simultaneous computations on several subwatersheds, and b) components were added to simulate weather, lateral flow, pond and reservoir storage, crop growth, transmission losses, as well as sediment movement through ponds, reservoirs, streams, and valleys. Figure 1 shows the system simulated and all of the hydrologic components.

SWRRB operates on a daily time and is efficient enough to run for many years (100 or more). Since the model is continuous in time, it can determine the impacts of management such as crop rotations, planting and harvest dates, and chemical application dates and amounts. Basins can be subdivided into subwatersheds based on differences in land use, soil, topography, vegetation, rainfall, and temperature. Sediment and associated chemicals are then routed to the basin outlet. In the vertical direction, the model is capable of working with any variation in soil properties since the soil profile is divided into a maximum of ten layers. SWRRB has been validated on basins up to 500 km^2 (Arnold and Williams, 1987), and a decision support system was developed to assist users in developing input data sets (Arnold and Sammons, 1988). The components of SWRRB can be placed into eight major divisions--hydrology, weather, sedimentation, soil temperature, crop growth, nutrients, pesticides, and agricultural management. A detailed description of the SWRRB components is given in Arnold et al. (1990) and Arnold et al. (in press).

SWRRB is currently in use throughout the U.S. by various government agencies and environmental consultants. SWRRB is being applied to quantify the impact of water management in the Little Colorado river basin in northern Arizona and New Mexico. This is part of an effort being undertaken by the Bureau of Indian Affairs (BIA) and the Hopi and Navajo Indian Tribes to quantify Indian rights to water in reservation basins. SWRRB was selected because the basins are ungaged and SWRRB is a continuous simulation model. As part of the National Coastal Pollutant Discharge Inventory, the National Oceanic and Atmospheric Administration (NOAA) is using SWRRB to estimate non-point source loadings from all coastal counties in the U.S. (Singer et al., 1988). The Environmental Protection Agency (EPA) has adopted SWRRB as a pesticide assessment model and have developed their own user's manual. Several chemical companies and consulting firms are using this version of the model for environmental assessment. SWRRB was one of six models chosen by the Soil Conservation Service (SCS) for water quality studies. The SCS will support and utilize the model for determining impacts on water quality at the watershed scale.

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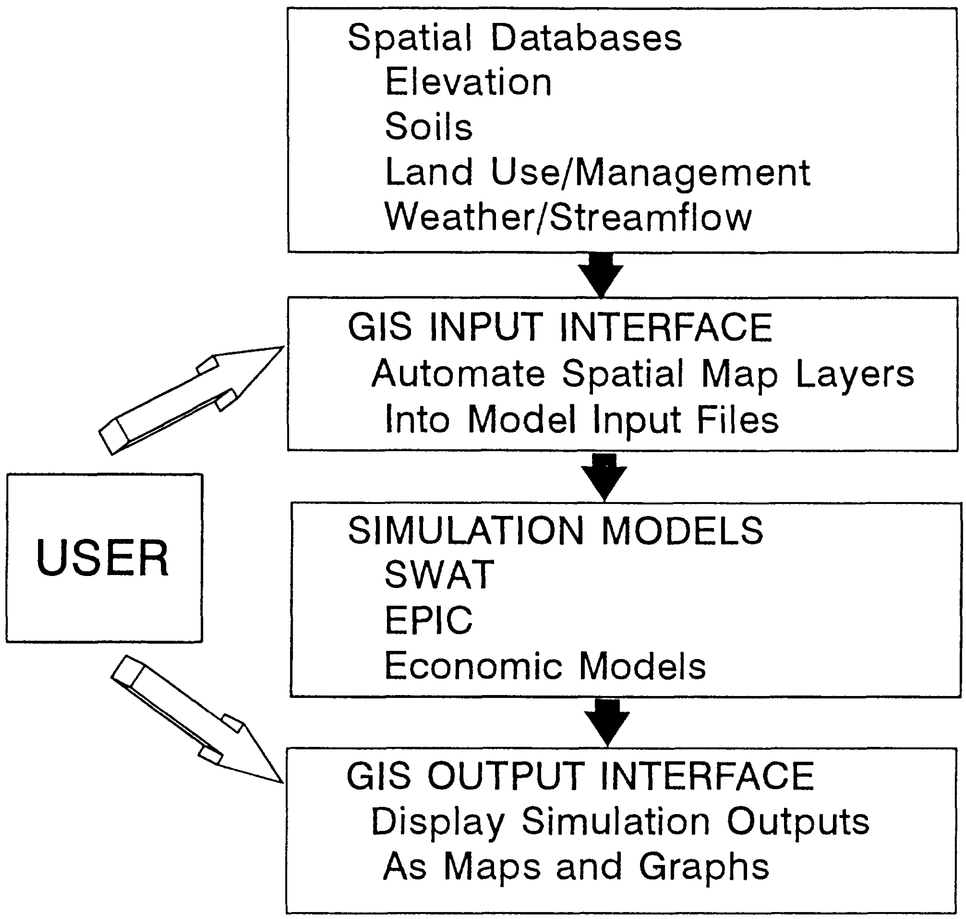

Figure 1. Integration of Models, GIS, and Databases

AN OBJECT-ORIENTED APPROACH TO GENERAL-PURPOSE RIVER-BASIN MANAGEMENT

JEAN M. BOYER[1]

ABSTRACT

Water resource management organizations which manage entire river basins need to consider the impacts of their decisions from a basin-wide perspective. Most planning and operations models are inextricably tied to a particular river basin in order to incorporate the institutional constraints specific to that basin. A few general purpose models exist but it is difficult to properly account for the many complicated institutional and administrative rules governing a particular system. Another problem with most river-basin management tools is it is difficult to make additions and/or modifications to the features used to describe the river basin without disturbing the rest of the program. In order to overcome these issues, Reclamation has developed a general-purpose modeling framework called CALIDAD for river-basin management.

In the CALIDAD system, institutional constraints and management objectives (referred to here as rules) are tied to the physical features of the river basin through the use of a search technique called tabu search. The user has the ability to incorporate a variety of management rules into the system including system-wide rules and conditional rules.

CALIDAD employs object-oriented programming techniques that treat each river basin feature as an object. Object-oriented programming provides many advantages in the areas of model development and maintenance. The user interface for CALIDAD includes a graphical network editor, based on the objects, to aid the user in building and changing the river-basin network.

Aspects of the modeling framework and applications to the Central Valley Project in California are discussed.

INTRODUCTION

Over the past several years, resource management organizations have been migrating towards a more holistic approach to decision making. Until recently, it has been difficult to accurately capture the complex interactions involved in a broad study area such as an entire river-basin. Advances in the areas of affordable computer hardware and software now make it possible to seriously analyze this type of problem.

Agencies which are tasked with managing several different study areas find that general

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purpose models, which can be applied to a variety of different areas and use a data-centered approach to modeling, can provide for a more efficient means of management (Cheney, 1993). Two issues often arise when using such models however. The first issue deals with the difficulties in accurately incorporating the site-specific management and institutional constraints governing a particular area. In reality, many site-specific laws and treaties are a complex function of many variables and are difficult to capture in a generic fashion.The second issue deals with the ability of the end-user to make modifications and additions to an existing model in order to customize the system for a specific application. Typical simulation and optimization models used by engineers working for government agencies are written in FORTRAN in a procedural fashion. Many aspects of computer programming using a procedural approach make it difficult to make modifications and additions without disturbing other parts of the model. A considerable amount of expensive labor can go into implementing and debugging these modifications.

In order to overcome these issues, Reclamation has developed a general-purpose river-basin management framework named CALIDAD. CALIDAD has been developed using object-oriented programming techniques, which simplifies the process of making modifications and adding site-specific river-basin features. It employs an artificial intelligence (AI) optimization technique called tabu search (Glover, 1990) to determine monthly release schedules that do not violate user-specified management and institutional rules. If such a release schedule does not exist, as in the case of conflicting rules, the search technique will satisfy the most important constraints at the expense of the least important constraints. The importance of each rule is specified by the user through the use of weighting factors.CALIDAD has a graphical user interface to allow the user to easily create or modify the river-basin network and to incorporate the management rules into the system.

The development of this framework was initiated for the government of Egypt through Reclamation by the Center for Advanced Decision Support for Water and Environmental Systems (Boyer and Makare, 1992). Additional and enhanced modeling capabilities have been developed by Reclamation for the Lower Nile river basin and for the Central Valley Project (CVP) in California. Future plans include the development of daily modeling capabilities. These capabilities will initially be applied to the Pecos River in New Mexico.

CALIDAD runs on SUN SparcStations, Data General Aviions, and DECStations. The software used for development includes C, Objective-C, FORTRAN, X, and Motif.

The purpose of this paper is to describe the components of the CALIDAD framework. A short discussion of the object-oriented programming paradigm is included. Aspects of applying this modeling framework to the CVP in California are also discussed.

OBJECT-ORIENTED PROGRAMMING

In general, object-oriented programming is a paradigm shift away from traditional procedural programming. It is a philosophy about how computer programs should be developed. Instead of modeling the system as a set of nested procedures, the system is viewed as a conglomerate of interacting objects. There are four basic concepts behind the paradigm. As one uses more and more of these concepts in a program, the closer the program comes to being developed in the object-oriented style. These philosophies are 1) data hiding, 2) data abstraction, 3) dynamic binding, and 4) inheritance. These concepts are described in more detail elsewhere (Boyer, 1993).

The advantages to using object-oriented programming in system development are numerous. The use of the paradigm:

- facilitates the addition of new objects or components;
- significantly improves data management;
- reduces the time spent on debugging;
- allows for significant reuse of code;
- facilitates the modification of existing components or objects; and
- forces modularity.

All of these advantages contribute to faster software development and facilitate the ease to which other programmers can understand computer code that has been written by someone else.

The main disadvantage of using object-oriented programming techniques is related to speed, although the actual difference in execution speed between traditional procedural programs and object-oriented programs is not very significant (Pascoe, 1986). Continuing advances in computer hardware and software help to minimize this issue. Also, many expensive effort days are spent in software development and debugging. Computer time is inexpensive (Doyle, 1990). This issue should also be taken into consideration when making decisions about whether or not to use this approach.

THE CALIDAD MODELING FRAMEWORK

The objective of the CALIDAD system is to determine monthly diversion and reservoir release schedules that do not violate user-specified management and institutional constraints. The main components of the system include: 1) the physical representation of the river-basin, 2) the designation of management rules, and 3) tabu search. Each of these components is discussed below followed by a general discussion of the system.

Physical Representation of the River Basin

The physical aspects of the river basin are described as interacting objects in a network editor (Figure 1). River-basin features are represented as objects and are displayed on a palette. Examples of such features include reservoirs, hydropower power plants, irrigation sites, gains, losses, and inflows. The physical behavior of each object is described by computer code in a file. For example, the reservoir object accounts for evaporation, seepage, and bank storage. If the user chooses to simulate reservoir sedimentation, the

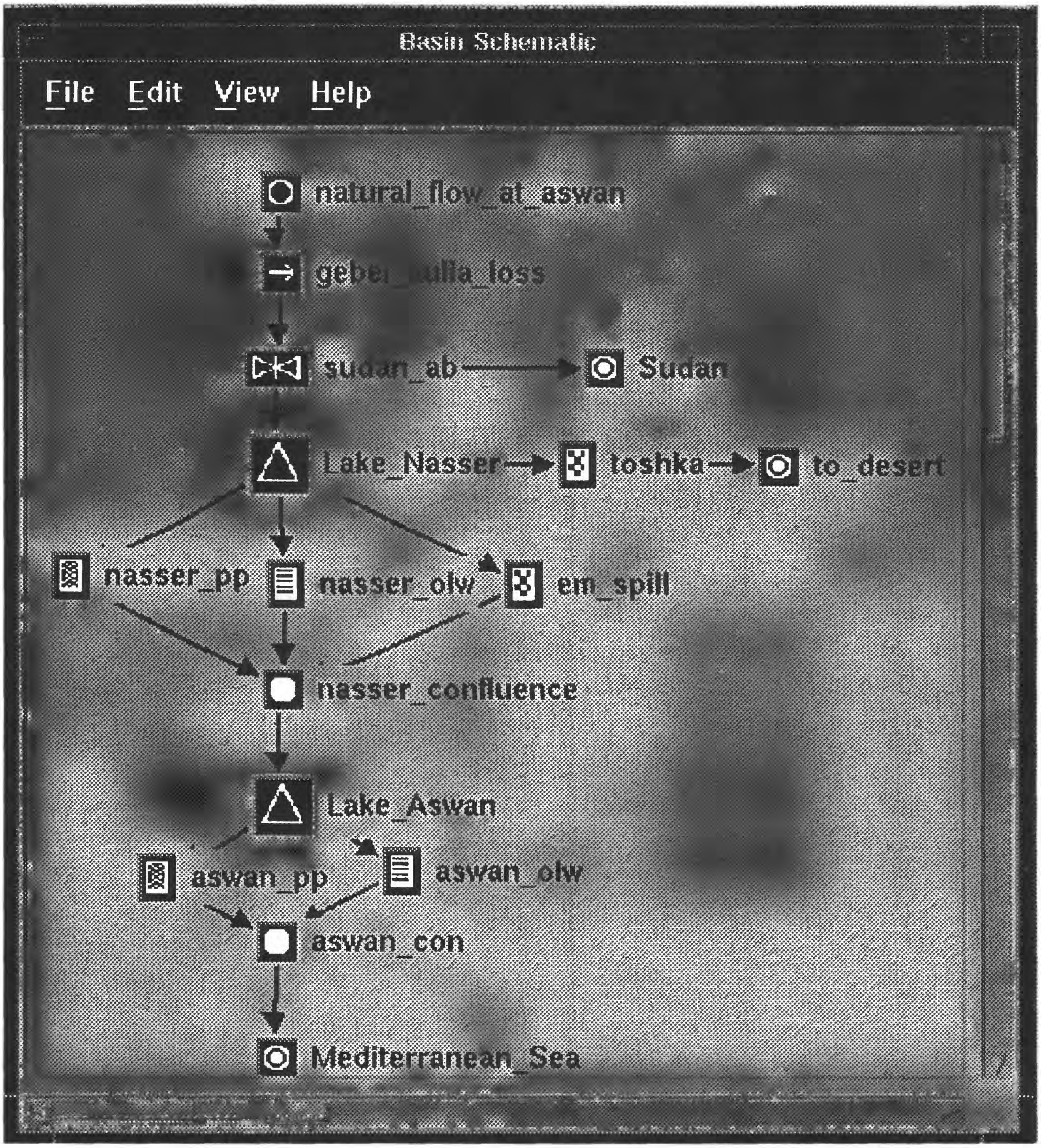

Figure 1

Network Schematic for the Lower Nile River Basin

object makes a call to a FORTRAN sediment distribution program which determines how sediment is distributed throughout the reservoir on a yearly basis (Orvis, 1991). The area-capacity relationships are also adjusted after the sediment is distributed via a call to another USBR FORTRAN program called ACAP85 (USBR, 1985). The user provides site-specific data for the mechanisms discussed above. The only constraints included in an object are physical constraints, such as reaches cannot have negative flow and reservoirs cannot have negative capacity.

Using a mouse, the user chooses features from the palette and places them on the network editor. Connections are then made so that the model knows where flows originate and terminate. Feature-specific data are entered into appropriate tables.

Designation of Management Rules

A rule editor is provided so that the user may specify the management and institutional rules governing the system. Examples of typical rules include rule curves, flood control rules, low flow requirements, and any site-specific laws and treaties describing river-basin operations. The user uses a combination of object names, object variables, numbers, relational operators, algebraic operators, and statements for conditional branching in order to describe the rule or constraint. Therefore, it is possible to construct a variety of rules, such as rules that contain equations, conditional rules, and rules that involve several objects in the system.

For example, a law governing the Colorado River system states that the storage in Lake Mead and the storage in Lake Powell must be equal each October. This rule in the CALIDAD system would appear in the rule editor as:

Lake_Powell storage = Lake_Mead storage

and be applied each October.

A rule governing the Lower Nile river basin illustrates the use of a conditional rule. If the water level in Lake Nasser is below the lower rule for the month, then the diversions to Sudan are decreased by a sliding scale reduction factor, k (United Nations Development Program, 1981). This rule is represented in CALIDAD as:

IF (Lake_Nasser level < lower_rule)
THEN (Sudan inflow = k * sudan_demand)

An example of a system wide rule is:

total_reservoir_storage > 5000 KAF

The user of the system has thus directed CALIDAD to determine a release schedule which will result in a total reservoir storage for the system of at least 5000 thousand acre-feet for the month. This rule would sum all end of month storages of each reservoir in the system in order to meet this rule.

Tabu Search

Tabu search serves as the main control for the system. The search technique is a heuristic optimization technique and is used in this application to determine release schedules that do not violate the management rules. Using the reservoir releases and diversions as decision variables, the search iteratively sets these variables, runs the simulation, and checks to see if any of the rules have been violated. If this is the case, the decision variables are modified and the simulation is run again. This continues until all rules have been met or in the case where the rules are conflicting and a solution cannot be found, the search will report the release schedule that meets the most important constraints and relaxes the least important constraints. In essence, the search minimizes an evaluation function based on user-provided weighting factors. The main advantage of tabu search is its ability to avoid local optima by imposing restrictions on moves or changes of state that would allow the search to fall back into or climb back up to local optima. The use of object-oriented programming greatly facilitates the implementation of this technique in this application.

General Discussion

One of the main strengths of the CALIDAD system is the ability to direct the system to determine a solution based on an overall management objective. Often, a general law or management objective is desired. In other simulation models, the user or programmer would need to make some assumptions and somehow code into the system how the answer should be computed under a variety of operating conditions. For example, if an objective was to meet a specific temperature objective at a point downstream of 5 reservoirs, traditionally, a multitude of sub-rules would need to be assumed in order to tell the system how to decide in a step-by-step fashion how to release in order to meet the temperature objective. In this case, the overall set of rules would need to be very complicated and cumbersome and is a direct result of the assumptions made in order to come up with the final solution.

In the CALIDAD system, the rule would appear as:

Reach_1 temperature < 56° F

It is up the to system to determine the best way to meet this objective. The user does not need to make additional assumptions about how to best satisfy this requirement. In this respect, CALIDAD can be viewed as a policy model. This major strength allows the user to step back and focus on the overall objectives of river-basin operation versus the fine details based on assumptions. Of course, if laws and other regulations deal with the finer details, the system is able to handle these situations also.

APPLICATION TO THE CENTRAL VALLEY PROJECT

The Mid-Pacific Region of Reclamation currently uses site-specific models to simulate CVP operations due to the complexity of the operating laws and constraints. Using CAL-

IDAD for CVP management will provide a flexible framework that is easily modified. This has become more important recently due to several additional laws and decisions affecting the project.

General System Description

The Central Valley Project (CVP) is a complicated, multipurpose water resources project in the state of California. It covers two major watersheds: the Sacramento River system in the north and the San Joaquin River system in the south. Major features include 20 reservoirs, (11 million acre-feet of combined storage capacity) 8 power plants and approximately 500 miles of major canals and aqueducts. The portion of the CVP that is currently being simulated in CALIDAD includes the Sacramento River system (including the Feather and American Rivers) down to the delta and two canals which deliver delta water to the southern parts of the state, the Delta-Mendota Canal (DMC) and the state-owned California Aqueduct (CAQ). These are the same features that are simulated in Reclamation's site-specific model, PROSIM.

Physical Representation

The physical representation of the CVP in CALIDAD consists of 151 objects, all linked together in a network. There are 18 distinct object classes: primary reservoirs, reregulating reservoirs, mainstream diversions, reservoir diversions, power plants, pumping plants, pumping-generating plants, weirs, gains, losses, inflows, state demands, project demands, non-project demands, reaches, river outlet works, confluences, and a delta.

System Objectives and Constraints

The CVP is governed by a complicated set of laws and management constraints. Among the typical constraints are flood control rules, minimum reservoir storages, maximum reservoir storages, target reservoir storages, commitments to meet agricultural and municipal demands, and power production objectives. There are 12 reaches where minimum flow requirements must be satisfied for fish and wildlife.

One of the issues which greatly complicates the management of the CVP is the fact that state and federal facilities are intertwined. Some of the facilities in the interconnected network are federally owned, some are state owned, and some are jointly owned. Also, state and federal agencies jointly use the Sacramento River and the delta as common conveyance facilities. The joint operation of the two systems is governed by a set of rules described in the Coordinated Operations Agreement (COA). These rules ensure that each system (state and federal) retains its share of water and also contributes its share of water to meeting in-basin obligations, including minimum delta outflow requirements.

Delta water quality standards exist as set by the State Water Resources Control Board. Also, temperature objectives exist at certain points in the CVP to protect salmon populations.

These rules are treated as data and entered by the user into the rule editor.

Status

The final incorporation of all CVP specific object classes and rules is expected to be complete in the summer of 1993.

CONCLUSIONS

The CALIDAD system framework, which is a data-centered river-basin management tool has been described. The strengths of the model include the ability to capture a variety of complicated management rules and constraints as input data into the program. The user can also easily step back and focus on the overall operational objectives of the river-basin system, making it an ideal tool for policy analysis. Physical and managerial aspects of the systems are easily modifiable through the interface - compilation is not required. The use of object-oriented programming also makes CALIDAD a flexible system, designed for easy customization if existing objects do not represent the features required.

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OBJECT ORIENTED SIMULATION MODELING OF WATERSHEDS

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ABSTRACT

Watersheds are complex and dynamic natural systems containing a number of interconnected sub-systems where the behavior of the total system depends on the behavior of the individual sub-systems, their interconnectivity, and the environment in which they function. Because of this complexity many watershed models are difficult to understand and operate. With object oriented simulation modeling numerical methods are imbeded in understandable objects which are connected so that flows, feedback loops, and control structures operate as an interconnected whole system. The resulting models are considerably more user-friendly and flexible than those coded with traditional programming environments. Analysis utilizing object versions of TR-55 and HYMO is demonstrated.

DYNAMIC SIMULATION MODELING OF WATERSHEDS

Watersheds are complex and dynamic natural systems that demonstrate highly variable behavior over time and space. Such dynamic systems fluctuate about some condition that is considered normal or baseline. When a dynamic system that is in equilbrium is perturbed by an external factor, a fluctuation in output may be induced, however, the system tends to return to its equilibrium state over time. A complex dynamic system is conceptualized as a number of interconnected sub-systems comprised of interconnected elements, each with its own unique dynamic behavior. The interconnections among the sub-systems and elements impart the notion of feedback behavior to the total system. Thus, the behavior of the total system depends on the behavior of the individual sub-systems, their interconnectivity, and the environment in which they function.

Many watersheds are at or near equilibrium when the exiting streamflow is totally baseflow. Perturbations such as rainstorms or seasonal weather patterns change streamflow, but it eventually returns to baseflow conditions. Thus feedback is clearly demonstrated in watersheds. Long term perturbations in watersheds, such as slow incremental change in land cover, may establish new baseline conditions that define equilibrium.

Most models that simulate real system behavior consist of many lines of computer code that few users are able to decipher. In addition, data input is often very demanding. Consequently the

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versatility of model use is reduced and, typically, only experienced users are able to customize most models for use in unique situations. Widespread use of models demands user-friendly interfaces for entering data, running simulations, and outputting results.

Dynamic simulation modeling views the system, or watershed, as a collection of individual elements connected in a fashion so that various feedback mechanisms are allowed to operate as observed in reality. We use simulation modeling as a process of creating and running models of a watershed in order to study and ultimately to predict the behavior of the watershed. Simulation modeling encourages construction of a framework that can enhance understanding of watershed processes. This understanding as well as ease of use increases the utility for such models for planning and management of natural resource systems.

OBJECT ORIENTED SIMULATION MODELING IN STELLA®II

Object oriented programming (OOP) is a development which utilizes objects to encapsulate both information and techniques for operating on the information received by the object. Object Oriented Simulation Modeling (OOSM) capitalizes on the user-friendly tools provided by OOP to enhance the ease with which models are created, understood, and used. STELLA® II (High Performance Systems 1990, 1992) provides a simple object oriented framework to model and simulate behavior of dynamic systems. It operates on Macintosh computers and relies on the extensive use of a single button mouse to locate the cursor, tool or object on the screen; to select, access or activate objects on the screen; and to move or place objects at desired locations on the screen. Pull-down menus contain options that are used to define conditions of a given simulation, the appearance of the screen, and a variety of editing and file management functions.

STELLA® II uses four different types of objects or building blocks that are placed on the screen to form a structural diagram for the dynamic process being modeled. Figure 1 shows the STELLA® II screen on which a simple model for compounding interest on a savings account has been created. The structural diagram shown within the box is comprised of the four STELLA® II objects, e.g., the *Stock*, the *Pipeline/Controller*, the *Converter*, and the *Connector*. The same structural diagram is shown in Figure 2 along with explanations of the function of the various objects. The object labeled **Interest Income** computes the interest income which is a function of or is "controlled" by the "connected" objects **Acct Balance** and **Mon Interest Rate**. The object **Acct Balance** accumulates the interest income calculated for each time period and adds it to the initial balance.

Actual simulation with the models is a highly interactive process, one that allows the modeler to observe how all parameters in the model change over time. Animation of the diagram allows viewing

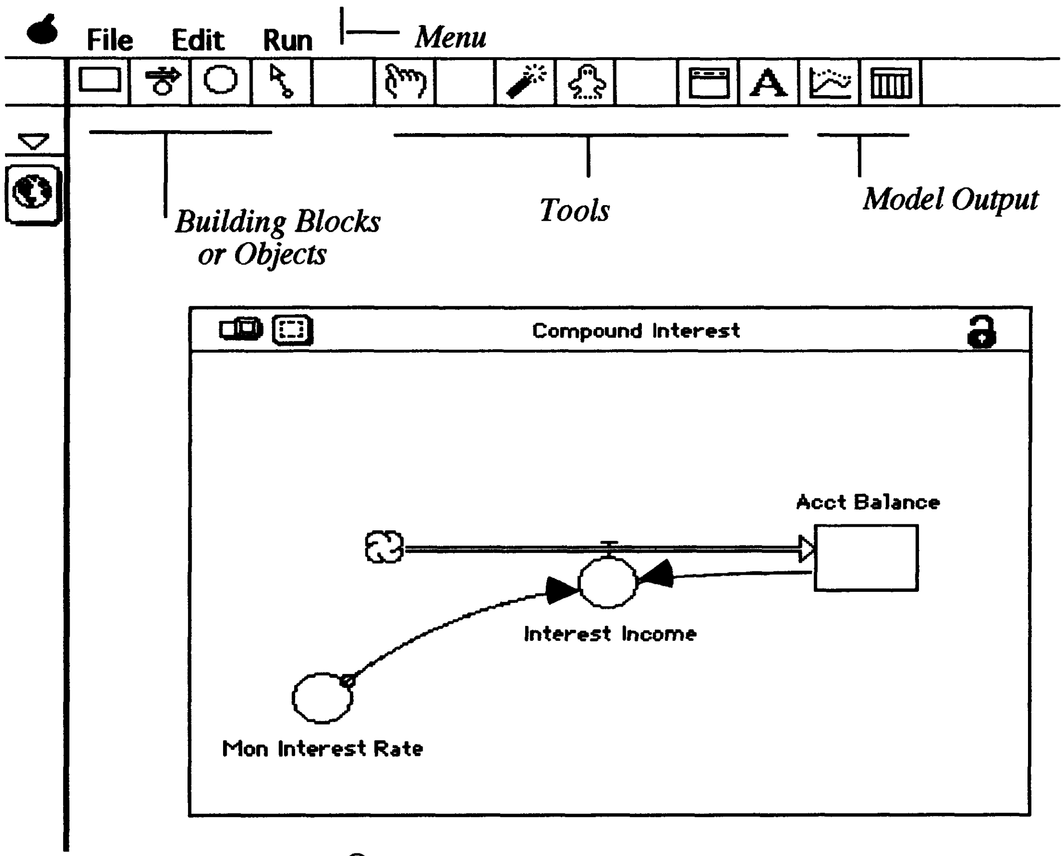


FIGURE 1 STELLA® II Screen showing a structural diagram of Compound Interest Model. The Building Blocks, Tools, Menus and Model Output select features are labeled in italics.

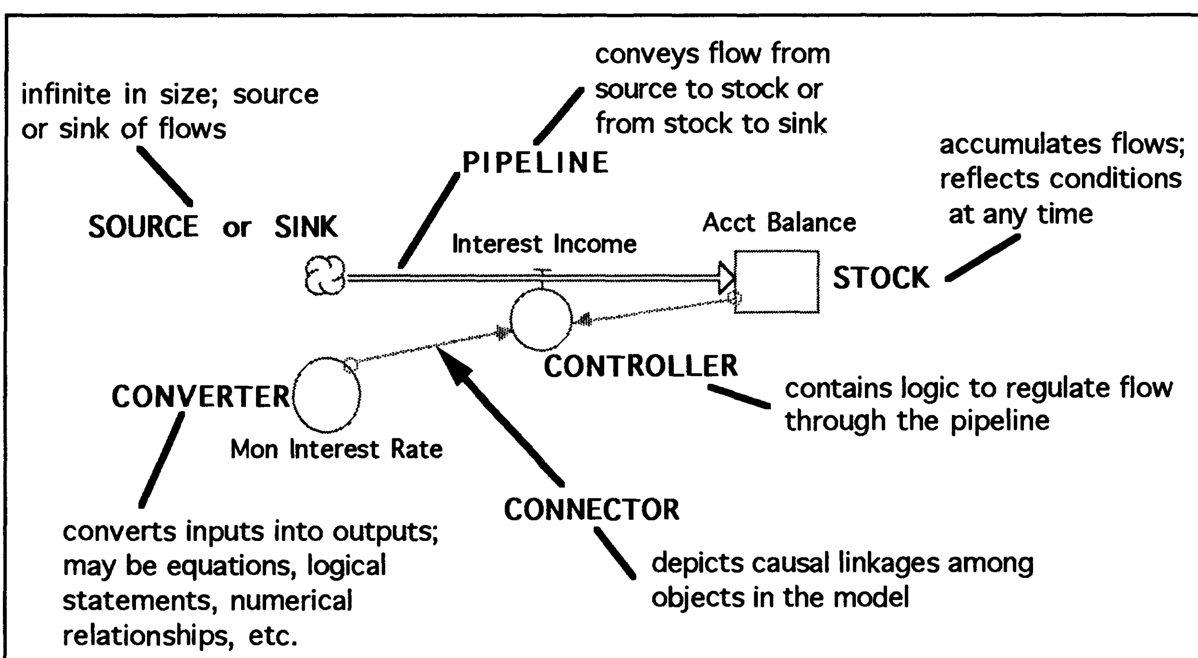


FIGURE 2 Structural Diagram for the Compound Interest Model. Each Building Block (Object) type is named and its function is briefly dscribed.

the dynamic behavior of the parameters in the model (e.g., the objects in the structural diagram). When the diagram is animated, stocks visually fill and empty as the simulation proceeds and the converters and controllers behave as dials. Observation of the objects in animation is a valuable aid in visualizing and understanding what is happening internal to the model during the simulation run. Additionally, it is simple to create output graphical plots or data tables for any or all the objects in the model. It is possible to view the active creation of the plots or tables as the simulation proceeds. Figure 3 shows how animation controls the appearance of the screen at three different times during a simulation run using the compound interest model discussed above. These features make it very convenient to examine the internal operation of the model over time to assess if the parameters are behaving as they should.

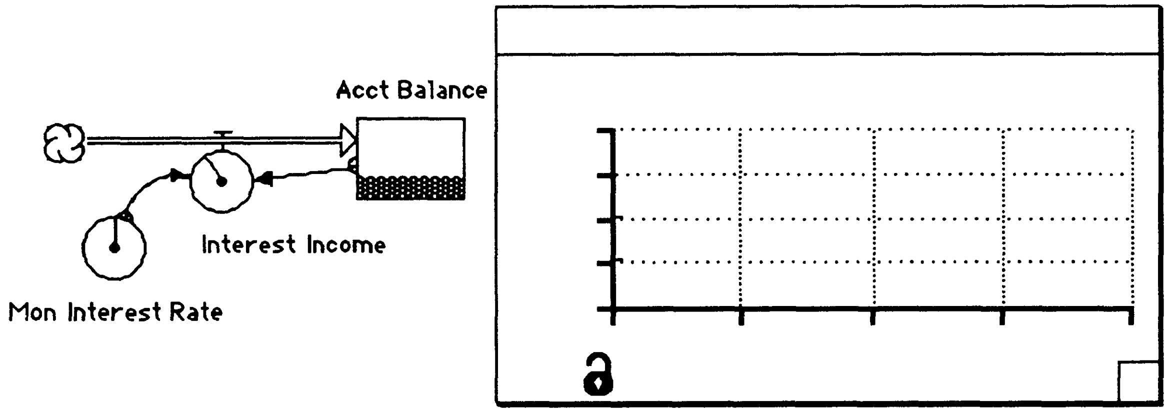
Numerical values and/or relationships of individual parameters are easily altered merely by clicking the cursor on the object in the structural diagram that represents the parameter you wish to change. Thus, when some portion of the model is not behaving as it should, you can quickly and easily enter the appropriate object and make the desired modification and immediately run another simulation to assess if the change made had the desired or expected effect. This allows sensitivity analyses to be carried out with ease and speed in comparison with non-OOSM modeling techniques. It cannot be over-emphasized how convenient the interactive nature of such object oriented simulation modeling makes the process of sensitivity analysis, the understanding of the underlying watershed processes, and the evaluation of alternative hydrologic management scenarios.

HYDROLOGIC MODEL DEVELOPMENT AND CHARACTERISTICS

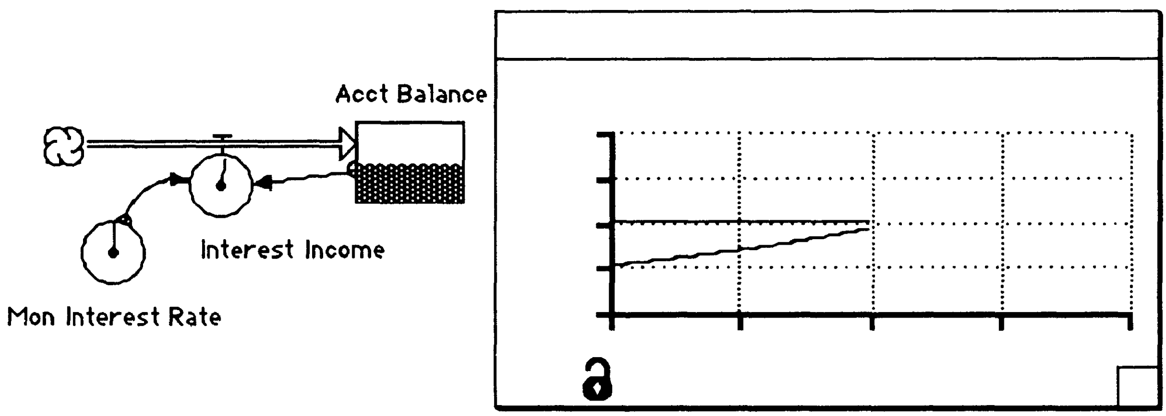
STELLA® II provides a creative environment for the development of hydrologic models. These models can be developed using a modular approach or design to allow for flexibility and direct comparison of specific model processes. Each model module contains a routine that simulates some specific hydrologic procedure or process. The final model consists of a series of modules linked together in a manner most appropriate to emulate the real watershed system. New or alternative algorithms easily can be inserted to modify individual modules. Such changes can be evaluated even though other modules in a given dynamic runoff model may remain unchanged.

Portions of the methods and algorithms for the well known TR-55, (USDA SCS 1986) program have been coded into the simulation framework provided by the STELLA® II software package (Figure 4). Two separate TR-55° structures are shown, one for the calculation of total runoff volume (Q) and the second for the determination of the peak discharge (Qp).

Time = 1 Month (beginning of simulation run)



Time = 60 Months (mid-way through simulation run)



Time = 120 Months (end of simulation run)

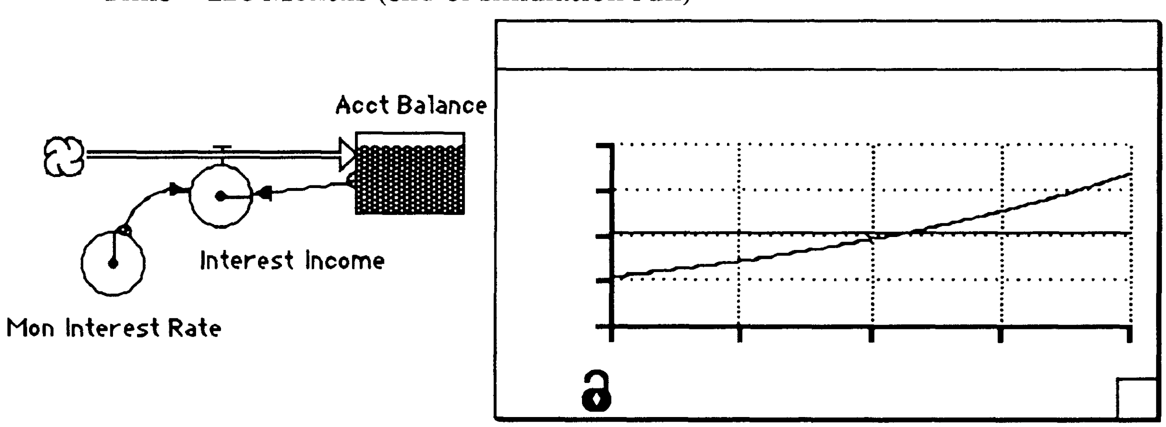


FIGURE 3 Illustration of the animation of the objects (note filling of Acct Balance and dial movement of Interest Income) and active creation of an output plot over the simulation period. The horizontal line is Mon Interest Rate and Acct Balance is the line having exponential form.

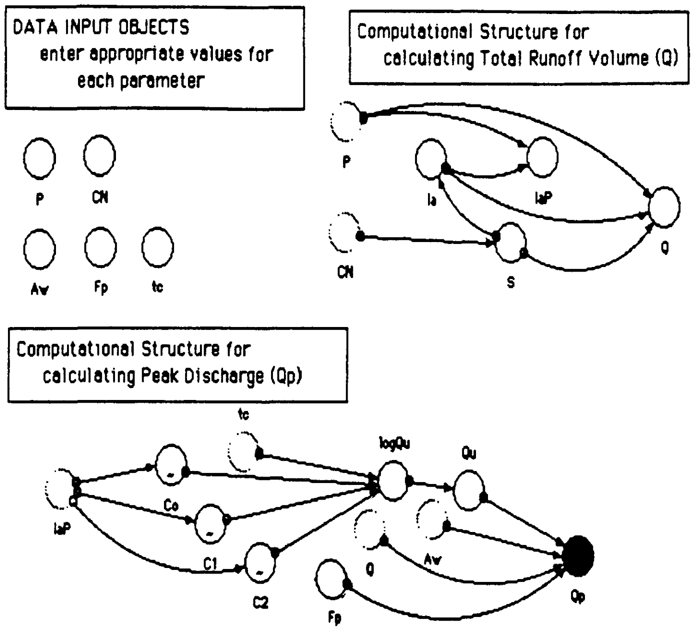


FIGURE 4 STELLA® II Structural Diagram for portions of TR-55.

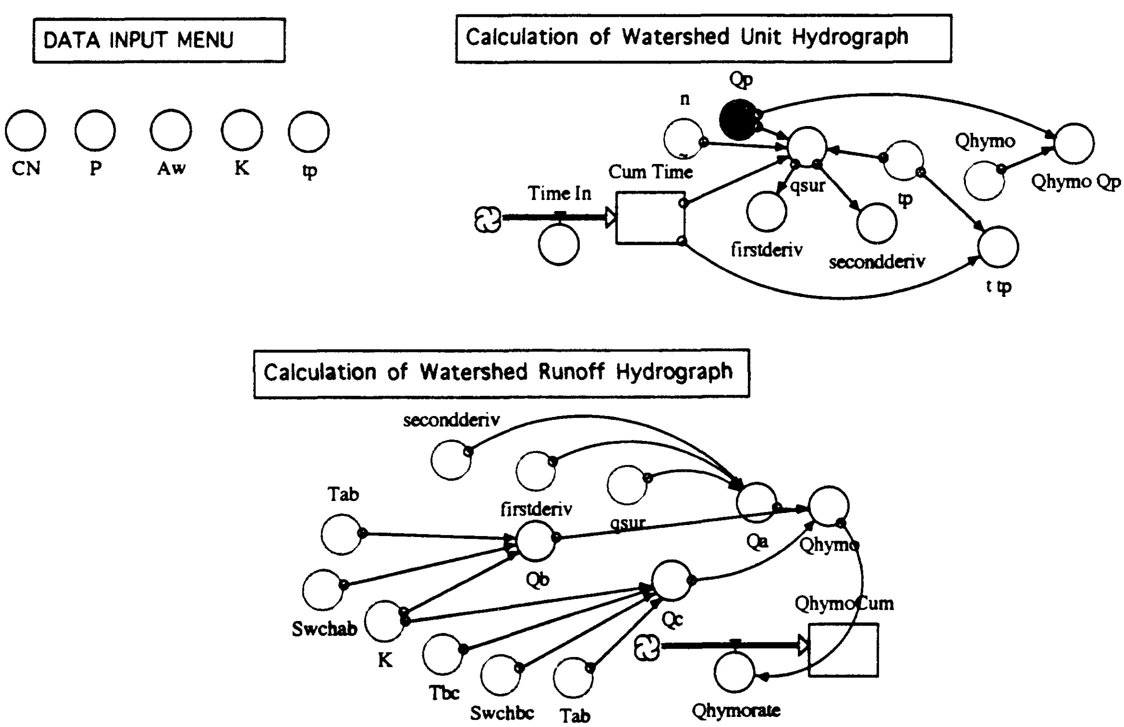


FIGURE 5 STELLA® II Structural Diagrams for portions of HYMO.

HYMO, (Williams and Hann 1973) is another popular model which determines watershed runoff and peak flow, utilizing routines that allow customization of the unit hydrograph to a given watershed. The routines in HYMO that permit the synthesis of unit hydrographs and the calculation of runoff hydrographs also have been placed in the STELLA® II environment (Figure 5).

In the STELLA® II environmment,linkage of different routines is quite easy. We have created a new hybrid object model, HY5©, by linking the TR-55© and HYMO© models. Specifically, HY5© links these models through the Qp objects (shaded objects in Figures 4 and 5). In HY5© Qp is calculated through TR55© and Qp serves as a basis for further calculations in HYMO©. HY5© could utilize any method for determining peak flow (Qp), but we chose the TR-55 method. It is this flexibility for linking modules that permits us to create complex hydrologic models such as the STELLA® II object model of the U.S. Army Corp of Engineer's SSARR: Streamflow Synthesis and Reservoir Regulation Model (Cassell and Pangburn, 1992).

The HY5© model rapidly generates watershed hydrographs consistent with input data parameters (see Figure 6). Additionally, we have used HY5© to (a) compare the effect of land use change on the watershed hydrograph by varying the CN, (b) assess differences among watersheds and (c) compare runoff from different storm events (USDA SCS & UVM, 1992). For example, to evaluate for a given watershed, how sensitive the peak discharge (Qp) is to change in mean areal curve number (CN), one simply selects the *Sensitivity Specs* option from the *RUN* menu (see Figure 1), defines the range of curve numbers to be evaluated, and runs the model. The results of this sensitivity analysis are shown in Figure 7.

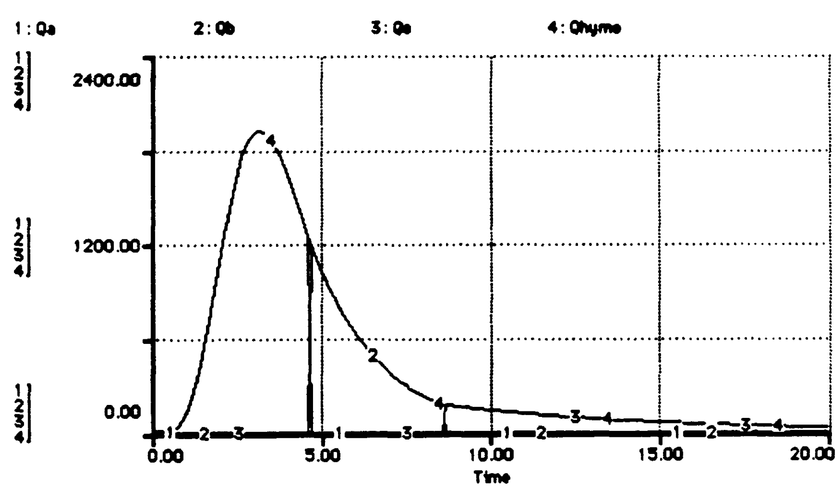


FIGURE 6 Runoff Hydrograph for a watershed generated with HY5©. Qa, Qb, and Qc are flow rates for the corresponding HYMO hydrograph segments. Qhymo represents the summation of the flow rates of the three segments. All flows are in cfs.

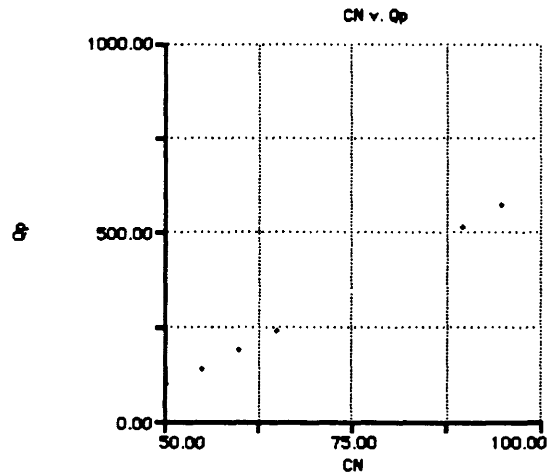


FIGURE 7 Sensitivity Plot of Peak Discharge (Qp in cfs) vs. Curve Number (CN). CN was varied from 50 to 95 while all other parameters remained constant.

CONCLUSION

Object Oriented Simulation Modeling provides a convenient tool for hydrologic modeling that can enhance the understanding of watershed behavior. These object models allow for linking the logic of existing hydrologic models to form hybrid models useful for custom application. They are easy to use and extremely efficient in allowing for sensitivity analysis of any model parameter. We believe that object oriented simulation modeling is a powerful new tool for watershed management and planning.

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ANN-AGNPS: A CONTINUOUS SIMULATION WATERSHED MODEL

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ABSTRACT

The Annualized Agricultural Nonpoint Source (ANN-AGNPS) model is a distributed parameter, continuous simulation model developed to simulate the behavior of watershed or catchments that have agriculture as their primary land use. It is based on the present AGNPS single event model and uses enhanced RUSLE routines. The basic components of the model include hydrology, sedimentation, and chemical transport. The model is cellular based with all characteristic inputs and calculations made at the cell level. Primary capabilities of the model include evaluation of the relative quantity and quality of outflow from a watershed in order to assess their pollution potential, identification of critical areas of nonpoint source pollutant production within a watershed, and evaluation of the effects on watershed outflow by applying alternative management practices on problem areas. A preliminary evaluation of the model on a monitored watershed is presented.

INTRODUCTION

Reducing agricultural nonpoint source (NPS) pollution loading has received reinvigorated interest inside and outside of the agricultural community. The 1990 Farm Bill's Water Quality Protection Program (WQPP) was designed to address this concern by targeting farm assistance to areas where meaningful reduction in agriculture's contribution could be achieved. The conservation agent, responsible for carrying out the program, has three basic tasks: (1) identify those lands that contribute the majority of pollutants, (2) estimate the level of contribution generated by those identified lands, and (3) based upon the level of contribution, design cost efficient alternative farm management strategies that effectively reduce pollutant loading.

A large number of computer modeling tools have been developed and enlisted to aid in resource conservation planning and management for soil erosion and NPS pollutant mitigation. A list of several of the more widely used models for agricultural landscapes include: CREAMS (Knisel, 1980), EPIC (Williams, et al., 1984), SWRRB (Arnold, et al., 1990), GAMES (Rudra, et al., 1986), HSPF (Barnwell and Johanson, 1981), ANSWERS (Beasley, et al., 1980) and AGNPS (Young, et al., 1989).

Efficiently and effectively implementing the 1990 Farm Bill's WQPP will require the increased use of computer models. These models must not only achieve the above stated three required tasks, but they should also be capable of the following: (1) allow operation by local agents without extensive training, (2) utilize input parameters that are easily obtained from available local sources, (3) not need complicated parameterization, and (4) generate results the resource planner feels comfortable with in making equitable and impartial decisions.

The updated continuous simulation version of AGNPS, ANN-AGNPS (Annualized - Agricultural Nonpoint Source model) is a computer tool capable of performing those tasks required to successfully carry out the intent of the new water quality program. Integrating continuous simulation to the existing distributed spatial abilities of AGNPS enables an even more representative description of the stochastic physical processes controlling the movement of sediments and agricultural chemicals from the field into the surrounding environment. At the same time, ANN-AGNPS's user interface and integrated data bases make the model easier to use.

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ANN-AGNPS STRUCTURE

The continuous version is based upon the AGNPS grid-cell representation of a watershed for delineating and identifying landscape and agronomic parameters as well as for entering the information into the data input spreadsheet. ANN-AGNPS routes water, associated sediments and nutrients through the watershed from cell to cell based upon directional flow information input by the user.

ANN-AGNPS, like AGNPS, generates results on watershed hydrology, including overland runoff volume, channel flow runoff volume, peak flow discharge rates, field erosion, channel sediment transport and deposition for five soil particle class sizes, and nutrient yields for Nitrogen (N) and Phosphorus (P) in both sediment-attached and water-soluble states, and for chemical oxygen demand (COD) in water-soluble form. Results can be viewed for any single cell within the watershed, a sub- basin within the watershed, or for the entire watershed in either tabular or graphical mapped format. Runoff events taking place within the simulation can be viewed individually, as a monthly or yearly accumulation of storm results, or as an average annual value derived from a multiple-year scenario.

MODEL COMPONENTS

AGNPS Routines in ANN-AGNPS

The ANN-AGNPS overland hydrology calculations continue to be based upon the use of the SCS curve number method. Instead of inputting a single static value, curve numbers are automatically determined by the model utilizing input parameters of soil hydrologic group, crop type, conservation practice, tillage system, and daily updated surface crop residue amounts (Rawls et al. 1980). The procedure for determining an "s" retention value for calculating runoff volume has been modified to reflect daily changes in soil moisture conditions (Smith and Williams, 1980). The peak discharge rate continues to be calculated using the morphological-based empirical formula used in CREAMS (Smith and Williams, 1980) with new modifications to compensate for high discharge rates observed in AGNPS.

Sediment transport and deposition by particle class size is calculated utilizing the steady state continuity equation described by Foster et al. (1981) and Lane (1982). The method incorporates a depositional rate equation from Young et al. (1986) as well as a modified form of the Bagnold stream power equation (1966). Mannings equation is used to solve for channel flow velocity.

The chemical transport model (Frere et al., 1980) has remained unchanged except for the accounting of daily nutrient losses from plant uptake and mineralization. These procedures were also derived from Frere et al. (1980).

Continuous Routines in ANN-AGNPS

Weather Generator

ANN-AGNPS incorporates a stochastic weather generator used by a number of other ARS erosion and water quality models. CLIGEN, described by Nicks and Lane (1989), is a separate model from ANN-AGNPS, generating daily weather parameters required by ANN-AGNPS to update key environmental variables. Daily weather parameter output of minimum and maximum air temperature, precipitation, solar radiation, and wind speed and direction are statistically estimated from a national data set of average monthly records. A daily erosivity value describing total storm energy multiplied by the maximum 30 minute intensity is calculated from storm duration and the time to the storm's maximum intensity.

Soils

The ANN-AGNPS soils data base is derived from the SCS SOILS 5 data base. Soil data are processed through initial calculations to derive specific information describing soil physical characteristics which are then continually updated to reflect changing environmental conditions. ANN-AGNPS incorporates many of the WEPP procedures for estimating baseline parameter values for soil bulk density, porosity, saturated hydraulic conductivity, field capacity and wilting point (Lane and Nearing, 1989).

ANN-AGNPS determines the amount of water available for infiltration by subtracting calculated runoff from precipitation. Moisture is then percolated from soil layer to soil layer whenever soil field capacity is exceeded in a layer. The percolation rate is determined using a linear storage routing function which modifies conductivity from a saturated conductivity value near soil saturation to 0 at field capacity (Savabi et al. 1989).

Soil moisture is modified daily due to percolation, soil evaporation and plant transpiration. Richie's ET model (1972) is the basic evapotranspiration component used in ANN-AGNPS. Evapotranspiration, leaf area index, and soil texture characteristics are used to determine an evaporation rate. Plant transpiration values also incorporate the evapotranspiration rate, leaf area index, a water use rate-depth parameter, root depth and soil moisture within the layers (Savabiet al. 1989).

Plant Growth and Residue Decomposition

The ANN-AGNPS model contains routines for simulating plant growth and decay. A simple heat unit index (HUI) accumulation procedure is used for growing the plant from planting date to a user input maximum plant maturity level (Williams et al. 1989). The biomass is then apportioned to above ground leaf and stems and below ground roots. The leaf area index is calculated incorporating updated biomass (Williams et al. 1984).

Residue that accumulates on the ground surface from leaf drop and harvest alters the hydraulics and erodibility of the soil. The rate of residue biomass decay is a function of accumulated weather and soil moisture conditions (Stroo et al. 1989). Field operations further modify the structure and location of residue which in turn influences decomposition rates.

Soil Erosion

Updating AGNPS from a single storm simulation to a multiple storm continuous simulation required selecting a new soil erosion model that would incorporate daily updated environmental parameter values. The Revised USLE, or RUSLE, was selected because of its enhanced capacity to calculate erosion on a 15 day continuous basis. ANN-AGNPS utilizes several RUSLE routines on a daily basis, calculating erosion whenever a rain event occurs.

The basic structure of RUSLE is the same as the USLE. The 5 USLE factors: R, K, LS, C, and P, are determined and then multiplied together for estimating rill and sheet erosion. The methods for deriving each RUSLE factor involve utilizing equations simulating temporal changes in the environment which alter physical processes affecting erosion (Renard et al. in press). This new capability, however, requires the use of a computer model to carry out the calculations.

C Factor

The RUSLE and ANN-AGNPS C-factor calculations are the most detailed and most necessary to have accurately representing the physical processes. Through the selection of management practices and the subsequent changes in environmental parameters, the user is capable of interacting with the model and testing the impact of alternative field management scenarios. Management and cropping impacts on erosion rates within ANN-AGNPS are represented through the soil loss ratio (SLR). SLR values are reflective of daily field condition changes brought about by a particular management practice and modified by weather conditions. The SLR itself is derived from a number of subfactors (Yoder, et al. in press):

$$SLR = PLU * CC * SC * SR \qquad (1)$$

where PLU is the prior land use subfactor, CC is the canopy cover subfactor, SC is the surface cover subfactor, and SR is the surface roughness.

Prior land use reflects the impact of subsurface residue from previous crops and the effect of previous tillage practices on soil consolidation. ANN-AGNPS accounts for daily changes in biomass, needed for the determination of the PLU subfactor.

The canopy cover subfactor represents the ability of crop cover to protect the soil surface from the erosive powers of raindrops. Through the growing season and including senescence, ANN-AGNPS keeps track of the fraction of land surface covered by canopy and the height of the canopy, the two plant growth parameters needed to determine the value of CC subfactor.

Surface cover influences erosion rates by reducing the transport capacity of water flowing over the soil surface by creating mini-barriers. It also protects the soil from raindrop impact. The parameters used to determine the surface cover subfactor are the current soil surface roughness, the percentage of land area covered by surface cover, and the effectiveness of surface cover in reducing soil erosion. The first two parameters are tracked by ANN-AGNPS and the third is a constant value in the model.

The surface roughness subfactor represents the roughness of the surface and its ability to dampen soil erosion. Soils that have been tilled contain depressions and barriers which inhibit the flow of water and the transport of sediments. Daily values of surface roughness decrease as a function of time and rainfall. ANN-AGNPS accounts for this decrease in the same way as RUSLE, with a function relating the net roughness following a field operation and a decay coefficient based on the accumulated rainfall amount since the last operation.

Utilizing the spreadsheet interface, the ANN-AGNPS user records the day a field operation takes place and the particular implement utilized. Based upon this information and the generated weather data, the model retrieves the needed parameters from the management operations data base.

LS Factor

ANN-AGNPS calculates a RUSLE LS factor for both single-segmented and complex, multiple-segmented slopes. The RUSLE LS calculation includes calculating slope steepness and slope length subfactors and combining them into a single LS value. The slope length value is modified based upon the susceptibility of the soil to rill and interrill erosion (McCool et al. in press).

P Factor

ANN-AGNPS calculates a P factor based upon the type of conservation - terraces, strip-cropping or contours. A P value is calculated once per growing year and is based upon how the placement or configuration of the practice relative to the hillslope affects the hydraulics of the hillslope, which in turn impacts the sediment transport capacity of runoff. The impact of previous cropping practices on surface roughness is also included when determining P values for strip-cropping (Foster et al., in press).

R Factor

The erosivity capacity of rainfall is determined by the CLIGEN program. A rainstorm duration and a time to peak rainfall intensity are used to calculate a per-storm intensity value which is used in the basic RUSLE equation whenever a rain event occurs.

K Factor

At present, ANN-AGNPS does not incorporate a time variable K factor. The K factor is loaded into the program from the soils data base and kept constant throughout the program.

MODEL INPUT AND OUTPUT

ANN-AGNPS has in some ways simplified data input to the model and at the same time required more detail. The extra detail comes not in defining particular parameter values, but rather in describing the type and timing of field management practices. ANN-AGNPS requires the same structural information needed in AGNPS for defining the watershed shape, size and the direction of flow within the watershed, including cell size, the number of the cell into which a cell drains (receiving cell number), and the cell flow direction.

Similar to AGNPS, ANN-AGNPS requires information on channels located within each cell, specifically the channel shape, channel slope, channel side slope, the length of the channel within the cell and Mannings' roughness coefficient.

Data entry for hillside topographic data has been expanded to enable input of multiple segmented slopes. Information required for both a single and multiple segmented slope include slope length, percent slope, and slope aspect.

ANN-AGNPS requires more detailed information on soil parameters. This soil information is accessed from the model's soils data base. The user is required only to select a state and county containing the watershed and then choose the dominant soil mapping unit for each cell. Soils information contained in the data base consists of the number of soil layers, depth of each layer, soil surface albedo, K factor, hydrologic group, and percent clay sand, rock fragments, organic matter, and cation exchange for each layer. If updates to the soil data are needed, the user can enter new values, and save the soil information under a new name.

Entering information for a particular cell's management practice requires the greatest number of inputs from the user. The user has to create a management scenario for each different set of field operations represented by a watershed grid cell. These scenarios may represent either actual practices or hypothetical conservation scenarios to be tested. The management input screen prompts the user for the number of crops per rotation and the type and order of crops in the rotation. Information on conservation management practices is prompted if they exist for a management scenario. Four different conservation practices can be applied (1) contours, (2) strip cropping, (3) terraces and (4) filter strips. Specific information describing the size, placement and orientation of these practices is requested.

The user then enters the type and date of field operations taking place within a rotation. Field operations are divided into tillage (soil disturbance), planting, harvest/cutting and fertilizing. The program requires the user to choose specific implements, fertilizer rates for both N and P, a fertilizer availability factor, and either a harvest amount in bushels or a remaining residue cover in either percent or lbs/acre. Management scenarios are saved in the management data base. A particular scenario can be copied to any other cell and used in its original form or altered to create a new scenario.

MODEL TESTING

The first preliminary test of ANN-AGNPS is being carried out on a monitored watershed south of Morris, Minnesota. The watershed is 1087 acres in size, with 1063 acres in cropland, 13 acres in woodlots, 8 acres in farmstead, and 3 acres in pasture. Cropland is broken down into 633 acres of corn, 235 acres of soybeans, 184 acres of small grain and 11 acres of set-aside fallow.

The dominant soil in the watershed is a Barnes-Buse Loam complex with approximately 70% Barnes and 30 % Buse. Both are deep, well drained soils located on gently rolling to hilly landscapes. The majority of the watershed is relatively flat and gently sloping, with slopes ranging from 0 - 3 %. The upper reaches of the watershed are somewhat steeper ranging from 3 - 5 % slope and dissected by short steeper slopes ranging from 6 - 7 %.

The watershed is entirely surface-drained through naturally occurring depressions and channels. Within some fields a buffer-strip has been left a few meters on each side of the channel, while in other fields the channel is tilled through. Channel width for those with definite form ranges from 1 to 3 meters, increasing in width down slope. Slopes of channels vary with land slope, ranging from 3 - 4 % in the uplands to near 0 - 3 % in the lower areas of the watershed.

The watershed was divided into 28 forty acre grid cells and data was collected from locally available sources and entered into the model's spread sheet. Data collection was facilitated by using a Geographic Information System in calculating flow directions and land slope, as well as determining which field and soil constituted the majority area within the cell. Additional field checking was required to gather data on channel characteristics and to validate values generated by the GIS.

Model Results

The watershed was monitored during the 1992 growing season. Data was collected for only 1 major storm episode consisting of several closely occurring rain storms with one major event.

Date	Rainfall inches	Runoff Volume inches		Peak Discharge cfs		Sediment Yield tons	
		obs	pred	obs	pred	obs	pred
6/16-6/17	2.69	0.60	0.65	46.8	40.8	16.97	28.65

Table 1. Summary of observed and predicted watershed response.

ANN-AGNPS simulated the one storm reasonably well. As can be observed, a large percentage of rainfall ended up as watershed runoff. The model's ability to account for antecedent soil moisture conditions perhaps helps the model to estimate runoff more accurately then if a single curve number value was required for the storm of interest. For this storm, sediment yield was over predicted by 68%. This may be due to inadequate accounting for the filtering effects of vegetation along several of the channels, as they affect upland eroded sediments entering laterally into these channels. This could possibly be corrected by subdividing some cells to more accuratley represent the filter strips along the channels.

One rainstorm obviously does not constitute a sufficient set of observations from which to assess the accuracy of the model. Also, nutrient observations were not included in this preliminary analysis. Since sediment is but one source of agricultural pollutants, a model that is to be used for the WQPP must also account for nutrients as well as pesticides. Continued validation will take place, looking at both sediment and agricultural chemical yields, using additional data sets from around the country.

CONCLUSIONS

Expanding AGNPS beyond a single event model has added considerable capacity to the model. ANN-AGNPS is better capable of accounting for temporal variations which greatly influence the generation and transport of agricultural pollutants. This accountability will result in better estimations of sediment and nutrient loading from the watershed. Another advantage of the continuous model is the ability of the user to interact with the model on a more direct and familiar level. Instead of inputting estimated coefficient values representing a particular antecedent condition, the model user can input the timing of the practice and the type of implement used. The true utility of ANN-AGNPS will be in its ability to generate alternative management scenarios and easily re-locate those practices around a watershed to evaluate changes in pollutant loadings.

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THE MODULAR HYDROLOGIC MODELING SYSTEM - MHMS

George H. Leavesley[1], Pedro J. Restrepo[2], Linda G. Stannard[1], and Michael J. Dixon[3]

The increasing complexity and interdisciplinary nature of environmental and water-resource problems require the use of modeling approaches that can incorporate knowledge from a broad range of science disciplines. Selection of a model to address these problems is difficult given the large number of available models and the potentially broad range of study objectives and data constraints. One approach to the model-selection question is to selectively couple the most appropriate process algorithms from applicable models to create an "optimal" model for the desired application. Where existing algorithms are not appropriate, new algorithms can be developed. The Modular Hydrologic Modeling System (MHMS) uses this approach.

MHMS is an integrated system of computer software that has been developed to provide the research and operational framework needed to support the development, testing, and evaluation of hydrologic-process algorithms and to facilitate the integration of user-selected sets of algorithms into an operational hydrologic model. MHMS uses a master library that contains compatible modules for simulating water, energy, and biogeochemical processes. A module consists of one or more subroutines and functions to simulate a given process plus system-specific code to declare and define parameters and variables used by the module.

A given process can have several modules in the library, each representing an alternative conceptualization or approach to simulating that process. Existing or new approaches for a selected process can be compared directly while keeping the remaining model components constant. Statistical analysis procedures developed and maintained within the system framework

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provide a common basis for comparing module performance. These statistical measures also can be used to aid in making decisions regarding the most appropriate modeling approach for a given set of study objectives, data constraints, and temporal and spatial scales.

Initial modules in the library were derived from the U.S. Geological Survey's Precipitation Runoff Modeling System (PRMS)(Leavesley et al., 1983). Additional modules have been included using selected process algorithms from the National Weather Service River Forecast System (NWSRFS) model (Anderson, 1973), the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U.S. Army, 1989), and TOPMODEL (Beven and Kirkby, 1979). New modules for channel transport of solutes and sediment also have been developed and included. Additional modules will be added to the library as research and operational applications expand MHMS use.

The MHMS framework has been developed for use in the X-windows environment on a UNIX-based workstation. A graphical user interface provides an interactive environment for users to access system features, apply selected options, and graphically display results. Graphical displays can be printed or saved for future comparisons. Optimization and sensitivity-analysis capabilities are provided to optimize selected model parameters and evaluate the extent to which uncertainty in model parameters affects uncertainty in simulation results.

A number of additional system enhancements and capabilities are being designed to facilitate model development, application, and analysis. A geographic information system (GIS) interface is being designed to provide tools for the analysis and manipulation of spatial data. The GIS interface will assist in model-parameter estimation using digital data bases for a variety of characteristics including elevation, soils, vegetation, and geology. It will also provide the capabilities to display model results and analyses.

A variety of resource-management and risk-analysis models will be included to interface with the hydrologic-process models for use in evaluating alternative resource-management policies and in developing operational short- and long-term resource-management plans. A data-management system will be developed to provide a consistent data interface among all the MHMS components. Interfaces will be provided to import and export data and model results from and to other external data-management and analysis systems.

System applications can range from single-objective problems such as simulating streamflow response to normal and extreme precipitation to more complex multidisciplinary problems such as simulating the transport and deposition of sediment, nutrients, and pesticides, or evaluating the hydrological and biogeochemical effects of potential climate change. MHMS provides a common framework in which to focus multidisciplinary research and operational efforts. Researchers in a variety of disciplines can develop and test model components to investigate questions in their own areas of expertise as well as to work cooperatively on multidisciplinary problems without each researcher having to develop the complete system model. Results can be used immediately to modify or enhance current operational models for application within the same framework.

Continued advances in hydrology and related sciences, computer technology, and data resources will expand the need for a dynamic set of tools to incorporate these advances in a wide range of interdisciplinary research and operational applications. MHMS is being developed as a flexible framework in which to integrate these activities.

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SOIL WATER HYDROLOGY AND CHEMICAL BUDGETS WITH THE ENHANCED SPAW MODEL

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ABSTRACT

Soil water is one of the most important hydrologic components for both crop production and water management, but it is determined by multiple climatic, vegetation, and soil variables. The Soil-Plant-Air-Water, SPAW, model simulates a one-dimensional soil water budget of an agricultural field from above the crop canopy to below the root zone. The model simulates daily values for the soil water profile, actual evapotranspiration components, runoff, percolation, and crop water stress by applying appropriate descriptions and parameters for the crop and soil characteristics and daily climatic data of precipitation and potential evaporation. Other capabilities include irrigation scheduling, soil nitrogen and chemical fate and wetland pond water storage. Program enhancements for micro-computers include screen driven menus, file management, a tutorial, manual, and graphical inputs and outputs.

INTRODUCTION

Soil water is one of the most important quantities within the hydrologic cycle. It is the storage capacity for precipitation and often accepts 70 to 90 percent of annual precipitation input through the infiltration process. In turn, soil water provides a water supply for plants, percolates water to groundwater reservoirs, and significantly influences runoff and erosion quantities. The importance of soil water increases as the demand for food production, water resources and environmental quality increase.

The time distribution of soil water within the upper soil profile supplying plant roots is a complex interaction of many variables related to current and past occurrences of weather, crops, and soils. While soil water principles have been studied for centuries, only in recent years have we begun to develop an integrated systems approach to understand and predict soil water, largely the result of modern computer capability. This mathematical simulation brings a wide range of scientific knowledge to bear on a particular system in a simultaneous, interactive mode which more closely predicts the physical and biological processes than any other previous method.

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The objective for developing a predictive model of the soil-plant-air-water (SPAW) system was to enhance hydrologic predictions of infiltration, runoff, erosion, water quality and the assessment of available soil water throughout the growing season for major agricultural crops. Once these mathematical representations were developed, a host of secondary objectives have appeared such as crop water stress effects on growth and yield, soil water influences on soluble fertilizer fate and leaching, soil water percolation for groundwater recharge and agricultural wetland pond budgets.

The SPAW model computes a daily estimate of surface runoff, the soil water profile, actual evapotranspiration (ET), plant water stress and deep percolation based on the environmental, biological and physical state of the control volume. The schematic representation in Figure 1 is used to visualize the approximate soil and air control volume which must be considered to accomplish this one-dimensional, vertical hydrologic budget.

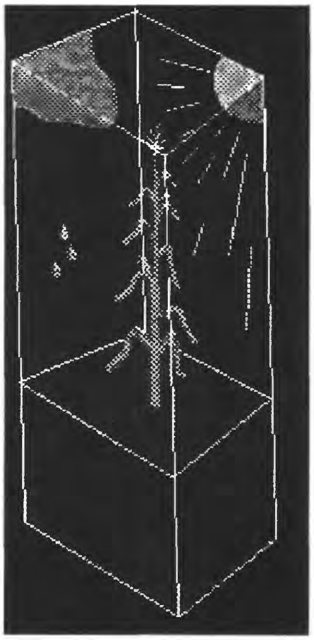

Figure 1: A schematic of the SPAW control volume.

Daily estimates are made of all quantities except redistribution of soil water which occurs multiple times each day to maintain computation stability, usually at maximum time steps of 1 to 4 hours. The soil profile is represented by a selected number of layers and depths to represent the average soil profile over the field or watershed being simulated. Each layer is assigned a unique set of soil water characteristic relationships (tension and conductivity). Each simulation is for a horizontally homogenous plant-soil-atmosphere description represented by parameters and data, thus the user must decide the allowable deviations before these simulation results are not valid and a second application must be described.

DATA AND SYSTEM REPRESENTATION

The SPAW model requires three general classes of data to describe weather, plants, and soils, plus a few run control parameters. The model data are entered by a keyword input routine which provides flexibility to enter data from variable computer devices, files, formats and sequences.

Weather

Daily precipitation (or irrigation if applied) is the primary driving variable. These data are often readily available from local or national data sources, but it is imperative that the precipitation data be representative of the field site. This can pose a particular difficulty for fields some distance from the measuring location in convective storm regions.

Daily maximum and minimum air temperatures are required if winter hydrology is to be simulated for the study site. Temperature data are used to estimate snow accumulation, snow melt, and freezing soil depths. If these winter processes are not influential in the simulation period, this data can be omitted.

Daily potential evapotranspiration (PET) is input as defined by one of several methods. Daily pan evaporation modified by a monthly variable pan-to-PET coefficient is most often used. If daily values are not available, or missing as in winter months, monthly average values of daily pan evaporation based on long term records are used as estimates. Other methods are equally applicable, however the concept and definition of PET is not universal and may require local calibration if the method contains surface or site conditions unique to the method or measurements. Reference crop ET is a method particularly used in irrigated agriculture, but often contains both meteorological and crop effects, thus needing local calibration.

Plants

Plant and soil surfaces are considered separately. Crop canopy is used as a measure of that portion of the PET impinging on the plant, expressed as a soil shading percentage. Values vary from 0.0 for bare soil to near 1.0 for dense canopies. The simulations are not highly sensitive to these values, and estimates of seasonal distributions for even fast-growing crops provide reasonable results.

All canopies do not freely transpire even if soil water is available because of biological development related to their normal phenology and maturation. Therefore, a second time distribution of "greenness" is input as a ratio of 0.0 to 1.0 to become a direct multiplier to the plant canopy to represent its relative ability to transpire. The canopy values times the greenness values are similar to crop coefficients often used in irrigation water management. Crop residues are treated as canopy cover and have a greenness value of 0.0.

Plant roots connect the evaporative demand at the leaf surfaces with plant available soil water. Each plant species has some habit of root pattern, but this can be modified by soil environment (physical, chemical, atmosphere, water). Most agricultural plants set the majority of their roots in the upper 2 or 4 feet of soil, thus this becomes the hydrological active zone even though a deeper profile is usually described.

A simple water abstraction pattern with depth is used to describe root water uptake. For selected dates, the percent of water to be abstracted from each soil layer is entered as input. This stepped time incrementation appears to function satisfactorily. The solutions are not highly sensitive to this description because of compensation by the soil water redistribution calculation which computes water movement among soil layers partially in response to root water abstraction.

Soil Profile:
The soil profile to below the root zone, usually six to eight feet, is represented by a user defined number of layers (maximum of 20). Each layer is described by its depth, percent sand and clay and bulk density. The textures are used to define complete tension-water content and conductivity-water content relationships to be used in the estimate of upward or downward water flux (Saxton et al., 1986). Saturation, field capacity, and wilting point values of each layer are estimated for use in crop water stress relationships. An option is available to input other estimates of these soil water characteristics should they be available from laboratory determinations or other sources. If measured soil water data are available, the texture values can be slightly modified to provide calibrated soil water characteristics.

Run Control
If the SPAW model is to be used for studies involving irrigation, nitrogen and chemical budgets, or wetland ponding, each of these options requires initial values and descriptive parameters. The user's manual describes these in detail. By including the appropriate data inputs, these options are automatically included in the computation and output sequences.

MODEL PROCEDURES

The computations first use the climatic PET input data to estimate actual evapotranspiration (AET) by soil layer. After subtracting the actual AET from existing soil moisture, daily runoff and infiltration are calculated, soil water is redistributed among the soil layers, (including deep percolation), and any supplemental simulations completed such as irrigation and chemical budgets.

Actual Evapotranspiration

A daily estimate of AET is obtained by the summation of interception evaporation, soil water evaporation, and plant transpiration. Interception evaporation is removed from interception storage on the leaf and soil surfaces, soil water evaporation from the first and second soil layers and transpiration from the appropriate soil layers containing roots.

Water intercepted by plant surfaces and soil depressions readily evaporates with little resistance. Therefore, the PET value is reduced by the amount of interception before plant transpiration and soil water evaporation are computed. Some data suggest that 0.10 inch is a nominal interception amount for agricultural fields and is used as the default value in SPAW, although another value can be input. Interception evaporation can accumulate to a significant proportion of the annual water budget where twenty or more precipitation events occur.

Soil water evaporation is estimated to occur from a thin (about 0.5 inch) upper boundary layer of the soil which is included in the soil profile incrementation. This boundary layer has the same functions as other layers (except no roots), plus the soil water is readily evaporated and limited only by PET. Upward water movement from the second layer into the evaporation boundary layer and its evaporation is estimated by a Darcian type equation using a reduced unsaturated conductivity rate.

Well-watered, healthy crops will usually transpire at nearly the rate demanded by the atmospheric conditions (PET), but as their water supply becomes limited, physical and biological controls begin to limit the rate of transpiration. The rate of transpiration, and thus soil water depletion, is reasonably clear and agreed upon at very wet and very dry conditions. Rates at intermediate soil moisture contents are not as clear and considerable differences exist among published results and contemporary scientists. A series of curves relating atmospheric demand, plant available water and relative transpiration are programmed similar to those reported by Denmead and Shaw (1960).

Infiltration and Runoff

Infiltration is estimated by one of two methods for each day that has precipitation. If measured daily runoff is available, then it can be entered as input and daily infiltration is computed as precipitation minus runoff. If measured data are not available, as is often the case, then a daily estimate of runoff is made by a modified version of the Soil Conservation Service (SCS) curve number (CN) method.

The SCS-CN method estimates an amount of the daily precipitation which becomes runoff by first an initial abstraction, and then a percentage of precipitation that becomes runoff, based on a series of curves. The curve numbers are input from tabulated CN values for crop-soil combinations plus an antecedent moisture adjustment. The standard SCS-CN method was modified to utilize the computed estimates of crop canopy and soil moisture. For the canopy adjustment, the CN values for fallow and the average canopy condition are entered and prorated according to the daily canopy estimate. Antecedent soil moisture is dynamically considered by setting limits for the application of the antecedent conditions I and III based on the estimated soil water of the second layer.

Snow accumulation is assumed to occur any day in which the average daily air temperature is zero or less and precipitation occurred. Snow melt is estimated by a linear relation with daily maximum air temperature. Soil freezing is based on cumulative freezing degree-days required to freeze the soil from the surface downward through a multilayered soil system (Jumikis,1966). Each additional layer has a freezing requirement and a thermal resistance of the overlying soil layers and snow. An accumulative degree day climatic freezing index (CFI) is computed from daily mean air temperatures and matched against those of the soil freezing index (SFI) to estimate freezing depth. A decrease of the CFI values for days with above freezing temperatures estimates soil thawing.

Soil Water Redistribution

The Darcian equation is used to estimate vertical water flux up or down between the selected soil layers by applying a simplified forward differencing solution. The objective was to keep the computations to a minimum, yet provide reasonable redistribution estimates and computational stability. The required pressure-moisture and conductivity-moisture relationships are determined by one of two methods. If measured soil water characteristic data are available, there is an input option. Otherwise, soil texture data are used in a set of generalized estimation equations developed to describe the pressure and conductivity relationships (Saxton et al., 1986). The upper and lower boundary conditions are specified by the evaporative layer and the lowest soil profile layer.

Optional Simulations

An extensive set of irrigation options are included to either account for this water source if known, or to estimate irrigation requirements by one of several criteria. Ten options to determine when to irrigate and six for how much to apply provide considerable flexibility to match existing methods or data. These range from fixed dates and amounts to computed time and amounts to satisfy specified minimum crop water stress.

A chemical routine estimates the quantity and profile distribution of nitrate, ammonium and a soluble salt tracer. These pools of chemical species are tracked daily, but the processes are largely limited to those interacting with soil water and plants. Input variables required are the initial profile amounts by soil layer, fertilizer additions, and total seasonal plant uptake. Adjustments are made for fertilizer additions, plant uptake, infiltration, water redistribution (including leaching), and organic matter decay. Daily plant uptake is a function of plant nitrogen requirements and plant water uptake. Ammonium fertilizers, primarily soil adsorbed, are converted to the soluble nitrate pool by nitrification.

A ponding budget to assess wetland inundation periods is a separate program linked to the output of multiple runs of SPAW to estimate daily pond depth-duration statistics, number of annual inundation periods and the length of these periods (days). Inputs include the number and sizes of fields in the watershed, maximum and minimum pond areas, maximum pond depth, and soil water storage and seepage rate of the pond bottom. Outputs include daily pond depths and volumes which are summarized into annual depth-duration statistics and inundation period lengths.

RESULTS AND APPLICATIONS

At the end of each daily computation, a wide range of state variables can be stored, printed or graphed. Three levels of printed output are available with increased detail. The variables usually included are those which have proven most useful during model development and applications, but they can readily be reprogrammed for tailored output. They include surface runoff, soil water profile, actual ET by components, plant water stress, plant growth and yield reduction, deep percolation, chemical profile, chemical leaching, irrigation amounts, and ponding statistics. Digital and graphical outputs are user selectable for analysis and verification. Example soil water and chemical budgets for a year are shown in figure 2. The thickness of each layer graph is proportional to the quantity in that layer and the total graph thickness represents the total in the profile.

The SPAW model is adaptable to a variety of applications through changes in data and descriptive parameters. It has been tested extensively for soil water and hydrologic regimes involving agricultural watersheds with crops of corn, soybeans, bromegrass, and wheat and to a lesser extent with some ten other crops. Example studies in which the SPAW model was applied include the development of crop curves followed by a crop water stress technique utilizing plot data in Iowa and Missouri (Saxton et al., 1974; Sudar et al., 1981); analysis of corn water stress across a broad region of the mid-west US (Saxton and Bluhm,1982); analysis of climatic variability on winter wheat yields for Canada (DeJong and Zentner, 1985) and similarly for the Wimmera region in Australia (Saxton et al., 1992); sorghum planting dates versus soil water availability (Omer et al., 1988) and the daily water balance of a grass covered lysimeter (Maticic et al., 1992). The model was used to define irrigation efficiencies of corn and wheat (Field et al., 1988) and the economics of irrigated farming (Bernardo et al., 1987). Chemical budgeting was applied to corn watersheds in Iowa (Saxton et al., 1977).

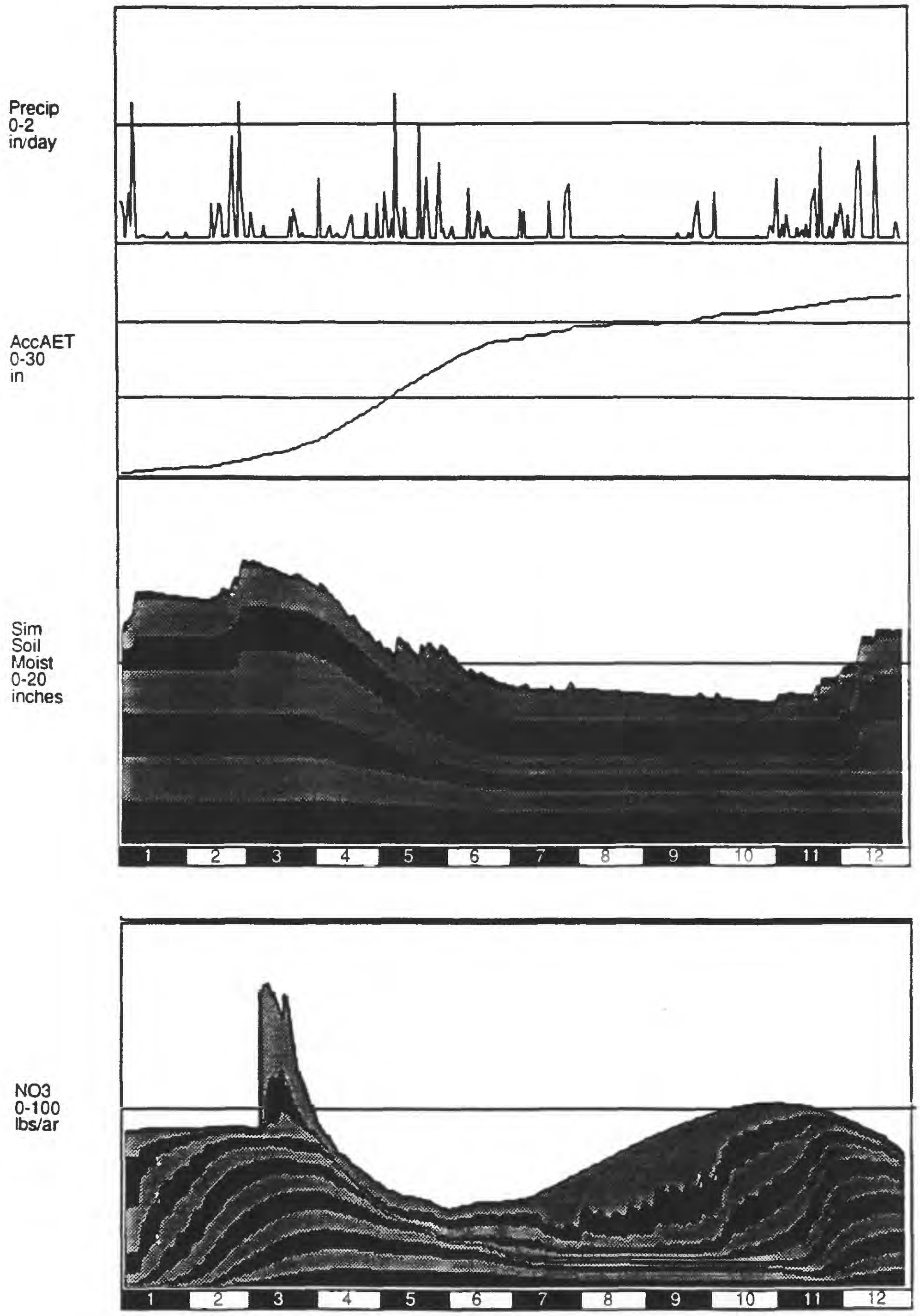

Figure 2. Example simulated AET, soil moisture, and nitrate nitrogen for 6 and 12 layer soil profile representations over one year.

The SPAW model has been adapted to personal computers with input screens, file management, graphic output, and a tutorial. Run times are generally 1/4 to 1/2 minute per simulated year using an INTEL-486 processor. This program is available from the author.

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Surface Water and Groundwater Model Developments at the Waterways Experiment Station

Jeffery P. Holland[1]

ABSTRACT

The Waterways Experiment Station's (WES's) Hydraulics Laboratory (HL) has the primary responsibility for the development of riverine, reservoir, wetland, and estuarine hydrodynamic and hydraulic models within the U.S. Army Corps of Engineers. Additionally, HL manages WES's expanding role in groundwater modeling research and development. Extensive numerical model research and development is ongoing and planned for these surface water and groundwater modeling systems. Presented herein is an overview of the more major of these developments.

INTRODUCTION

Numerical hydrodynamic, hydrologic, and hydraulic model development is being conducted within the Hydraulics Laboratory (HL) of the USAE Waterways Experiment Station (WES) in support of a broad spectrum of water resources concerns. These concerns include:

* hydraulic structure and waterway design/operation
* water and environmental quality management
* cleanup of contaminated groundwater resources
* wetlands maintenance and management
* flood control channel design and operation
* control of overland, bank and near-structure erosion
* watershed runoff and flow analyses

Many of these studies are extensions of HL's historical modeling efforts in estuaries, reservoirs and rivers. In fact, over the next five years, numerical hydrodynamic, hydrologic, and hydraulic modeling relative to flows in wetlands, estuaries, groundwater, and within watersheds is expected to take the forefront. Additionally, many of these studies will be in support of water quality, environmental quality, or contaminated groundwater restoration concerns. This, coupled with an ever increasing ability within HL to numerically model phenomena that were once strictly investigated within physical models, points to the changing focus of HL's numerical modeling mission.

The WES Hydraulics Laboratory, in concert with other WES, Department of Defense (DOD), Department of Energy (DOE), and Environmental Protection Agency (EPA) laboratories, is developing several modeling tools for meeting the hydrodynamic, hydrologic, and hydraulic demands of the next five years. These developments include creation or enhancement of the computational and process understanding within the models, and improved modeling productivity through the coupling of these models with graphical user interfaces, visualization, and parameter estimation methods. In this way, modeling systems are being developed which can increase the efficiency and efficacy of modeling. Several of the more major of these developments are overviewed herein.

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Estuarine Hydrodynamics

Estuarine hydrodynamic modeling within HL has traditionally been conducted in support of salinity and sediment management associated with navigation or flood control project operation. Most of these studies utilized the WES-developed TABS hydrodynamic/sediment transport modeling system. Recently, the emphasis of estuarine hydrodynamic studies has shifted to water and environmental quality management questions. Studies of this type, done most often in conjunction with the WES Environmental Laboratory and Coastal Engineering Research Center, have required sophisticated three-dimensional hydrodynamic and water quality model developments. Due to the differing questions and physical settings associated with these studies, both finite element and finite difference models have been developed. Two hydrodynamic models have resulted: RMA10-WES and CH3D-WES.

The RMA10-WES code is a Galerkin-based finite element program that simulates three-dimensional (3D) unsteady flows in estuaries and rivers. The model, originally developed by Resource Management Associates (King, 1988), has been extensively modified by the HL staff. The code represents 3D hydrodynamics using conservation of fluid mass, horizontal momentum, and salinity transport equations. As is typical of shallow water models such as RMA10-WES, vertical accelerations are assumed to be negligible (the hydrostatic assumption). In the interest of computational efficiency, the code also simulates 1D and 2D flow as well as transitions between 1, 2 and 3D calculations. The code is implicit in time and resolves the nonlinearities via Newton-Raphson iteration. Vertical turbulence is a combination of the Mellor-Yamada Level II (Mellor and Yamada, 1982) and Henderson-Sellers (1984). The model includes tidal forcing, density effects, freshwater inflow, and Coriolis effects.

The model has sufficient existing features to address many of the problems that one typically faces in estuaries, including gradual wetting and drying of elements. The model is particularly adept in simulating abrupt and irregular geometries such as one might observe when a deep navigation channel is cut through a relatively shallow estuary. Other than the more basic model capabilities, these more exotic features have not been thoroughly verified. It is very likely that the present wetting and drying algorithm, as well as the transition elements between 1D to 2D or 2D to 3D, will need to be improved. An additional area in which modification is expected involves the investigation of iterative solvers and adaptive refinement to improve the speed of calculations. A companiion 3D sediment model computes transport of fine-grain materials.

RMA10-WES is presently being used to simulate a series of environmental management actions in conjunction with a proposed navigation channel deepening in Galveston Bay, TX. Of primary concern is development of management strategies to mitigate adverse impacts to aquatic habitat due to increased velocities or salinities that might result from the proposed channel deepening. The model is also being applied to San Francisco Bay and the James River.

CH3D-WES (Curvilinear Hydrodynamics in Three Dimensions) is a timevarying, 3D numerical hydrodynamic model that can be applied to rivers, estuaries, and reservoirs. The model has been coupled to a companion water quality model for efficient long-term simulations (up to decades) of estuarine hydrodynamics and water quality. Major physical processes affecting circulation and vertical mixing are modeled. These include tidal forcing, wind, density effects, freshwater inflow, surface heat exchange, and Coriolis effects. Vertical turbulence is modeled using the concept of eddy viscosity and diffusivity to represent the velocity and density correlation terms that arise from a time averaging of the governing equations. These eddy coefficients are computed from mean flow characteristics using a simplified second-order closure model based on the assumption of local equilibrium of turbulence. The water surface, 3D velocity field, salinity and temperature are computed.

To resolve complex geometries better in the horizontal directions, CH3D-WES makes computations on boundary-fitted or generalized curvilinear grids. This necessitates transformation of the governing equations into boundary-fitted coordinates. One feature of the model is that not only are the independent Cartesian coordinates (x,y) transformed, but the velocity is also transformed such that its contravariant components are computed. With the governing equations written in terms of the contravariant components of the velocity, boundary conditions can be prescribed on a boundary-fitted grid in the same manner as on a Cartesian grid.

CH3D-WES continues to undergo modification and additional development. Examples include an investigation into techniques for reducing the false currents induced by the use of the sigma stretching version of the code, casting the transformed horizontal diffusion terms into a form consistent with the convective terms, and employing a spatially third-order scheme called QUICKEST to represent the convective terms in the momentum equations.

The first application of CH3D-WES was on Chesapeake Bay, during which the model was extensively modified from the original development. Other applications include New York Bight, Green Bay, Los Angeles-Long Beach, Indian River, and the Delaware Bay. An application on the lower Mississippi River has resulted in contracting with the University of Iowa for the development of a companion 3D sediment transport model. Enhancement of the graphical display of output from CH3D-WES is being accomplished through contracting with the Oregon Graduate Institute of Science and Technology.

Wetland and Watershed Hydrology

A detailed knowledge of wetland hydrology is one of the primary pieces of information required to manage wetlands. Wetlands are, of course, a vital component of the Earth's ecosystem. Hydrologic inputs define the frequency and depth of inundation of the wetland which, in turn, defines habitability for various plants and wildlife. Wetlands are, in fact, defined and typed in part by the frequency of their inundation. Since there is a wide variety of wetland types, generalized tools for studying hydrologic behavior in wetlands and the upland watersheds that support and supply them are needed.

A wide variety of hydrologic modeling tools are available for meaningful hydrologic analyses. Typically, the most time-consuming aspect of their use involves discretization of the watershed, definition of major streams and sub-basins, calculation of drainage areas, and the preparation of these data in formats amenable to hydrologic models. To ameliorate this concern, HL is developing a graphical user interface/environment for hydrologic models. A pre-processor program (GeoSHED, written by the Engineering Computer Graphics Laboratory of Brigham Young University in Provo, UT in cooperation with HL), that was originally developed for military hydrology applications, is currently being used to automate the time-consuming tasks listed above. Triangulated Irregular Networks (TINs) are employed for defining the topography and calculating vital hydrologic statistics. A TIN is a set of data points that are connected by irregular triangles that together describe an irregular surface such as that of a watershed or wetland. TINs are created by inputting digitized data, either from digital topographical maps or from manually digitized data, and triangulating the points. Once the TIN is created, a continuous surface is modeled by interpolating between the corners of the triangles.

After the surface is modeled, GeoSHED automatically defines the dominant streams and flow paths on the user's screen. Path lines are drawn from the centroid of each triangle down slope in the direction of steepest descent. After the primary streams and flow paths are defined, GeoSHED calculates the contributing drainage area to each of the user-defined stream junctions. Presently, GeoSHED then writes out the data into a form the HEC-1 hydrologic model (developed by the Corps of Engineers Hydrologic Engineering Center, Davis, CA) accepts. In these ways, the software eliminates most of the tedious tasks required for data assemblage.

The GeoSHED software runs on UNIX workstations using X-windows graphics. Future developments for this system include its coupling with other hydrologic models, including two-dimensional overland flow codes, to allow more rigorous evaluations of wetland and watershed types.

Rivers, reservoirs, and estuaries have been modeled for many years using the Corps of Engineers' TABS numerical modeling system. TABS is a family of 2D numerical models that simulate hydrodynamic, sediment, and constituent transport processes in these water bodies. One of the most attractive features of the system is its ability to simulate wetting and drying of shallow areas caused by either discharge fluctuations in rivers or tidal fluctuations in estuaries. Recently, this capability has been applied where wetlands are of primary interest.

A new graphical user interface (FastTABS) has been developed for the TABS system in concert with Brigham Young University that addresses the need for efficient model setup, execution, and analysis. The interface is mouse driven with pull-down menus and requires a minimum of manual data entry. The interface was designed to allow easy application of each of the models in the TABS family. The interface also provides access to several state-of-the-art visualization and animation capabilities. Several wetland demonstration sites, as well as estuarine locales, have been modeled via FastTABS. FastTABS software runs on Macintosh and DOS-based personal computers as well as most UNIX workstations.

Near-field Hydrodynamics

The design and operation of hydraulic structures has traditionally been accomplished through use of physical hydraulic modeling. These models have been used to evaluate the multi-dimensional flow patterns associated with approach geometries, riverine bendways, scour, internal hydraulics and cavitation, energy dissipation, etc. These flow concerns differ from those discussed above in several ways, two examples of which are: the assumption of hydrostatic pressure used in the above physical problems is generally invalid for near-field problems; and, curvature is quite important in near-field flow field development. These considerations have lead HL to develop a suite of near-field hydrodynamic models which, used in concert with physical models, provide an often optimum approach to modeling.

STREMR (Bernard, 1989, 1991) is an HL-developed, 2D hydrodynamic model that generates discrete solutions of the incompressible Navier-Stokes equations for depth-averaged or width-averaged flow. It is suitable for routine use by field engineers and others with an interest in depth-averaged flow modeling. STREMR can be used as a training aid for prospective modelers, as a handy means of qualitative flow visualization, and as a practical device for quantitative flow prediction. If its empirical coefficients are fine-tuned for agreement with a particular physical model, the code can also be used to extrapolate test data from laboratory scale to full scale. Even without site-specific tuning or adjustment of any kind, however, STREMR predictions are still accurate enough to expedite the design of a new hydraulic structure or the rehabilitation of an existing one. The model has proven useful in studies concerning bendways, diversion tunnels, pump stations, training structures, and bank protection.

STREMR eliminates a great deal of user guesswork by incorporating a k-ε turbulence model and a three-dimensional secondary flow correction. The turbulence model generates an eddy viscosity from the computed primary flow, and the secondary flow correction accounts for the interaction between lateral curvature and vertical nonuniformity which causes high velocities to migrate toward the outsides of channel bends. Manning's coefficient for bottom friction is the only empirical parameter required in the code input.

STREMR imposes a rigid-lid approximation instead of a free surface, but it can be used for free-surface flow wherever the local Froude number is 0.5 or less. The absence of a true free surface makes STREMR unsuitable for calculations involving hydraulic jumps and moving surface waves. Such phenomena are usually of little import for approach, bendway, and internal flow predictions.

To generate physically meaningful predictions of the depth-averaged flow in channels of practical interest, STREMR requires a computer with at least one megaword of addressable memory and can be run on 386- and 486-class PC's as well as workstations, conventional mainframes, and supercomputers. The user's package for PC's includes an interactive shell that allows grid generation, flow calculation, and flow visualization to be carried out (on screen) from a single window with pull-down menus. Plots are generated in color for presentation on screen, and in black-and-white for reproduction as hard copies. In both cases, optional contour labels indicate the magnitude of the plotted variables.

MAC3D is a finite-volume computer code currently under development that extends the basic STREMR formulation to calculate 3D, non-hydrostatic, incompressible flow on staggered Marker-and-cell grids. The code accepts nonuniform, nonorthogonal grids for any curvilinear domain that can be mapped onto a single rectangular block. This enables the solution of fluid interactions with an arbitrarily shaped domain having multiple obstructions or inlets and outlets. It is applicable for free-surface flow at low Froude number, and for confined flow in general. The code will accommodate fully-advective laminar or turbulent flows in a stratified or nonstratified environment. The target applications for this model are fluid-structure interactions, strongly three-dimensional open-channel flows, and environmental fluid mechanics. This code is being developed to support the design of hydraulic structures and large-scale mixing devices for water quality enhancement in stratified reservoirs. Computed results from the MAC3D program are presented for laminar flow in channels with internal obstacles and curved boundaries in the literature (Bernard and Schneider, 1992). Development of this code is scheduled to continue through fiscal year 1994. At present, no production version of the code is yet available. Code validation, 3D grid generation automation, visualization, and input interface development are ongoing.

High Velocity Channels

The design, modification, and operation of high velocity channels is of prime importance in the control of flooding, particularly in urban areas. The HIVEL2D model is being developed by HL to simulate the flow conditions of these channels. The model solves the depth-averaged unsteady equations of motion implicitly using finite elements. The model is designed to predict the water surface in high velocity channels in and around boundary transitions, bridge piers, confluences, bends, and other geometric features. The model is applicable to supercritical and subcritical flow regimes, and within any regime transitions. HIVEL2D includes Manning's formulation for bottom resistance and turbulence closure. It does not consider Coriolis, buoyancy, or wind stresses as these are generally of little concern for high velocity channels. Model input, and certain model outputs (i.e., water surface elevations) are conducted via the FastTABS user interface.

The model is currently being improved to include moving boundary capabilities to increase its utility for trapezoidal channels. Additional improvements to the code will include enhancement of its coupling to the FastTABS graphical user interface to assist in the output of differing types of spatial data. Production versions of this code are expected within the next two years.

Demonstration Erosion Control (DEC) Project

The DEC Project involves the development of a system for the control of sediment, erosion, and flooding in the foothills area of the Yazoo Basin, MS. This area is subjected to severe channel bed degradation and streambank erosion. A number of differing structural means, such as drop structures, levees, pumping plants, and other developing technologies are being considered for implementation as part of the project.

HL is contributing to the DEC project through the monitoring and analysis of the watershed responses to various DEC implementations. An important feature of this monitoring regime is the development of a set of coupled numerical modeling and analysis tools within a workstation environment. The modeling and analysis package features integration of geographic information systems (GIS) with several hydrologic and sediment transport models. These models include HEC-1, HEC-2, and HEC-6 along with the SAM and CASC2D models. HEC-1 and HEC-2, both developed by the Corps of Engineers' Hydrologic Engineering Center, are being used to estimate stream discharges within several DEC watersheds. CASC2D is a two-dimensional overland flow model developed recently by Colorado State University that is being evaluated for its ability to provide detailed hydrology in selected DEC watersheds. The possibility of adding sediment yield calculations to this model is also being considered.

HEC-6 is the Corps of Engineers' one-dimensional sediment transport model. SAM is a new at-a-station channel design package, developed within HL, which includes hydraulic, sediment transport, and sediment yield modules. Both models are being used to test design procedures related to the channel-forming-discharge concept. Successful development of such procedures could result in significant design cost savings in the DEC and similar projects. Additionally, the integration of hydrologic and sediment modeling with GIS technology in an amenable computational framework that allows easy access to multiple tools will further improve design efficiency.

GROUNDWATER MODELING SYSTEMS

The Waterways Experiment Station, in conjunction with the U.S. Air Force, has begun initial development of a Groundwater Modeling System (GMS) for simulating groundwater flow, the transport/fate of subsurface contaminants, and the efficacy of remedial actions. An essential feature of the GMS will be user interfaces which augment model application and visual presentation of results. The primary product from the proposed research will be a two and three-dimensional modeling system centered around both single and multiphase flow in concert with single and multiple-component groundwater contaminants. The system will be capable of simulating flows in both the saturated and unsaturated zones. Although the system will be keyed to the specific requirements of the DOD, the system will also be formulated in a fashion general to support its use by others. Partnering with other Federal agencies (particularly the DOE and the EPA) has been established as a means of extending the range of applicability of the proposed modeling system. The GMS will integrate the following components:

(a) site characterization tools, including data base managers, visualization software, and contaminant screening tools in the form of analytic and simplified numerical groundwater flow and solute transport algorithms. These will be coupled to graphical user interfaces to form the backbone of the GMS. Additionally, methods for estimating geophysical parameters will be developed. These methods will couple visualization, estimation mathematics, guidance on field data collection and sampling, and some aspects of uncertainty to aid site cleanup specialists.

(b) contaminant assessment and transport tools, including two and three-dimensional groundwater flow and contaminant transport models. These models will simulate time-varying conditions in the coupled saturated and unsaturated zones for a variety of common, and several military-unique, contaminants. These models will be incorporated within the GMS framework mentioned above.

(c) tools to simulate the efficacy of various remediation methodologies for cleaning up specific sites. These tools will be tailored to simulate the most attractive remedial treatment technologies. Additionally, this level of simulation will provide the user with optimization capabilities for the design and operation of various treatment technologies. Uncertainty will also be built into the system to allow for potential changes in simulated results as a function of incomplete site characterization (i.e., sparse field data, poor parameter estimation, etc.) and/or poor process understanding.

The development overviewed above has been initiated. Present research is centered around the improvement of explosives process formulations, multiphase constitutive equations, and model scaling relationships; model testing and evaluation; and the integration of the better of these models with visualization and graphical user interfaces to form the basis of the groundwater model system. Versions of the DOD groundwater modeling system are scheduled for implementation in fiscal year 94, 96, and 98 at present. A variety of intermediate products will also be provided. Note that the products from this research will be equally applicable for civil works concerns and military installation cleanup. In fact, several classes of problems, such as traditional surface water/groundwater interactions and salinity intrusions in estuarine environments, will be addressable directly with the tools being developed.

SUMMARY AND FUTURE DIRECTIONS

Presented herein are the current, and near-term planned, hydrodynamic, hydrologic, and/or hydraulic modeling developments within the Hydraulics Laboratory, USAE Waterways Experiment Station. Primary components of most of these developments include algorithm development, improved process understanding, and the coupling of advanced graphical user interfaces and visualization with numerical models for improved ease-of-use.

There also is clearly a longer-term need for continued research into more efficient numerical algorithms, parameter estimation techniques, grid generation, and integrated modeling systems development. Even with ever-increasing computational power, algorithm efficiency will be of prime importance due to the ever-increasing complexity of the problems simulated. Parameter estimation and grid generation represent the two parts of numerical studies that are the most time consuming and allow for the greatest user-generated errors. Methods for parameter estimation and grid generation which aid novice users, while allowing control for the experienced modeler, must become routine components of modeling systems. Methods to evaluate parameter uncertainty, and the ramifications of this uncertainty on modeled results, must also be incorporated into routine modeling efforts. Finally, the problems of the next decade would seem to demand the development of integrated modeling systems capable of simulating surface water, groundwater, and the interactions there between in a holistic framework.

ACKNOWLEDGEMENT

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SECTION 5

COMPUTER DEMONSTRATIONS AND POSTERS

COMPUTER DEMONSTRATIONS

Page

RZWQM to Model Management Effects on Water Quality
R.W. Rojas, L.R. Ahuja, Q.L. Ma, D.G. DeCoursey, V. Ferreira, J.D. Hanson, and M.J. Shaffer 5-1
Water Erosion Prediction Project (WEPP) Hydrology Submodel
M.R. Savabi 5-8
Developing Hydrologic Parameters Using GIS
Billy E. Johnson 5-17
Snowmelt Runoff Forecasting
Timothy Pangborn, Joyce A. Nagle, and Robert E. Davis 5-20
Intergration and Use of the Nitrate Leaching and Economic Analysis Package (NLEAP) in the GIS Environment
M.J. Shaffer, M.K. Brodahl, and B.K. Wylie 5-28
A Graphical User Interface for ARS Water Data on CD-ROM
Ralph T. Roberts and Jane L. Thurman 5-36
HYDROSS Simulation Support System
Mike S. Brewer 5-42
A Comprehensive System for Surface Water and Groundwater Modeling
H.C. Lin, J.D. Jorgeson, D.R. Richards, and W.D. Martin 5-47
Program for Daily Weather Simulation
C.L. Hanson, K.A. Cumming, D.A. Woolhiser, and C.W. Richardson 5-55
Interior Drainage Analysis, West Columbus, OH
Dr. Surya Bhamidipaty and Jerry W. Webb 5-62

Figures and Tables

RZWQM To Model Management Effects on Water Quality 5-1

Figures: 1. Measured and predicted runoff water and atrazine in 1973 5-3
2. Measured and predicted runoff atrazine and cyanazine in 1975 5-3
3. Measured and predicted soil water distributions in watershed P2, Watkinsville, G.A. 1974 and 1975 5-4
4. Measured and predicted atrazine persistence in watershed P2, Watkinsville, GA. 1973 and 1974 5-5
5. Measured and predicted atrazine distributions in the soil profile, P2, Watkinsville, G.A. 1973 5-5
6. Measured and predicted atrazine distributions in the soil profile, Watershed P2, Watkinsville, G.A. 1974 5-5
7. Measured and predicted atrazine and cyanazine distributions in the soil profile. Watershed P2, Watkinsville, G.A. 1975 5-5

Page

Water Erosion Prediction Project (WEPP) Hydrology Submodel 5-8

Figures: 1. Schematic computational sequence of the WEPP hydrology component, Eu is potential evaporation, Esp is potential soil evaporation, L is leaf area index, Ep is potential plant transpiration, Es is potential soil evaporation for area covered by plant residue 5-11
2. Schematic representation of WEPP artifical subsurface drainage. ET is actual evapotranspiration 5-13

Integration and use of the Nitrate Leaching and Economic Analysis Package (NLEAP) in the GIS Environment 5-28

Figure: 1. Average Groundwater $N0_3$-N from 1989 to 1991 (la) and NLEAP $N0_3$-N Leached (NL) Index for Irrigated Areas near Greeley, Colorado (1b) 5-33

A Graphical User Interface for ARS Water Data on CD-ROM 5-36

Figures: 1. ''Desktop'' of GUI 5-38
2. Linked list query 5-39
3. Graphical query 5-40

Hydross Simulation Support System 5-42

Table: 1. Output reports available in HYDROSS 5-44

A Comprehensive System for Surface Water and Groundwater Modeling 5-47

Figures: 1. The scattered set of data points of Walnut Creek, Iowa 5-50
2. Delineated sub-basins for Walnut Creek, Iowa 5-50
3. Display of hydrograph at two selected points, Walnut Creek, Iowa 5-51
4. Finite element mesh for Cape Fear River, North Carolina 5-52
5. Bathymetry in gray scale for Cape Fear River, North Carolina 5-52
6. Velocity contour plot in gray scale for Cape Fear River, North Carolina 5-53
7. Water surface elevation contour in gray scale for Cape Fear River, North Carolina 5-53
8. Sample of a 3-D finite element mesh 5-54

Program for Daily Weather Simulation 5-55

Table: 1. Historical and generated mean monthly climatic data for Boise, Idaho 5-59

Interior Drainage Analysis, West Columbus, OH 6-62

Plate: 1. Scioto River, Columbus, Ohio 5-69

Table: 1. Flood depths area subject to inundation 5-68

RZWQM TO MODEL MANAGEMENT EFFECTS ON WATER QUALITY

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ABSTRACT

The Root Zone Water Quality Model (RZWQM) is a process-based model developed by USDA-ARS scientists. It integrates physical, chemical, and biological processes to predict the effects of agricultural managements on water and chemical movement over and through the root zone. The model was evaluated using field data for its capabilities to predict water and pesticide movement over soil surface and in the root zone. Results demonstrated that the model reasonably predicted soil water distribution and the amount of runoff water if surface crust was assumed. Prediction of pesticide persistence required a two-compartment dissipation model. Runoff of pesticide and pesticide movement in the soil profile were predicted reasonably.

INTRODUCTION

The RZWQM is a comprehensive, numerical, and generally modular integrated model of an agricultural system. It is designed to study the effects of various management practices on water and chemical movement over and through the root zone that may cause surface and ground water quality problems. It consists of six major process components and two generator components. Following is a brief description of the model components. Interested readers may refer to the model Technical Documentation (GPSR Technical Report No.2, 1992) for more detailed information of the RZWQM processes.

Hydrologic Processes simulate soil matrix infiltration, macropore flow, surface runoff, heat flow, evapotranspiration, soil water redistribution, and chemical transportation and extraction from the top two 1-cm soil layers. Chemicals in these two layers are subject to ununiform mixing by raindrops during precipitation and transfer to surface runoff [Ahuja & Hebson, 1992].

Soil Chemistry Processes describe the soil inorganic chemical conditions to supply necessary information for nutrient and pesticide simulations. Biocarbonate buffering, dissolution and preicipitation of calcium carbonate, gypsum, and aluminum hydroxide, ion exchanges, and solution chemistry of ion pair complexes are included in the processes. The chemical state of the soil is characterized by soil pH, solution concentration of the major ions, and the adsorbed cations on the exchange complex [Shaffer, Rojas, & DeCoursey, 1992].

Nutrient Processes simulate transformation and sorption of nutrients within the soil profile including mineralization, nitrification, immobilization, denitrification, and volatilization of nitrogen. A multi-pool approach is used for organic matter cycling. Process rate equations are based on chemistry

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kinetics theory, and controlled by soil microbial population and environmental conditions, such as soil temperature, soil pH, soil water content, and soil salinity [Shaffer, Rojas, & et al., 1992].

Pesticide Processes simulate transformation of a pesticide in different compartments of the soil-water-plant system. Pesticides applied on plant and plant residues are subject to washoff and degradation. Either equilibrium sorption or kinetic sorption is allowed for simulating the pesticide sorption process. Four options are available for pesticide dissipation modelings: lumped dissipation including one-compartment model and two-compartment model; individual dissipation; and daughter product dissipation. The effects of temperature, rainfall, relative humidity, wind run, pesticide formulation, soil characteristics, plant leaf characteristics, surface layer water content, and soil oxygen content on pesticide dissipation were quantitatively described [Nash & Ma, 1992].

Plant Growth Processe simulates carbon dioxide assimilation, carbon allocation, dark respiration, periodic tissue loss, plant mortality, root growth through the soil profile, and water and nitrogen uptake. A population development model was coupled with plant growth model to form a generic crop-production system that simulates both plant growth and phenological development. A model specific for potatoes was also formulated as an alternative [Hanson & Hodges, 1992].

Management Processes consist of typical tillage operations for most crop rotations, and quantification of the effects of these operations on soil surface roughness, chemical distribution, soil bulk density, and soil macro- and microporosity [Rojas, Johnsen, & Ghidey, 1992].

In addition, an input generator is built around menu-driven entry screens with facilities for on-line help and determinations of model default values. The output generator provides output in both tabular and graphic forms. The latter is more convenient for comparisons of results from different model runs.

Presently, the model has been verified and is being tested extensively against experimental data from different sources. Herein, data collected from three-year's field studies in Watkinsville, GA. were used to evaluate the model's capability to simulate the movement and distribution of water, and degradation and transport of adsorbed pesticides (cyanazine and atrazine) in the soil profile and over the soil surface, including responses to various management operations. Results show that the model reasonably simulated soil water and pesticide movement. Future model enhancements are also discussed in the paper.

MATERIALS AND METHODS

Field Studies: The field research project was designed to study chemical movement in and from an agricultural field, and the effects of management practices on soil water and chemical movement. It is located in Watkinsville, GA. The experiments were conducted continually from 1973 to 1975. There are four watersheds, each with different plant-chemicals combinations and management operations. The watershed used here is watershed P2. Its area is 1.29 ha. Prior to this study, the field had been in general farm production, planted to corn. Before planting and pesticide application, the watershed was tilled 20 cm deep, then corn was planted, followed by application of pesticides and fertilizer. The results presented here are only for water, atrazine, and cyanazine's behaviors in the watershed. Smith, et al. (1978) described the soil properties in detail.

Model Parameter Estimation: Most of the model input parameter values not available from field and laboratory measurements. We used the equilibrium sorption model (one-site sorption model) to describe atrazine behavior, and two-site sorption model to describe cyanazine behavior. The second site adsorption and desorption rate constants for cyanazine were drawn from Boesten, et al [1989]. Herbicide equilibrium sorption constants were estimated from model default values.

We used two-compartment dissipation model to describe atrazine dissipation in the soil profile. Atrazine dissipation rate constants in watershed P2 were borrowed from Donigian, et al. [1977]. For cyanazine, only one-compartment dissipation model (first-order) was used.

Soil hydraulic properties were estimated from the measured average soil bulk density and soil texture at seven depths in ten positions, and soil water content at 1/3 bar. Soil water content at 1/3 bar in each horizon was drawn from model default values based on the soil classification and soil texture as the measured data were not available. Plant transpiration was simulated using modified Pennman Monteith equation on the measured pan evaporation data [DeCoursey, 1992].

RESULTS

Water and Herbicide Runoff: Figure 1 shows the measured and simulated runoff water and atrazine in 1973. In these simulations, we assumed surface crust was formed during precipitation. Under this assumption, the predicted runoff water amount matched well with each measured amount throughout the simulation period. But the model generally over-predicted atrazine concentration in runoff water.

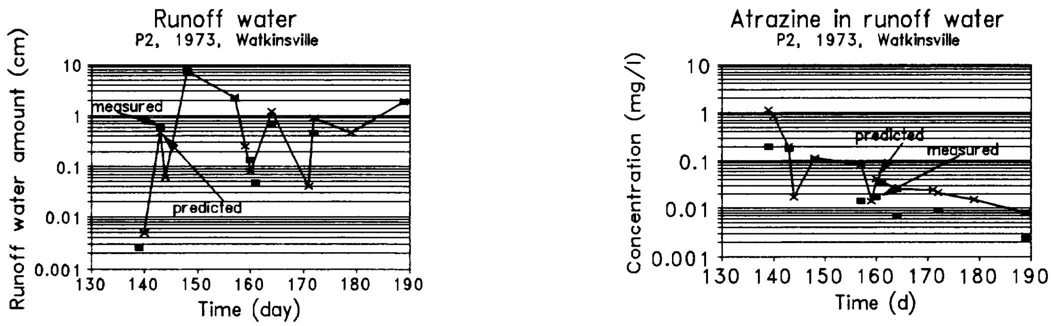

Figure 1. Measured and predicted runoff water and atrazine in 1973.

The same method was used for simulating water and chemical runoff in 1974 and 1975. Generally, the model gave reasonable prediction for both water and chemical (atrazine and cyanazine) runoff. Figure 2 shows measured and predicted atrazine and cyanazine concentration in runoff water in 1975.

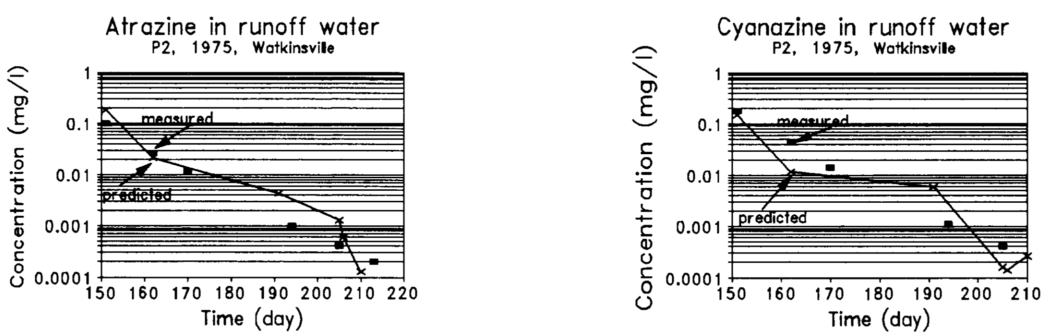

Figure 2. Measured and predicted runoff atrazine and cyanazine in 1975.

Soil Moisture Profile: Figure 3 shows some examples of the observed and simulated soil water distributions in 1974 and 1975. No comparisons of soil water distribution in 1973 were made as the measured data were not available. Generally, the prediction is reasonably good.

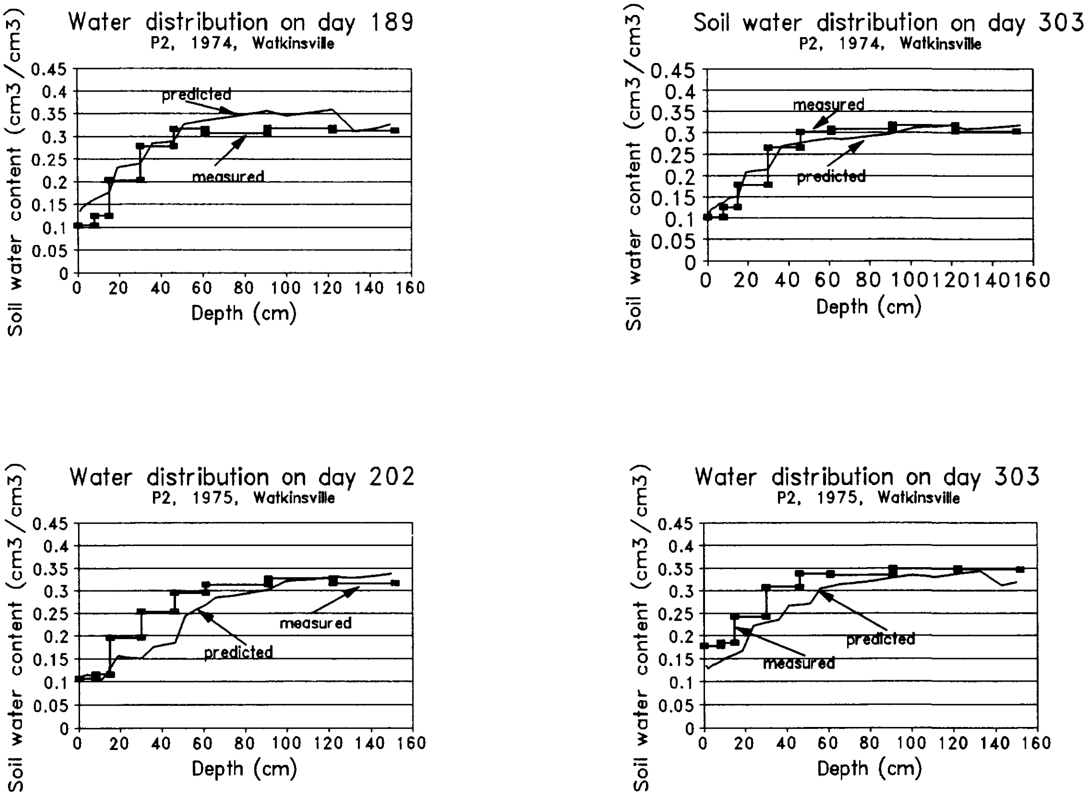

Figure 3. Measured and predicted soil water distributions in watershed P2, Watkinsville, G.A. 1974 and 1975.

Herbicide Persistence in Soil: Figure 4 shows two examples of atrazine residue persistence in the soil profile in 1973 and 1974. In these simulations, two compartment model (2-CM) was used as the observed data showed that atrazine dissipated very quickly during the period between pesticide application and the first rainfall event, and slowed down thereafter. Comparison showed that the 2-CM dissipation model gave much better prediction of atrazine persistence in the soil profile than the first-order dissipation model (not shown here). Cyanazine persistence was simulated using one-compartment dissipation model; it under predicted cyanazine persistence eariler.

Herbicide Movement and Distributions in Soil: Figure 5 shows two examples of atrazine distributions in the soil profile in 1973. The predicted atrazine distributions matched the measured ones satisfactorily (except on day 144[1]. On this day, a heavy rain fell just before sampling). Figure 6 gives atrazine distributions in the watershed in 1974. The model gave reasonable prediction except on day 210 on which the model over-predicted atrazine movement. The over-prediction of atrazine movement on day 210 reflects the limits of the equilibrium sorption model in describing pesticide long-term behavior. Figure

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[1]**Atrazine was applied on days 131, 119, and 141 in 1973, 1974, and 1975, respectively. Cyanazine was only applied on day 141 in 1975.**

7 shows atrazine and cyanazine distributions in the soil profile on day 156 in 1975. The over-prediction of atrazine dissipation on days 156 caused atrazine concentration in the soil profile lower than that measured. Generally the model gave reasonable prediction of the two herbicides distribution and movement in the soil profile.

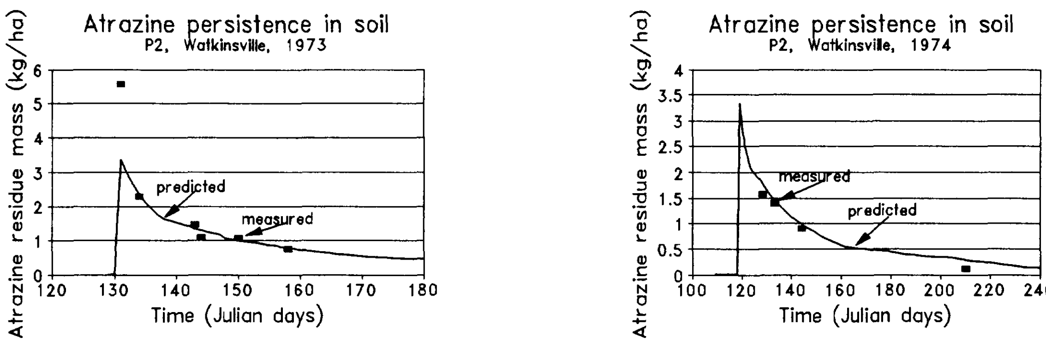

Figure 4. Measured and predicted atrazine persistence in watershed P2, Watkinsville, GA. 1973 and 1974.

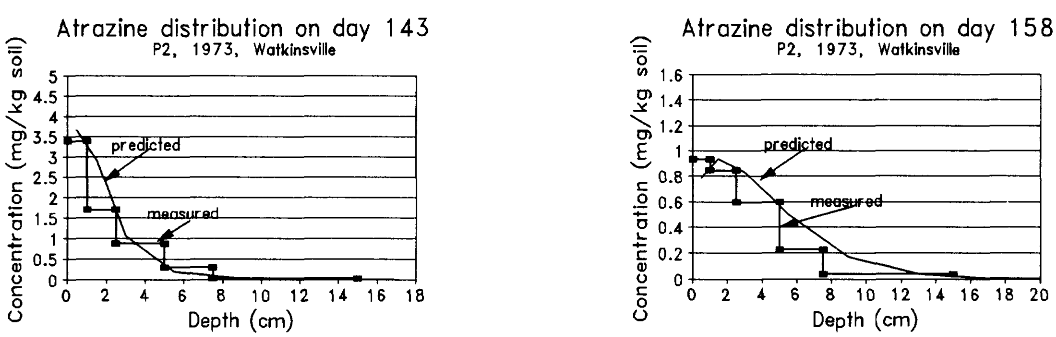

Figure 5. Measured and predicted atrazine distributions in the soil profile, P2, Watkinsville, G.A. 1973.

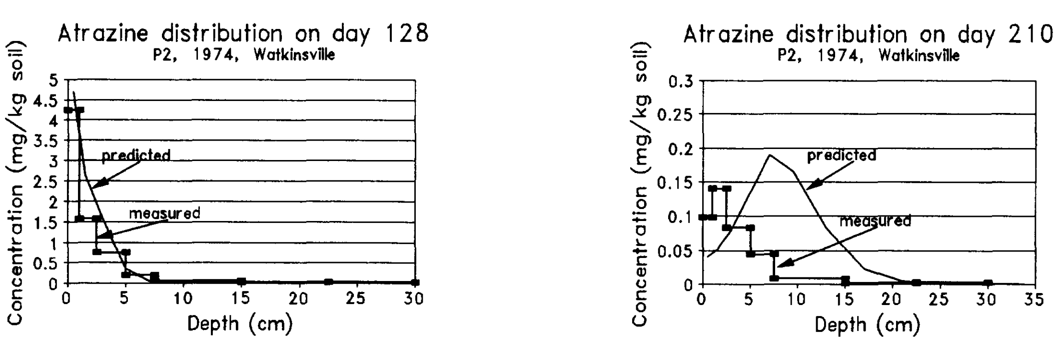

Figure 6. Measured and predicted atrazine distributions in the soil profile. Watershed P2, Watkinsville, G.A. 1974.

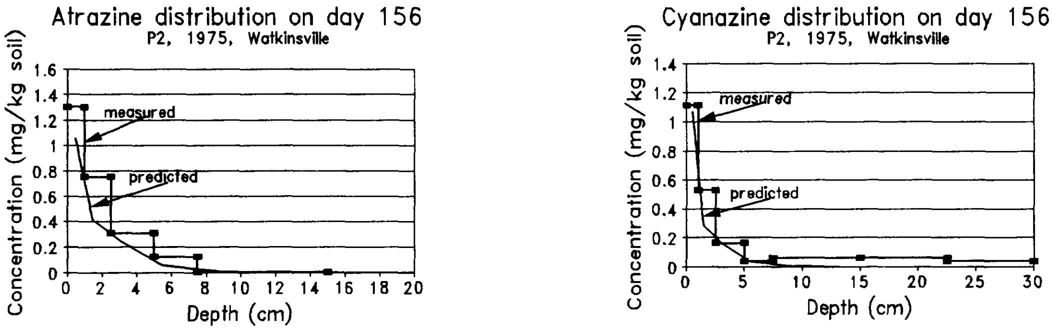

Figure 7. Measured and predicted atrazine and cyanazine distributions in the soil profile. Watershed P2, Watkinsville, G.A. 1975.

GENERAL DISCUSSION

Generally, the model reproduced the distribution and movement of water and adsorbed pesticides (cyanazine and atrazine) in the soil profile reasonably well. Further tests of the model are being undertaken.

We applied one-compartment dissipation model to atrazine dissipation process in the first place, and found that the one-compartment dissipation model could not describe the herbicide dissipation in the soil profile satisfactorily. The model underestimated atrazine dissipation earlier and overestimated its dissipation later. Considering this, we introduced a two-compartment dissipation model. Comparisons showed that the two-compartment dissipation model could describe atrazine dissipation in watershed P2 much better than the one-compartment dissipation model (not shown here).

We also had problems when applying equilibrium sorption model to cyanazine movement in the root zone. We found the equilibrium sorption model extremely over-predicted cyanazine movement in the soil profile long after pesticide application. Boesten, et al. [1986] also found that the equilibrium sorption model could not reasonably describe cyanazine movement in a loamy sand soil in The Netherlands. They developed a three-site sorption model, and using this model, cyanazine's movement in the loamy sand soil was well simulated. In describing cyanazine's movement in watershed P2, we applied a two-site sorption model (coupled instantaneous equilibrium sorption model and kinetic adsoption-desorption model). Comparisons from our studies showed that the two-site sorption model described cyanazine distribution and movement in the soil profile much better than that of equilibrium sorption model. Sensitivity analysis also showed that pesticide movement and distribution were very sensitive to the non-equilibrium adsorption and desorption processes, especially the non-equilibrium desorption rate.

For the further improvement of chemical runoff process of the RZWQM, sediment loss estimation should be added. Also, the mixing coefficients of chemical(s) by raindrops or irrigation water should be more accurately determined.

As observed data become available, pesticide uptake from soil into plants should be activated and tested (presently, this process has been incorporated into the RZWQM, but not activated because of the unavailability of observed data.). In this way, pesticide fate in the soil-water-plant ecosystem can be better simulated.

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WATER EROSION PREDICTION PROJECT (WEPP) HYDROLOGY SUBMODEL

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ABSTRACT

The USDA Water Erosion Prediction Project (WEPP) hydrology model is designed to use soil physical properties, meteorological, and vegetation data to simulate surface runoff, soil evaporation, plant transpiration, percolation, surface and subsurface drainage, and root zone soil water content on a hillslope scale. The hydrology submodel of WEPP utilizes the Green and Ampt infiltration equation to estimate the rate and volume of storm excess rainfall. Excess rainfall is routed downslope to estimate the overland flow hydrograph using the kinematic wave method. In WEPP, surface runoff is used in calculating rill erosion and runoff sediment transport capacity. The infiltration equation is linked with the evapotranspiration, drainage and percolation components to maintain a continuous daily water balance on a hillslope.

INTRODUCTION

Since the 1960's, the Universal Soil Loss Equation (USLE), an empirical equation (Wischmeier and Smith, 1978), has been used widely to estimate water induced soil loss. In the 1980's, there was a pressing need for a physically based, process oriented model to overcome many of the deficiencies associated with the USLE in predicting soil loss. In light of this, the USDA-Water Erosion Prediction Project (WEPP) model was initiated in 1985. The WEPP model represents a new erosion prediction technology based on fundamentals of infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Lane and Nearing, 1989). The model provides several major advantages over existing erosion models, namely, it reflects the effects of land-use changes due to agricultural, range and forestry practices and it models spatial and temporal variability of the factors affecting the hillslope hydrologic and erosion regime.

A physically based model to predict water induced soil loss requires a physically based rainfall-runoff component. Therefore, unlike other hydrological models such as; Chemical, Runoff, and Erosion from Agricultural Management System (CREAMS, Knisel, 1980); and Erosion Productivity Impact Calculator (EPIC, Williams et al., 1983) which use the basically empirical USDA-SCS Curve Number (USDA, SCS, 1972), WEPP uses the physically based Green and Ampt infiltration equation for unsteady rainfall (Chu, 1978), to calculate infiltration and excess storm rainfall. Excess rainfall is routed downslope to estimate the overland flow hydrograph using the kinematic wave method (Eagleson, 1970). Storm runoff is used in calculating rill erosion and flow sediment transport capacity (Lane and Nearing, 1989).

There have been several modeling approaches to simulate evapotranspiration processes on a watershed (Ritchie, 1972; Saxton et al., 1974; Wight and Neff, 1983; Shuttleworth and Wallace, 1985; and Lascano et al., 1987). These models are varied in their complexity and accordingly incorporate various physical processes. However, each allows for the integration of physical and biological factors to simulate evapotranspiration over a variety of surface conditions. In WEPP, Ritchie's approach (Ritchie, 1972) was selected because it uses readily available climate and vegetation data and had been tested over a range of conditions (Savabi et al., 1989b; Arnold and Williams, 1985; Pochop et al., 1985).

The purpose of this article is to describe the hydrology component of the WEPP model. The governing equations for infiltration, soil evaporation, plant transpiration, percolation, surface and subsurface drainage are presented.

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MODEL DESCRIPTION

Only a brief description of WEPP hydrology is provided; readers may refer to Lane and Nearing (1989) for more details. The WEPP hydrology component (Fig. 1) maintains a continuous daily hillslope water balance by linking infiltration, evapotranspiration, percolation, and subsurface drainage flow using the following equation:

$$\theta_d = \theta_{d-1} + p_d - (RO_d + D_d + Qd_d + ET_d) \qquad (1)$$

where

θ	=	root zone soil water depth, cm
d	=	day of simulation
p	=	daily precipitation, cm
RO	=	daily surface runoff, cm
D	=	daily deep seepage, cm
Qd	=	daily subsurface drainage, cm
ET	=	daily evapotranspiration, cm

Subsurface lateral water movement and rainfall interception by vegetation are not simulated in the current version of the WEPP hydrology model. However, work is underway to incorporate these processes into the model.

Precipitation is partitioned between rainfall and snowfall using average air temperature. If the average daily air temperature is zero degree Celsius or below, the precipitation is snowfall; otherwise, it is considered rain. Accumulated snowpack will be subject to evaporation and melt. Soil evaporation is considered first to come from snowpack, if present, and then from soil. Snow is melted on days when the maximum temperature exceeds zero degree Celsius. Melted snow is treated in Eq. 1 as rainfall for estimating runoff and percolation computations (For more detail see Lane and Nearing 1989).

Surface Runoff

In the WEPP model excess rainfall is calculated as the difference between rainfall rate and infiltration rate. The infiltration equation used in the WEPP hydrology model is a solution of the single layer Green and Ampt equation (1911) for unsteady rainfall as presented by Chu (1978):

$$f_t = K_e \left(1 + \frac{Ns}{F}\right) \qquad (2)$$

where

f	=	infiltration rate, cm h^{-1}
K_e	=	effective saturated hydraulic conductivity, cm h^{-1}
t	=	time, h
F	=	cumulative infiltration depth, cm
N_s	=	effective matric potential cm, and = $(\eta_e - \theta)\ \psi$
η_e	=	effective porosity of 0-20 cm of soil, $cm^3\ cm^{-3}$
θ	=	volumetric soil water content of 0-20 cm of soil, $cm^3\ cm^{-3}$
ψ	=	the average wetting front capillary potential, cm

Soil water content is calculated daily by Eq. 1. Soil saturated hydraulic conductivity can be either input by the user or calculated based on soil physical properties (Rawls et al., 1982). Saturated hydraulic conductivity is adjusted within the model for the effects of soil surface disturbances such as tillage, soil surface crust formation, macroporosity, canopy cover, ground cover, and frozen ground (Rawls et al., 1989). Calculated infiltration is added (Fig. 1i) to the top soil layer where it is subjected to evapotranspiration, percolation, and/or flow to draingae tiles and/or ditches.

Rainfall excess is produced when the rainfall intensity exceeds the infiltration rate. Calculated rainfall excess is then routed downslope to estimate the overland flow hydrograph using the kinematic wave method. The kinematic wave equations for one-dimensional overland flow are derived by assuming that the land slope is equal to the friction slope (Stone et al., 1992). The Chezy equation is used in the WEPP model to describe flow characteristics. The Chezy friction coefficient, C, is calculated for rill and interrill areas based on soil surface roughness and surface cover (Gilley et al., 1989).

Evapotranspiration

The evaporation equation used in the WEPP model is the Penman equation (Penman, 1948, 1963):

$$LE_{to} = \frac{\Delta}{\Delta + \gamma}(R\,(1\text{-alb}) - G) + \frac{\gamma}{\gamma + \Delta} 6.43\,(1.0 + 0.53u_z)\,(e_z{}^{\circ} - e_z) \tag{3}$$

where

LE_{to}	=	latent heat of evaporation, $MJm^{-2}d^{-1}$
G	=	soil heat flux, $MJm^{-2}d^{-1}$
R	=	solar radiation, $MJm^{-2}d^{-1}$
alb	=	albedo, (0-1)
U_z	=	wind speed, ms^{-1}
$e_z{}^{\circ}$	=	saturated vapor pressure, kpa
e_z	=	vapor presure, kpa
Δ	=	slope of the saturated vapor pressure curve at mean air temperature
γ	=	pyschrometric constant

The albedo is evaluated by considering the soil, crop, and snow cover. If a snow cover exists with at least 5 cm water content, the value of albedo is set to 0.80, otherwise the soil albedo is used. The albedo is estimated during the growing season .

Potential soil evaporation, E_{sp}, is predicted (Fig. 1b) as function of leaf area index. Bare soil evaporation (without residue cover), E_{sb}, is calculated in two stages (Fig. 1c). In the first stage, soil evaporation is limited only by the energy available at the soil surface and, therefore, it is equal to potential soil evaporation E_{sp}. When the accumulated soil evaporation exceeds the stage one upper limit, E_{su}, stage two evaporation begins. If precipitation is greater or equal to accumulated stage two soil evaporation, the stage one soil evaporation is assumed (Ritchie, 1972). During a drying cycle, evaporation from the soil continues until the soil water content is at a residual moisture content, a moisture content below which no more water can be evaporated from the bare soil. The residual water content is calculated using soil organic matter, percent clay, and soil bulk density (Rawls et al., 1982). Computed bare soil evaporation, E_{sb}, in either stage is reduced with increased plant residue (Fig. 1d). Potential plant transpiration (Fig. 1e) is computed as a linear function of leaf area index and E_u when L is less than 3 (Savabi et al., 1989a). Daily leaf area index, root depth, total plant biomass, canopy cover, and residue cover are simulated in WEPP by the plant growth and residue decomposition component. The plant growth water stress factor (Fig. 1g) is computed by considering supply and demand. (Savabi et al., 1989a).

Percolation

The WEPP model uses a storage routing technique to predict flow through each soil layer within the root zone. The water that percolates below the root zone is called deep seepage and it is considered lost from the WEPP water balance. Percolation of water in excess of field capacity from a layer is computed using the equation:

$$PE_i = (\theta_i - \theta_{FC_i})\left(1 - e^{\left(\frac{-\Delta t}{t_i}\right)}\right) \qquad \theta_i > \theta_{FC_i} \qquad (4)$$

$$PE_i = 0 \qquad \theta_i \le \theta_{FC_i}$$

where

PE	=	percolation rate through the layer, cm d^{-1}
θ	=	soil water content for the layer, cm
i	=	soil layer
θ_{FC}	=	field capacity water content (water content at 33 kPa matric potential for many soils) for the layer, cm
Δt	=	travel interval (24h)
t	=	travel time through the layer, h and depends on soil hydraulic conductivity of the layer.

The saturated hydraulic conductivity of each layer is adjusted for rocks, frozen soil, and entrapped air (Savabi et al., 1989a).

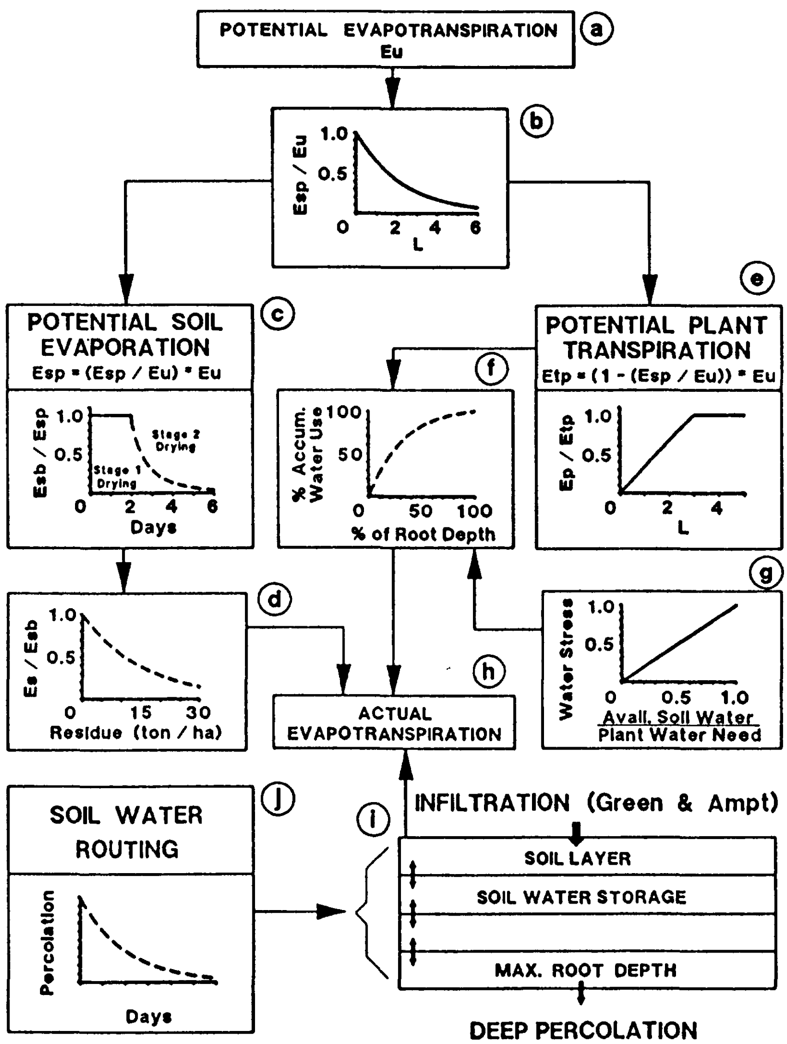

Figure 1 - Schematic computational sequence of the WEPP hydrology component, Eu is potential evaporation, Esp is potential soil evaporation, Esb is potential bare soil evaporation, L is leaf area index, Ep is potential plant transpiration, Es is potential soil evaporation for area covered by plant residue.

Surface Drainage

In the WEPP model, surface drainage is characterized by the depressional storage. Depressional storage is directly related to soil surface micro-relief feature and is generally enhanced by various soil mechanical practices, such as tillage. The method developed by Onstad (1984) is used in WEPP. Maximum depth of depressional storage (cm) is calculated using the following equation:

$$DS = 0.112\ RR + 0.031\ RR^2 - 0.012\ RR*S \tag{5}$$

where

DS	=	depressional storage, cm
RR	=	random roughness, cm
S	=	slope steepness, percent

The amount of runoff leaving the hillslope, while depressional storage is filling, is determined using the equation:

$$Qi = \frac{DS}{PR} * V_i \qquad FL < DS \tag{6}$$

$$Qi = V_i \qquad FL \geq DS$$

where

Q	=	runoff rate leaving the profile, cm h^{-1}
V	=	the excess rainfall rate, cm h^{-1}
PR	=	rainfall excess required to completely satisfy the hillslope depressional storage, cm
i	=	interval of rainfall intensity distribution
FL	=	accumulated amount of excess rainfall filling the depression storage, cm

The volume of water filling the depression storage for each rainfall event can be obtained by subtracting Q from V:

$$FL = \sum_{i=1}^{n} (Qi - Vi) \qquad FL < DS \tag{7}$$

Subsurface Drainage

The algorithm for simulation of subsurface flow to artificial drain tubes or ditches in WEPP is heavily drawn from DRAINMOD (Skaggs, 1978). The subsurface flux into drain tubes or ditches depends on the soil hydraulic conductivity, drain spacing and depth, soil depth and water table elevation. Assuming flow in the saturated zone only (Fig. 2), drainage flux in any simulation day is calculated using the equation:

$$Qd_d = \frac{8K_{dr}\ h_e\ m_d + 4K_{dr}\ m^2{}_d}{L^2} \tag{8}$$

where

Qd	=	drainage flux per unit width, cm d^{-1}
K_{dr}	=	effective hydraulic conductivity for subsurface drainage, cm d^{-1}
m	=	midpoint water table height, cm
L	=	distance between drains, cm
d	=	day of simulation
h_e	=	equivalent depth (calculated using method by Moody (1968))

The equivalent depth, h_e is used in Eq. 8 to correct for flow convergence near the drain tiles. For the case of flow into the drain ditch, h_e, is replaced by h (Fig. 2).

Effective hydraulic conductivity, K_{dr}, for the direction of drain flow in anisotropic media is calculated using the following equations:

$$\frac{1}{K_{dr}} = \frac{\cos^2\alpha}{K_z} + \frac{\sin^2\alpha}{K_y}, \qquad \tan\alpha = \frac{m}{L/2} \tag{9}$$

where

K_z = horizontal saturated hydraulic conductivity in saturated zone, cm d^{-1}
K_y = vertical saturated hydraulic conductivity in saturated zone, cm d^{-1}

Direction of flow is assumed horizontal ($\alpha = 0$) for the case of ditch drainage (Fig. 2).

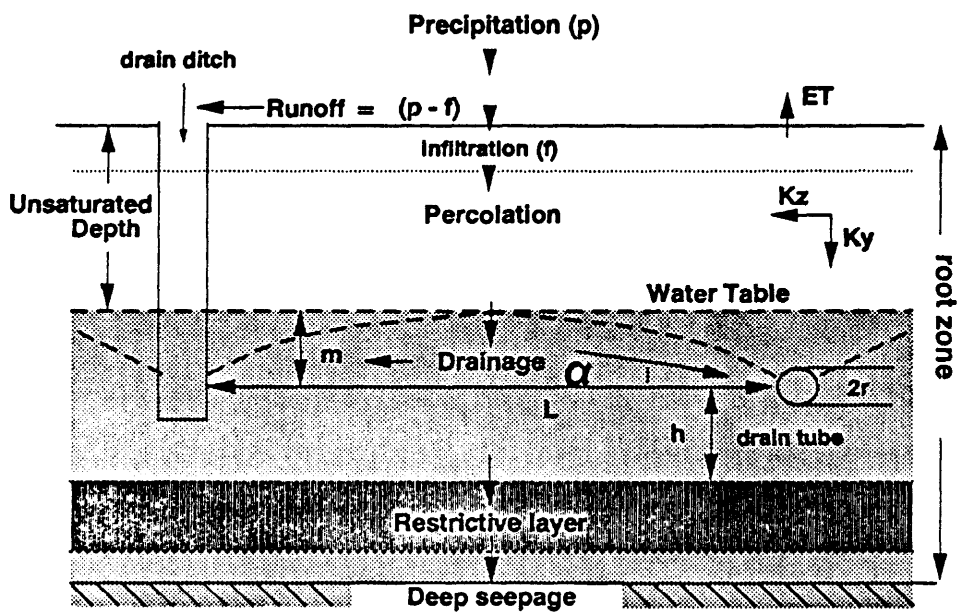

Figure 2. Schematic representation of WEPP artificial subsurface drainage. ET is actual evapotranspiration.

The drainage flux calculated with Eq. 8 is limited by the hydraulic capacity of the drain tubes or ditches. The hydraulic capacity of the drain tubes, also called the drainage coefficient (D.C.), may be obtained from USDA-SCS-NEH-16 (1971) or by using the Manning equation. When calculated drainage flux is more than D.C., the drainage flux is set to D.C. More detail is given by Savabi et al., (1991).

Percolation of water from unsaturated layers into the saturated zone raises the water table. Within a saturated zone, soil water is subjected to percolation to lower layers, evapotranspiration, and subsurface flow to drain tiles or ditches. Water table draw down due to subsurface drainage is calculated by the following equation:

$$m_d = m_{(d-1)} - \frac{Qd_d}{\phi_{di}} \tag{10}$$

$$\phi_{di} = \phi_i - (\phi FC_i + \theta_{ai})$$

where

d = day of simulation

ϕ_d	=	drainable porosity, $cm^3\ cm^{-3}$
ϕ	=	soil porosity, $cm^3\ cm^{-3}$
ϕ_{FC}	=	volumetric water content at field capacity, $cm^3\ cm^{-3}$
θ_a	=	entrapped air, $cm^3\ cm^{-3}$
i	=	uppermost soil layer in saturated zone

The volume of entrapped air is calculated using soil physical properties such as the percent of sand, clay, and soil cation exchange capacity (Lane and Nearing, 1989).

Water flowing to the drains (ditch or tile) is assumed to be drawn from the upper saturated layer until the water content approaches drainable porosity. Thereafter, the water will be drawn from the second layer in the saturated zone, and so on. The process continues until the water table is drawn below the tiles or ditch bottoms. At this time water flow to the tiles or ditches is considered negligible and soil water content in each layer is subjected only to percolation and evapotranspiration (soil evaporation and water uptake by plant roots). For more details see Savabi et al., (1989a).

SUMMARY

The hydrology component of WEPP utilizes the Green and Ampt infiltration equation to calculate the infiltration rate and excess rainfall rate. Saturated hydraulic conductivity is determined based on soil physical properties and adjusted for the effect of vegetal cover, crust formation, and macroporosity. The model simulates evapotranspiration losses, percolation, and drainage flow. The infiltration component of WEPP is linked with the evapotranspiration , percolation, and drainage components to maintain a continuous soil water balance. Infiltrated water is added to the upper soil layer water content and routed through the soil layers. Soil water in each layer is subjected to percolation, flow to drain tiles and/or ditches, and evapotranspiration . The upper layer soil water content is used to establish initial moisture conditions for the infiltration component . Percolation below the root zone is considered lost from the WEPP water balance. Excess rainfall is routed downslope to estimate the overland flow hydrograph. Storm runoff is used in calculating rill erosion and flow sediment transport capacity.

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DEVELOPING HYDROLOGIC PARAMETERS USING GIS

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ABSTRACT

In looking at the Hydrologic Modeling Demands for the 1990's, there exist new technology that can change the way we do hydrology studies significantly. One of these new tools is GIS.

Some of the objectives to setting up a GIS system are to increase our accuracy in hydrologic modeling, decrease our time spent in setting up hydrology models, and decrease our time in running different alternatives where landuse and/or physical geometry may change at some future date. A GIS system also allows quick access of data and easy storage of data. A centralized GIS system allows one or more groups to use the same data, thus decreasing the cost of data collection and reduces the chances of duplicating work due to a lack of communication between different officies.

This paper will focus on what steps need to be done in order to get data into the system and how a person can use that data once it is in the system to setup a hydrology model. There will also be a discussion of how the same data used to setup a hydrology model can be used by other officies.

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INTRODUCTION

Purposes and Scope

The purpose of this paper is to familarize the reader with the different types of data that are available to create a GIS, where to go and get the data, how to use the data once it has been placed into the GIS, and how a centralized GIS/Database can be used by different personnel.

TYPES OF AVAILABLE DATA

In setting up a GIS for the purpose of performing hydrologic studies, there are a number of different types of data needed. Among these, are landuse grids, soil type grids, elevation grids or elevation ttn models, digital line graphics, aerial photography, and slope grids.

Landuse grids can be generated from satellite imagery. Once a person has gone out into the field and gathered preliminary ground truth data, there are software packages that can translate an image into a landuse grid using the field data.

Soil type grids can be generated from digital line graphics. The graphic elements can be digitized into the system off of hardcopy maps supplied by the Soil Conservation Service. The SCS is also in the process of creating digital line graphic files of their soil maps which can be grided.

There are a number of ways to place elevation data into a GIS. The USGS currently has Digital Elevation Maps made up for most of the United States. These maps come in different scales. Elevation data can be gathered from a contracted survey and added to the USGS data for a more accurate map in areas where detailed designs may be necessary. An example of where this may be necessary is merging detailed channel cross-section data with general overbank elevations for the purpose of performing a watersurface profile study. A product of the elevation data is the capability of creating slope grids. These grids can be used to estimate the average slope over an area for the purpose of calculating overland flow.

Digital Line Graphics can be ordered from the USGS for most of the United States. Once these maps are loaded into the system, a person can add or delete data for a particular project. The DLG files ordered from the USGS contain a variety of features. Among these are major and minor roads, rivers and streams, power lines, and railroads.

Aerial Photography can be contracted out to an aerial survey company or satellite images can be ordered from the Defense Mapping Agency. Photography taken from an airplane will need to be scanned into the GIS and then warped into place using known coordinates. The satellite images ordered from the DMA come registered to a specified coordinate system.

GIS APPLICATIONS

Once a GIS has been developed, there are numerous applications. A person can generate new grids using existing grid data by developing a goal script. An example of this is creating an SCS Curve Number Grid using a landuse and soil type grid. Once a goal script has been written to correlate the landuse and soil type to a specific curve number, it is an easy process to generate the curve number grid for use in estimating infiltration parameters.

As mentioned above, elevation grids can be used to develop slope grids for use in calculating overland flows. Elevation ttn models can be used to calculate volumes below a given elevation or the difference in volume between two elevation surfaces. An example of this would be determining the difference in volume between a before dredging survey and after dredging survey.

Digital Line Graphics can be used to measure stream lengths, delinate watershed boundaries, and to calculate watershed areas. There exists the capability to use linestrings to delinate the path of a cross-section, take the cross-section from a ttn model, and place it into a watersurface profile model. Once a watersurface profile has been calculated, Digital Line Graphics can be used to delinate a flood outline using an elevation ttn model.

CENTRALIZED GIS/DATABASE

GIS data is not limited to use by one particular discipline. Landuse data can be used by hydraulic engineers to estimate overland roughness coefficients and environmental engineers can use the data to perform environmental impact statements. Soil type data can be used for estimating infiltration parameters and for soil stability analysis. Elevation data can be used to extract stream cross-sections and used for site layouts by a planning engineer. All of these data can be stored in a centralized database, such that the team members on a project can use the same maps, tables, and models. This centralized GIS/DATABASE will increase efficiency by decreasing the time and cost to collect data, decrease the chances of duplicating work, and increase the speed in which to analyze different alternatives.

CONCLUSIONS

In conclusion, the time and cost to prepare a GIS is going down everyday because of the **availability** of data to be purchased for a reasonable cost. This data allows a person to perform studies in a fraction of the time. Storing this data in a centralized database allows different branches to use the same data thus cutting cost for data collection and duplication of effort.

SNOWMELT RUNOFF FORECASTING

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ABSTRACT

This paper describes the history of operational snowmelt forecasting by the U.S. Army Corps of Engineers and recent developments in modeling tools. Since the early 1940's, the U.S. Army Corps of Engineers has been instrumental in developing methodologies for snowmelt forecasting. These methodologies have been applied in numerous simulation models, including SSARR, HEC-1F, and NWSRFS. Recently developed modeling tools include the application of object-oriented programming, the development of interfaces to Geographic Information Systems (GIS), and the use of remotely sensed snow cover information. These tools have led to improved physically based models that characterize internal watershed processes, such as flow path and source area delineation, snowpack accumulation and distribution, and surface energy exchange. Examples of these technologies will be presented.

INTRODUCTION

Snowmelt runoff is a major component of the hydrologic cycle in many regions and is an important consideration in design flood analysis. Since the 1940's the U.S. Army Corps of Engineers has been instrumental in developing operational systems for snowmelt forecasting. The publication Snow Hydrology (U.S. Army Corps of Engineers, 1956), which summarized the findings of Cooperative Snow Investigations with the U.S. Weather Bureau, has been cited (Bras, 1990; Gray and Male, 1981) as the most comprehensive and useful treatise on methodologies for computing snowmelt and snowmelt runoff. These methodologies have been applied in numerous simulation models, including SSARR, HEC-1F and NWSRFS. Other studies and reports, for example, by the U.S. Army Corps of Engineers (Speers et al., 1978; Colbeck and Ray, 1978), by the National Weather Service (Anderson, 1973) and by the U.S. Geological Survey (Leavesley et al., 1983) have added to the state of the art of operational snow hydrology.

The World Meteorological Organization (WMO, 1986) conducted one of the most comprehensive comparisons of snowmelt forecasting models,

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classifying these models into two categories: 1) snowmelt models that simulate snow accumulation and melting, and 2) transformation models that take rainfall and snowmelt input and transform this to basin outflow. Recently developed modeling tools include the application of object-oriented programming, the development of interfaces to Geographic Information Systems (GIS), and the use of remotely sensed snow cover information. The pace of development of these tools and the enhancement of computer capacity in the past 10 years has outstripped the capability to forecast snowmelt. In the near future, improved physically based models, employing these tools, will greatly enhance forecasters' ability to characterize watershed processes such as flow path delineation, source areas, snowpack accumulation and distribution, and surface energy exchange. In this paper, we will describe the history of snowmelt forecasting in the U.S. Army Corps of Engineers and discuss application of the modeling tool technologies.

BACKGROUND

The Cooperative Snow Investigations Program, begun in the late 1940's (Rockwood, 1978) by the Corps of Engineers and the Weather Service, was the beginning of a long-standing application of hydrologic principles to techniques for forecasting watershed snowmelt. These investigations concluded in the development of water balances for the study areas, the determination of the theoretical heat balance between the atmosphere and the snowpack, and the determination of liquid water content and transmission within the snowpack. These findings resulted in methodologies to forecast runoff hydrographs from snowmelt and to apply these techniques to multi-purpose water control systems, and are described in _Snow Hydrology_ (U.S. Army Corps of Engineers, 1956).

The Snow Investigations Program led to the design of the Streamflow Synthesis and Reservoir Regulation (SSARR) model in 1956. The program was initially used in the Columbia River basin to develop a system for combined planning, design, and operational considerations. The SSARR program models snowmelt using several options that allow it to be tailored for particular applications. The SSARR model has two options for computing snowmelt, the temperature index approach and the generalized snowmelt equations as derived from _Snow Hydrology_ (1956). The state of the basin snowpack can also be defined by two options, the snow cover "Depletion Curve" model or the "Integrated-Snowband" model. In the first, the snow-cover depletion curve method uses a theoretical relationship between snow-covered area as a percent of watershed area versus accumulated runoff as a percentage of seasonal total. The Integrated-Snowband model was added in 1978 (Speers et al., 1978) to improve the physical basis by adding the following elements: 1) snow conditioning or accounting for the snowpack heat deficit, 2) a vegetation interception algorithm, 3) a more flexible evaporation simulation, and 4) a fourth component or routing to simulate long-term return flow from groundwater. The Integrated-Snowband model uses Anderson's (1973) heat deficit approach for its snowpack conditioning routine. The reader is referred the SSARR manual (U.S. Army Corps of Engineers, 1991a) for a full description of its capabilities. More recently, modifications to SSARR have been made by a number of researchers (Stokely, 1980; Peaco, 1981; Pangburn and McKim, 1984; and Pangburn, 1987). These modifications have centered on improving SSARR's capabilities in cold regions. They include improvements in characterization of the effects of temperature on the timing of flood peaks and on soil moisture retention, frozen ground, ice cover on rivers, and differing spatial and temporal scales on thermal budgets of watersheds.

RECENT RESEARCH FINDINGS

Advancements in three areas have greatly improved the potential of physically based operational techniques for forecasting snowmelt. These areas are the development of modular object-oriented modeling techniques, the development of interfaces to geographic information systems, and the use of remotely sensed snow cover information. Research in these areas has centered on field and modeling experiments to develop a framework for a mass and energy modeling scheme that is physically based over a drainage basin scale, which will produce the thermal and hydrologic response of a basin within snowmelt regimes. The applicability of field studies of distributed mass and energy processes has become more critical with the use of geographic information systems and remote sensing technology in water resources.

Object-Oriented Modeling Techniques

There is an increased emphasis on process-related research and studies that are concerned with the interrelation of all phases of water, energy and biogeochemical budgets. Such research benefits from a modeling approach that maintains modular components of "known" physical processes and offer a combinational structure to account for the complete system's dynamic behavior. Cassell and Pangburn (1991) discuss the development of SSARR-DS, an object-oriented systems-dynamic model created within the structure of the STELLA software package (Richmond et al., 1987). This model, based on the watershed portion of the original SSARR model, incorporates all previous cold regions capabilities. SSARR-DS provides an extremely user-friendly environment that offers convenient data input, superior output capabilities and constructive interactive features. Because SSARR-DS is in STELLA, the model can be conveniently and rapidly dissected to examine its internal workings and assess the sensitivity of the model to various parameters. In the object-oriented environment, levels and rates are animated, which, along with the tabular and graphical capabilities of SSARR-DS, allows the modeller to visualize the dynamic behavior of the physical system.

SSARR-DS is one example of modular snowmelt forecasting systems, having a physical basis, that are being developed. The National

Weather Service is currently employing NWSRFS Version 5 and the U.S. Geological Survey is employing the Precipitation-Runoff Modeling System (PRMS, Leavesley et al., 1983), which use modular forecasting systems. The modular scheme has the highest potential for creating multi-application operational systems.

Geographic Information Systems (GIS)

Geographic information systems are designed to store, manipulate, and display information such as maps of soils, topography, land use and land cover. The characteristic that distinguishes a GIS from a general mapping program is its ability to link topographic data, such as elevation, slope, and watershed boundaries, to descriptive data, such as land use and cover, soil type and properties, rainfall and runoff, and snow cover. Because of the spatial data handling capabilities of geographic information systems, they have become an integral tool in hydrological model development (Drayton et al., 1992; DeVantier and Feldman, 1993; Vieux, 1991).

Chou and Ding (1992) discuss several advantages to linking spatial models to GIS. First, data may be integrated into the GIS from a variety of sources, such as remotely sensed data, digital models of the terrain, or nonspatial data that are compiled in the form of maps, tables or reports. Second, topological relationships can be built for the model using the basic structure of the GIS. Grid cell or raster storage of information, Triangular Irregular Network (TIN) representation of watersheds, and vector description of streams are all examples of using the topological structure of the data to provide information to a model. Third, the display and organizational capabilities of GIS often provide the user with information about the model that is not readily apparent.

Geographic information systems have been integrated into models in several ways, ranging from using GIS spatial modeling techniques, but not actually using a GIS, to developing a user interface that links the GIS to the model. Cline (1992) used geographic information processing techniques to model snow redistribution by wind. Cline's spatial modeling techniques are commonly found in raster-based GIS, although an actual GIS was not used in the model. Sambles and Anderson (1992; Sambles et al., 1990) developed a digital model to simulate the pattern of snowcover and snowdepth distribution over a small catchment during the melt season. The model uses a GIS and a clustering routine to subdivide the catchment into homogeneous areas. These areas are used as the computational and spatial basis of the model. Each area is homogeneous with respect to slope, aspect, elevation and vegetation cover. No particular GIS was used in this work; in fact, aspects of several were incorporated for the catchment discretization procedure.

Another method is to use the GIS for developing a network over which the hydrological model is applied. Vieux (1988, 1991) integrated a distributed process model of overland flow using the finite element method and the GIS ARC/INFO TIN module. The TIN facets are used to provide land surface slope in the finite element solution. Maidment (1992) reviewed the network representation used in current HEC models and discussed the network modeling capabilities of current GIS systems. A proposal was made to create a hybrid grid-network GIS representation to support hydrologic modeling. The need to determine the order of hydrologic computations through card image sequencing of the HEC models could be eliminated by using a geographic representation of the landscape as the basis for constructing a hydrologic model of connected flow systems. The attributes, such as area, length, and land surface properties, of some of those systems could be determined directly from the GIS.

Frederickson (1993) developed a Graphical User Interface (GUI) to link the GIS GRASS and HEC-2 for flood prediction and assessment using XGEN (U.S. Army Corps of Engineers, 1991b). The interface is integrated with GRASS in such as way that the users think that they are using a single software application, at the same time that the GIS and the model are compartmentalized as much as possible. The user interface incorporates GRASS for graphical display and surrounds it with an X-server application manager and window manager.

Remote Sensing Techniques

Over the last few years there have been significant advances in mapping snow-covered area from satellites and aircraft. As previously mentioned, snow-covered area is a critical parameter in many snowmelt runoff models. Snow has higher reflectance in the visible near-infrared spectral region than most other natural surfaces, and spaceborne instruments have been used to map snow-covered areas, based on the spectral signature.

During the 1970's and 1980's, most snow mapping procedures relied on operator interaction to produce the snow maps. For example, Rango and Itten (1975) used both supervised and unsupervised computer classification techniques to map snow-covered area in the Wind River Range from Landsat MSS data. Snow in the trees and melt-freeze snow were classified, but the criteria were not specified. Many others have reported semi-interactive snow mapping algorithms for Landsat, AVHRR, and other data throughout the 1980's. Clouds were a problem for some time because they are as bright as snow cover, and temperature data did not prove to be an adequate discriminator. However, DMSP reflectance data in a near-infrared band, coupled with visible and thermal infrared measurements, were used by Crane and Anderson (1984) to discriminate clouds from snow and water clouds from ice clouds.

Procedures for automatically mapping snow have only recently been described. Dozier (1989) demonstrated automatic snow mapping based on apparent planetary (spectral) reflectance. Thresholding and normalized difference ratios for TM bands 1, 2, and 5 were used to identify snow in shadow, and to discriminate sunlit rocks, soils and clouds from sunlit snow. More recently, a fully automatic procedure was described by Rosenthal et al. (1992) that used spectral mixture analysis and regression tree classifiers to map snow in open areas, in forests, and in partially snow-covered areas using Landsat TM.

The current issue in using satellite imagery in the visible and near-infrared spectral region for operational hydrology is the timely acquisition of data by hydrologists. In the microwave spectral region, snow mapping for operational hydrology has also been problematic.

Until recently, measurements of snow in the microwave region by existing spaceborne instruments consisted mainly of observations of microwave emissions. Because of the relatively low amounts of energy being measured, the footprints of these instruments are large, on the order of 35 km. The large footprints compound the problem of recovering snow parameters because the mixed-pixel problem is severe. Hence, to date, there is no standard algorithm for recovering snow water equivalence. Progress has been made in mapping the snow-covered area and identifying snow areas that begin to melt. However, the use of these data on small- to medium-sized watersheds is marginal at best because of the coarse spatial resolution and the lack of algorithms to recover snow parameters at sub-resolution scales.

Progress has also been made recently in mapping snow with airborne synthetic aperture radar (SAR). Shi and Dozier (1993) have shown that single-polarization's SAR signature can be used to recover snow-covered area. With the launch of the ESA ERS-1, a C-band, single-polarization SAR, there is the potential for recovering snow area at scales suitable for input to hydrologic forecasting.

CONCLUSIONS

Progress has been made toward better operational forecasts of snowmelt runoff with the application of modular modeling techniques, advances in melt and runoff algorithms, incorporation of GIS technologies, and the automation of snow mapping methods. We expect that integration of these tools will produce better snowmelt runoff forecasting because information on snowmelt and runoff processes, and on the hydrologic state of watersheds, will be readily and quickly available to hydrologists.

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INTEGRATION AND USE OF THE NITRATE LEACHING AND ECONOMIC ANALYSIS PACKAGE (NLEAP) IN THE GIS ENVIRONMENT

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ABSTRACT

NLEAP is a national screening model for identification of NO_3-N leaching hot spots. The original model was point-based for use on a field by field basis with its own databases, user template files, and output analysis package. Application of the model across larger geographical areas such as aquifer systems, drainage basins, counties, and conservation districts requires the use of Geographical Information System (GIS) technology in conjunction with the existing model. Test cases run for the Sycamore Creek Watershed in Michigan and the South Platte drainage basin in eastern Colorado have demonstrated the feasibility and utility of using NLEAP in the GIS environment to identify NO_3-N leaching hot spots across large areas. In particular, the NLEAP NO_3-N Leached (NL) index was significantly correlated with regional groundwater NO_3-N concentrations in eastern Colorado. Automation of the NLEAP-GIS interface is under development with emphasis placed on an updated NLEAP model that can run in conjunction with a range of existing (and future) GIS software tools both in the UNIX (e.g. GRASS) and DOS (e.g. IDRISI) systems.

INTRODUCTION

Regional assessments of agricultural impacts on groundwater quality have been receiving increased attention in the literature. This has been especially true since the development of GIS and remote sensing technology. State-wide assessments have relied on a ranking index approach within a GIS (Hamlett et al. 1992, Lemme et al. 1989, and Halliday and Wolfe 1991). Other studies range from combination remote sensing/GIS studies reported by Bishop et al. (1992) and combination empirical vulnerability models and GIS (Christy, 1992) to approaches involving remote sensing, GIS, and mechanistic modeling taken by Wylie et al. (In press). The use of a GIS in combination with pesticide leaching models has been demonstrated using LEACHM (Bleecker et al. 1990 and Petach et al. 1991). Pickus and Hewitt (1992) used a decision-support tool (PUMPS) which integrated modeling techniques and GIS to map pesticide leaching vulnerability. Models such as AGNPS have been used within a GIS to evaluate runoff characteristics and transport processes (Young et al. 1989).

Most models capable of simulating the movement of nutrients and pesticides from soil profiles to groundwater are point (soil) or field specific, and were not originally designed for use across landscapes, regions, drainage basins, or counties. Examples include NLEAP, Shaffer et al. (1991); NTRM, Shaffer and Larson (1987), RZWQM, USDA (1992); EPIC, Williams et al. (1984); and GLEAMS, Leonard et al. (1986). Field testing of these models has been generally limited to small scale research plots and farm fields. However, leaching of contaminants

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such as NO_3-N from diffuse agricultural sources does not occur in a uniform (nor random) fashion especially when viewed on a scale approaching hundreds of square kilometers. Rather, the pattern tends to be patchy with well defined hot spot areas that appear to be tied to soil texture and farm management practices in the area (Wylie et al., In press).

The Nitrate Leaching and Economic Analysis Package (NLEAP) model was developed as part of a national effort to consolidate knowledge about managing nitrogen in agriculture, provide a screening tool to assess potential NO_3-N leaching, and suggest alternative management techniques (Follett et al. 1991; Shaffer et al. 1991). NLEAP estimates NO_3-N leaching indices at the field scale. However, recent research efforts by Pierce et al. (1991) and Wylie et al. (1992) have suggested that NLEAP leaching indices can be extended to a watershed or regional scale by combining NLEAP simulations with Geographical Information System (GIS) technology. In particular, both Pierce and Wylie have shown that an NLEAP/GIS combination can be used to predict NO_3-N leaching hot spots across broad geographical areas. Wylie et al. (In press) have completed a pilot study that validated the use of the NLEAP NO_3-N leached (NL) index for identifying NO_3-N distributions and hot spots across a shallow regional aquifer under irrigated agriculture. From the standpoint of action agencies and regulators, identification of NO_3-N hot spot areas would allow direction of limited resources to areas with the greatest need and potential payoff. Producers want to know if they are located in hot spot areas and, if so, are their management practices contributing to the problem and what Best Management Practices (BMP's) are available to minimize NO_3-N leaching at their site.

The purpose of this paper is show how the NLEAP model was integrated into the GIS environment thus allowing regional assessments of NO_3-N leaching hot spots and potential BMP's.

METHODS

GIS technology provides georeferencing of data layers across fields, farms, and entire regions. GIS software packages such as the public domain GRASS (GRASS 1991) and the commercial ARCINFO (Morehouse 1985) for larger workstations and IDRISI (Eastman 1992) for smaller PC's are available for general use. NLEAP simulates NO_3-N leaching indices for specific datasets that can be derived from GIS data layers. The key to effective use of NLEAP in this environment is efficient transfer of information between NLEAP and the GIS.

The methodology for using a GIS in conjunction with a point-process simulation model such as NLEAP can be broken down into three major components. First, the GIS is used to delineate the region of interest and then to "overlay" the environment (soils, climate, & aquifer) and management data layers within the region to create a single data layer of environment/management combinations. Initially, this combination layer is used to identify the set of unique environment and management combinations found over the region and which need to be processed by NLEAP. This step requires the acquisition of the baseline data layers needed for a regional analysis (ie. digitized soil surveys; climate data; identification of cropped areas and crop distributions; location/extent of management practices such as irrigation, chemical fertilization, and manuring;

and aquifer location and properties). This acquisition is the most resource demanding process in the regional analysis and will dictate the extent of the region which can be included in an analysis. The resulting unique environment/management combinations are written into a regional data table in the form of an ASCII file. This table becomes the primary transfer medium for information exchange between the GIS and NLEAP, including leaching indices sent back to the GIS from NLEAP.

Second, NLEAP data files must be constructed and processed for each unique environment/management unit. The data files will be a combination of information obtained from the GIS, the NLEAP databases, and the user. In general, steady state NLEAP simulations appear to be the most appropriate when using generalized management and residual soil NO_3-N assumptions. This is so because the long term effects of management on that soil are brought out and the errors associated with regionalized assumptions are reduced (Wylie et al. in press). NLEAP leaching indices such as NO_3-N Leached (NL), NO_3-N Available for Leaching (NAL), Movement Risk Index (MRI), Leachate Volume (LV), Annual Leaching Risk Potential (ALRP), and Aquifer Risk Index (ARI) for each environment/management scenario are examples of indices of interest. These indices can then be georeferenced and mapped using the GIS systems.

The last step in the analysis is to use the regional table in the GIS to identify, analyze, and map the distribution of the NLEAP results over the study area. This GIS process will link the NLEAP results for each environment/management unit to the distribution of these units in the initial integrated map overlay.

In the case study below, the three steps were "done by hand" and were somewhat time consuming. We are currently working on a system that will "build" NLEAP datasets from information in a regional table constructed by any GIS and consisting of the unique environment/management units and their components. We are also working on a second system that will process a set of datasets through NLEAP and will build a file which combines the NLEAP results with the regional table.

SOUTH PLATTE NO_3-N LEACHING CASE STUDY

A cooperative regional pilot study involving an NLEAP/GIS interface has been completed for a 642 km^2 irrigated area along the South Platte River and its tributaries in northeastern Colorado, Wylie, et al. (In press). The region is typical of many irrigated areas in the western U.S. that are underlain with shallow aquifers subject to leaching from agricultural non-point sources. Previous and on-going studies and surveys by ARS, CSU, SCS, USGS, and local water districts provided extensive information on aquifer water quality and properties, soil properties, climate history, cropping patterns, and agricultural management. The NLEAP pilot project included close collaboration with the U.S. Soil Conservation Service (SCS), the North Front Range Water Quality Planning Association (NFRWQPA 1991), Colorado State University, and the Northern Colorado Water Conservancy District (Crookston and Hoffner 1992).

This study involved a direct test of a combined NLEAP/GIS approach on a regional scale. Extensive GIS mapping of aquifer, soil, irrigated agriculture, and agricultural management data layers was done over the pilot area using GRASS 4.0. By overlaying and/or masking, GRASS produced a base regional data table which was saved as an ASCII file and consisted of a listing of the soil map units located within areas of irrigated agriculture on the alluvial aquifer. The results of the NLEAP simulations associated with each irrigated soil/aquifer unit were added to this regional file.

The data exchange to and from the regional data table and the GIS was relatively easy. Reformatting of ASCII files from the data table for use by the GIS involved selecting the two columns of data needed (soil map unit number and the NLEAP index of interest, e.g. NL) and, in the case of GRASS, inserting an equal sign between the two columns of numbers. These processes are easily accomplished by most database, spreadsheet, and/or wordprocessor software packages.

The regional data table allowed rapid entry of variables associated with the soil's physical and chemical properties (e.g., texture and percent organic matter) as well as the NLEAP post-simulation leaching indices associated with that soil. GIS maps could be quickly made from any data entered in the regional data table.

The data transfers between the regional data table and NLEAP are more cumbersome. NLEAP data files were made for each soil in the regional table. Since irrigation amounts were assumed to be different on coarse and fine textured soils, two base template files with management (inorganic fertilizers), climate, and irrigation inputs were created within NLEAP for coarse and fine textured soils, respectively. Each respective coarse texture soil in the regional table was loaded from the NLEAP soils database into the base template file for coarse textured soils and saved as a data file. This process was repeated for the fine textured soils using the fine textured base template file. This resulted in the rapid generation of the necessary data files needed for NLEAP simulation of NO_3-N leaching with inorganic fertilizers. Similarly, the two base template files were modified to reflect manure applications and the data file creation process repeated, taking care to use unique data file names. NLEAP simulations for one year and at steady state were then conducted on each data file and the results printed. The resulting NLEAP leaching indices (NL, NAL, MRI, and LV) were entered into the regional data table for one year of simulation and at steady state.

The process of NLEAP data file creation (124 files = 62 soils x 2 nitrogen treatments) and NLEAP simulations for the set of soils was rather laborious and tedious. It took about 8 work days to create the data files and run 62 soils through organic and inorganic simulations for one year and at steady state (average of 6 years of simulation) or about 744 years of simulations (62 x 2 x 6). The two most time consuming steps were the steady state simulations where inorganic fertilizer applications were revised every two years of simulation and the generation of the NLEAP data files.

Aside from the GIS and NLEAP analytical time, the development of the necessary GIS map layers from digitizing maps, importing DLG files, scanning, and use of a Landsat remote sensing image had large time demands. To implement this analysis on a state-wide basis would require significantly more resources and probably should be restricted to areas with known NO_3-N leaching problems or areas vulnerable to leaching such as regions with irrigated agriculture over shallow alluvial aquifers. One advantage of GIS analysis is that the effects of changes in the analysis or assumptions can be quickly altered and new maps produced. Analyses comparing several NLEAP indices can be done taking into account their spatial variability.

The NLEAP model in this case study was used to compute the NO_3-N leached (NL) index across a 642 km^2 irrigated region along the South Platte River. Direct validation comparison of NLEAP results with groundwater NO_3-N concentrations in the shallow alluvial aquifer indicated that the NLEAP NO_3-N leached (NL) index shows promise for identification of regional NO_3-N leaching distributions and hot spots, Figure 1a and 1b. The Pearson correlation coefficient for the predicted NL index values versus the observed groundwater NO_3-N concentrations at 108 wells was 0.59 ($p < 0.0001$).

SUMMARY AND CONCLUSIONS

The case study has shown the capability and utility of using NLEAP and a GIS to identify sites across regional areas with potential NO_3-N leaching problems. However, the GIS/NLEAP linkage needs to be further automated before routine use across large geographical regions. The methodology developed in the Michigan and Colorado pilot studies has identified the processes that must be incorporated into a fully automated system for linking NLEAP to a GIS.

The Colorado pilot research also reinforced the concept identified in a related study done with NLEAP on the Sycamore Creek watershed in Michigan (Pierce et al. 1991) that regional leaching of NO_3-N from agriculture tends to occur in localized hot spot areas that are a function of soil properties and management history.

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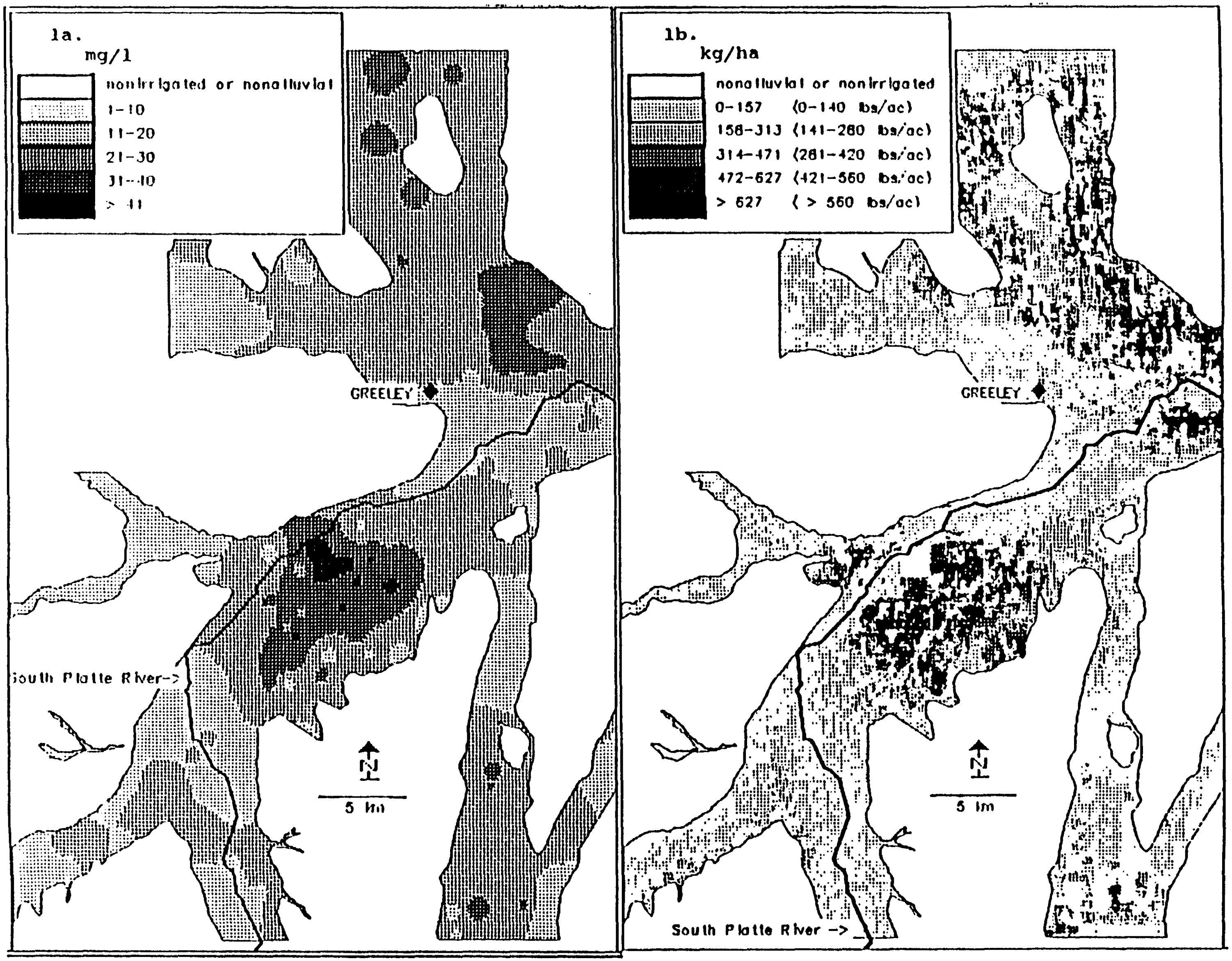
Figure 1. Average Groundwater NO_3-N from 1989 to 1991 (1a) and NLEAP NO_3-N Leached (NL) Index for Irrigated Areas near Greeley, Colorado (1b).



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A GRAPHICAL USER INTERFACE FOR ARS WATER DATA ON CD-ROM

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ABSTRACT

Over the past 70 years, the USDA has initiated and supported a variety of watershed hydrological research projects, some in continuous operation since the early 1930's. In the late 1960's, recognizing the value of the unique hydrologic data collected in support of the project's research activities, the Agricultural Research Service (ARS) created the Water Data Center (WDC), to develop and maintain a centralized storage and retrieval system for archiving and disseminating their hydrologic data. Beginning in 1990, the mainframe data base, stored on 200+ magnetic tapes was downloaded to microcomputer optical disk storage media. The WDC is currently in the process of developing a CD-ROM version of these data. Microcomputer software is under development that will provide a graphical user interface (GUI) for accessing this CD-ROM. This software will provide an easy-to-use "window" into the collection of approximately 14000 files of rainfall and runoff data that constitute the ARS Water Data Base. The program includes a graphical browse/query facility, allowing the user to "point and click" through several map layers, obtaining more detailed information as each layer is traversed. Map layers will progress from macro-level (U.S. map with icons marking the location of ARS data collection activities), to micro-level (an individual watershed's topography, land use, etc.). Data retrieval can be initiated while browsing the program's map set, or alternatively, by clicking on tables of locations, recording stations, and/or years available. Retrieval of the digital line graph files used to generate map images will also be supported. Several program features allow the user to integrate "local" data files and programs into the GUI. The software will be distributed with the CD-ROM to ARS research locations, universities, libraries, and any interested parties.
KEYWORDS: Graphical user interface, GUI, CD-ROM, optical disk, microcomputer

INTRODUCTION

Background

Though the data have been available to the general public since the late 1960's, there have always existed numerous technical and physical barriers to an individual's ability to directly access and use the WDC's database. The processing platform, data storage media, data communications speed limitations have until very recently dictated that any interested user community access the database remotely, or, more often, through the staff of the WDC (Thurman, et al, 1983).

In the past few years, technological advances in microcomputers, especially in their processing speeds, memory capacity, and in PC compatible data storage devices, storage media, and data management software have radically altered our ability to acquire and use large data sets. With this technological surge, managers of large databases now find it not only feasible, but cost effective to migrate their systems to microcomputer or work station platforms.

Advances in storage media have played a critical role in allowing this move away from traditional "mainframe" database management. Where it once took

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over 200 reels of magnetic tape at the USDA computer center in Kansas City, MO to store the Water Data Base, we now find it conveniently located on site in Beltsville, MD on several 5"x 5" Write Once, Read Many (WORM) optical disks. (Thurman and Roberts, 1993)

PROGRAM DESIGN

Approach

The Graphical User Interface (GUI) for accessing ARS Water Data was originally conceived and developed to facilitate in-house access to the WORM drive data by nontechnical lab personnel charged with responding to outside data requests. Shortly after we began to think about the project, two CD-ROM manufacturers, Phillips and JVC, announced the availability of inexpensive, in-house, CD-ROM mastering systems, which has effectively removed the last cost-related impediment to using the technology for storage and distribution of large, non-commercial archival databases.

The target audience of the GUI is now envisioned as anyone with an interest in water data, with the only limiting requirement being access to a personal computer equipped with a CD-ROM reader and a mouse.

The basic design concepts of the GUI are borrowed from several successful commercial window managers, primarily Microsoft Windows and OSF/Motif for X Window. The overall objective of these GUI's is identical: making the computer easier to use. The basic facilities found in all successful GUIs are: extensive use of visual control elements, direct manipulation of on-screen elements, consistency across applications and platforms, simultaneous multiple applications (not supported at this time), and attractive, easy-to-use systems (Reiss and Radin, 1992). Our design goal has been to try to incorporate all these facilities into the GUI for the ARS Water Data Base.

Features of a Graphical User Interface (GUI)

The primary interface "object" is the "desktop", which in this application is simply the screen display (see Figure 1). The philosophy of constraining all processing, display and communications within the logical "desktop" establishes compliance with the evolving, de-facto GUI standards, and will simplify porting the GUI to other processing environments (Windows, UNIX) in the future.

Across the top of the desktop is a second object, the "menu bar", that displays the high level functional categories available to the program user. The interface is designed to be controlled almost completely via the computer mouse, though keyboard equivalents ("access keys") for each mouse click are provided. Selecting a menu bar item either invokes the item's activity, or displays a new object, a "pulldown" menu, with several related activity choices available for selection. Several other GUI "objects" are used at various points in the interface that guide and control use of the program. The "text window" is an object that presents a visual slot into which text may be entered through the keyboard. An "attention" window suspends program activity, displays a message or other information, then waits for the requested user response. A "List Box" is similar to a pulldown window, displaying multiple items available for selection. The "Dialog Box" is an object that links together two or more other "objects". A common example is a file dialog box, made up of a file list box of existing filenames and a text box to enable entry of a new filename.

As mentioned above, the main means of control of the GUI is the computer mouse. Each mouse command has a keyboard equivalent. Each menu bar selection may be accessed by pressing ALT_{letter} (pressing the ALT key and the menu choice's underlined letter simultaneously). Each pulldown menu choice is selected by pressing the {letter}. For frequently used pulldown menu selections that involve multiple clicks/keypresses to invoke, a "shortcut" key or key combination may be provided, appearing to the right of the menu choice ("F2", "Shift+F2", etc.).

Additional information about an individual menu choice may be graphically communicated in several ways. A "dotted" menu command (Location...) implies that additional "objects" will be forthcoming, typically a dialog or list box, for providing the GUI additional, required information. A menu item that toggles a binary (off/on) program condition will indicate its current "state", displaying a check mark ("√") if the condition is "on". A "disabled" menu choice is one that is not currently available for use (i.e. the query report is disabled when no query is in progress). Disabled menu choices are displayed with a "grayed" or "dithered" appearance.

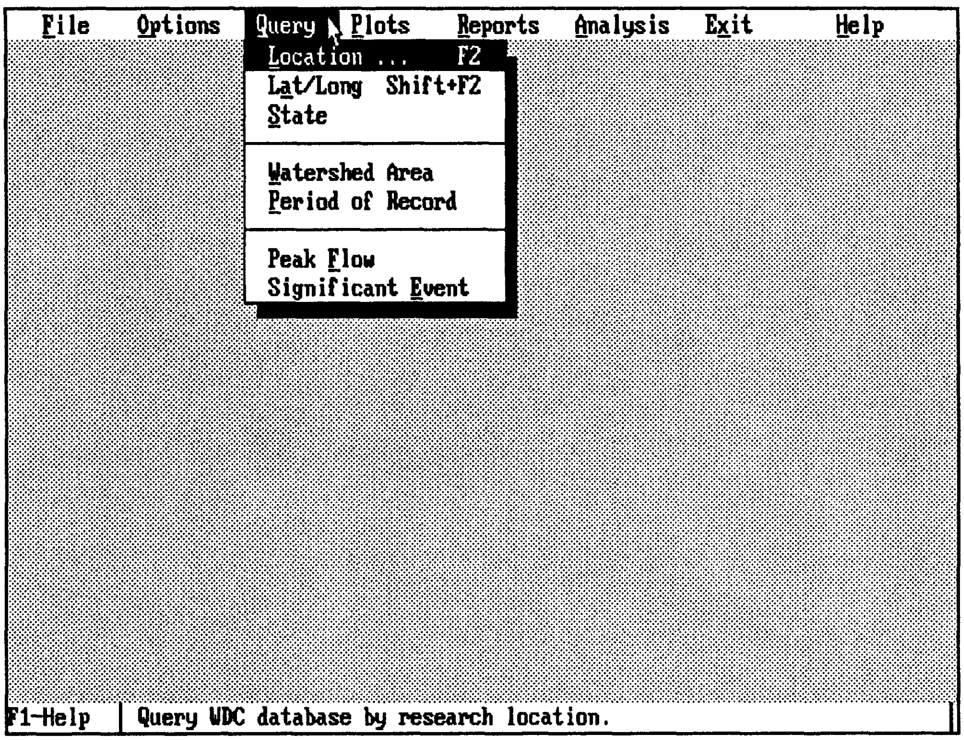

Figure 1. "Desktop" of GUI

Functional Areas

The ARS Water Data CD-ROM graphical user interface has seven main functional areas represented as menu bar choices.

Input/output functions are grouped under the "FILES" menu category. Included in this category are functions to load and save local (non CD-ROM) files, a browse function for visually inspecting the contents of a file, a "SHELL" function that allows a user to temporarily suspend GUI processing while one or more operating system functions are performed, and the EXIT function, which terminates the GUI.

The GUI's "Options" category provides the tools that allow the user to customize the GUI for a given processing environment. Two environmental function areas are provided in the GUI prototype, COLORS and PATHS. PATHS is the critical component, and must be defined for each system, particularly the path to the CD-ROM device. The file structure on the CD-ROM is compliant with the International Standards Organization's definition for CD-ROM file structure, ISO 9660/High Sierra (Fricks, 1992). All filenames on the CD-ROM are established by the Water Data Center, consisting of a directory for each location (\L67) and a file for each recording station (runoff weir or rainfall gage) maintained at that location that generated data included in the database (\L67\RG000001).

The "QUERY" functional area is the heart of the GUI. Several types of queries are, or will be, supported. The "Locations" query option supports the standard basic query for some combination of location id, station-id, and year-range. The query is defined through a series of linked list boxes, containing locations, station-id, and years (Figure 2). A "shortcut" key (F2) invokes selection of all stations/years for a location, or all years for a specific station. As stations/years are added and removed from the query definition, query statistics are displayed, including physical size of the query file being developed and an estimate of the external media (i.e., number of 1.2 MB diskettes) required to contain the query results. Additional queries planned for the prototype will include selection by peak flow/significant event, watershed area, geographic (State), and by period of record.

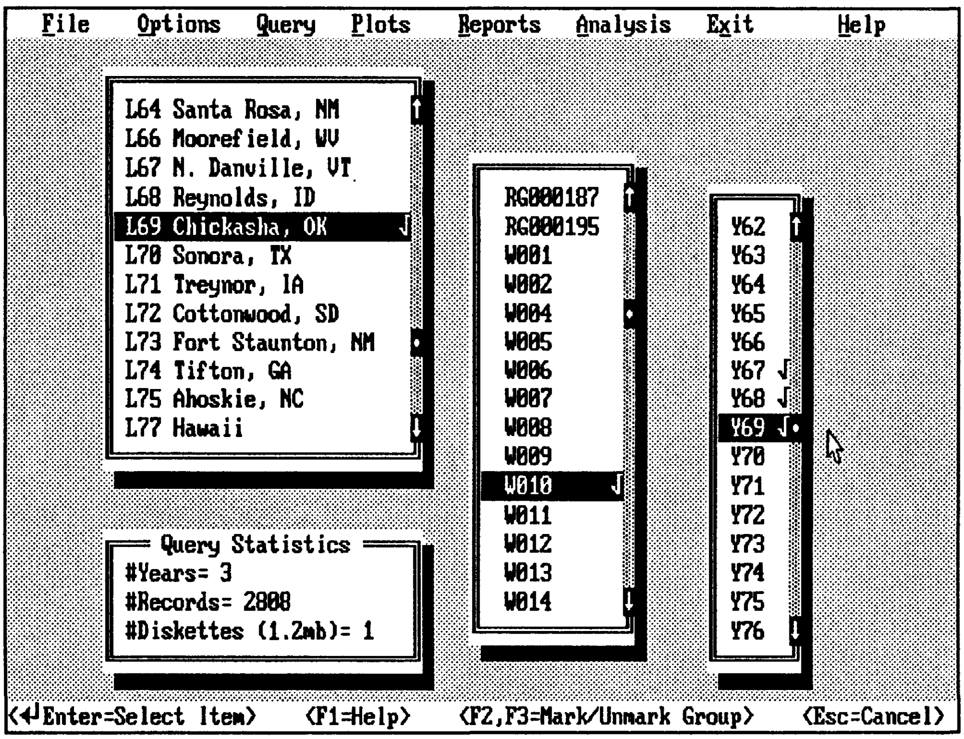

Figure 2. Linked list query

The "PLOT" component of the GUI groups the graphically oriented procedures together. The "Hydrograph" and "Hyetograph" plots are designed to work with a specific database (station) file. Each of these plots begins by plotting an entire period of record. In succeeding iterations, the user can obtain increasingly detailed plots by zooming on a subset of the preceding plot. At any point in the process, the user can create an "event" query file of the data displayed on the plot.

For the novice/infrequent user, the most valuable PLOT procedure available will probably be the ARS Locations menu option. This option generates a United States map with each location representing data in the database marked with an icon. Using the computer mouse, the user can interrogate (click on) a map icon (location), obtaining increasing levels of detail about a specific location, such as watershed boundaries/sub-boundaries, topography, land use, and recording station location. By clicking on the appropriate command button, the user can "popup" a list of station-ids for the displayed location (Figure 3), or a list of data years available for a selected station. Using these popup list boxes and the "F2" shortcut key described above, a user can define a data query exactly as that of the above-described "locations" query.

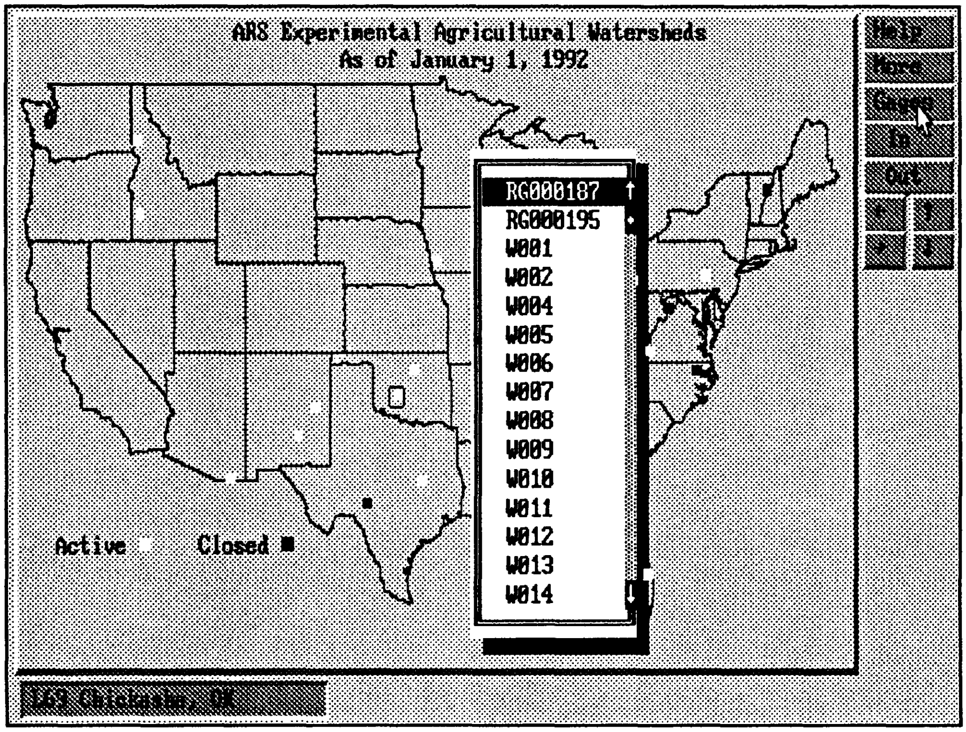

Figure 3. Graphical Query

The "REPORTS" functional area will include WDC generated reports with any local reporting software a user may choose to integrate into the GUI. This area of the prototype is currently still in the design phase. The only active menu option, "Query Results", prints a detailed report of the locations/ stations/years that constitute the "in-process" query. This option is "dithered", or inactive, when no query is under development.

An ultimate goal for the CD-ROM database is that it eventually contain adequate information to allow interactive production of the yearly "green book" series, Hydrologic Data for Experimental Agricultural Watersheds in the United States, currently printed as a miscellaneous publication by the Water Data Center (Thurman and Roberts, 1989).

The "ANALYSIS" functional area is similar to "REPORTS" in that it will include WDC, and optionally, user analysis software.

"HELP", the final menu-bar function, displays information describing the particular function, program option, etc. that is current when the function is invoked by the user.

CONCLUSIONS

The expanding requirement for high quality, long term hydrologic data collections places more and more pressure on data base managers to improve not only their databases, but in particular, the delivery systems they employ to make their databases conveniently available to all interested parties. In particular, it is becoming increasingly important for data base managers to develop methodologies which put their data directly at the fingertips of the data user, unconstrained by traditional complicating factors imposed by physical conditions such as data storage requirements, data transmission speed, etc. The maturing of microcomputer hardware and software, and in particular, the cost and availability of CD-ROM storage media, has made it possible for the first time for the Water Data Center to provide the entire

ARS Water Data Base, contained on a single CD-ROM disk, to each individual data user. To assist in using this new resource, a Graphical User Interface (GUI), has been developed using many established, de facto standard graphics building blocks, called "objects" or "widgets", resulting in a program with a standard "look and feel". The GUI allows the user to comfortably navigate through the massive amounts of data that make up the Water Data Base. The contents of the data base can be examined, and queries developed, in a tabular fashion using a series of linked lists, as well as graphically, through the display of maps, overlaid with icons representing data collection activities or data. Graphical icons can be "interrogated" by the user via a "mouse click", resulting in display of increasingly detailed maps. At the lowest icon level, a data collection station, an interrogation displays a table of data years of data available for the station. A separate feature found in several of the graphical plot routines will allow a user to isolate and save one or more individual storm events. The GUI includes functional areas for analysis and reporting procedures, and will include an ability to be "extended" with each individual user's local programs. The design of the application is influenced by the long term goal of porting the program to other processing environments, especially Microsoft Windows and X Window for UNIX.

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HYDROSS SIMULATION SUPPORT SYSTEM

Mike S. Brewer[1]

ABSTRACT

A generalized surface water network flow model called HYDROSS has been coupled with a graphical user interface (GUI) and a relational database management system to create a simulation support system on a UNIX workstation. HYDROSS is a surface water supply model developed by the U.S. Bureau of Reclamation to assist in planning studies for evaluating existing and proposed demands on a river system. HYDROSS operates over a discrete period of record, simulating the effects of factitious development on historical pristine flows. The X windowing system was used to develop the GUI which includes an interactive network builder to schematically define a river network for calibrating, verifying, and interpreting model results. The Ingres relational database management system was used to manage a hierarchical scenario database for further analysis and comparison.

INTRODUCTION

Managing the development and operation of river basins requires an understanding of many different aspects and interests associated with these basins. In addition, planning for future development implies an interactive process where varying levels of potential river basin development are analyzed to determine if conflicts result. The advent of water resource models, for the most part, has resulted in a greater understanding of river basin management. However, the growth of these models, coupled with the growth of ancillary computer applications, has led to a huge amount of technical information which is difficult to manage and analyze. Another problem is that existing river models are difficult to use; model input and output is strictly text-based which results in an arduous decision-making process.

To overcome existing difficulties in using complicated river system models, the U.S. Bureau of Reclamation (BOR) is moving towards the UNIX-based engineering workstation. Personal computers currently lack the speed and graphics to perform effective technical applications, but the UNIX environment is fast enough and has the multitasking capabilities necessary to allow for the display of multiple images which is well suited for iterative decision making. The process of trial-and-error simulation is best approached using an interactive, graphically oriented simulation system where the user does not have to spend time managing data input and output in the form of computer printouts. Instead, the user can make numerous runs during one session and generate comparisons among scenarios right on the screen.

The simulation support system presented here includes a surface water supply model, a system controller where information is displayed and data paths are defined, a GUI that symbolically and graphically displays all simulation activities, and a relational database for managing model input and output. This paper presents an introduction to each component in the simulation system.

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WATER SUPPLY MODEL

Background

The Hydrologic River Operation Study System (HYDROSS) model was selected for simulating the operation and management of the river basin (Bureau of Reclamation, 1991). HYDROSS is a system of computer programs written in FORTRAN-77; it is used to conduct monthly water supply studies for evaluating existing and proposed demands in a river basin. HYDROSS was originally developed on a Control Data Corporation cyber computer in 1977 by BOR. The programs were converted to the DOS operating system in 1991. The physical system modeled is characterized by a capacitated flow network. The network includes nodes, called stations in HYDROSS, which represent reservoirs, demands, river confluences, and points of known flow. Arcs between nodes represent river reaches and canals. The basic input into HYDROSS includes flow data, table data, and network data. Flow data represents pristine monthly flows at each station in the network. Table data includes operational parameters needed to perform simulations. Network data provides information about the physical relationship between stations and arcs.

Allocation of Water Supplies

Water allocation in HYDROSS structured so that flows are spatially and temporally allocated in accordance with water right priorities. Within a river basin, two types of flow are allocated, including natural flow and project flow. Natural flow is the flow which would occur in the absence of factitious development. Project flow is the water which has been stored in a reservoir or previously allocated through water right procedures. Natural flow is first used to satisfy demands with natural water rights; then, demands with project water rights are satisfied if remaining natural flow exists. Project flow is used to satisfy project demands when natural flow cannot. The above definitions contain an asymmetry in that a natural water right may be satisfied using project water, but project water cannot be used to satisfy natural water right demands.

Demands and Water Rights

Instream flow, power, diversions, and storage are the four types of demands described in HYDROSS. An instream flow is a demand that requires flow to be maintained in the stream at a given station. Water flowing through a station with an instream flow demand is available for use below the station. A power demand is the flow required at a power plant. Power plants only occur at reservoirs. The actual flow volume is calculated from the reservoir content (head) and efficiency data. Water used to satisfy power demands is not withdrawn from the stream. A diversion demand depletes water from the stream and potentially denies water to other users with junior water rights. A diversion can have a natural water right and a supplemental project right. A storage demand is similar to a diversion except that HYDROSS automatically assigns the lowest priority to the storage facility.

Reservoir operations

The operation of reservoirs is performed using five reservoir content levels. The physical limits of the reservoir are described using an absolute maximum and minimum content. Reservoir operations are simulated using maximum and minimum limits which can vary temporally. A pool maintenance routine is available to balance storage among a system of reservoirs. Power at a reservoir is computed at the downstream end of a station using discharge, head, and efficiency data.

Return Flows

Return flows in HYDROSS originate from both diversion sites and canal losses. Return flows re-enter the network at any station and may be delayed up to eleven months.

Output

HYDROSS creates one output file called ODS which contains the results of a given run. A separate HYDROSS program is used to generate reports about the run, and these reports are selected by the user. The units used to display values and the number of decimal places displayed can also be controlled by the user. A brief description of each report is in Table 1.

Table 1. Output Reports Available in HYDROSS.

Report 05	A reproduction of all HYDROSS output
Report 10	Water accounting by station
Report 15	Water quality report
Report 16	Water quality input to salinity model
Report 20	Detailed reservoir activity
Report 40	Detailed diversion activity
Report 60	Station inflows and outflows
Report 62	Water shortages
Report 65	Descriptive statistics
Report 70	HYDROSS output in comma and quotes format
Report 71	Single station in comma and quotes format
Report 90	Limitations and constraints

GRAPHICAL USER INTERFACE

A portable GUI to carry out simulations and generate graphic displays of data from the simulations was developed using the X Window System (X11) and Motif. X11 is a windowing system for bitmapped graphic displays; it has been adopted as a standard by most workstations manufacturers, and versions are now available for personal computers (O'Reilly & Associates, Inc., 1990). An important aspect of X11 is that it supports many interface styles. Thus, X11 does not provide user interface controls such as menus and dialogue boxes. As a result, most GUIs developed using X11 rely on higher-level tool kits designed to be used with X11. Motif is one such tool kit; it provides a set of guidelines and tools necessary to develop a user interface for graphical computers (Open Software Foundation, 1991). The GUI used in this system was segregated into canvas, menu, and message areas.

The canvas area is used for building a network representation of the river basin. The user builds a network using icons and links. The icons represent stations and are used to form a comprehensible image of reservoirs, diversions, instream flows, and return flows. The user interacts with theses icons using basic mouse and keyboard actions. To connect stations in the canvas, the user clicks on an upstream and downstream station. The network topology can be stored in the database or a flat file. The menu area provides pull-down menus required to edit input and output data and for HYDROSS run control. The message area provides feedback to the user as a sequence of tasks is competed.

DATABASE

The Relational Model

The Ingres database management system, based on the relational model (Malamud, 1989), was used to support the storage and retrieval of data necessary to operate HYDROSS. The organizational structure for data in the relational model is a two-dimensional table made up of rows and columns. Each table stores data about entities. These entities are objects or events such as reservoirs or monthly flows. The columns in a relation represent characteristics of an entity, such as a reservoir or diversion name or location. The rows in a relation represent specific occurrences of reservoirs or diversions. Each row has an attribute or combination of attributes which uniquely identifies a specific row in a relation.

Using a relational database to manage water resource data has many advantages. Databases enhance model usage because modelers can concentrate on simulation instead of managing text-based input and output. Databases also insure that data stay consistent when many users are accessing the same information. Finally, the database can be used to easily store, retrieve, log, and identify results from many simulations.

Scenario Control

An important problem in water resource management is development and simulation of numerous model runs or scenarios. A hierarchical scenario database was developed to overcome the difficulties of keeping these scenarios well organized and to provide for a mechanism necessary to compare the results of multiple runs. The philosophy behind this hierarchical database is similar to the Revision Control System (RCS) discussed by Tichy (1982) and available for many Unix workstations. The database arranges scenarios into an ancestral tree. The tree has a root scenario which is the HYDROSS data initially used to populate the database. The user creates a workspace and modifies the original data to create a scenario. Scenarios represent changes that evolve from the root. Changes to the root are stored in the database as differences between scenarios, thus conserving disk space.

Database Input

Basic input into HYDROSS, including flow data, table data, and network data, are stored in the database. In addition, the starting and ending period of simulation and initial reservoir contents are stored in the database for each scenario. A separate utility can be used to populate the database with existing HYDROSS input files. Input editing tools are provided to view, plot, and edit input data.

Database Output

The information architecture for the simulation system output defines a set of key interfaces between the tools, the data, the user, and the underlying network topology. Essentially, the database output is a planning tool that allows the user to group together, for comparison, the results from a series of HYDROSS runs. The user first selects the reports and plotting tools necessary to compare results. The simulation system amalgamates the results from a group of runs into a family of scenarios for display through the GUI using the reports and plotting tools selected by the user. The database keeps track of the following information so the user can reproduce results in the future as necessary:

- The user who owns the family of scenarios.
- A unique name that represents the scenario family.
- The control information necessary to reproduce the results including time periods and initial reservoir contents.
- The network topology for each scenario in the family.
- The file name and disk location of the input files necessary to run HYDROSS to produce results.
- The report and plotting information needed to compare results.

SUMMARY

Current Use

The simulation system is currently being used by BOR to evaluate future water supplies in the Upper Missouri River basin. The purpose of the study is to determine if additional irrigation demands in the basin can be met without having an adverse impact on existing water resource users. The system is also being applied to the Flathead-Lower Clark Fork River basin to determine future water availability for irrigation, municipal needs, hydropower, recreation, and fisheries.

Future Enhancements

HYDROSS should be modified to directly account for multiple ownership of water stored in reservoirs. In addition, the integration of a geographical information system to manage spatially defined irrigation data would give the user instant visual information about the distribution of delivered water and existing shortages.

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A COMPREHENSIVE SYSTEM FOR SURFACE WATER AND GROUNDWATER MODELING

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ABSTRACT

The U.S. Army Engineer Waterways Experiment Station (WES) and Brigham Young University (BYU) have developed a computer interface system that greatly facilitates the pre-processing, execution, and post-processing of watershed, surface water, and groundwater models. The use of the interface is described for an example problem. The actual computations are made with the models HEC-1 (hydrology), TABS-MD (surface water) and 3DFEMFT (groundwater). A common TIN-based data structure is used to ensure consistency between hydrology, surface water hydraulics, and groundwater flows. The interface allows easy construction of drainage basins and computes needed input parameters for hydrologic computations and display of hydrographs and flood boundaries. For surface water, the computational meshes and the boundary conditions are easily created and edited. Post-processing tools allow the display of velocity vectors and color-shaded contours of velocity magnitude and water surface elevations in additional to time histories at any point of interest. The groundwater module allows generation and editing of 3-D computational meshes and viewing of results through slices and color contours.

INTRODUCTION

The task of constructing finite element meshes has traditionally been the most time-consuming and error-prone part of the numerical modeling processes. Most automatic mesh-generation programs are not well-suited for building unstructured meshes. As a result, the meshes are often constructed manually by coding the mesh in an ASCII file. Manual construction of large meshes is very tedious and can take many weeks to complete. The task of changing model parameters has also been time-consuming in the numerical modeling processes. Additionally, the models generate huge data sets that cannot be easily analyzed by viewing printed output. Manual input of character based graphical software is no longer feasible due to the large number of screens that must be created. To overcome these difficulties, graphical interface software capable of combining a mesh generator and a tool for viewing the results is needed.

SYSTEM

The comprehensive system for surface water and groundwater modeling consists of three modules; drainage basin analysis (HEC-1 and others), 2-D surface water hydrodynamics

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(TABS), and 3-D groundwater flow and transport (3DFEMFT). Since each module uses a common TIN-based data structure, boundary and initial condition, communication between each module is easily implemented. Each module has a flow code and a graphical interface software. The system runs on UNIX workstations using X-Windows graphics. Executable versions are available for most UNIX workstations.

Drainage Basin Analysis

This module consists of a watershed model (HEC-1) and graphical interface software (GeoShed). HEC-1 is a watershed simulation computer program that was developed by the U.S. Army Engineer Hydrologic Engineering Center (HEC). GeoShed is the graphical pre- and post-processor for the HEC-1 program. GeoShed uses triangulated irregular networks (TINS) to represent the surface model which can be used for stream network and drainage basin delineation. GeoShed was developed by the Brigham Young University Engineering Computer Graphics Laboratory in cooperation with the WES.

GeoShed constructs triangular elements from a scattered set of xyz-coordinate data points (Figure 1). These points can be obtained from existing sources such as digital cartographic data from U.S. Geological Survey, Earth Science Information Center, or field surveys. Points are triangulated using the Delauney criterion. Once a TIN has been constructed for the surface, streams can be formed by tracing paths of maximum upward gradient and drainage basin boundaries (Figure 2) can be delineated. Basin characteristics such as drainage area, stream length and stream slope can be computed and are saved in a file for use in the HEC-1 program.

HEC-1 then conducts the drainage basin analysis and outputs the results in binary form that can be graphically viewed by GeoShed. Typically this includes hydrographs (Figure 3) and flood boundaries at user-selected points of interest.

Surface Water Hydrodynamics

This module consists of a hydrodynamic model and graphical interface software (FastTABS). The hydrodynamic model is a two dimensional, depth-averaged, free surface, finite element program and is a component of the TABS-MD numerical modeling system (Thomas and McAnally, 1991). The TABS-MD system was developed by the U.S. Army Engineer Waterways Experiment Station based on original development by Resource Management Associates in Davis, California. FastTABS is a graphical pre- and post-processor for the TABS-MD system. FastTABS was developed by BYU in cooperation with the WES.

FastTABS constructs finite element meshes (Figure 4) based on geometrical data in the form of xyz coordinates. It aids the user in assigning boundary conditions to the constructed mesh. The bathymetry can be displayed in color-shaded or gray scale contours (Figure 5). The mesh geometry is saved by FastTABS in an ASCII text file and the boundary conditions are saved by FastTABS in an ASCII text file separate from the geometry file. The hydrodynamic model then reads the boundary condition and geometry files, and then computes the hydrodynamic solutions and outputs binary solutions for post-processing.

FastTABS can be used to view velocity vector plots and color-shaded contour plots of velocity magnitude (Figures 6) and water surface elevation (Figure 7). Time history plots for selected nodes and animation sequences can also be generated. Upon viewing the hydrodynamic solution and field measurement data, the user can verify the model by refining the mesh or changing the input parameter coefficients and the solution can be recomputed.

3-D Groundwater

This module consists of a flow and transport model (3DFEMFT) and a graphical user interface (GeoSolid). The flow and transport model is a three dimensional finite element model of density dependent flow and transport through saturated and unsaturated media. The 3DFEMFT model (Yeh, 1991) was developed by the Pennsylvania State University in cooperation with the WES. The flow code uses the Galerkin finite element method and the transport code uses a hybrid Lagrangian-Eulerian finite element method. GeoSolid is the graphical pre- and post-processor for the 3DFEMFT model and was developed by BYU in cooperation with the WES.

GeoSolid constructs a 3-D finite element mesh (Figure 8) based on the subsurface geological data in the form of xyz coordinates. The mesh is saved by GeoSolid in an ASCII text file. Once a mesh has been constructed, the user assigns boundary conditions (head or flux) to the mesh. All the boundary conditions and model parameters can be assigned interactively using the GeoSolid software. The boundary conditions are saved by GeoSolid in an ASCII text file separate from the geometry file. The flow and transport program then reads the boundary and geometry files, computes the solution, and outputs a binary solution file for post-processing. GeoSolid can be used to view the results (head, or concentration or velocity) through slices and color contours.

DEVELOPMENT PLAN

Current development plans focus on converting the codes to run on a personal computer using the new Microsoft Windows NT operating system. Other modifications will be made as deemed necessary.

ACKNOWLEDGMENTS

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Figure 1. The Scattered Set of Data Points of Walnut Creek, Iowa (Original data from USGS digital data)

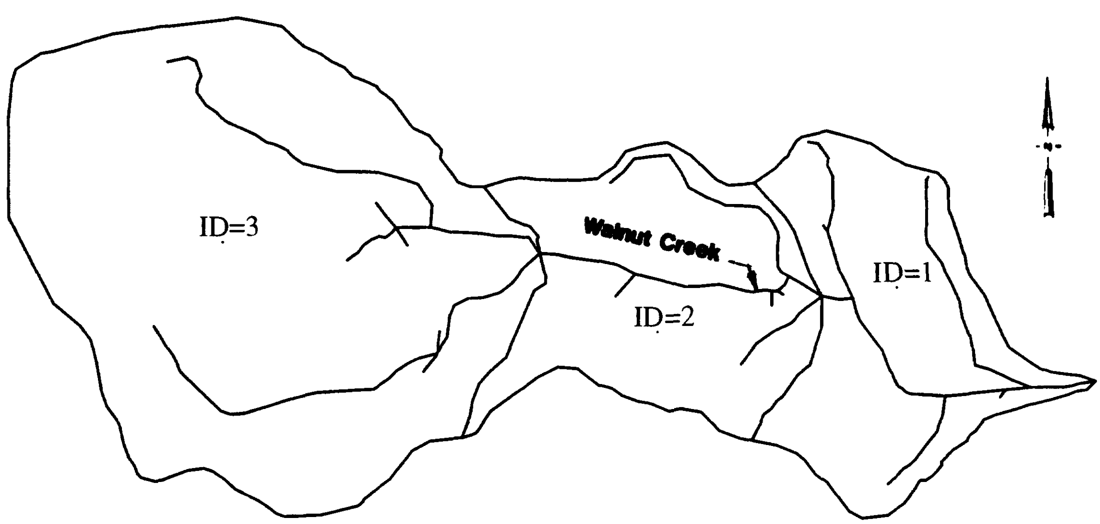

Figure 2. Delineated Sub-basins forWalnut Creek , Iowa

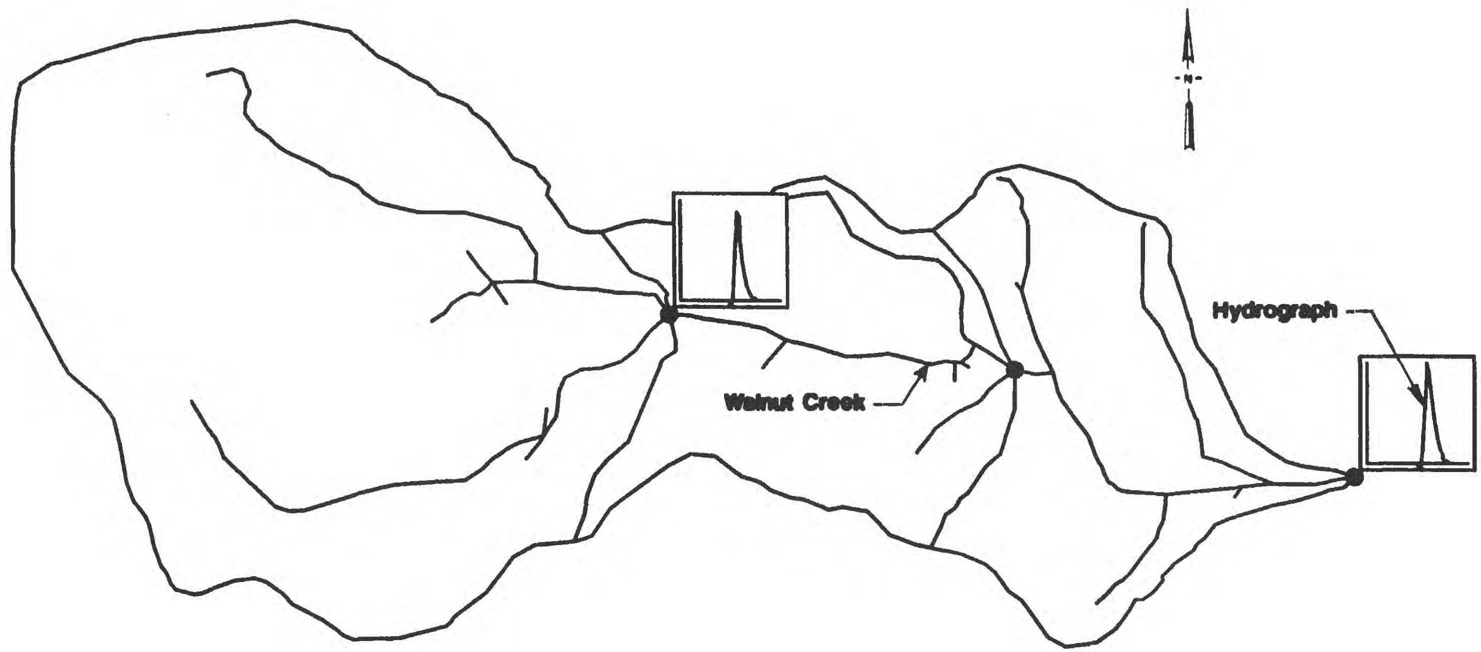

Figure 3. Display of Hydrograph at Two Selected Points, Walnut Creek, Iowa

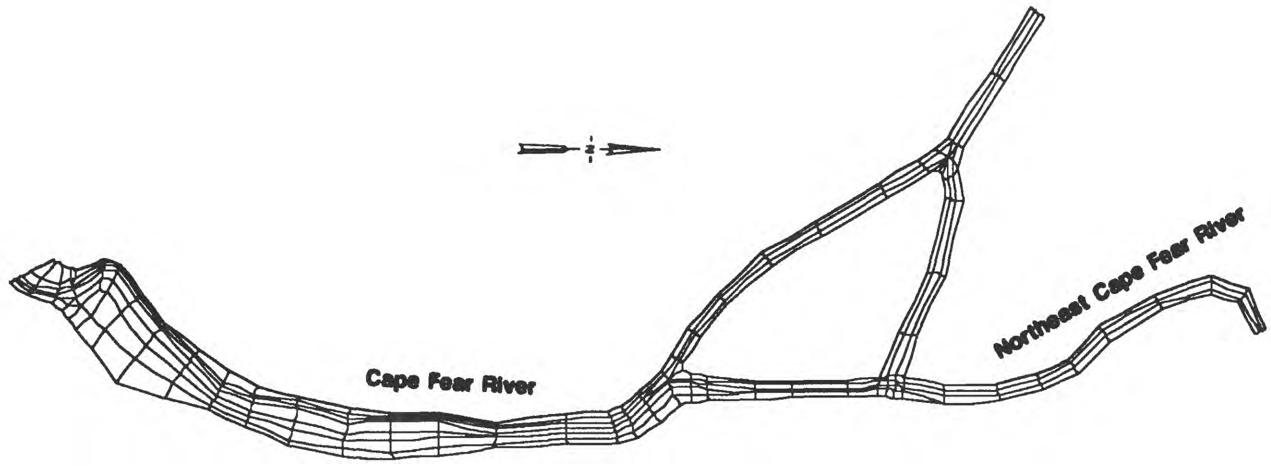

Figure 4. Finite Element Mesh for Cape Fear River, North Carolina

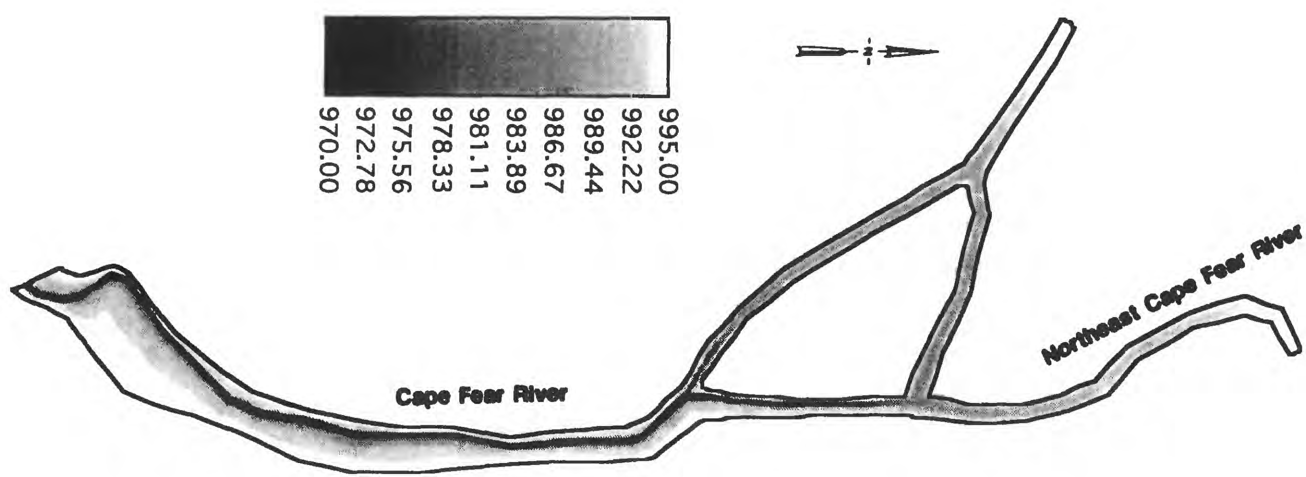

Figure 5. Bathymetry in Gray Scale for Cape Fear River, North Carolina

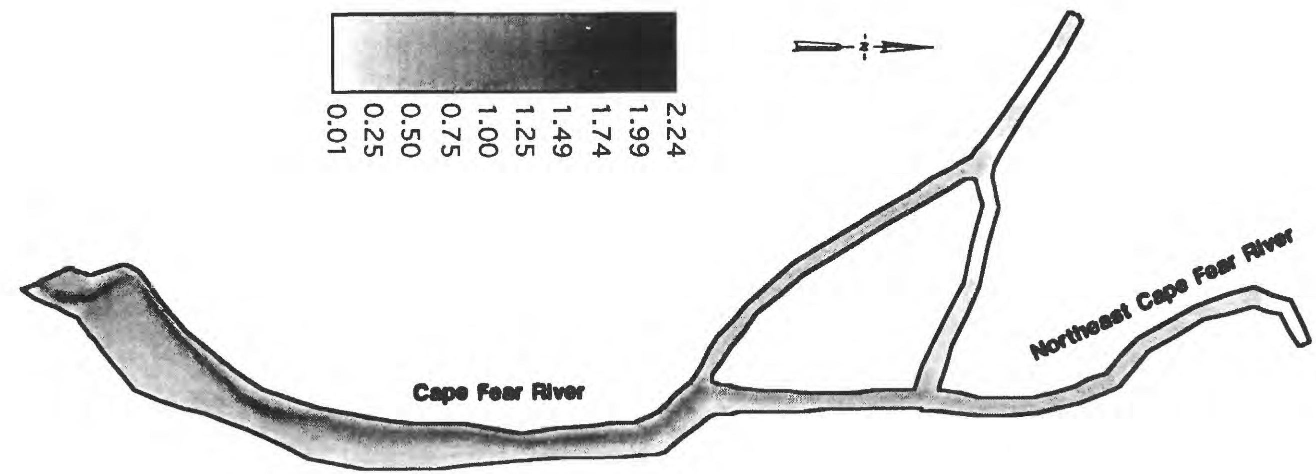

Figure 6. Velocity Contour Plot in Gray Scale for Cape Fear River, North Carolina

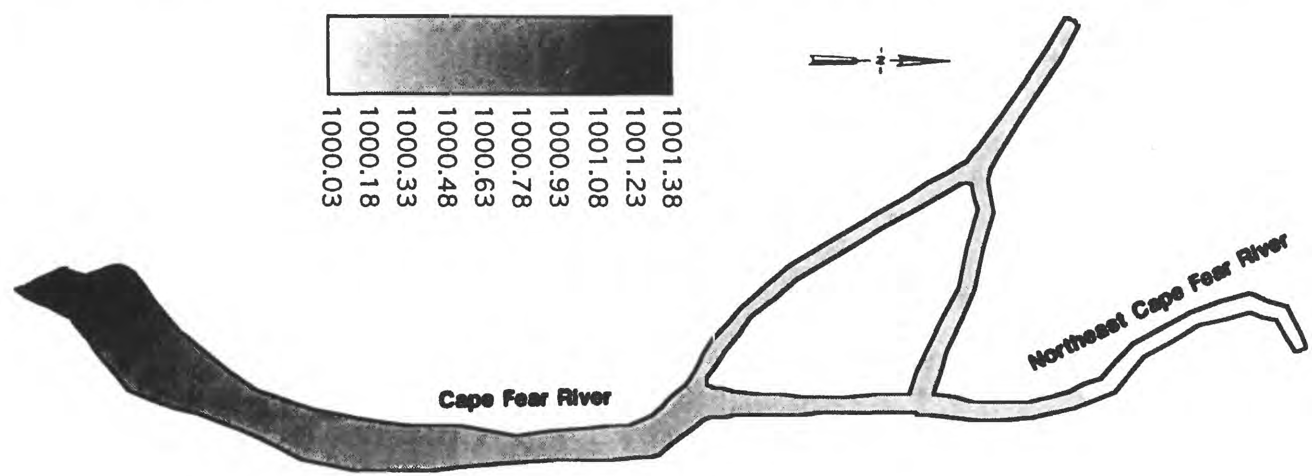

Figure 7. Water Surface Elevation Contour in Gray Scale for Cape Fear River, North Carolina

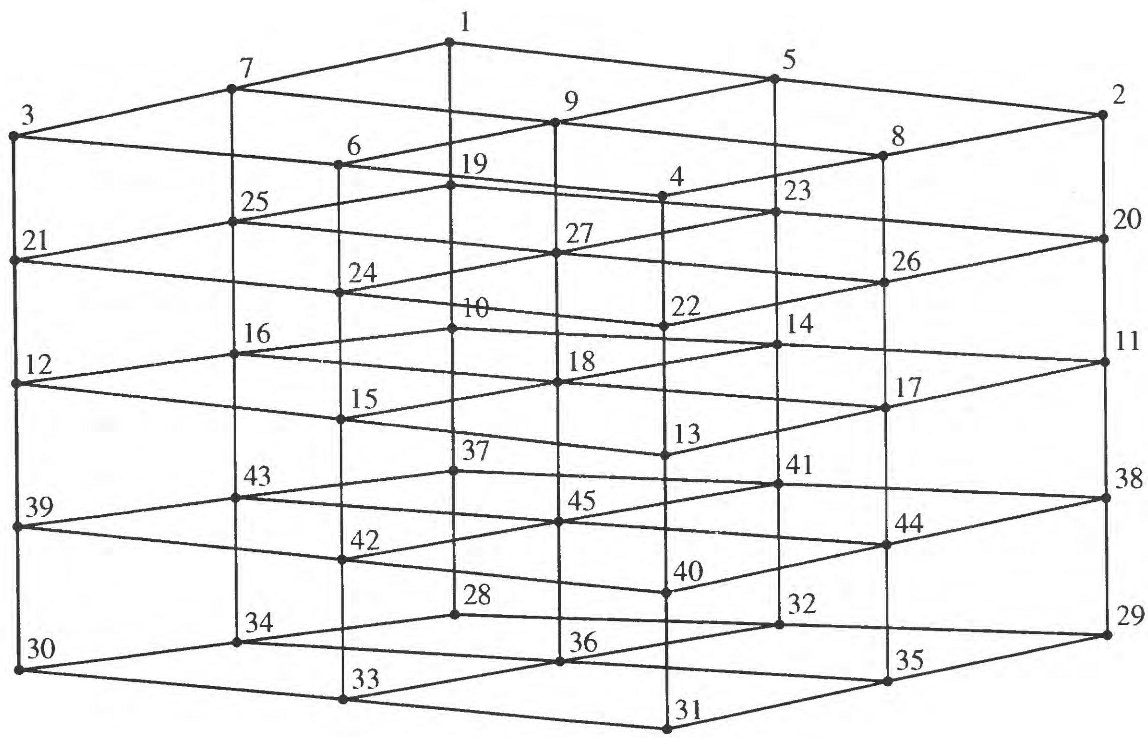

Figure 8. Sample of a 3-D Finite Element Mesh

PROGRAM FOR DAILY WEATHER SIMULATION

C.L. HANSON, K.A. CUMMING, D.A. WOOLHISER, and C.W. RICHARDSON[1]

ABSTRACT

The microcomputer program USCLIMAT.BAS (Hanson, et al. 1993) provides precipitation probabilities or simulates daily precipitation, maximum temperature, minimum temperature and solar radiation for an n-year period at a given location within the contiguous United States. The model is designed to preserve the dependence in time, the internal correlation, and the seasonal characteristics that exist in actual weather data. Daily maximum temperature, minimum temperature, and solar radiation are simulated using a weakly stationary generating process conditioned on the precipitation process which is described by a Markov-chain/mixed-exponential model. Parameters for a specific station within a region can be accessed directly, or they can be estimated for points between stations. The seasonal variations of parameters are described by Fourier series.

INTRODUCTION

Climate and day-to-day variations in weather have major influences on agricultural and engineering management decisions. Crop yields, insect infestations, rangeland stocking rates and hydrological processes such as runoff and erosion are all highly weather dependent. Weather data are needed to assess the effects of climate on agricultural and rangeland activities and as inputs to management models. For many sites, climatic records of sufficient length are not available for making the desired agricultural or engineering analyses. Therefore, it is often desirable to have the capability of generating climatic data series which have the appropriate statistical characteristics for the location.

In this report we describe USCLIMAT.BAS which provides easy access to rainfall probabilities or simulated daily weather for a location within a state or region. Daily climatic data, including February 29 (leap year), can be simulated with USCLIMAT.BAS for most locations within the contiguous United States from instructions that are displayed on the screen after the latitude and longitude of an area of interest are entered into the computer.

Daily precipitation is described by a first-order Markov chain with precipitation amounts distributed as a mixed exponential. In addition, daily maximum temperature, minimum temperature and solar radiation can be simulated using a weakly stationary generating process first described by Matalas (1967) and adapted to daily weather by Richardson (1981). The seasonal variations of

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parameters are described by Fourier series providing a very parsimonious model. Through the interactive microcomputer program a user can access the information for a single station or can estimate weather characteristics for points between stations through a simple interpolation procedure.

This program is designed to supplement, not replace, actual climatic data and real-time weather data. One advantage of the simulation approach described here is that it doesn't require a great deal of computer memory or data storage capacity and can be used on rather modest microcomputer systems. Another advantage is that solar radiation can be estimated for locations where it has not been measured. Finally, the interpolation procedures allow estimates of daily weather characteristics at points between weather stations.

Theoretical Description of the Precipitation Process

Daily Precipitation Occurrence

The occurrence or nonoccurrence of precipitation on day n of year τ can be represented by the random variable $X_\tau(n)$; $\tau = 1, 2, \ldots M$; $n = 1, 2, \ldots 365$, where

$$X_\tau(n) = \begin{cases} 0 & \text{if day n is dry} \\ 1 & \text{if day n is wet.} \end{cases} \tag{1}$$

The dependence between wet and dry occurrences on successive days is described by a seasonally varying first-order Markov chain with transition probabilities $p_{ij}(n)$ $i = 0,1$; $j = 0,1$,
where

$$p_{ij}(n) = P\{X_\tau(n) = j \mid X_\tau(n-1) = i\} \text{ for } n > 1, \text{ and} \qquad (2)$$
$$p_{ij}(1) = P\{X_\tau(1) = j \mid X_{\tau-1}(365) = i\}$$

With this in mind we will drop the subscript τ in subsequent developments. Because $p_{11}(n) = 1-p_{10}(n)$, only two parameters are required for each day. Seasonal variations are accounted for by expressing the transition probabilities as a Fourier series.

Distribution of Daily Precipitation

Daily precipitation on wet days with amounts above a threshold, T, are described by the mixed exponential distribution (Smith and Schreiber 1974):

$$f_n(y') = \frac{\alpha(n) \exp[-y'/\beta(n)]}{\beta(n)} + \frac{[1 - \alpha(n)] \exp[-y'/\delta(n)]}{\delta(n)} \tag{3}$$

where $y' = y-T$, the daily precipitation amount minus a threshold, T, provided $y > T$; $\alpha(n)$ = a weighting parameter with values between 0 and 1; and $\beta(n)$ and $\delta(n)$ are the means of the smaller and the larger exponential distributions, respectively. Let $\mu(n)$ be the mean of $y'(n)$. It can be described in terms of the other parameters by the relation:

$$\mu(n) = \alpha(n)\beta(n) + (1-\alpha(n))\delta(n) \tag{4}$$

The seasonal variations of these parameters are also represented by Fourier series, and the means, amplitudes, and phase angles were estimated by numerical maximization of the log likelihood function as described by Woolhiser, et al. (1988). Significant harmonics were determined by the Akaike Information criterion (AIC) (Akaike, 1974).

Theoretical Description of Temperature and Radiation Process

The procedure used in this program to describe the multivariate process of maximum temperature, t_{max}, minimum temperature, t_{min}, and solar radiation, r, has been described by Richardson (1981). It is based on the weakly stationary generating process used by Matalas (1967) for generating streamflow at multiple sites. The basic equation is

$$t_j(n) = \chi_j(n)\ s_j(n) + \mu_j(n) \tag{5}$$

where $t_1(n)$ is the daily value of t_{max} (on day n), $t_2(n)$ is t_{min}, $t_3(n)$ is the value of r, $s_j(n)$ is the standard deviation, and $\mu_j(n)$ is the mean of t_j. The values of $\mu_j(n)$ and $s_j(n)$ are conditioned on whether the day was dry or wet, as determined by the Markov chain occurrence model. $\chi_j(n)$ is a vector of residuals obtained from the equation

$$\chi_j(n) = A\chi_j\ (n-1) + B\epsilon_j(n) \tag{6}$$

where $\chi_j(n)$ is a vector whose elements are the standardized residuals of t_{max}, t_{min}, and r, A and B are 3 X 3 matrices with elements defined to maintain the appropriate serial and cross correlation coefficients and ϵ_j is a vector of independent, normally distributed random variables with mean 0 and standard deviation of 1. The A and B matrices are given by

$$A = M_1\ M_0^{-1} \tag{7}$$

$$B\ B^T = M_0 - M_1\ M_0^{-1}\ M_1^T \tag{8}$$

where the superscripts -1 and T denote the inverse and transpose, respectively.
The A and B matrices are:

$$A = \begin{bmatrix} 0.567 & 0.086 & -0.002 \\ 0.253 & 0.504 & -0.050 \\ -0.006 & -0.039 & 0.244 \end{bmatrix} \tag{9}$$

$$B = \begin{bmatrix} 0.782 & 0 & 0 \\ 0.328 & 0.637 & 0 \\ 0.238 & -0.341 & 0.873 \end{bmatrix} \tag{10}$$

Equation (5) can be written in the form

$$t_j(n) = \mu_j(n)[\chi_j(n)\ c_j(n) + 1] \tag{11}$$

where $c_j(n)$ is the coefficient of variation.
The seasonal changes in the means and coefficients of variation are represented by an equation of the form:

$$u_j(n) = \bar{u}_j + c_j \cos [0.0172(n - D_j)] , n = 1, 2, \ldots 365 \tag{12}$$

where $u_j(n)$ is the value of the mean or coefficient of variation on day n, u_j is the annual mean, c_j is the amplitude of the first harmonic, and D_j is the phase angle in days. These variables were originally determined from 20 years of data for 31 U.S. locations, and are presented in maps and tables in Richardson and Wright (1984).

The Microcomputer Program

Latitude and longitude are the only data required to initiate the map routines in USCLIMAT.BAS. After the latitude and longitude have been entered, the program will draw the state boundaries that are within an area bounded by 2 degrees latitude and 3 degrees longitude on either side of the central point. Any of the 360 climatic stations located within the area, are plotted on the screen. A small rectangular cursor, located in the middle of the grid, is moved by the arrow keys to the desired location on the map and circles with radii of 30 and 100 miles are projected on the screen as an aid to the user.

Parameter Interpolation

The two options in USCLIMAT.BAS for interpolation of parameters are the arithmetic average of parameters within a radius of 100 miles and the nearest neighbor. In USCLIMAT.BAS, if the nearest station is closer than 30 miles, as identified by the inner circle on the screen, the user is asked if the parameters for the nearest station are to be used. If the response is yes, the method becomes a nearest neighbor estimate. If the answer is no, the estimated parameters will be averages of those for the stations within the 100-mile radius. The user has the option to omit any of these stations or to obtain any or all of the parameters from a set of maps. Precipitation is strongly affected by orographic factors, so parameter averaging should not be used if adjacent stations differ widely in elevation.

Temperature and Radiation Corrections for Specific Locations

The user has the option of adjusting all 17 parameters to be more representative of specific locations, such as mountain sites, if information is available to justify the action. For example, because there are relatively large differences between the average solar radiation parameters used in USCLIMAT.BAS and those shown on the maps for southwest Arizona and southern Florida, adjustments can be made through linear interpolations from the figures for these areas. The temperature and radiation correction procedure in WGEN (Richardson and Wright, 1984) is included in USCLIMAT.BAS.

Parameter Adjustment to Correct Mean Annual Precipitation

When the parameters for a station have been estimated by averaging those of surrounding stations, the theoretical annual average precipitation as calculated may be slightly different from the estimated annual precipitation obtained by interpolation on an isohyetal map. An option within the program allows the parameters α and p_{10} to be adjusted by a Newton-Raphson iterative procedure so that the theoretical mean is within $\pm$ 0.1% of the known average annual precipitation. α and p_{10} where chosen for adjustment because they typically have greater variances than the other parameters.

EXAMPLE OF THE MODEL

A 30-year weather record from Boise, Idaho was used as an example of the weather generation procedure. The mean monthly precipitation and number of wet days for four months and annual totals are shown in Table 1 for the historical and generated data. The generated mean monthly precipitation amount and number of wet days was a very close approximation to the historical record as was the total annual precipitation and number of wet days. The generated mean maximum temperatures for the four months shown in Table 1 were within 1°C of the historical values and the mean annual was the same. The mean monthly minimum temperatures were all within 3°C. For the four months shown in Table 1, the generated mean monthly solar radiation was within 11% of the historical value. The generated mean annual solar radiation was within 2% of the historical value.

Table 1. Historical and Generated Mean Monthly Climatic Data for Boise, Idaho

	Precipitation		Number of Wet Days		Maximum Temperature		Minimum Temperature		Solar Radiation	
	H	G	H	G	H	G	H	G	H	G
	(mm)	(mm)			(°C)	(°C)	(°C)	(°C)	(ly)	(ly)
Dec	34	34	12	11	4	4	-4	-5	124	111
Jan	42	39	13	14	3	2	-5	-6	141	125
Jul	7	9	2	3	33	32	15	13	672	658
Aug	10	7	3	2	31	30	14	11	579	565
Annual	298	297	91	94						
Monthly					17	17	4	3	395	387

H = Historical (1951 - 1980)
G = Generated (30-yr simulation)

SUMMARY

USCLIMAT.BAS is an update of the weather simulation program CLIMATE.BAS by Woolhiser, et al. (1988). USCLIMAT.BAS provides simulated daily precipitation, maximum temperature, minimum temperature and solar radiation for an n-year period at a given location. The model is designed to preserve the dependence in time, the internal correlation, and the seasonal characteristics that exist in actual weather data. Maximum temperature, minimum temperature and solar radiation are generated conditional on whether the day is wet or dry. The precipitation process is described by a Markov-chain/mixed-exponential model.

The daily weather information available through USCLIMAT.BAS has many applications but is most useful as input to other models that require daily precipitation, maximum and minimum temperature and solar radiation. Several water resource models such as SWRRB (Arnold, et al., 1990), WEPP (Lane and Nearing, 1989), and ERHYM-II (Wight, 1987) require daily weather information which is not available for many locations in the United States. Therefore, simulated weather data can be used to estimate hydrologic processes such as runoff and erosion rates. Sequences of daily weather data can also be used as input for many other applications from estimating plant growth and chemical transport to developing farm and ranch management plans and helping to improve knowledge of the climatology of the United States.

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INTERIOR DRAINAGE ANALYSIS, WEST COLUMBUS, OH

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ABSTRACT

The interior drainage analysis of the West Columbus, Ohio area poses a challenge to standard techniques and methodologies of hydrologic investigation. Located along a long meandering bend of the Scioto River, this highly urbanized area is drained by an extensive storm and sewer system that provides a relatively low level of protection against interior storm events. The Corps of Engineers has designed a levee and floodgate system which will provide protection against flooding from an exterior source, but has not resolved the issue of residual flooding associated with an interior storm event. The analysis performed by the Corps of Engineers addressed coincidental frequency of flooding, flood warning systems, existing capacity of storm and sanitary systems, existing pump station capacities, and routing of flows across a maze of geometric controls. The modeling efforts included use of the Storm Water Management Model (SWMM) developed by the Environmental Protection Agency; HEC-1, Flood Hydrograph Package and HECIFH, HEC Interior Flood Hydrology, both developed by the Corps of Engineers Hydrologic Engineering Center. The interaction of these models, strengths, weaknesses, and limitations of application to this complex watershed will be presented. The problems encountered during this study clearly indicate the need for development of a comprehensive model that can accommodate the variety of drainage conditions associated with urban drainage systems.

INTRODUCTION

The project described in this paper is located on the right bank of the Scioto River, in the western part of the City of Columbus, Ohio, generally bounded by the Scioto River on the north and east and Interstate 70 on the south and west. Without the proposed Corps flood control project, the West Columbus area, sometimes referred to as the Franklinton area, is subject to flooding from the river by overtopping and/or possible breaching of existing levees and elevated railroad embankments on the north side, and backwater flooding through the Interstate 70 underpasses on the south side. Localized areas could also be flooded by significant rainfall events that would exceed the capacity of the existing storm sewer system. For these events, overland flow is impeded by existing topographic features, such as the elevated road and railroad embankments that subdivide the interior area. The proposed plan of improvement that is recommended by the West Columbus, Ohio LPP Reevaluation Study, dated September 1991, and shown on Plate 1 consists of a levee/floodwall combination for protection against flooding from the river, and a collector/interceptor and pump station system to remove interior flood waters. The levee/floodwall project baseline is approximately 5.3 miles long and protects approximately 1300± acres.

DESIGN PROCEDURE

Interior Flood Control Simulation Models.

The Interior Flood Control analysis was conducted, using three mathematical

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models to simulate the operation and response of each interior flood hydrology system considered. The three models that were used are the U.S. Environmental Protection Agency's Stormwater Management Model(SWMM), the Flood Hydrograph Package(HEC-1) and the Interior Flood Hydrology Package(HECIFH). Previous modeling efforts did not account for the underground drainage network. This limitation resulted in the need to perform this study to a higher level of detail than previous investigations. A more detailed computational scheme which would account for underground capacities for various operational scenarios was necessary.

Storm Water Management Model.

Due to the complex nature of the storm sewer network and surface drainage patterns, careful consideration was given to the selection of the mathematical model that would be used for the interior flood control analysis. The existing drainage network is extensive and modeling limitations were established before proceeding with the computer model. A meticulous process was involved in ascertaining each sub-catchment size with regard to each runoff intrusion node in the stormwater system. West Columbus storm sewer profiles and 1-foot contour mapping of the project area were used to develop this data for the SWMM model. RUNOFF block hydrographs were then used to generate hydrographs that were then entered into the EXTRAN block at these predetermined nodes. The EXTRAN block then computed network flow routings. In order to improve the functionality of the model, it was decided that only those storm sewers of 24 inches in diameter or larger would be used in this model.

Rainfall data was entered into the RUNOFF block of SWMM for the Standard Project Flood centered over Columbus. The idea behind this was to weigh the largest rainfall event with the SWMM model and thus deal with the worst situation involving runoff. Time was spent developing an EXTRAN surface drainage model. The effort was eventually abandoned because of program instabilities and the need for runoff volume accountability. A new approach was taken which was based on using the 5, 10 and 25 year hypothetical rainfall events. The underground network results from the SWMM model were reasonable and a new modeling procedure was adopted using the total maximum underground discharge at subarea boundary exit points. These discharges were applied to the HEC-1 model developed for West Columbus.

HEC-1.

It became evident, after developing a surface network model, that runoff volume accountability would not be easily accomplished with the SWMM computer program. A prudent solution to this situation was to pursue the development of a HEC-1 model to route and combine the surface runoff. HEC-1 is a computer program that models the precipitation-runoff process. The model is limited to single event analysis and routing techniques that do not account for downstream backwater conditions.

Surface runoff in this project generally flows in a southern direction. The floodwall and elevated railroad and highway embankments are the controlling boundaries that divide the interior into hydrologic subareas. Each subarea functions as a small reservoir with respect to overland flow, with the highway and railroad underpasses serving as spillways. The SWMM model provided the peak discharge capacity of the underground system for incorporation into the HEC-1 surface model. It should be noted that each of the subareas has a major ponding area. This reasoning governed the development of the HEC-1 model for the West Columbus LPP. The overland flow discharge capacities of the railroad and highway underpasses were estimated by normal depth computations.

A sensitivity analysis was conducted of the HEC-1 computation of runoff for a sample subarea. The subarea was subdivided into smaller drainage areas, similar to the sub-catchment areas defined in the SWMM model. The discharge hydrographs were extracted for each sub-catchment from the RUNOFF block, and combined and routed with HEC-1 to the location of low point ponding in the subarea for comparison with the hydrograph that was computed with the drainage area defined as the entire subarea. The results of this study show that the ponding elevations computed by either method are comparable, and that the timing effects produced by the single area computation with HEC-1 are more representative of anticipated timing. Because the ponding elevations were comparable and because the sub-catchment computations were extremely time consuming, the single area computation was retained as the adopted method for development of flood frequency data for the remaining areas.

HECIFH.

Existing conditions were evaluated using the HEC-1 model. A problem was encountered when a need developed to examine the proposed plan of improvement in the West Columbus project. These plans consisted of a combination of interceptors and pump stations designs. HECIFH was used to evaluate the numerous alternatives. The HEC-1 model was used prior to HECIFH because of the multi-basin drainage scheme of the West Columbus project.

HECIFH is a menu driven computer program that can be used to determine runoff into a ponding area adjacent to a levee and then route the inflow though the levee utilizing gravity outlets and/or pumping capacity. The rainfall-runoff process, streamflow routing, auxiliary inflow, diversions, and seepage can be simulated as well as complex configurations of gravity outlets and pumping facilities. Period-by-period, monthly, annual and total analysis summaries are generated for all applicable parameters during simulation. Interior area elevation-frequency relationships can be determined for various alternative plans by using continuous simulation or hypothetical storm event analysis.

DESIGN CRITERIA

Rainfall.

Rainfall for West Columbus was obtained from Technical Paper No. 40, Rainfall Frequency Atlas of the United States published by the National Weather Service, for durations from 30 minutes to 24 hours and return periods from 1 to 100 years. This study addressed the 2-year, 5-year, 10-year, 25-year, 50-year and 100-year rainfall amounts based on a 24-hour duration. Total rainfall amounts were applied to a triangular precipitation distribution, with the maximum rainfall depth occurring during the central part of the storm. The Standard Project Flood rainfall data was developed by distribution methods, outlined in EM 1110-2-1411, Standard Project Flood Determination, for a 96 hour period with an isohyetal pattern centered directly over West Columbus.

Infiltration Losses.

As with the drainage area, the percentage of impervious area was extracted from the contour mapping during preparation of sub-basin data for the SWMM model. The sub-basin impervious area data within each subarea was totalled, and the resulting percentage of impervious area ranged from 52% to 30%. The Green-Ampt infiltration loss rate method was selected to compute rainfall loss rates for the project area. The first component of this method predicts the volume of water which will infiltrate into the soil before the surface becomes saturated. Then, infiltration capacity is predicted by the Green-Ampt equation. Thus, infiltration is rated based on the volume of water infiltrated as well as the moisture conditions in the soil surface zone. Data for the Green-Ampt input parameters, were obtained from a report entitled "Soil Survey of Franklin County, Ohio", published by the Soil Conservation Service, and from information in the SWMM user's manual.

Hydrographs.

Unit hydrographs were developed from the Soil Conservation Service(SCS) unit hydrograph method. Values of 1.51, 0.96, 2.35, 3.25,and 1.11 hours were estimated for time of lag for the five subareas included in the model. The 10-year, 25-year, 50-year, 100-year and Standard Project Storm rainfall was applied to each of the designated subarea unit hydrographs based on a 5 minute incremental time period.

Coincidental Frequency Considerations.

Sufficient records for extreme historic events on the Scioto River with the associated local interior storms are not available, whereby a coincident statistical analysis could be performed that would produce meaningful results. Therefore, a method had to be developed for the determination of the joint probability, or coincidental frequency, associated with interior and exterior events. This was accomplished by determining interior ponding frequency information both for low and high river conditions, to establish the upper and lower bounds of the joint probability curve. The coincidental frequency in each subarea was determined through engineering judgement and graphical analysis of results of the two conditions. In the absence of statistical approaches, graphical analysis dictates that the upper and lower bounds of the curve are controlled through the operational scenario that predominantly produces ponding.

Low river conditions would most likely occur coincident with frequent interior storms such as a 10-year event, or less. The capacity of the existing storm sewer system is exceeded and interior flooding begins between a 5- and 10-year event. Therefore, based on SWMM results, the low river condition was used to represent the coincidental curve, up to the 10-year event.

The high river scenario involves the operation of a complex arrangement of gates and closures that begin operation at various frequency storm events. The existing storm sewer system begins to become ineffective with a 10-year water surface on the Scioto River and would be totally ineffective with a 25-year water surface on the river. High river conditions would most likely control interior events in excess of the 50-year event. This means that a 10- to 25-year water surface profile on the Scioto River would occur coincident with a 50-year or greater interior storm event. Therefore, with the upper and lower bounds of the curves for the individual subareas established, the portion of the curve between the 10- and 50-year storms was graphically smoothed to fit the boundary conditions. Acknowledging the subjective nature of this procedure, an envelope curve was developed to evaluate the sensitivity of these assumptions on the economic analysis. The curves were fully developed and furnished for use in the economic analysis of project benefits and damages.

Low River Existing Ponding Elevations.

The existing condition ponding elevations were derived by using SWMM to determine the maximum underground discharge capacity at the boundaries of each subarea evaluated in this study. After comparing the computed discharges of the individual conduits at each subarea boundary for the 5-year, 10-year and 25-year events, it was observed that peak discharges do not increase significantly for the increasing rainfall amounts. The maximum underground discharge from each subarea was then established by the summation of each of the individual conduit discharges at each subarea boundary. This discharge was then incorporated into an HEC-1 model for the final determination of the existing condition elevations by removing it as a constant flow rate from the bottom of each of the reconstituted hydrographs for each subarea. The HEC-1 model was developed using existing facilities between each subarea and rating the outflow areas based on computed ponding.

Maximum Existing Ponding Elevations.

The "worst case" condition for the interior was derived by using the HEC-1 program with no outlet at Renick Run and only existing pumping facilities at ST-2 and ST-8. Reconstituted hydrographs for each of the subareas were routed and combined through the existing interior area. The hydrographs represented the worst possible condition since the underground storm sewer capacity was not eliminated. HEC-1 calculated elevations in each ponding area. These elevations represent instantaneous existing condition elevations and do not represent the steady-state situation. In order to evaluate this situation, rainfall excess from each frequency and theoretical event for each subarea was changed to a volume. These amounts in each subarea were accumulated and converted to final static elevations. The largest elevation between the static and steady-state conditions was then used to derive the final maximum existing ponding elevations in each subarea.

INTERIOR FLOOD CONTROL SYSTEMS

Existing Storm Drainage and Collection Systems.

The existing storm water collection system in the interior of the proposed local protection project consists of a complicated network of gravity flow conduits and two storm water pump stations. Generally, this system, along with the existing surface topography, collects and transmits storm runoff toward the central and southern region of the interior. Then, large underground conduits provide relief from the interior by transmitting storm water to the south under Interstate 70 to the existing Renick Run storm and sanitary sewer pumping facilities, located approximately two miles to the south of the proposed project area, for disposal into the Scioto River.

Recommended Interior Flood Control Plan.

The proposed interior flood control plan consists of two storm water pump stations. Both are associated with gatewells and sluice gates that are required as a part of the proposed levee/floodwall system that will provide a positive cut off during Scioto River flood conditions. The Dodge Park facility will have a capacity of 100,000 gpm. A section of the existing 72-inch storm sewer between the proposed pump station and the river will be replaced along with an existing headwall. A 72-inch pipe with a network of inlets along Rich Street will also be provided to improve the supply capability of the sewer system to the proposed pump station.

The Cypress Avenue pump station will have a capacity of 180,000 gpm. A 60-inch collector/interceptor will be provided to divert flow from the existing storm sewers at Nace, Glenwood and Yale Avenues to the proposed pump station. The existing storm sewer from the proposed pump station to the existing junction box south of Mound Street will be replaced by two 8 foot by 7 foot box culverts.

Project Cost of NED Plan.

The costs associated with construction of the West Columbus local protection project, interior flood control features have been estimated to be $9,409,000 in October 1992 price levels. This estimate includes the design and construction of two pumping facilities, (100,000 GPM at Dodge Park and 180,000 GPM at Cypress Avenue), other appurtenant items and required relocations and real estate.

Benefits of Recommended IFC Features.

The selected plan would alleviate approximately 75% of the $1,391,000 of average annual flood damages resulting from interior flood events. In excess of one million dollars in average annual benefits would be directly attributable to the recommended Interior Flood Control features. The recommended features would produce $218,000 in net NED benefits and have an incremental benefit-to-cost ratio of 1.3.

Of the 1160 structures damaged by the 100-year interior event only 274 would experience damage with the recommended features in place. Of the 274 structures damaged only twenty two would experience flooding above the first floor. The remainder would suffer only basement or foundation related damage. Under baseline conditions approximately 324 acres of the study area would be inundated by the 100-year interior event. The recommended plan would reduce this area of inundation to less than 30 acres.

Residual Flooding.

The recommended plan will not completely eliminate interior flooding. The project area will continue to experience the nuisance flooding associated with the minor interior low points and incidental street flooding. These pockets of stored water in most cases eventually drain into the stormwater system. The technical analysis involved in determining the volume of water associated with each of these low points would have been time consuming and would not alter the formulation of the recommended plan. It is for this reason that resources were not used to determine the elevations in these ponding areas.

The following table provides flood depths and the extent of inundation produced by the 100-year frequency flood for various operational conditions and with the recommended plan of improvement.

FLOOD DEPTHS
AREA SUBJECT TO INUNDATION
(100-YEAR FREQUENCY FLOOD)

Subarea Description	DEPTH IN FEET			
	High Scioto River w/ No Project	Low Scioto River w/ No Project	Coincidental w/ No Outflow	NED Plan
Western	5.0	2.3	3.8	3.8
West-Central	10.7	4.0	5.1	3.0
East-Central	9.3	3.9	6.2	2.9
Eastern	5.7	2.9	3.3	1.4
Inundation Area	870 Acres	75 Acres	324 Acres	30 Acres

The proposed pump stations were designed strictly for relief of interior flooding during high river events for which levee/floodwall closures will be required. However, it appears that the proposed Dodge Park facilities could be used to relieve interior flooding along Rich Street during moderate river rises, such as occurred on 13 July 1992. This is due to fact that the invert of the flap gates at the outfall of the 72-inch storm sewer are positioned at normal pool formed by the Greenlawn weir, and even a moderate rise in the river closes the gates. Therefore, the only outflow capability from the eastern section of the project is through the 36-inch by 48-inch combined sewer and by backflow into the 42-inch pipe from the junction box at Davis Avenue, where the existing 72-inch storm sewer begins. Therefore, outflow from the eastern section of the project during a significant interior rainfall with moderate river conditions will occur though the combined sewer. If the proposed pump station could be activated during an event similar to the 13 July 1992, outflow capability from the eastern section would be significantly improved. It is reiterated that this condition would occur coincidentally with the design for high river conditions. Since low river condition improvements were not considered to be a part of the scope of this study, and the potential was not recognized until late in the study, the potential improvements have not been analyzed or guaranteed.

SUMMARY

The problems encountered with the interior hydrology analysis of the West Columbus, OH LPP are typical of many urban areas throughout the country. There appears to be a need for a comprehensive model that can account for underground and surface drainage in a more efficient manner. This study utilized three independent models that required a significant amount of engineering judgement and experience to apply to the site specific requirements of the project. Each model had it's strong points and weaknesses. None of the models are capable of performing the variety of analysis necessary to assess the flooding problem experienced in the West Columbus area.

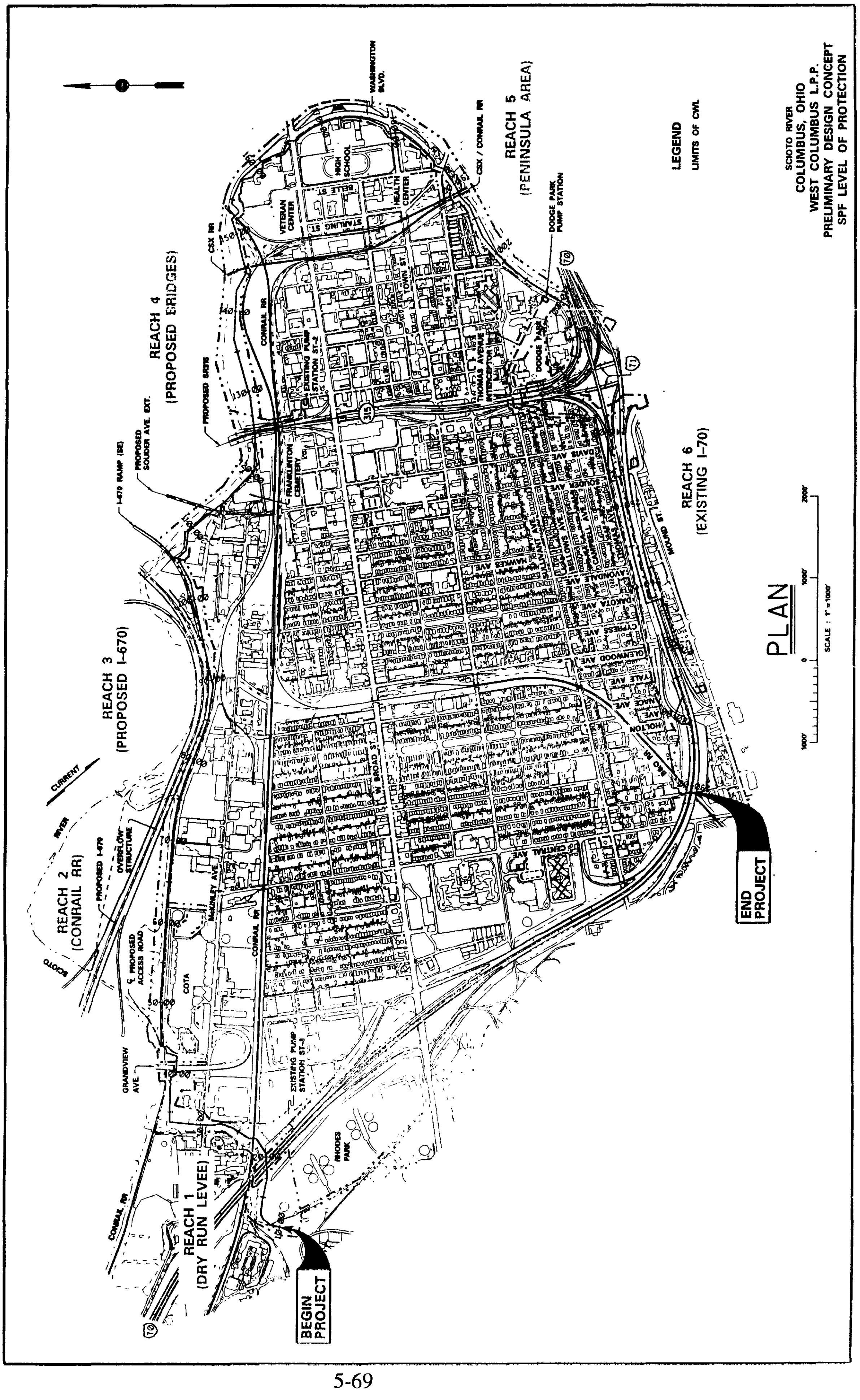
PLATE 1
SCIOTO RIVER
COLUMBUS, OHIO
WEST COLUMBUS L.P.P.
PRELIMINARY DESIGN CONCEPT
SPF LEVEL OF PROTECTION
LEGEND
LIMITS OF CWL
PLAN
SCALE : 1" = 1000'
REACH 1 (DRY RUN LEVEE)
REACH 2 (CONRAIL RR)
REACH 3 (PROPOSED I-670)
REACH 4 (PROPOSED BRIDGES)
REACH 5 (PENINSULA AREA)
REACH 6 (EXISTING I-70)
BEGIN PROJECT
END PROJECT
SCIOTO RIVER
CURRENT
CONRAIL RR
GRANDVIEW AVE.
PROPOSED ACCESS ROAD
COTA
PROPOSED I-670
OVERFLOW STRUCTURE
McKINLEY AVE.
I-670 RAMP (SE)
PROPOSED SOUDER AVE. EXT.
PROPOSED BRIDGES
CSX RR
VETERAN CENTER
HIGH SCHOOL
HEALTH CENTER
BELLE ST.
STARLING ST.
WASHINGTON BLVD.
CSX / CONRAIL RR
DODGE PARK PUMP STATION
DODGE PARK
THOMAS AVENUE INTERCEPTOR
EXISTING PUMP STATION ST-2
FRANKLINTON CEMETERY
EXISTING PUMP STATION ST-3
RHODES PARK
W. BROAD ST.
CENTRAL AVE.
HOLTON AVE.
NACE AVE.
YALE AVE.
GLENWOOD AVE.
CYPRESS AVE.
DAKOTA AVE.
AVONDALE AVE.
HAWKES AVE.
SULLIVANT AVE.
BELLOWS AVE.
CAMPBELL AVE.
THOMAS AVE.
SOUDER AVE.
DAVIS AVE.
MOUND ST.
TOWN ST.
RICH ST.

SECTION 5
COMPUTER DEMONSTRATIONS AND POSTERS
POSTERS

Page

A Disparity Detected in Hydrologic Soil Grouping
Geoffrey A. Cerrelli 5-70
Current Issues in River Ice Forecasting
Kathleen D. White, Jon E. Zufelt, and Steven F. Daly 5-74
Watershed Modeling—Spatial Partitioning Using GIS
Ann E. Jeton and J. LaRue Smith 5-81
TR-20 Proves Viable Flood Reduction Alternative
Laurel F. Mulvey 5-89
GIS Application for NWS Flash Flood Guidance Model
Timothy L. Sweeney, Danny L. Fread, and Konstantine P. Georgakakos 5-94
Adaption of TR-20, Project Formuation-Hydrology
John W. Chenoweth, PE 5-102
Multi-Dmensional Analysis of a Surface Coal Mine
Judith Schenk, Keith Kirk, and Alan Wilhelm 5-109

Figures and Tables

Watershed Modeling—Spatial Partitioning Using GIS 5-81

Figures: 1. Location of part of East Fork Carson River basin (above Markleeville, California) and North Fork American River basin (above North Fork Dam) 5-82
2. Schematic diagram of Precipitation-Runoff Modeling System (modified from Leavesley and others, 1983) 5-83
3. Flowchart for watershed characterization and hydrologic-response-unit (HRU) delineation 5-86
4. Hydrologic-response unit (HRU) overlay for East Fork Carson River basin 5-87

Tables: 1. Source data for geographic information system 5-84
2. Data layers for East Carson River basin geographic information system 5-85
3. Characteristics of combination permutation identification number 121 5-86

GIS Application for NWS Flash Flood Guidance Model 5-94

Figures: 1. Threshold runoff values for 1-hour rainfall duration based on 2-year return period discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.5 (darkest color) to 0.8 inches. Raccoon River in Iowa, CU 07100007 5-100
2. Threshold runoff values for 1-hour rainfall duration based on Manning's equation at bankful discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.2 (darkest color) to 1.2 inches. Raccoon River in Iowa, CU 07100007 5-101

Adaptation of TR-20, Project Formulation-Hydrology 5-102

Plates: 1. Kanakakee River Basin 5-108
2. Kanakakee River at Shelby, Ind 5-108

A DISPARITY DETECTED IN HYDROLOGIC SOIL GROUPING

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ABSTRACT

The SCS TR-20 computer model was used to detect a fallacy in the hydrologic soil group (HSG) classification of soils in a watershed draining to a potentially hazardous embankment.

INTRODUCTION

Purpose and Scope

This report describes the process used in detecting improper HSG classifications resulting from an investigation of a potentially hazardous dam. A hydrologic evaluation combined with historical information were used in the analysis.

Description of the Study Site

The dam is located just above the town of Lonaconing, MD (pop. 1,122) in Allegany County, Maryland. It has a drainage area of 693 acres. The land use of the watershed is predominantly (80%) wooded. The embankment was reportedly constructed in the 1920's by dumping mine waste from a deteriorated railroad trestle. A 36 inch RCP conveys streamflow through the embankment. The railroad has since been abandoned and replaced by a roadway. The height of embankment is 38 ft. One house is located at the downstream toe of the embankment while others crowd the channel banks further downstream.

Problem

In November 1985, a 3.6 inch storm brought the water level behind the embankment within 1 foot of the top. This condition is believed to have been the result of high intensity rainfall, high antecedent soil moisture from previous rainfall, and a partially blocked pipe entrance. Seeps formed on the downstream slope of the embankment eroding away some of the soil. Residents downstream of the embankment are concerned about their safety should a major storm cause a catastrophic failure of the embankment. Allegany County officials requested that the SCS make an assessment of the potential hazard of impounding storm runoff behind this embankment.

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Page

Adaption of TR-20, Project Formulation-Hydrology–continued

Tables: 1. Annual floods 5-107
2. Shelby local cumulative rainfall (abbreviated) 5-107
3. Kankakee River peak comparison (cfs) 5-107

Multi-Dimensional Analysis of a Surface Coal Mine 5-109

Figures: 1. Mine area ground-water model grid and location of the sediment pond and ground-water seep 5-110
2. Simulated transient water levels in mined-out area 5-112
3. Multi-dimensional analysis of ground-water model results and overburden quality 5-113

INVESTIGATION

Analysis

The SCS TR-20 computer program was used to hydrologically model the watershed and hydraulically model the outlet structure. The runoff curve number (RCN) and time of concentration (T_c) were evaluated using standard SCS procedures. The pipe and its inlet were analyzed to determine the stage vs. discharge characteristics exhibited during the November 85 storm when the inlet was partially plugged. Interviews with local long-term residents produced comments stating that prior to 1985 the pool level never went above halfway up the embankment (in its 60 years plus life). It was also stated that the inlet had never been blocked before. Precipitation data for the entire history of the structure is not available although the largest 24 hour precipitation was recorded as 5.58 inches at nearby Savage River Dam in October, 1954. For the purpose of this study a 50 year (5.7inch), Type II distribution, 24 hour storm was imposed on the watershed with no inlet blockage in an attempt to match the historical statements of water halfway up the embankment. In addition, keeping the same RCN and T_c but partially (40%) obstructing the inlet and imposing a 3.6 inch (Nov 4, 1985 volume), Type II distribution, 24 hour storm, a peak reservoir stage was expected within a foot of the crest. If both of these conditions could be satisfied with one T_c and one RCN then it was felt that a good model had been produced.

Findings

The initial attempt at modelling the watershed using standard SCS procedures produced an RCN of 69 and T_c of 1.77 hours. Using these parameters with the aforementioned 50 year frequency storm resulted in a peak reservoir elevation 8.3 ft over the embankment when the historical statements revealed that it should not have exceeded halfway up the embankment. Modeling the November 85 storm with the same hydrologic parameters but altering the antecedent runoff condition (ARC) from 2 to 3 (higher soil moisture)and stage-discharge data in the to reflect the $\pm$ 40% plugging of the inlet yielded results in which, again, the peak elevation in the reservoir exceeded the top of embankment by 10.3 ft. It was clear from these two attempts that an error existed somewhere in the input parameters. The T_c was the first parameter reevaluated. A new method of shallow concentrated flow analysis[1], rather than either "Paved" or "Unpaved", was employed. This resulted in a T_c of 1.93 or a change of 9% from the original figure. Typically a 9% increase in T_c will result in a 4% decrease in peak discharge.

[1]Reevaluation of Shallow Concentrated Flow, analysis by G. Cerrelli, USDA-SCS, Annapolis, MD April 1990.

If this were the only change made, the model would still extremely overpredict peak discharges, and therefore peak reservoir stages. The only other features that were reasonable to reexamine was the drainage area determination and the RCN. The watershed was delineated and planimetered again resulting in the same acreage thereby dismissing an error in the drainage area determination. That left the RCN as being the only parameter to be scrutinized. The RCN was lowered incrementally from 69 original to 56 where upon its use along with the new T_C yielded reasonable peak reservoir elevations for both of the aforementioned simulations. This lower RCN (56) that brought about the desired results was then examined.

The land use coupled with the HSG of the soil are used to derive a RCN. The wooded landscape left little room for alteration of the land use parameter. The predominant soils in the watershed, as found in the Allegany Co. Soil Survey, were all listed under HSG "C". By assuming a misclassification of these soils and placing them in HSG "B" a RCN of 54 was obtained (56 was found to be the "expected" value). A reevaluation of the hydrologic properties of the soils in the watershed, by a SCS soil scientist, was requested.

The soil scientist determined, through his investigation, that indeed there was a disparity in the Hydrologic Soil Grouping of the watershed's soils. He determined that due to the vast amount of subsurface storage found in the so-called "stony" soils, approximately 1/3 of the soils in the watershed should fall under HSG "A" while the remainder stay in "C". This results in a RCN of 56, the expected value.

SUMMARY

While attempting to hydrologically model, a potentially hazardous embankment using SCS TR-20, a fallacy in the hydrologic soil grouping of the watersheds soils was found. The RCN (directly related to HSG) came under scrutiny while trying to simulate two different flood stages behind the embankment resulting from two separate storms. The model substantially overpredicted flood stages behind the embankment using standard SCS procedures for determination of both T_C and RCN. Though the Tc was altered slightly, resulting in a minor lowering of floodstages, the RCN was significantly decreased (From 69 to 56) to produce the anticipated floodstages in the reservoir when running the two simulations. An on-site investigation then revealed that some of the watersheds soils should have their HSG reclassified.

Reanalyzing the RCN using the results of the soils investigation resulted in a RCN of 56 which was expected. In effect, by attempting to model the watershed with TR-20, a fallacy in the HSG classification of the watersheds soils was detected and subsequently verified. This investigation gives credibility to the use of the SCS TR-20 computer program as a valid hydrologic model.

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CURRENT ISSUES IN RIVER ICE FORECASTING

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INTRODUCTION

Ice formation and breakup can affect the operation of hydraulic structures in a number of ways. Adverse impacts include blockage of water intake trash racks by frazil ice, increased transit time through locks due to ice accumulations in the lock chambers and on gates, freeze-up of dam gates, channel bed and bank erosion and flooding due to ice jams, and structural damage to hydraulic structures from ice impacts.

The ability to forecast river and lake ice formation and breakup provides the opportunity to make operational decisions that could reduce or prevent some ice-related problems. Forecasting river ice formation or breakup involves understanding and predicting complicated thermal, meteorological, and hydrologic processes. Successful ice forecasting requires that all three processes be forecast accurately over the period in which the ice forecast is to be made. Limitations in any of these three forecasts will limit the usefulness of the ice forecast.

River ice models are therefore a fundamental test of our knowledge of river ice processes, our ability to numerically model these processes, our ability to collect and manage a wide variety of field data, and our organizational ability to integrate the data and operate the models to produce reasonable and timely forecasts. This paper presents an overview of current issues in river ice forecasting.

REVIEW OF RIVER ICE PROCESSES

Thermal Processes

The heat exchange between rivers and the surrounding environment drives the ice formation and growth process. The major component of the heat balance is the heat transfer between the water and the atmosphere, which includes long-wave radiation (infra-red), short-wave radiation (solar), evaporation, and direct heat conduction. Other components of the heat balance are convection, precipitation, heat transfer between the water and the river bed, the influx of groundwater to the river, and artificial heat input such as sewage treatment plant discharges and cooling water discharges from electrical generating facilities. It is currently not possible to provide forecasts for all the modes of heat transfer because the necessary data is not available. However, heat transfer from the water surface is calculated from the difference

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between the water and air temperatures. Heat transfer models must be calibrated using field data to account for local variations, such as wind.

The water temperature distributions in rivers can be highly variable both horizontally and vertically. The degree of temperature stratification within rivers is very difficult to predict and can affect ice formation in a variety of ways, thus limiting the usefulness of ice forecasts. For forecasting purposes, the water temperature is generally assumed to be uniform both across the channel and throughout the depth, and only slowly varying along the channel. This is a good assumption for fast flowing rivers without significant heat input from exterior sources. However, vertical stratification of water temperature may occur in rivers moving slower than about 0.6 m/s, and in those with significant heat exchange.

River Ice Generation and Cover Formation

When the river water temperature reaches the freezing point (0°C), ice begins to appear in a variety of forms depending on the hydraulic conditions. Under very quiescent conditions, a smooth ice cover will form, similar to that formed on lakes or ponds. This may form in very slow moving reaches such as just upstream from a dam or in a deep river bend. With continued sub-freezing air temperatures, the smooth ice cover will thicken, thereby increasing its strength. A smooth ice cover may act as the downstream barrier or initiation point for other types of river ice covers. Although smooth ice covers generally have a benign effect on the operation of riverine structures, their appearance is often the first sign that the water temperature has reached freezing and that other forms of ice cover are possible.

Smooth ice that moves with the flow can also form on low-turbulence water moving at velocities less than 0.5 m/s and is referred to as skim ice. It may increase in thickness as it moves downstream but generally does not exceed 2 cm in thickness. Skim ice is usually broken up as it passes through rapids sections or hydraulic structures. Upon reaching an area where ice passage is impeded, such as a downstream ice cover, broken skim ice can accumulate into a very rough cover. Skim ice runs usually do not cause many problems to the operation of hydraulic structures unless a significant broken skim ice cover has accumulated.

Unlike skim ice, which tends to form in calm, slower moving waters, frazil ice is formed in turbulent, slightly supercooled (less than 0°C) water. Frazil ice initially forms as very small discs that are suspended in the flow and grow rapidly. The discs tend to agglomerate together, rising to the surface of the water to form floes or pans of ice. When frazil pans moving downstream reach an obstruction, they may begin to form a cover that progresses upstream in a variety of ways depending on the hydraulic conditions. These are explained in the next section. Frazil ice in its active, rapidly growing state adheres to almost anything, including water intakes, trash racks and the river bed. Because of possible significant impacts on riverine structures, the ability to forecast the formation of frazil ice is highly desirable.

Another form of ice is border ice, which forms along the edges of rivers and lakes. Border ice also forms around rocks, piers, and other objects that protrude through the water surface. With continued sub-freezing air temperatures, border ice grows out into the flowing river and may eventually form a complete cover across the river. A form of border ice, sometimes referred to as ice collars, may accumulate on lock walls, miter gates and mooring bits due to the constant rewetting of these surfaces by oscillating water levels within the lock or splashing. These ice accumulations may grow to several feet in width and thickness, reducing the allowable tow width. Ice collars on lock miter gates and dam gates increase the weight of the gate significantly and may inhibit gate opening and closure.

Forecasting the initial appearance of ice in a river usually consists of developing a heat balance model of the system in order to determine when the water temperature will reach the freezing point. Some knowledge of river hydraulics is necessary to locate areas where smooth or skim ice might form. The locations of frazil ice production areas are a bit more difficult to predict and modeling the conditions that lead to supercooling requires verification through field data collection.

Ice Cover Growth

Ice covers can grow through thermal processes or through dynamic processes controlled by river hydraulics. Thermal ice growth occurs primarily by thickening of static covers due to additional heat transfer from the water, through the ice to the atmosphere. Thermal ice growth is commonly associated with smooth ice covers, yet will occur once any type of ice cover is established, even in more turbulent areas.

Ice cover growth can also occur dynamically, both in terms of thickening the cover and in progression of the cover upstream. As additional frazil floes or pieces of fragmented skim or border ice arrive at the upstream edge of an ice cover, they may lengthen the cover by simple juxtaposition of the floes. If the water velocity is great enough, incoming ice pieces may underturn and pass beneath the cover. If the hydraulic conditions downstream are suitable, some of this ice may deposit beneath the ice cover, further thickening it. As long as the forces inducing downstream movement (weight of the cover and shear of the water flow on the underside) are balanced by those resisting movement (the shear at the banks and the internal strength), the cover will remain stable. If the shear of the water flow beneath a cover is great enough, the cover will collapse and thicken, thereby increasing its internal strength and bank shear so as to resist the forces inducing further downstream movement. This failure and thickening are accompanied by increases in upstream water levels and reduction in water velocity, making further upstream cover progression possible.

Ice Cover Breakup

Breakup is often termed as either thermal breakup or dynamic breakup but both essentially involve downstream forces that exceed the strength of the cover. Thermal breakup is characterized by warm air temperatures and increased solar radiation that causes melting of the cover, thereby reducing its strength. The cover is usually eroded to such an extent that a small increase in river discharge is all that is needed to flush the cover downstream. Thermal breakups rarely cause large increases in water elevation. Dynamic breakups are typically associated with fairly strong ice covers that experience large, unsteady fluctuations in water discharge due to rapid snowmelt or intense rainfall. This strong ice cover is lifted and pushed downstream, often resulting in heavy ice runs or jams. Dynamic ice breakup is very difficult to forecast without a thorough knowledge of the river basin as well as historic records of past events. Ice jams and flooding are often associated with dynamic breakup, hence the intense desire to forecast its occurrence.

Ice Jam Formation

An ice jam is defined as "a stationary accumulation of fragmented or frazil ice which restricts flow" (IAHR, 1986). While this definition would theoretically include almost any ice cover, ice jams are normally considered to be multi-layered and to significantly affect water levels upstream and downstream. Ice jams are most commonly associated with dynamic breakup events or ice runs. When moving ice reaches a location where the ice transport capacity is reduced, such as a reduction in slope or a downstream barrier, ice begins to accumulate and build upstream. The resulting cover thickness is determined by the balance of forces inducing and resisting downstream movement. If the shear on the underside of the cover increases, the cover will fail and thicken in order to resist further downstream movement. Breakup jams result in the most severe ice jam flooding due to the highly unsteady water discharges associated with jam initiation and failure. Forecasting the occurrence and severity of these events would be extremely desirable from an emergency operations standpoint. While jam thickness and the resultant water levels can be estimated by current ice jam theory, the location of jam initiation and the incidence of jam failure is less distinct. Historic records of past ice jam events are often required to determine where ice jams will form.

Freeze-up or frazil ice jams can also cause considerable increases in water levels. These jams are associated with air temperatures well below freezing and fairly steady flow conditions and are usually less severe than breakup jams. Freeze-up jams often result in a large portion of the river flow area being filled with frazil ice which can block water intakes for power plants or municipal water supplies. Drought or low winter flow conditions can exacerbate freeze-up jamming, requiring a tight control on discharge such that water levels are high enough to insure water supplies yet low enough to prevent ice jam flooding. Being able to forecast freeze-up jams can assist in scheduling winter flow releases from storage dams in order to prevent these problems.

RIVER ICE FORECASTING

River ice forecasting models are often characterized by their time horizons. Long term models generally address annual ice processes and are suitable for long-term planning studies. Short term forecasts might be made for time periods ranging from hours to several days, and are essential for wintertime flood warning and preparedness. Mid-term forecasts, with a time horizon of several days to a week, can be used for a number of purposes, including both planning and emergency preparedness.

Long term models assess the likelihood that river ice will develop and if so, its extent and duration over a whole winter season. These models are usually probabilistic in nature and are based on an analysis of ice conditions in past winters. Development of a long-term river ice forecasting model requires an extensive data base on the discharge, meteorological, and ice conditions of the watershed. Although methods exist to synthesize missing data, these models must be calibrated using local field data.

Midterm river ice forecast models are based on numerical models of river ice processes. Reasonable forecasts depend on a good understanding of river ice processes. The forecast horizon, about five to seven days, is limited by the availability of accurate local meteorological and hydrologic forecasts. An extensive data collection network is required, in addition to the capacity to effectively collect and use field data so that the models may be continually updated.

Short term river ice models, also based on numerical models of river ice processes, may model more closely the dynamic processes involved in river ice breakup. They rely upon accurate, extensive field data collection that can be rapidly integrated into a numerical model of river ice processes. They may also rely upon highly empirical insights in order to produce estimates of ice jam flood levels. Real time data collection is particularly useful in these models, which continuously update ice forecasts based on this data and on short term meteorological and hydrologic forecasts as they become available. Again, the accuracy of the model depends heavily on the accuracy of these forecasts.

Past Research Efforts

Past U.S. Government Agency research efforts in river ice forecasting have taken place under a variety of auspices, primarily the Ice Engineering Research Program and the River Ice Management Program carried out by the Corps of Engineers (USACE, 1990; Shen et al, 1991). These forecasting efforts have been concerned mostly with long-term and midterm water temperature and ice formation forecasts on large rivers. Because of the complexity of river ice processes, past research concentrated first on developing a good physical understanding of the processes important to the formation, development, and breakup of ice covers. Once physically based procedures for predicting these processes were developed, numerical methods could be created to describe the ice processes. The numerical models of ice processes were then integrated into larger, more comprehensive models of river systems. Unfortunately, modeling efforts often utilize approximate or empirical approaches to describe river ice processes, which can limit the accuracy of river ice forecasting. In contrast to the past, current efforts in forecasting are concentrating on the more difficult short-term forecasts.

CURRENT ICE FORECASTING EFFORTS

Data Collection

There are two main issues which must be addressed under the topic of data collection. The first is the continued development of equipment used to collect relevant information. Currently, through the use of data collection platforms, or DCP's, it is possible to collect a wide variety of information at a number of remote stations. Much of this information, such as water levels, water temperature, and air temperature, are of vital importance to forecasting river ice processes. Unfortunately, it is virtually impossible to obtain information on equally important ice cover parameters, such as the existence, extent, thickness, and condition of the ice cover. The use of observers and direct measurements remains necessary. Remote sensing of river ice conditions by satellites has so far yielded little in the way of data that might be useful in river ice forecasting systems. This is because the width of most rivers in the continental United States are at the limits of the available imaging systems, and because fast changing ice conditions cannot be sampled frequently enough. Extensive winter cloud cover also remains a practical impediment. The overall lack of ice data has provided a serious impediment to developing and improving ice forecasting procedures. Therefore, the development and testing of new ice data collection equipment are a priority in current research efforts. Recent work has concentrated on instrumentation that can relay information on ice thickness, strength, and existence via DCP's or which can increase the effectiveness of on-site observers.

The second issue of importance is the effective use of data that is collected. Ice forecasts require a clear understanding of the actual ice conditions at the time that the forecast is made. A large amount of data required must be effectively and rapidly analyzed and used in an optimum manner. The accuracy and variance of the data must be carefully assessed to determine not only the confidence band of the data but also the sensitivity of the forecast to these data variations. Advances in automation procedures for assessing, evaluating, and displaying the available data will be necessary.

Improvements in River Ice Forecasting Systems

The first requirement in improving existing river ice forecasting systems is to improve the understanding and modeling of the relevant river ice processes. Determining the major sources of uncertainty in the data and in the models will allow the reduction of overall forecast uncertainty in the most cost effective manner. Developing reliable procedures for updating the forecast, through data collection and assessment will reduce overall model uncertainty and will increase the system's effectiveness and accuracy. Methods for preparing and efficiently disseminating river ice forecasts also need to be improved as the lead time to prepare a forecast can be extensive, particularly for large river systems. Finally, the needs of the user should be reviewed so that forecasts provide the necessary information required for decision making.

SUMMARY

River ice forecasting models are a fundamental test of our knowledge of river ice processes and our ability to numerically model these processes. The ability to collect and manage a wide variety of field data and to integrate this data into numerical models of ice processes is crucial to the development of reasonable and timely river ice forecasts. Major current research issues remain in the areas of river ice processes, data collection, and model operation. An increased understanding of complex ice processes, particularly initial ice formation and ice cover breakup, will improve the current numerical models used in river ice forecasts. Data collection issues include the development of field instruments that can provide information on river ice conditions and the effective assessment and integration of the collected data into improved models of river ice processes. The actual operation of river ice forecasting systems needs to be improved to more accurately and efficiently calibrate, verify, and update forecasts, particularly at a time when emphasis is placed on reduced staffing and increased workloads.

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WATERSHED MODELING--SPATIAL PARTITIONING USING GIS

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ABSTRACT

Techniques were developed using vector and raster data in a geographic information system (GIS) to define the spatial variability of watershed characteristics in the north-central Sierra Nevada of California and Nevada, and to assist in computing model input parameters. The U.S. Geological Survey Precipitation-Runoff Modeling System, a physically based, distributed-parameter watershed model, simulates runoff for a basin by partitioning a watershed into areas each of which has a homogeneous hydrologic response to precipitation or snowmelt. These land units, known as hydrologic-response units (HRU's), are characterized according to physical properties such as altitude, slope, aspect, vegetation, soil, geology, and climate patterns. Digital data were used to develop a GIS data base and HRU classification for the East Fork Carson River and North Fork American River basins. The result is an objective, efficient methodology for characterizing a watershed and for delineating HRU's. Also, digital data can be analyzed and transformed to assist in defining parameters and in calibrating the model.

INTRODUCTION

The U.S. Geological Survey, as part of its Global-Change Research Program, is investigating the potential effects of climate change on the water resources of several river basins in the United States. Precipitation-runoff models were developed and calibrated for the East Fork Carson River and North Fork American River basins in the north-central Sierra Nevada, located on the leeward and windward sides, respectively (fig. 1). The watershed model selected for the present study is the U.S. Geological Survey Precipitation-Runoff Modeling System (PRMS) (Leavesley and others, 1983), a deterministic, modular-component model designed to simulate snowpack accumulation and snowmelt-runoff processes (fig. 2). PRMS is an accounting model in which changes in moisture are conceptualized as fluxes from a series of reservoirs. A water-energy balance is computed daily for each hydrologic response unit (HRU) and is summed on a weighted unit-area basis to produce a basin response. Therefore, partitioning of the watershed into HRU's effectively results in the computation of a water budget for the entire watershed or for specific areas (selected HRU's), identification of physiographic properties affecting runoff, and simulation of hydrologic responses to land-use or climate changes.

This paper summarizes work completed on the development of geographic-information-system (GIS) techniques used to determine watershed characteristics and to define model parameters for the two basins. Processes and results described in this paper are modified from Jeton and Smith (1993).

Approximately 80 percent of annual precipitation on both the eastern and western slopes of the Sierra Nevada occurs from November to March. Precipitation in the high-altitude East Fork Carson River basin is mostly snow, whereas both rain and snow characteristically fall in the moderate-altitude North Fork American River basin.

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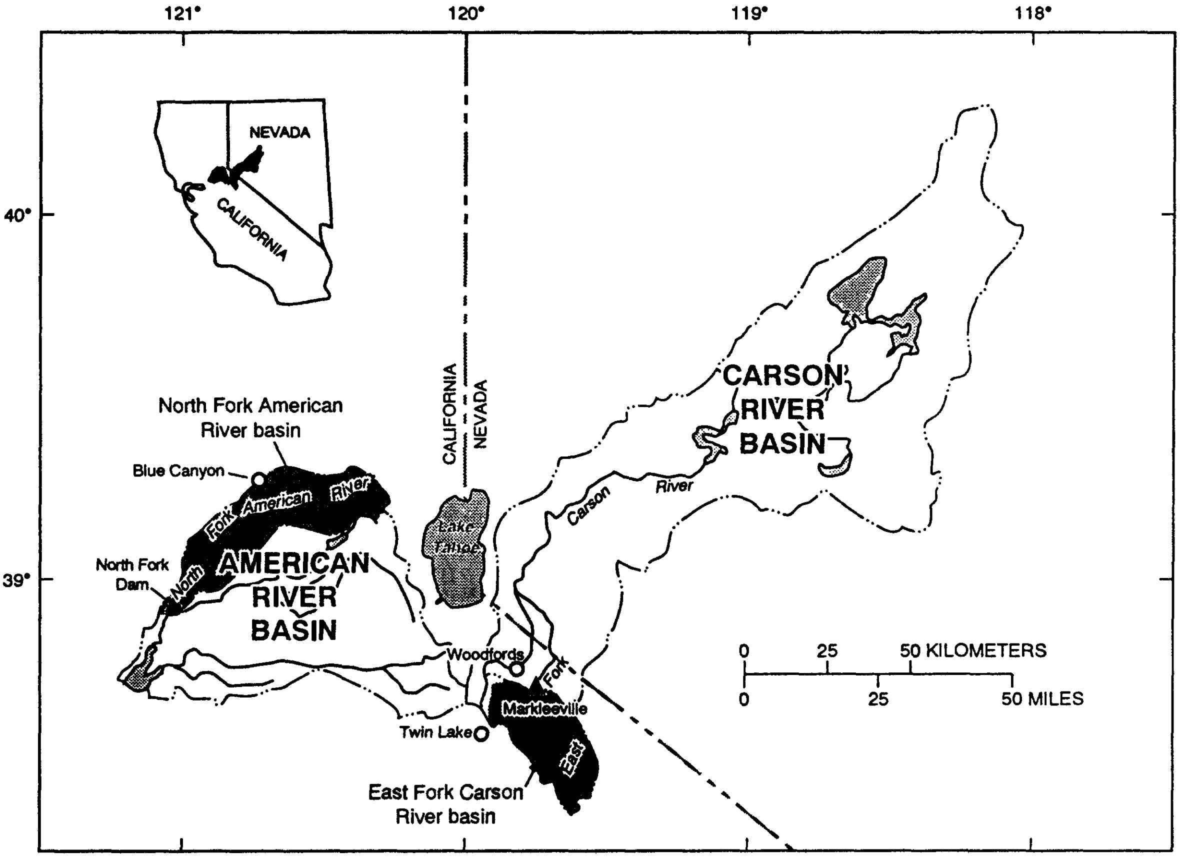

Figure 1. Location of part of East Fork Carson River basin (above Markleeville, California) and North Fork American River basin (above North Fork Dam). Open circles are climate stations; triangles are stream-gaging stations.

The East Fork Carson River drains a 714-km^2 basin with a median altitude of 2,417 m. Vegetation cover is dominated by rangeland in the lower altitudes and conifer forests in the upper altitudes. Shallow sandy and clayey soils reflect the basin bedrock geology, dominantly volcanic and granitic rocks. The North Fork American River drains an 886-km^2 basin with a median altitude of 1,270 m. Pine-oak woodlands, shrub rangeland, and ponderosa pine forest characterize the vegetation. Soils are dominantly clay loams and coarse sandy loams, reflecting variable bedrock material that includes metasedimentary and granitic rocks. The western slopes of the Sierra Nevada are more gently tilted and less dissected than the eastern slopes.

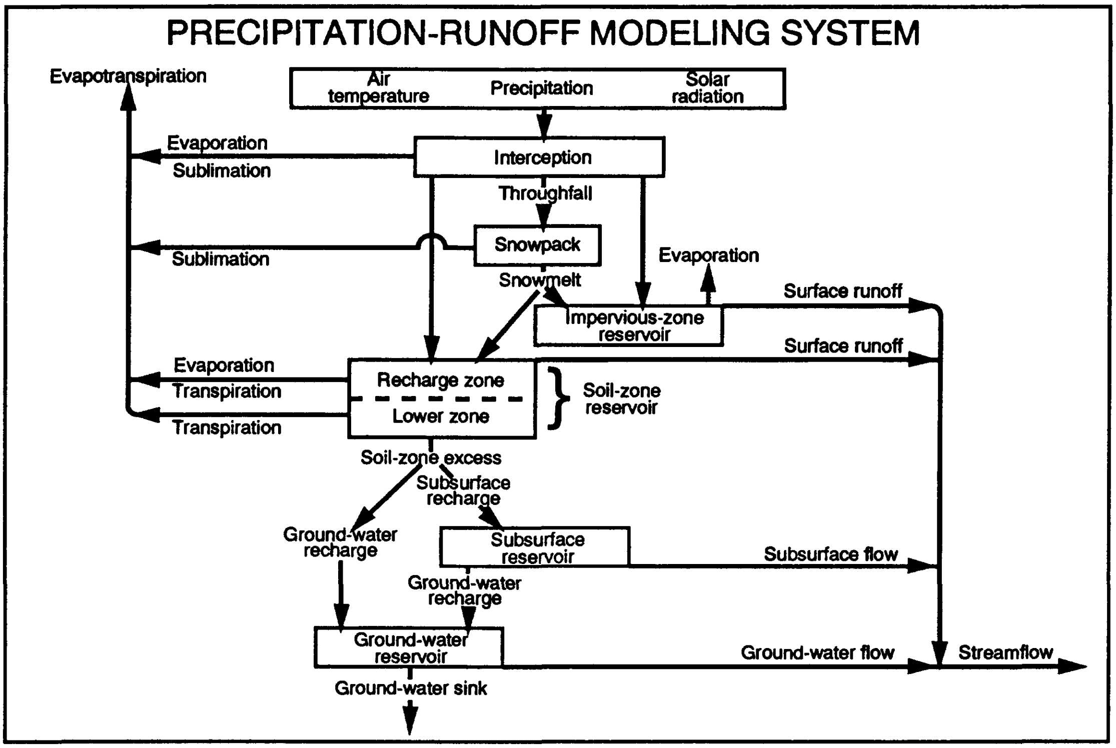

Figure 2. Schematic diagram of Precipitation-Runoff Modeling System (modified from Leavesley and others, 1983).

METHODOLOGY

Objective methods for watershed characterization and HRU delineation were developed and model parameters for the basin and individual HRU's were determined to define and simulate the spatial and temporal variation of hydrologic processes. An integrated GIS was generated for the East Fork Carson River and North Fork American River basins in the following formats: digital vector files, grid- or raster-format files, and ASCII-format attribute tables. GIS source data are described in table 1. The following criteria are used in delineating HRU's: (1) Data layers are hydrologically significant and have a resolution appropriate to the watershed's natural spatial variability, (2) the technique for delineating HRU's accommodates different classification criteria and is reproducible, and (3) HRU's are not limited by hydrographic subbasin boundaries. HRU's so defined are spatially noncontiguous.

The HRU eight-step delineation process (fig. 3) is summarized as follows. Steps 1 to 3: Source-data categories within each GIS data layer are regrouped into new categories (grouped data) according to hydrologic-response characteristics and sensitivity to climatic factors (table 2). The watershed is divided into 100-by-100-m areas, or representative cells, and all possible combinations of five data layers (altitude, land cover, soil, slope, and aspect) for a given basin are identified and tabulated. (The geology source-data layer was not used in the HRU delineation process, though the source layer is used in model parameter determination, step 7.) Step 4: Each cell is character-ized by a permutation of the five data layers. Each unique combination is given a permutation identification number (PIN). For example, PIN 121, com-prising 1,741 not necessarily contiguous cells or areas within the East Fork Carson River basin, is characterized in table 3. Step 5: To accommodate the 50-HRU limit of PRMS, the total number of separately defined PIN's is reduced to 50 by using a relational data-base management system.

Table 1. Source data for geographic information system.

[USSCS, U.S. Soil Conservation Service; USFS, U.S. Forest Service; USGS, U.S. Geological Survey; --, not applicable]

Type of source-data layer	Source data Scale	Format	Reference or derivation	Comments
Altitude	1:250,000	Raster	USGS, 1987	Grid spacing, 3 arc seconds.
Slope	1:250,000	Raster	Derived from altitude data (USGS, 1987).	
Aspect	1:250,000	Raster	Derived from altitude data (USGS, 1987).	
Land cover	1:250,000	Vector	USGS, 1986	Minimum mapping unit, 4 or 16 hectares.
Soil	1:250,000	Vector	USSCS, 1991	Statewide data base; used for North Fork American River.
	1:62,500	Vector	USFS (written commun., 1991).	Soil survey (unpublished); used for East Fork Carson River.
Geology	1:750,000	Vector	Jennings, 1977	Used for North Fork American River.
	1:250,000	Vector	Stewart and others, 1982	Used for East Fork Carson River.
Landsat (thematic mapper)	--	Raster	USFS (written commun., 1991).	Used for canopy cover; cell resolution, 30 meters.
Hydrography	1:24,000; 1:62,500.	Vector	Digitized from unpublished USGS drainage-basin maps.	Used for North Fork American River.
	1:62,500	Vector	Digitized from unpublished USGS drainage-basin maps.	Used for East Fork Carson River.

Selected PIN cell types are combined and assigned a single PIN in the permutation table. (Unlike the previous steps, this PIN-combining process requires some subjectivity to identify the most hydrologically significant areas.) Step 6: The final permutation table, otherwise known as the HRU characterization table, is used to assign each cell an HRU number on the basis of the 50 unique PIN's. The result is a new HRU data layer or image, to which further processing, such as nominal filtering, is applied. Step 7: This final HRU layer is intersected with the five original data layers. Then, frequency distributions are computed to determine the spatial variability of physical characteristics within each HRU. Step 8: These spatial data are used to develop the parameter input file that is required for PRMS modeling. An example of a HRU overlay resulting from step 8 (fig. 3) is shown in figure 4 (East Fork Carson River basin). The enlarged area illustrates the raster-based framework of cells composing the HRU overlay and shows that both contiguous and noncontiguous cells may have the same HRU number. The percentage of basin area for individual HRU's ranges from 0.5 to 6 percent of the East Fork Carson River watershed. The average HRU comprises 1,433 hectares or 2 percent of the basin area.

Table 2. Data layers for East Carson River basin geographic information system.

[HRU, hydrologic-response unit; --, not applicable]

Type of data layer	Ungrouped categories	Grouped HRU-characterization categories	
		Number	Description
Altitude	--	3	1,683-1,981 meters. 1,981-2,438 meters. 2,438-3,413 meters.
Slope	68 degree classes	4	0°-7°. 8°-30°. 31°-45°. >45°.
Aspect	9 compass points (plus level land).	4	North facing. Northeast and east facing. Southeast-, southwest-, and south-facing and level land. Northwest and west facing.
Land cover	9 type classes	6	Evergreen forest. Mixed forest. Deciduous forest. Shrub rangeland. Herbaceous rangeland. Shrub tundra.
Soil	35 type classes	4	Clay. Clay loam. Gravelly sand. Sandy loam.
Geology	23 type classes	5	Basin-fill sediments. Metasedimentary rocks. Silicic volcanic rocks. Felsic intrusive rocks. Mafic intrusive rocks.

DISCUSSION

In theory, each HRU should exhibit a distinct hydrologic response to rainfall or snowmelt, enabling the modeler to identify those HRU's and their physical properties most sensitive to producing runoff, snowmelt, or any of the water-budget components. However well-defined, limitations do exist for land-unit classes such as HRU's that exhibit extensive spatial scatter of noncontiguous pixel clusters. For example, HRU's are indexed to a particular climate station. Thus, error in precipitation simulation can occur if the areal distribution of HRU pixels is not coincident with the zone of climatic influence, particularly when orographic effects are present. Similar types of error are possible for other parameters, such as the indexing of HRU's to subsurface reservoirs, which controls the baseflow component of streamflow, should the underlying geology not be homogeneous. Preliminary work in correlating simulated HRU snow cover to Advanced Very-High Resolution Radiometer (AVHRR) snow cover typifies this problem by over-simulating snow cover when HRU's exhibit extensive spatial scatter.

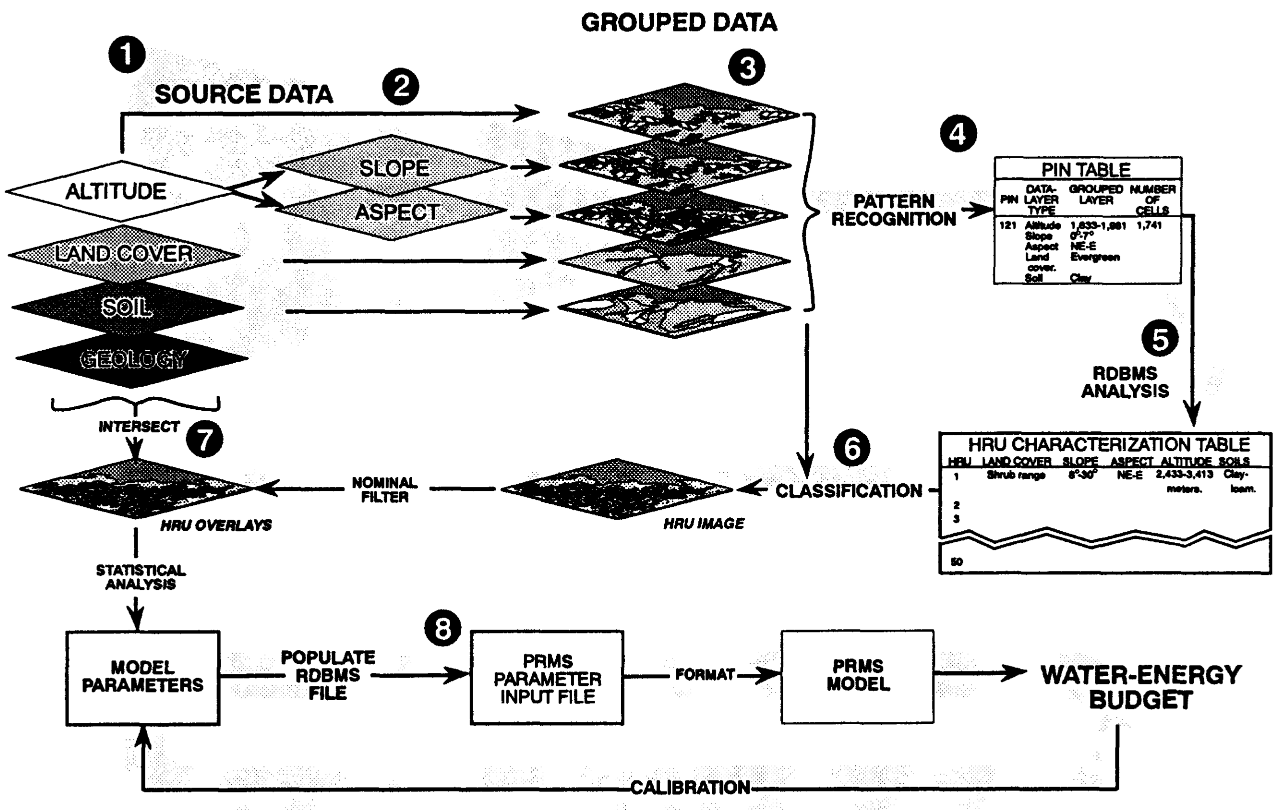

Figure 3. Flowchart for watershed characterization and hydrologic-response-unit (HRU) delineation. See figure 4 for HRU overlays (step 7). Altitude in meters. NE-E, northeast and east facing; NW-W, northwest and west facing; PIN, permutation identification number; PRMS, Precipitation-Runoff Modeling System; RDBMS, Relational Data-Base Management System. Black circled numbers are steps in model process (see text).

Table 3. Characteristics of combination permutation identification number 121.

Type of data layer	Grouped category
Altitude	1,633-1,981 meters.
Slope	0°-7°.
Aspect	North and east facing.
Land cover	Evergreen forest.
Soil	Clay.

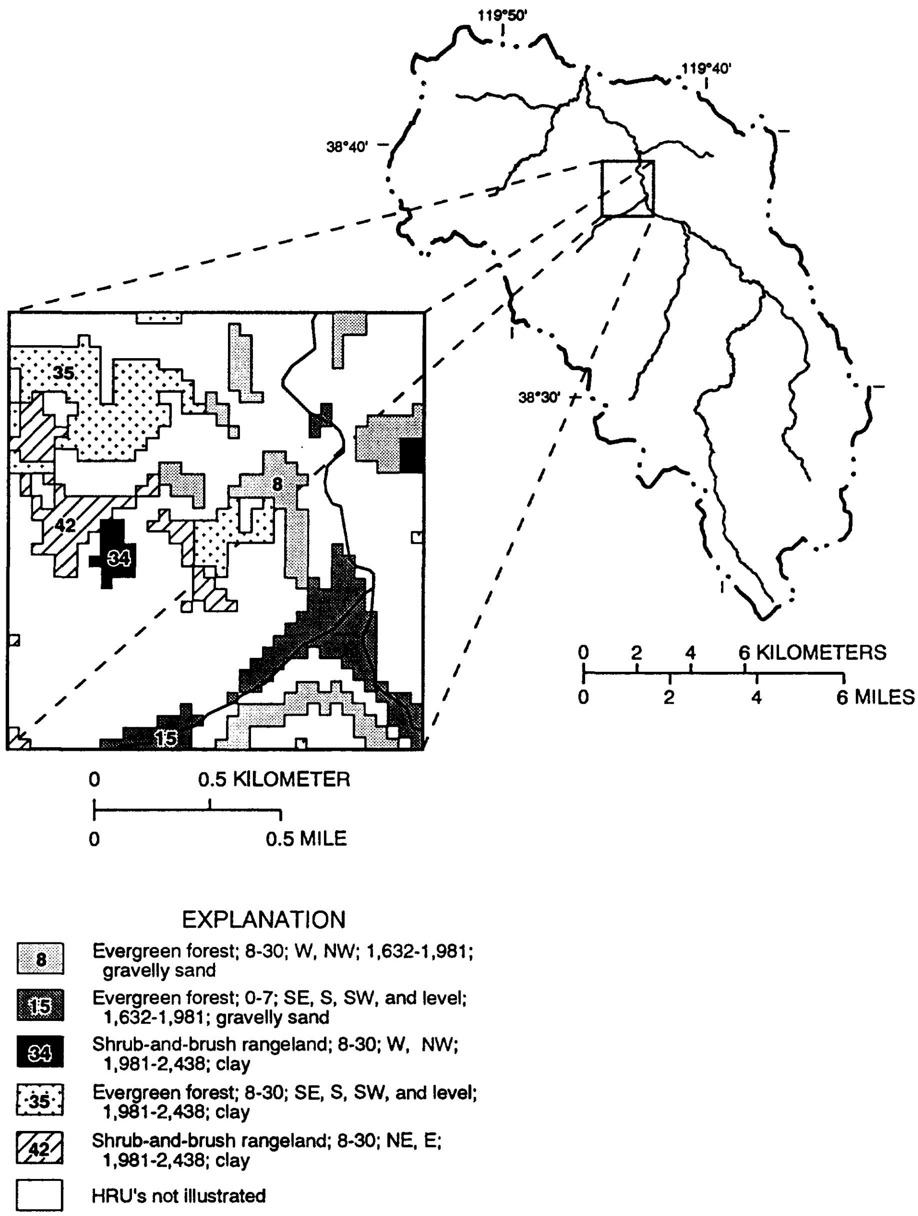

Figure 4. Hydrologic-response unit (HRU) overlay for East Fork Carson River basin. Explanation of units lists attributes of selected HRU's, which are identified by HRU number. Attributes are listed in order of land cover, slope (in degrees), aspect (compass facings, if applicable), altitude (in meters), and soil.

Evidence from this study indicates that further research is needed to determine the minimum threshold number of HRU's required to model watershed-scale hydrologic processes, determine the resolution and number of source and grouped data layers appropriate to model development, and, given the sensitivity of snowmelt processes to canopy cover, improve land-cover classification and canopy-cover estimates through the use of higher resolution, remotely sensed satellite data.

CONCLUSIONS

Techniques were developed using vector and raster data and a geographic information system to define the spatial variability of watershed characteristics and to assist in determining model parameters. The development of a geographic information system and its application to watershed modeling resulted in new techniques for partitioning a watershed into land units (called hydrologic response units--HRU's) and for characterizing the watershed. The strength of this approach is the ability to capture spatial detail within a watershed. The physical properties affecting runoff are quantified at the HRU level. These techniques result in an objective and efficient model-building process that produces acceptable simulations of observed streamflow. Disaggregating the watershed into these units provides the watershed hydrologist or resource planner the option of looking at total basin yield or at water budgets derived from an individual HRU. A modeling framework based on digital data also allows for modifications to be made to reflect natural or human-induced land-cover changes when it is used as a real-time management tool or as a predictive tool.

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TR-20 PROVES VIABLE FLOOD REDUCTION ALTERNATIVE

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ABSTRACT

The hydrology model developed from Technical Release 20, Computer Program for Project Formulation - Hydrology (TR-20), was the tool used by the Soil Conservation Service (SCS) to analyze the effects of detention structures on flooding in the Perry Creek watershed at Sioux City, Iowa. The model routed flood hydrographs through detention structures showing a 56 percent reduction in the 100-year discharge. TR-20 provided information to show a viable alternative for flood control compared with a proposed excavated channel to convey unaltered peaks.

INTRODUCTION

Purpose

Soil and Water Conservation District Supervisors for Woodbury and Plymouth Counties requested the Soil Conservation Service (SCS) to investigate detention structures as an alternative to a proposed large channel excavation and conduit modification in an urban area of Sioux City, Iowa. With use of the hydrology model, TR-20, nine alternatives, with various combinations of structures were run to show effects of detention structures on peak discharges. This model was chosen for several reasons:

1) Capable of developing historic or synthethic runoff hydrographs, and routing hydrographs downstream and through structures.

2) Adapts quickly to formulation changes, which provides rapid analysis of different alternatives using various combinations of detention structures.

3) Minimal requirements for field surveys.

4) A model recognized by hydrologists as giving credible answers.

Description of Study Area

Perry Creek, a left-bank tributary to the Missouri River, has a drainage area of about 73 square miles, and at the lower end flows for five miles through a densely developed area of Sioux City, Iowa.

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Since 1905, many alterations have been made to the Perry Creek channel in Sioux City including: construction of a conduit, bank stabilization, and channel straightening. The existing closed conduit at the outlet is a reinforced concrete box structure 4,000 feet long, constructed in stages between 1925 and 1960. Between 1931 and 1941, the channel was straightened from the entrance of the conduit upstream to the city limits, a distance of about five miles. Also, the banks of Perry Creek have been partially stabilized in several locations with riprap or retaining walls.

Approximately 80 percent of the Perry Creek drainage area (47,000 acres), is made up of cropland (26,000 acres), pastureland (7,000 acres), forest (1,000 acres), and other (2,100 acres). About 20 percent of the watershed is urban, which includes 1,300 acres of flood plain and 9,500 acres of upland.

Past Floods

Records show that 24 damaging floods have taken place on Perry Creek from 1892 to present. The most common cause of these floods was heavy rainfall during the months of May through September, although one flood occurred because of snowmelt and ice jams in March. The most damaging flood occurred in July 1944, causing over one million dollars in damages. The most recent damaging flood occurred in May 1990, when 86 city blocks were inundated, with an estimated 98 commercial and 634 residential buildings sustaining some degree of damage.

A recent economic analysis for conditions without a flood control project indicate average annual urban damages to be 5.8 million dollars. In the rural area, crop and pasture damages average 37,800 dollars annually.

FLOOD CONTROL ALTERNATIVES

Several alternative plans were considered to reduce the flooding and sediment damages. Non-structural measures such as flood proofing, flood warning systems, and flood plain acquisition were not considered totally adequate for flood damage reduction, were too expensive, or not locally acceptable. Two plans have been submitted to the potential sponsors of a flood control project.

Plan With Channel and Conduit Modifications

This proposed project consists of extensive channel modifications and a new conduit system which would provide 100-year flood protection throughout most of the urban area. The watershed above the improved channel would not be affected by the project as the proposed channel enlargement was not planned to extend all the way to upstream urban areas leaving remaining areas unprotected.

Plan With Flood Detention Structures

Several systems of smaller dams were considered, and were located throughout the watershed so they would solve problems at least cost. Initially, 85 structure sites were identified with 37 of these sites chosen for the most effective, least cost plan. The plan would include an increased rate of land treatment upstream of the structures to help reduce soil erosion and sedimentation into the pools.

Program Input

The TR-20 model computed runoff and flood routings to determine hydrographs and peak discharges at 107 locations. Nine synthetic rainfall events (500-,100-,50-,25-,10-,5-,2-,1-,1/2-year) plus the natural rainfall event which caused the flood in May 1990, were used to determine the flood routed runoff rates. Synthetic rainfall came from depth-frequency 24-hour charts in Technical Paper 40. Features of the TR-20 input data were:

1. Anticedent Moisture Condition II curve numbers (CN 74-79) from analysis of eight sample areas with balance of watershed estimated from samples.

2. Subwatershed drainage areas all planimetered from USGS 7-1/2 minute quadrangle maps.

3. Times of Concentration (Tc) from calculations of a small sample, estimated times for remainder of local drainage areas from plot of Tc versus drainage area.

4. Main time increment = 0.1 hour for hydrograph development.

5. Rainfall distribution by SCS Table II for the synthetic events.

6. Reach routing lengths for channel and flood plain measured from USGS quads.

7. Tc and CN for "With Project" same as used for "Without Project".

8. Structure outflows are all 15 cubic feet/second/square mile.

9. Historic rainfall distribution input.

The historic rainfall event of May 1990 was modeled for verification of model validity using an isohyetal rainfall map, and an hourly precipitation record at Sioux City Gateway Airport for rainfall distribution within the 10-hour rain period. U.S.

Geological Survey reported a peak of 8,670 cfs at the 38th street stream gage. Result of the natural rainstorm computation of peak discharge using TR-20 was 9,800 cfs which is 13 percent higher than the measured peak.

Effects of Proposed Detention Structure Project

Installation of the detention structures would mean a reduction in urban damages of 87 percent due to floodwater being temporarily impounded and resultant peak flows being reduced. Agricultural floodwater damages would also be reduced from 603 average annual acres to 425 acres. Long term productivity on cropland and pastureland would be improved by reduction in erosion, flooding, and sediment deposition. Flood damages would be reduced at 35 bridge and culvert locations in the rural area. Although at present only minimal flood related damage begins to occur at about the five year frequency, these damages would be virtually eliminated downstream of floodwater retarding structures. Debris and sediment trapped by the dams and reduced peak flood flows will reduce operation, maintenance, and replacement cost at culverts and bridges.

HYDROLOGIC AND ECONOMIC EFFECTS

	Without Project	With Project
Peak @ 38th Street (cfs)		
100-year	16,000	7,100
25-year	13,700	5,200
Average Annual Urban Flood Damage ($1000)	5,900	790

Additional benefits of the detention structure project include the reduction of sediment delivered to Perry Creek and to the Missouri River. An accelerated land treament program would reduce soil erosion while most of the remaining sediment produced from the 37.7 square miles controlled would be trapped by the dams. Crop production and terrestrial wildlife use on 970 acres would be lost to sediment pools, however, the pools would be suitable for fish habitat and recreational opportunities, and would provide a source of water supply for fire protection, and livestock. There would be less stream degradation in main streams and principal tributaries due to reductions of flood peaks.

SUMMARY

Flood reduction benefits from implementation and construction of a detention structure project were proven through information provided by the computer model TR-20. Although the model output includes hydraulic data such as peak rates and elevations, the consequences of reduced flows could show positive effects by a reduction of sediment deposition in downstream channels and flood plains, improvement of water quality, reduction of maintenance costs to bridges and roads, increased ground water recharge, providing water supply for recreation, fire protection, and livestock, and the lessening of stream degradation. TR-20 is user-friendly and very adaptable for computing the hydrologic/hydraulic effects of alternative structural plans.

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GIS APPLICATION FOR NWS FLASH FLOOD GUIDANCE MODEL

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ABSTRACT

In response to a requirement for more uniform and consistent flash flood guidance procedures, the National Weather Service (NWS) with the assistance of the Iowa Institute of Hydraulic Research developed techniques for computing threshhold runoff for flash flood guidance. These techniques use a Geographic Information System (GIS) and Digital Elevation Models (DEM) to determine the required sub-basin boundaries and additional physical parameters for assessing threshold runoff values for 1-, 3-, and 6-hour rainfall durations. A rainfall-runoff model combined with an optional snow model computes the rainfall required to cause the threshold runoff responses. These procedures are being integrated with other NWS forecast office procedures. NWS expects to become operational with these procedures as part of the implementation of a modernized communication and distributed data processing system known as the Advanced Weather Interactive Processing System (AWIPS). The first field operations are expected to occur around the early part of 1994. The application of the GIS to determine the basin boundaries and the derivation of the various parameters for determining threshold runoff values are presented. The use of threshold runoff values with rainfall-runoff models to compute flash flood guidance is briefly described.

INTRODUCTION

This paper describes an objective method developed to compute threshold runoff values required in the computation of flash flood guidance at the NWS River Forecast Centers (RFC) (Sweeney, 1992). The method utilizes hydrologic and hydraulic principles, digital elevation model databases, and a geographical information sytem (GIS) applicable over the entire United States.

THRESHOLD RUNOFF THEORY

In the NWS, threshold runoff is defined as the runoff (in inches) from a rain of a specified duration that causes a stream to slightly exceed bankfull. When available, the flow at flood stage is used instead of slightly over bankfull. The method of determining threshold runoff value for a catchment is based on the threshold runoff value definition when it is assumed that the

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catchment responds linearly to rainfall excess (runoff), i.e., unit hydrograph theory applies. Since q_{pR} is the unit hydrograph discharge per unit area corresponding to unit volume of runoff of duration t_R, the peak discharge at the catchment outlet corresponding to a volume R of runoff of duration t_R is:

$$Q_p = q_{pR}RA \tag{1}$$

where Q_p is the peak discharge at the catchment outlet in cfs, A is the catchment area in mi^2, and R is the runoff amount in inches. Solving Eqn. (1) for R gives

$$R = \frac{Q_p}{q_{pR}A} \tag{2}$$

The problem is determining Q_p, q_{pR}, and A from observed field data that are expected to be available on a national basis. As a general guideline, utilization of GIS and national digital elevation databases allows the determination of geometrical catchment characteristics. Channel cross-sectional characteristics that determine Q_p cannot be resolved with present-day GIS databases and, if they exist at all, are the product of surveys limited in regional coverage. We present several options depending on data availability. A more detailed discussion of the theory is given in Sweeney (1992).

<u>Bankfull Discharge</u>

The value of Q_p can be determined by the use of Manning's formula for turbulent flow (Linsley, et al., 1982) to relate the runoff discharge to the channel geometrical and roughness characteristics for bankfull flow conditions. Bankfull discharge Q_p in cfs is given as a function of the local channel slope S_c in ft/ft, the hydraulic radius R_b in ft, and the channel bankfull cross-sectional area A_b in ft^2 by

$$Q_p = \frac{1.49 S_c^{0.5} R_b^{\frac{2}{3}} A_b}{n} \tag{3}$$

where n is Manning's roughness coefficient. After substituting a power function of local slope and hydraulic radius for Manning's n (Jarrett, 1985), and using D_bB_b for A, and then substituting hydraulic depth D_b expressed as $y_b/(m+1)$ for R_b, Eqn. (3) becomes

$$Q_p = 4.14 S_c^{0.13} \left(\frac{y_b}{m+1} \right)^{1.82} B_b \tag{4}$$

where y_b is the channel depth in ft at bankfull, m is the channel cross-section shape factor, and B_b is the bankfull width in ft.

Bankfull discharge can also be approximated by the two-year return period discharge Q_2 which is the discharge expected to be equalled or exceeded once every two years (Wolman and Leopold, 1957, pgs. 88-89). Q_p becomes Q_2:

$$Q_p = Q_2 \tag{5}$$

Typically, the return period of about 1.5 years is associated with bankfull discharge, but the values vary from about one to two years. The higher value of two years for the return period is chosen since more than bankfull flow is needed for flooding. For both cases, Manning's formula or return period, the data is limited and not available on a uniform basis over the U.S. The US Geological Survey (USGS) has compiled discharges for various return periods including the two-year return period (Jennings, 1992). Regionalization of the required parameters is necessary for each case in order to estimate their values in ungaged catchments from the values observed in a few gaged catchments in the region of analysis.

Peak Discharge

Snyder's synthetic unit hydrograph approach (Chow, et al., 1988, pg. 224-228) is a familiar method to determine the relationship between the effective rainfall of a given duration and peak runoff discharge q_{pR} and timing given geometric drainage basin characteristics as observed parameters.

$$q_{pR} = \frac{640C_p}{0.955t_p + 0.25t_R} \tag{6}$$

with

$$t_p = C_t \left[\frac{LL_c}{S^{0.5}}\right]^{0.38} \tag{7}$$

where C_p is a coefficient accounting for retention and storage with values typically in the range between 0.4 and 0.8 (Bras, 1990), t_p is the time to peak in hours, t_R is the duration in hours of the rainfall excess (duration of unit hydrograph), L is the main stream length in miles from the outflow point to the most distant basin boundary, L_c is the main stream length in mi from the outflow point to the basin centroid, S is the weighted channel slope in ft/mi, and C_t is a coefficient that takes the value of 0.35 for valley drainage areas, 0.72 for foothills, and 1.2 for mountainous areas (Linsley, et al., 1982).

Unfortunately, reasonable rainfall-discharge data to derive unit hydrographs are not available for most flash flood prone catchments. However, a more recent approach to deriving unit hydrographs based on the morphological structure of the channel network and channel cross-sectional data is being investigated (Rodriguez-Iturbe and Valdes, 1979).

APPLICATION OF THE GIS

The first consideration regarding the use of GIS is the available digital databases. The watershed program in the GIS GRASS (Geographic Resources Analysis Support System, CERL, 1991) determines watershed boundaries from a digital elevation model (DEM). Since nearly flat terrain complicates the process of locating boundaries, locations of known flat areas such as lakes and reservoirs are obtained from a Land Use, Land Cover (LULC) database. Elevations of streams in the DEM are lowered (or carved) by a fixed amount to better delineate the streams. Stream locations are obtained from the Environmental Protection Agency's (EPA) River Reach Files RF3. Some DEM data was initially obtained on 9-track tape from the USGS but is now available on

CD-ROMs from private vendors and from the Defense Mapping Agency (DMA). Likewise, some LULC data was initially obtained from the USGS and is now available on a CD-ROM from private vendors.
The digital databases are divided into USGS Hydrologic Cataloging Units (CU) and threshold runoff values are determined for each CU. The various steps for the GIS analysis are as follows:

LULC is scanned to determine the CUs within a given analysis window. A GRASS window is defined around each CU.

After defining the GRASS windows, the CU boundary vectors are converted to a GRASS cell file. Each DEM file falling within the GRASS window is converted into a cell file, too.

The EPA River Reach stream file for the CU inside the GRASS window is then converted to a cell file.

The various cell files are then overlayed to form a composite cell file. The analysis employs Universal Transverse Mercator (UTM) zones. The zone containing the major portion of the analysis area is made the zone of analysis. Files from the adjacent zone are converted into cell files with respect to the analysis zone. Considering the areal extent of a 1 degree by 1 degree DEM grid, no more than one zone crossing is expected for a particular analysis window.

Next, the mosaic is scanned for discontinuities across file boundaries. A cubic spline surface generation algorithm is used to mend these "seams".

Watershed analysis is then performed using the GRASS program R.WATERSHED (Ehlschlaeger, 1990). This program determines the network of streams in a certain analysis area and certain geometrical characteristics such as drainage area, stream length, and stream slope. The software package R.WATERSHED determines catchments by moving upward from the lowest elevation sections of the digital map. Land is given to the drainage basin which encroaches it first. When two basins meet, a ridge is formed. The travel uphill is done one contour line at a time. Digital data other than the elevation data (i.e., LULC) can be used to increase the accuracy of the procedure. Several tests of the procedure were made with 7.5 minute and 1 degree digital maps. In all cases R.WATERSHED correctly identified all basins and streams even in very flat areas. Only at the boundaries of the analysis maps the procedure failed. Such a problem is not expected when the CUs are used as described above. The scale of the minimum area considered to form a first order stream is set by the user (i.e., 5 km^2).

COMPUTING THRESHOLD RUNOFF

Using the program developed by Georgakakos, et al., (1991) called "thresR," threshold runoff values are computed for both stream branches that form each of the stream junctions determined by the GIS within the analysis area. An upper cut-off point is set for the largest drainage area for which a threshold runoff value is computed in order to be consistent with the assumptions of the unit hydrograph method used, i.e., uniform rainfall excess over the basin under study for a certain rainfall duration.

An upper cut-off is imposed since the larger scale streams and rivers contain forecast points for which the NWS RFCs routinely issue flood forecasts. However, sections of large drainage basins that drain into the downstream reaches of large streams and rivers are of interest since they can be prone to flooding from local rainfall over their tributary drainage basin. Such areas that have an identifiable stream draining as a tributary to the main stream or river would have been identified by the GIS for areas of moderate to high relief. Due to errors involved in the definition of the digital elevation data in very flat areas, a small draining stream of low order might not be identified. Such areas would create gaps in the map of the drainage basins with threshold runoff values assigned (assuming that the large stream or river would not have an associated threshold runoff value due to having too large of a drainage area), and some interpolation is needed to assign reasonable threshold runoff values in that vicinity. Such an issue should arise in the very flat areas of the Central U.S. in the downstream portions of large streams. A nominal value of 2,500 km^2 is used for the upper cut-off of areas for which a threshold runoff value is computed. Such a value corresponds to the scale of the smaller catchments for which the RFCs routinely issue site specific forecasts. It is also well within the scale of mesoscale convective complexes that cause flash flooding in the Central U.S.

An important input parameter is the minimum drainage area used to define the smallest streams. For compatibility with WSR-88D gridded data, the minimum area selected is 5 mi^2. The radar grid is approximately 6.25 mi^2 (16 km^2).

SUMMARY of ANALYSIS

Examples of 1-hour threshold runoff values are presented below for the Raccoon River catchment in Iowa, CU number 07100007. The threshold runoff values obtained are reclassed on an integer scale ranging from 2 to 254, and used for display with a gray scale color table. The final display gives the variation of threshold runoff values over the area of analysis. The catchment parameters have been produced using R.WATERSHED with a 5 km^2 minimum area. Theshold runoff values were computed for source areas up to approximately 50 km^2.

The threshold runoff values derived from Manning's equation for bankfull discharge and from Snyder's unit hydrograph are depicted in Figure 1 using a gray scale with dark shading implying low threshold runoff values and light shading implying high values. Each catchment was shaded based on its threshold runoff value. The values ranged between about 0.6 and 1.0 inches. Figure 2 depicts threshold runoff values derived from the two-year return period flow and Snyder's unit hydrograph. Values range from about 0.5 to 1.6 inches.

In all cases the variation in threshold runoff values is rather small for the area of analysis. Also, there is a rather smooth variation of values, with a few high values observed in small basins. The white areas adjacent to the main streams and rivers are areas with no threshold runoff values and interpolation using near-by values is needed in those cases.

DERIVATION OF FLASH FLOOD GUIDANCE

Flash flood guidance is the general term which refers to the average rainfall needed over an area during a specified period of time to initiate flooding on small streams in the area. Current moisture conditions and threshold runoff representing channel and basin characteristics described above are the major components of flash flood guidance. The Flash Flood Guidance System being developed in the NWS uses rainfall-runoff models with an optional snow model to determine the amount of rain necessary to produce an amount of runoff equal to the threshold runoff. This amount of rain is the flash flood guidance (Sweeney, 1992, pgs. 16-17). The process is repeated for each duration of rainfall and the corresponding threshold runoff for that duration. Flash flood guidance is computed for 1-, 3-, and 6-hour durations.

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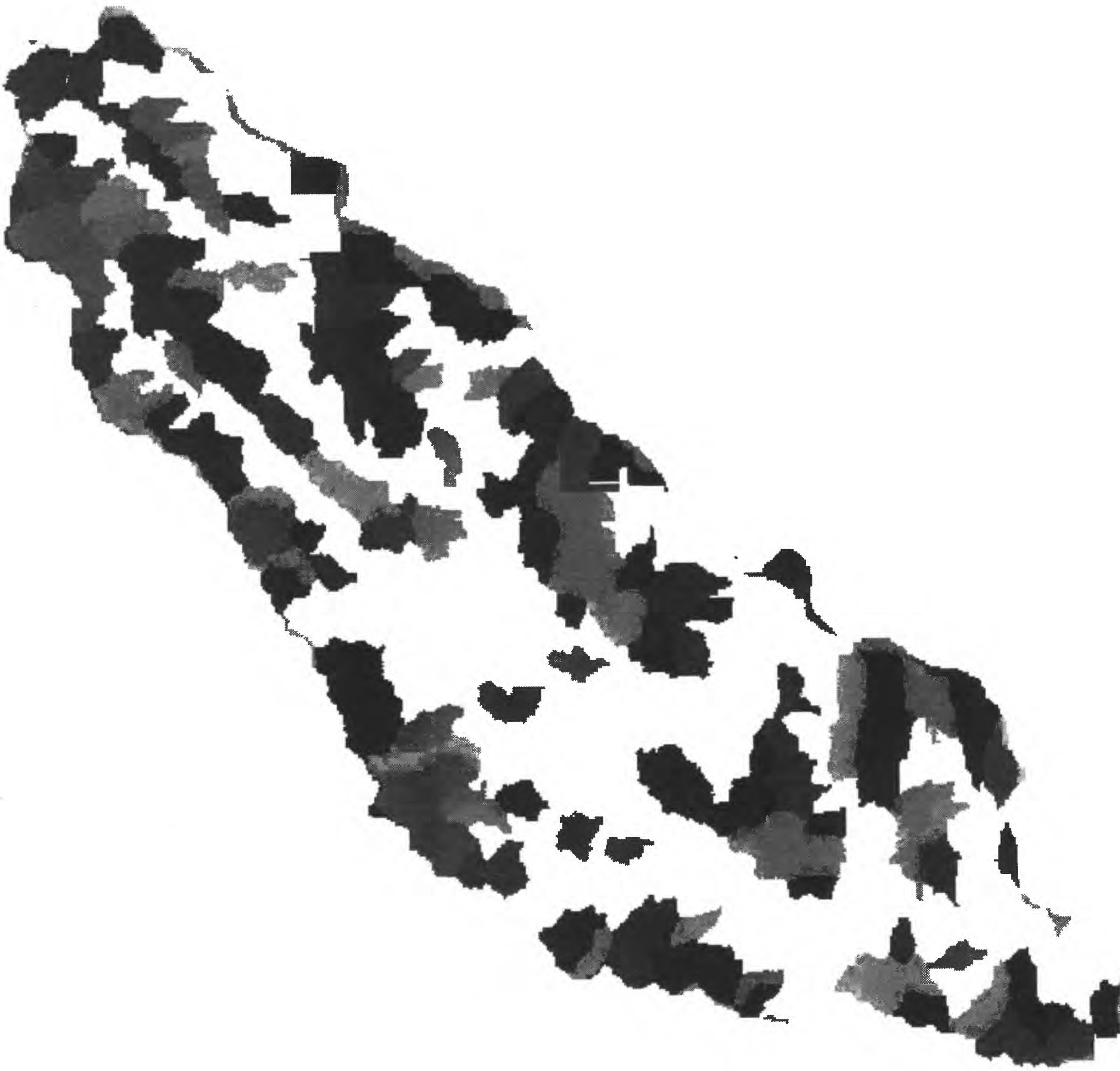

Figure 1. Threshold runoff values for 1-hour rainfall duration based on Manning's equation at bankfull discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.6 (darkest color) to 1.0 inches. Raccoon River in Iowa, CU 07100007.

Figure 2. Threshold runoff values for 1-hour rainfall duration based on 2-year return period discharge and Snyder's unit hydrograph for source basins only. Values range from about 0.5 (darkest color) to 1.6 inches. Raccoon River in Iowa, CU 07100007.

ADAPTATION OF TR-20, PROJECT FORMULATION-HYDROLOGY

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ABSTRACT

The computer program, TR-20, Project Formulation - Hydrology, was used successfully to flood route the main stream Kankakee River as a series of reservoirs. Locations of stream gages were chosen as "pseudo" structure sites where reservoir routings were performed. Routed existing condition hydrographs were a close match with historic data, adding validity to "with project" routings.

Each tributary was conventionally routed so that both "existing" and "with project" conditions were done by the same computer run. Using SUBHYD, an innovative subroutine for subtracting hydrographs, the existing condition hydrograph at the mouth of each tributary was subtracted from the "with project" hydrograph for each flood. This remainder (delta) hydrograph represented effects of changed conditions on the main stem.

INTRODUCTION

Study Area

The Kankakee River drains 5,165 square miles in northwest Indiana and northeast Illinois. This study pertained primarily to the Indiana 2,996-square mile subarea (the Basin).

This Basin is rich in natural water areas and prime wetlands. There is an identified need to protect and maintain wildlife and fish habitat, and to improve flood control and drainage on land dedicated to agricultural crops. This paper relates a brief overview of techniques used to measure effects of flood reduction schemes.

A broad outwash plain, with much sand and gravel, is the dominant physiographic feature. It ranges from 15 to 25 miles wide from the city of South Bend to the Indiana-Illinois state line. The relatively shallow groundwater level is closely correlated with the water surface elevation in nearby open channels. Sand ridges are scattered throughout much of the area, breaking the relatively flat and monotonous landscape.

Flooding occurs periodically in the Basin, affecting about 222,000 acres of which 180,000 acres are used for agricultural

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crops. The flood problem area is nearly equally divided between the main stem and the tributaries. Average annual flood damage is estimated to be $2.7 million.

Model Selection

A computer program was required to model the Kankakee River Basin for determining hydrologic effects of several proposed channel changes, new levees, and detention structures. Conventional use of the Soil Conservation Service hydrology computer program, TR-20, was not practical because of these Basin characteristics:

*Size - 5,000+ square miles, difficult to adequately power by rainfall

*Large base flow - coarse textured soils, high water table, difficult to separate floods

*Main stem routing problems - very low gradient, much flood water storage but virtually no downstream conveyance in flood plains

Positive aspects of the TR-20 program include these features:

*Read-in hydrographs

*Store and process hydrographs

*Develop hydrographs from mass runoff tables

*Flood route by both storage-indication and convex methods

Previous Kankakee Basin investigations prompted adaptations to TR-20 for modeling the main stem hydrology with use of historic flood hydrographs as the principal input. An extensive Kankakee River Basin stream gage network yields information regarding high and low flows, discharge-duration, volume-duration, and stage-discharge. See Plate 1, Hydrologic Data Network, for location of the stream gages.

FEATURES OF STUDY

Modeling the main stem Kankakee River and tributaries required two different techniques. The goal was to synthesize hydrographs of flood flows for existing condition and for structural improvement conditions.

Kankakee River Hydrographs

The "Dodson Report"(1), prompted use of routing techniques described below. Dodson successfully synthesized hydrographs of historical floods by manual methods at Kankakee River stream gages using the storage-indication method for routing. For the more recent study stage-discharge and stage-storage data were updated based on station rating curves and recent topographic maps with data processing being done by computer.

Main stem stream gages are located about every 20 miles. These gage locations were used as floodwater detention structure sites. The Kankakee valley supports this assumption as gages are at comparitively narrow flood widths, with expanded flood widths upstream of each. Flood plain gradient is less than one foot per mile with virtually no downstream flow outside of the channel(3).

MAIN STEM STREAM GAGES

Location	River Mile	Drainage Area
		sq mi
North Liberty	126.91	174
Davis	110.94	537
Dunns Bridge	90.83	1352
Shelby	67.87	1779
Momence	47.33	2340

Hydrographs for local drainage between Kankakee River stream gages at Momence, Shelby, Dunns Bridge, Davis, and North Liberty, and for the area upstream of North Liberty were taken from the Dodson supporting data file. Origin of these hydrographs (the Kankakee locals) was the tributary, Singleton Ditch, where records from three stream gages were chosen selectively for the Kankakee River local drainage areas. Hydrographs for the Kankakee locals were developed by adjusting the volume of the selected gaged area hydrographs. No adjustment was made in form or duration of runoff. The three gaged watershed records used were selected in a weighted proportion according to estimates of watershed characteristics. Observed hydrographs at North Liberty were altered during this study so that they represented inflow hydrographs to the local drainage area without effects of temporary storage. Alteration was done by "upstream flood routing" using the storage indication method. Seventeen annual events, 1950 through 1966, were used. This period included a wide range in size of flood events.

Stage-discharge-storage ratings at the gage stations were developed from these data:

Water surface profile computations

Historic discharge-profile information

U.S.Geological Survey stream gage rating curves

Valley cross-section surveys

Computations involved summing the upstream inflow hydrographs and flood routing this total hydrograph by the RESVOR subroutine (storage-indication method). Routings through these gages were completed for existing condition and for alternate structural conditions using the annual flood for each of the 17 years, 1950 through 1966.

Project alternatives involving modification of channels, and/or levees, required updating stage-discharge and stage-storage ratings. Structure data at the gages were changed to reflect the stage-discharge-storage condition under investigation. Dodson local hydrographs were not altered. Each improved condition alternative was hydrologically tested with the same floods used in existing condition runs.

Tributary Hydrographs

Tributaries to the Kankakee River in Indiana are among the lower peak producing streams in the state. Factors which affect the amount and rate of runoff include: topography, soils, channel condition, and land use and treatment.

Tributary hydrology was performed to provide a basis for economic flood damage analysis along tributaries, and to determine effects of tributary improvements upon Kankakee River flow-frequency.

Using the 17 annual floods, 1950-1966, a complete hydrology analysis was made on 20 tributaries to the Kankakee River. Peak-frequency data were developed for existing and improved conditions. Improved condition primarily involved channel excavation and a few detention structures.

The TR-20 program was used to compute local runoff hydrographs (RUNOFF), flood route these downstream (REACH), flood route detention structures (RESVOR), and add hydrographs (ADDHYD). Use of the subroutine, SUBHYD is described below.

The Dodson local hydrographs were used as basic data for the rain tables. Hydrographs were converted to mass volume tables. These were considered mass runoff curves for the drainage area which the original hydrograph represents. A refinement was necessary before these mass curves were suitable for rain table use. Each table was then organized into rainfall bursts. The bursts were positioned in time to occur shortly before the peak of each rise in the runoff hydrograph. Coupled with time of concentration and reach routing effects these refined rain tables proved very satisfactory for tributary hydrology studies. Of course, Runoff Curve Number 100 was required for conservation of mass.

Local hydrographs for Dunns Bridge, Davis, Shelby and Momence are so similar in shape and timing that the mass curves developed for rainfall at Dunns Bridge were then used for the other above named local areas. Volumes were corrected for each local area. An example of a refined rain table as used for TR-20 modeling is displayed by Table 2, Shelby Local Cumulative Rainfall. Note the three distinct rainfall bursts which historically occurred and are responsible for three humps in the Shelby local hydrograph for that flood.

Tributary routings were computed so that both existing condition and improved condition for all 17 floods were done for a tributary by the same computer run. Cross-sections were named by numbers less than 100 for existing condition and by the same number plus a one in front for the improved conditions. Thus a Standard Control for the TR-20 was written for each tributary watershed to direct the computations through both conditions. Using an innovation, SUBHYD, a subroutine for subtracting hydrographs, the existing condition hydrograph at the foot of each tributary was subtracted from the improved condition hydrograph for each flood. This remainder (delta) hydrograph represents effects caused by changes in tributary hydrology upon the main stem flood hydrograph. Selective use of the "deltas" for desired combinations of tributaries being improved allowed efficient testing of effects upon main stem flood flows.

For each alternative studied, peak flood discharges for the 17 annual events were used to establish a peak-frequency relationship. A widely used conversion table to convert annual series data to partial duration data was used to adjust for economic analysis.

CONCLUSIONS

Results of the existing condition routings were compared with historic records. Synthetic routings compare very closely with the record data such that essentially no important difference in hydrograph form was noted and the peaks when submitted to a frequency analysis result in nearly the same peak-frequency relation. See Plate 2 and Table 3. These data show synthesized floods for existing condition are consistently in close agreement with historical records. Therefore, strong confidence was placed in computed estimates for alternative conditions tested.

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(4) U.S.D.A. Soil Conservation Service, Revised May 1983, TR-20 Computer Program for Project Formulation - Hydrology.

TABLE 1 - ANNUAL FLOODS

Water Year	Beginning Date	Ending Date	Starting Time
			hour of month
1950	April 1	April 30	0
1951	February 11	February 26	240
1952	January 14	January 25	312
1953	March 11	March 20	240
1954	April 20	May 5	456
1955	October 9	October 24	192

Partial listing of the 17 annual floods 1950 through 1966.

TABLE 2 - SHELBY LOCAL CUMULATIVE RAINFALL (abbreviated)

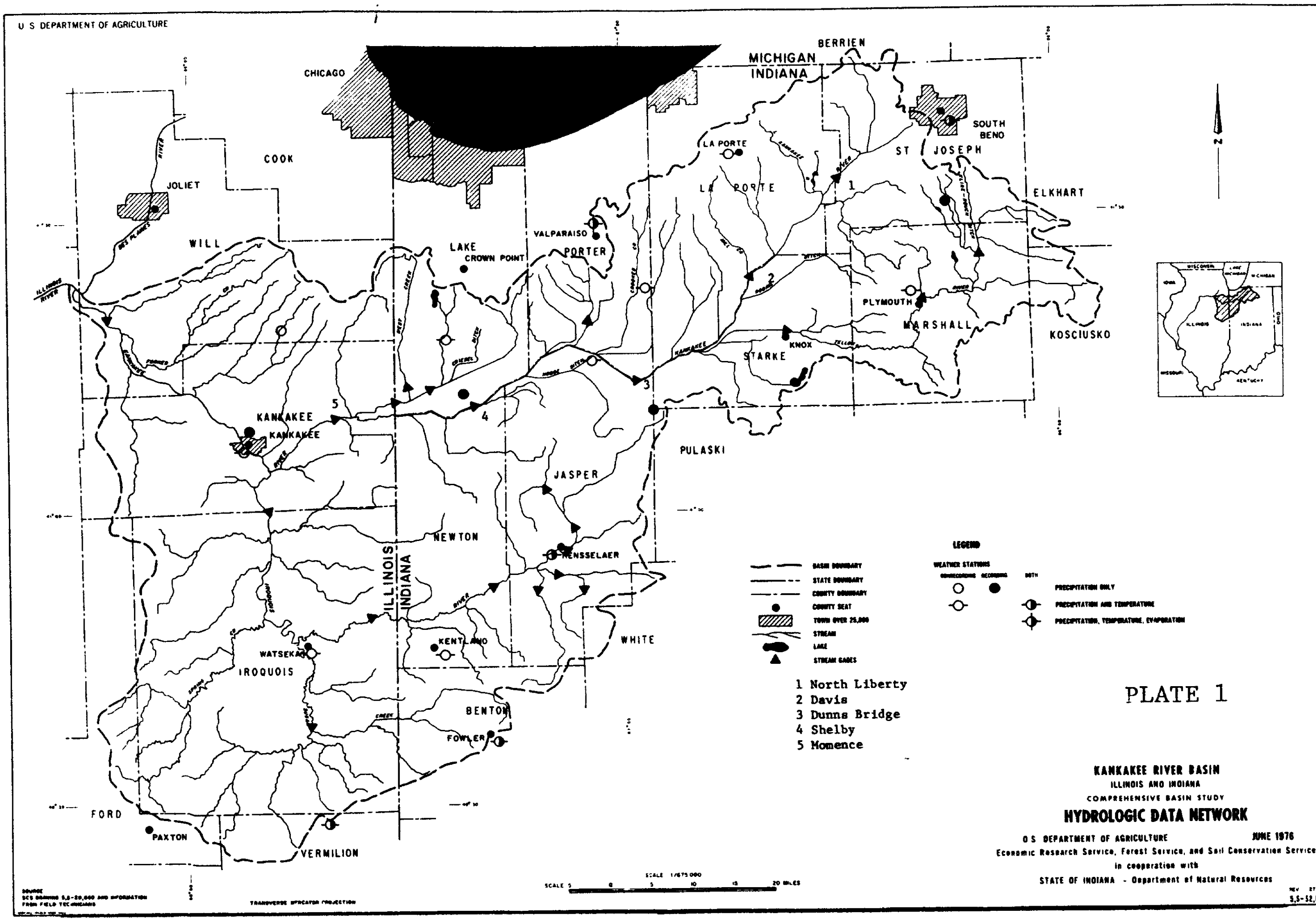
Time	Depth (time increment 7.2 hours)				
hour			inches		
36.0	.12	.56	.91	1.08	1.08
~					
180.0	1.09	1.61	1.94	2.09	2.19
~					
518.4	2.33	2.44	2.91	3.22	3.34

Partial table of mass runoff showing rainfall bursts during the April 1950 flood period. Complete table used as RAINFL table in TR-20 with Curve Number 100 for tributaries in Shelby local area.

TABLE 3 - KANKAKEE RIVER PEAK COMPARISON (cfs)

Return Period	Stream Gage Location			
years	Davis	Dunns Bridge	Shelby	Momence
2	1140[1]	3320	4090	6400
	1200[2]	3500	3850	6300
10	1410	4620	5270	8270
	1490	4830	5050	8120
50	1530	5490	5870	8890
	1630	5790	5810	8840

[1] Observed station record   [2] Synthesized by TR-20



RECONSTITUTION OF OCTOBER 26,1954 FLOOD

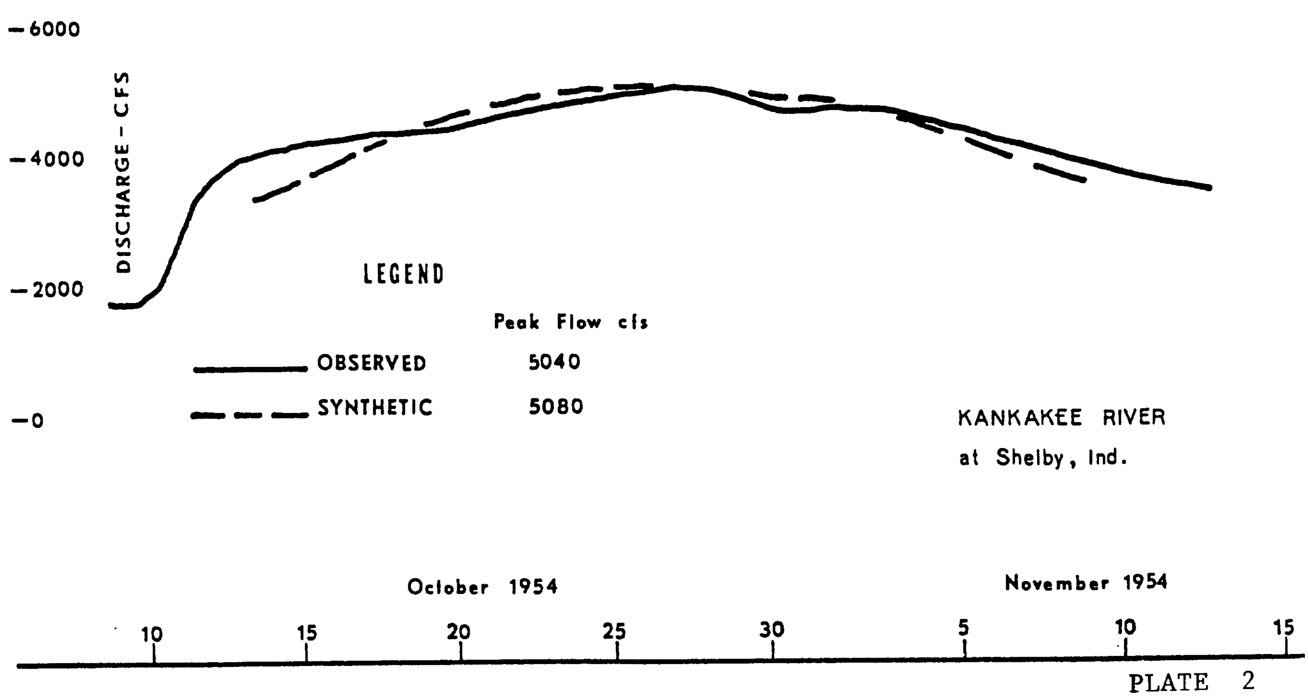


PLATE 2

MULTI-DIMENSIONAL ANALYSIS OF A SURFACE COAL MINE

Judith Schenk, Keith Kirk and Alan Wilhelm[1]

ABSTRACT

The relationship between geochemical properties of overburden material and post-mining hydrogeology at a mine site was explored using multi-dimensional data analysis. Three-dimensional analysis of geochemical data of overburden material indicates acid-producing material in the overburden will generate sulfuric acid and mobilize dissolved iron into the ground water. Results of a ground-water model indicate steady-state water levels in the reclaimed mine pit will be reached in approximately eight years. We assumed post-mining disturbed overburden material (mine spoil) will occupy the same relative position in the mined-out area as currently observed in the undisturbed overburden. A merged data display that includes transient water levels and three-dimensional analysis of geochemistry of the overburden material indicates 1.39 million cubic meters of acid-producing material will be exposed to oxidation, generating sulfuric acid and leaching iron during the eight years the mine spoil is filling with water. Approximately 0.47 million cubic meters of acid-producing material will remain above the water table when steady-state water levels are reached. This unsaturated portion of acid-producing material will be exposed to oxidation as water moves through this zone to the water table.

INTRODUCTION

We explored the relationship between geochemistry of overburden material overlying a coal deposit and rising water levels in a surface coal mine located in the southeastern United States. Analysis of the mine site required an integrated study of hydrogeological and geochemical processes at the site. This study has three components: hydrogeological analysis, geochemical analysis and a combined analysis of hydrogeological and geochemical information. Integration of the temporal data of simulated water levels from the ground-water model and three-dimensional data of overburden quality were merged to provide a multidimensional analysis of post-mining conditions at the mine.

GROUND-WATER MODEL

Ground-water Model Overview

A two-dimensional finite-difference ground-water flow model of the mine was constructed using the U.S.G.S. ground-water modeling

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code, MODFLOW (McDonald and Harbaugh, 1988). The purposes of constructing the ground-water model are: a) estimate post-mining transient and steady-state ground-water levels in the mine, b) estimate when steady-state water levels will occur, and c) determine the spatial and temporal relationship between acid-producing material in the overburden and water levels in the mine.

A finite-difference grid of 38 rows and 19 columns overlies the area with active cells being those that overlie the mine area (Figure 1). Each grid cell is 61 meters by 61 meters. The following parameters were examined to construct the ground-water model of the mine: a) physical boundaries of the system, b) recharge and discharge of water in the mine, and c) hydraulic parameters of the mine spoil.

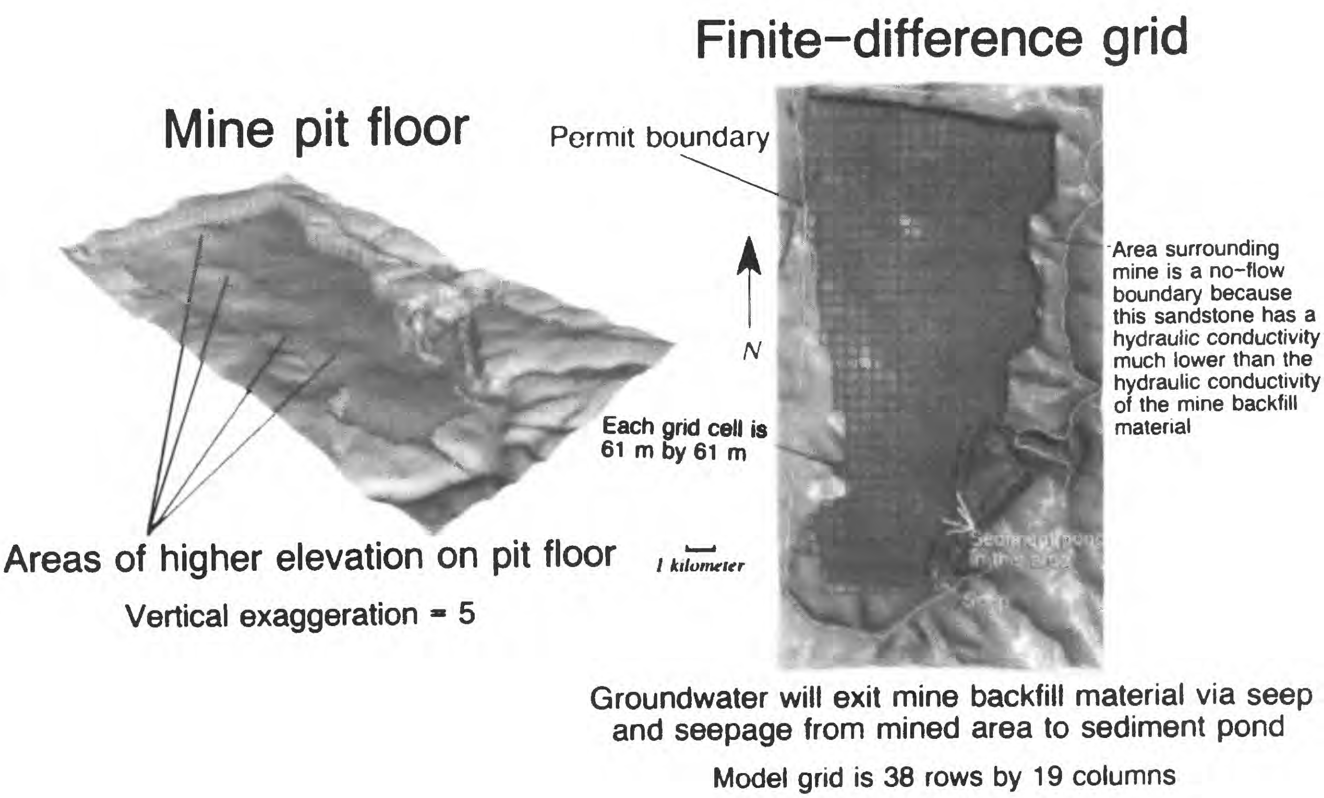

Figure 1. Mine area ground-water model grid and location of the sediment pond and ground-water seep.

Physical Boundaries

We assumed the surrounding parent rock, composed of sandstone and shale, has a hydraulic conductivity much lower than the hydraulic conductivity of disturbed overburden material backfilled in the mined area (mine spoil). Therefore, the highwall of the mine constitutes a no-flow boundary to the mined area because the amount of seepage out of the mine into the surrounding parent rock is much less than seepage that will occur in other areas disturbed from mining in previous years (see "Recharge and Discharge" below). The mine pit floor, composed of shale, constitutes a second no-flow boundary. Areas of higher elevation on the pit floor will obstruct movement of ground water as the mine spoil fills with water (Figure 1).

Recharge and Discharge

A recharge rate, estimated by the mining company, of 30.5 cm yr^{-1} ($9.7x10^{-7}$ cm s^{-1}) was used in the ground-water model. Ground water exits the mine in the southeast area by seeping into a sediment pond (Figure 1). This sediment pond is located in a reclaimed area that has been mined in previous years. A seep discharges at the southeast corner of the mine into the adjacent river in the reclaimed area (Figure 1). We consider these the principal post-mining discharge areas for ground water.

Hydraulic parameters

No data were available to determine hydraulic characteristics of the mine spoil. The mining company claims that most of the acid-producing material will be saturated when the reclaimed mine area fills with water. Simulation of the mined area filling with water with a recharge rate of 30.5 cm yr^{-1} requires a hydraulic conductivity value of .018 cm s^{-1} to be used in the ground-water model.

Water percolating through unsaturated mine spoil will result in oxidation of the acid-producing material producing sulfuric acid and mobilizing iron into the ground-water. Therefore, simulating saturation of a large portion of mine spoil is favorable to the mining company's claim that much of the acid-producing material will be saturated and not exposed to oxidation as oxygen levels in the mine-spoil aquifer decrease. In reality, based on the composition of the mine spoil which is approximately 50% sandstone and 50% shale, hydraulic conductivity of the mine spoil is probably greater than .018 cm s^{-1} (Hawkins and Aljoe, 1991, 1992), and water levels will most likely be lower in the mine at steady state. A specific yield of 0.2 was used in the transient simulation.

Ground-Water Model Simulations and Results

Because the ground-water regime is currently in a transient state and most of the mined area is currently dry, the ground-water model was run in reverse. A steady-state model run was completed to determine the water level in the mine-spoil aquifer at steady state. A transient simulation was done by using steady-state water levels as starting water levels and removing water at a recharge rate of -9.7×10^{-7} cm s^{-1} (30.5 cm/yr).

Comparing present day water levels in wells located in the mine spoil to the ground-water model results indicate steady-state conditions will be reached in eight years (Figure 2). Therefore, assuming the recharge rate of 30.5 cm yr^{-1} and that the mined area will fill with water, steady-state water levels will be reached in the year 2001.

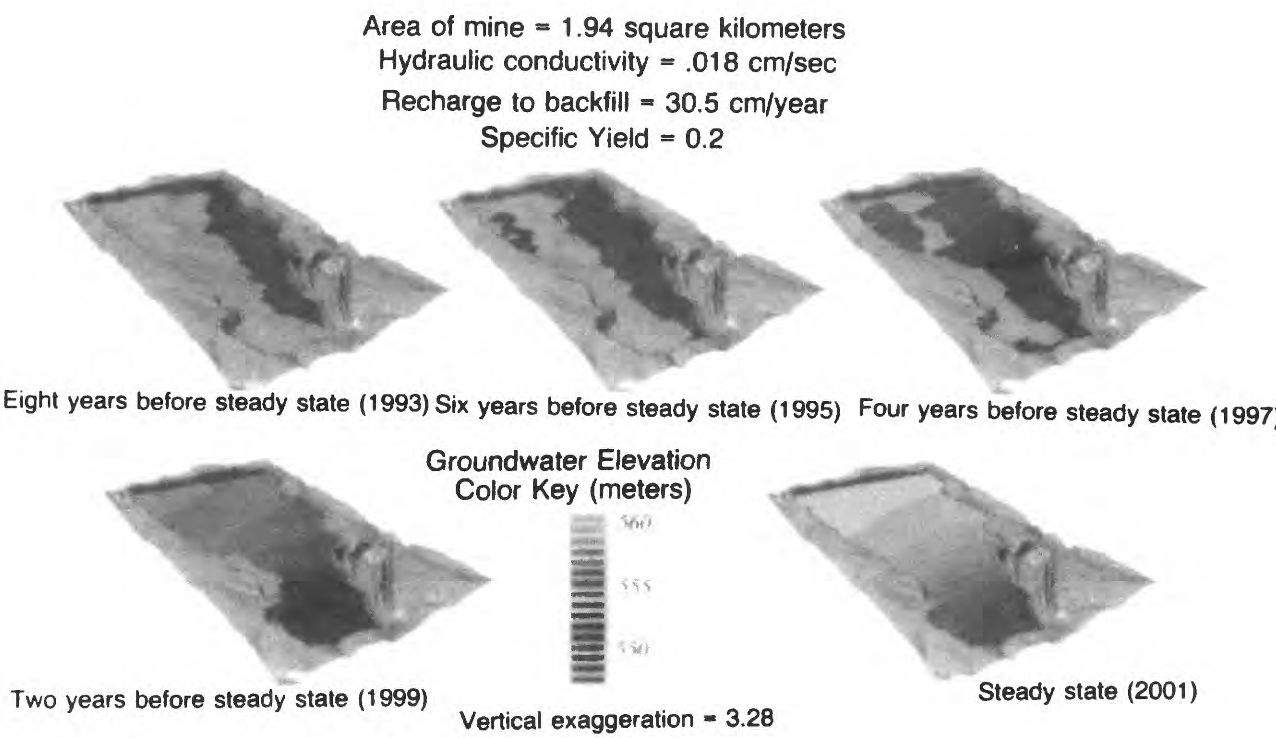

Figure 2. Simulated transient water levels in mined-out area.

THREE-DIMENSIONAL ANALYSIS OF GEOCHEMICAL DATA OF OVERBURDEN

Multi-dimensional analysis was used to quantify the three-dimensional spatial distribution of geochemical data of undisturbed overburden material in the northern area of the mine (Figure 3). Data include a three-dimensional location tied to a global coordinate system (easting, northing, elevation), and geochemical data or net acid/base potential (NAB) measured in tons calcium carbonate equivalent per kilotonne of overburden ($tCaCO_3$ kt^{-1}). If NAB is less than -5 $tCaCO_3$ kt^{-1}, the overburden material is considered to be acid-producing and there is a likelihood of the mine spoil to generate sulfuric acid and dissolved iron in the ground water through the oxidation of pyrite (Perry, 1985; Skousin, Sencindiver and Smith, 1987).

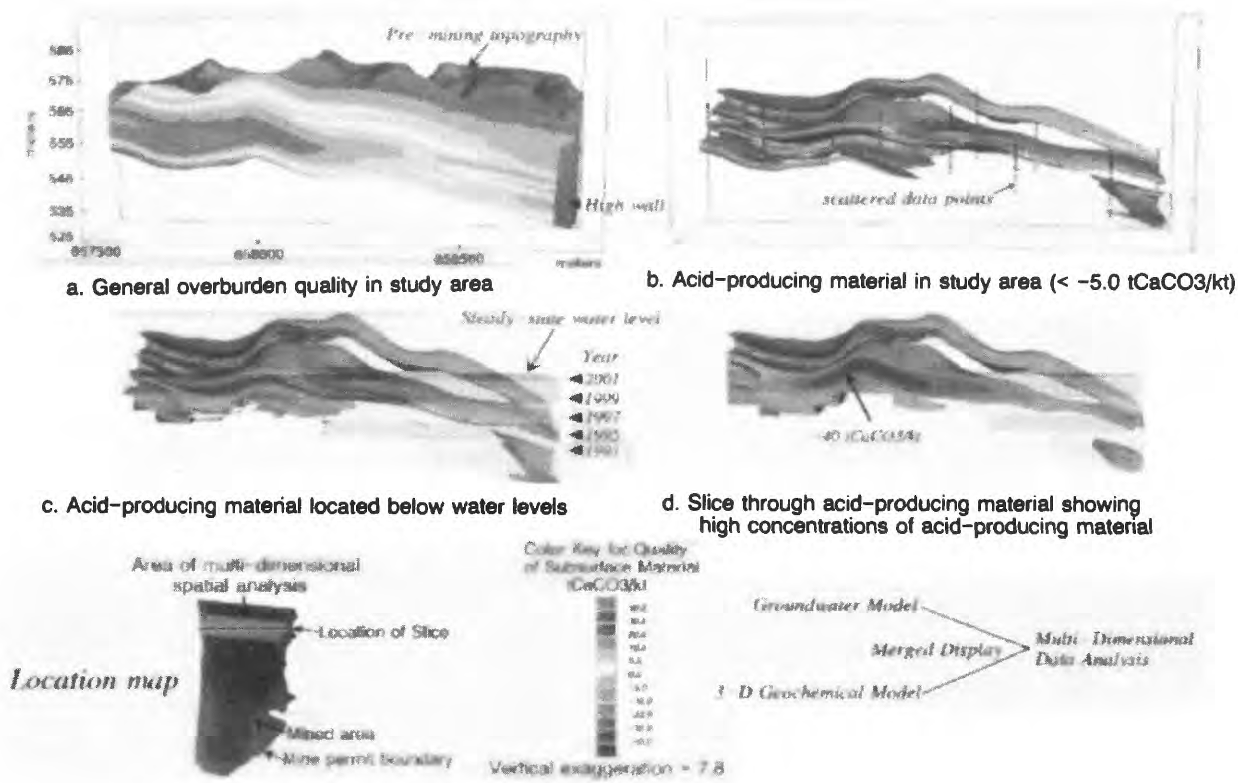

Figure 3. Multi-dimensional analysis of ground-water model results and overburden quality.

Undisturbed distribution of acid-producing material at the site is controlled both by paleodepositional environment and local geologic structure. To account for geologic structure, elevations for bottom of the coal seam obtained from bore hole data were used to create a two-dimensional structure contour grid (easting, northing, elevation). This two-dimensional grid was used to control the three-dimensional grid of acid-producing material so that it conformed to local geologic structure. Three-dimensional spatial distribution of acid-producing material was determined by creating a three-dimensional grid (easting, northing, elevation, NAB) representing the distribution of NAB in the subsurface above the coal (Figure 3a).

The display can be manipulated so that three-dimensional contours in space can be examined. The visual display shows qualitatively a considerable proportion of overburden contains acid-producing material as illustrated by exposing the -5 $tCaCO_3$ kt^{-1} contour (Figure 3b). Using the volume calculation in the gridding software, total volume of the acid-producing material in this area of the mine is 2.06 million cubic meters.

MERGED DATA DISPLAY AND COMBINED ANALYSIS

The relationship between temporal data of transient and steady-state ground-water levels, topography, geologic structure and spatial distribution of acid-producing material is critical to quantify potential hydrogeologic impacts. These interrelationships were quantified by creating a multi-dimensional model that includes each of these components. This merged model allows determination of volumes of material with various NAB concentrations between structural zones and within transient time periods, and simultaneously quantifies spatial relationships between all of these variables.

Generation of sulfuric acid and mobilization of dissolved iron from acid-producing material in the mine spoil requires the presence of oxygen. Once oxygen is removed from the reaction process, the rate of oxidation of pyritic material is greatly reduced. Therefore the operational recommendation is to place acid-producing material below the water table to reduce contact with oxygen. However, some oxygen will remain in solution within the ground water through infiltration from precipitation. Therefore, not all pyrite oxidation will be stopped.

The spatial relationship between pyritic material and steady-state and transient ground-water levels is required to determine how much pyritic material will remain above the ground-water table and for how long. This spatial relationship was quantified using a merged display of the three-dimensional model of geochemical (NAB) data and three-dimensional ground-water model (two-dimensional flow through time).

Results of Multi-Dimensional Analysis

Results of the multi-dimensional spatial quantification indicate that of the 2.06 million cubic meters of acid-producing material, approximately 0.47 million cubic meters will remain above the steady-state ground-water table and 1.39 million cubic meters will eventually be below the steady-state ground-water level (Figure 3c). This is a conservative estimate because the analysis assumes that the mine will fill with water. More of the acid-producing material may be above the steady-state ground-water level.

Assuming that the recharge rate is 30.5 cm yr^{-1} and that the mined area will fill with water, steady-state water levels will occur in approximately 8 years from the present. Successively smaller portions of the 1.39 million cubic meters will be exposed to oxidation during that time period. Sulfuric acid and dissolved iron will be added to the hydrogeologic system and contaminate ground water and surface water. Acid-producing areas of up to -40 $tCaCO_3$ kt^{-1} are found in the overburden (Figure 3d).

CONCLUSIONS

Multi-dimensional analysis of spatial and temporal data for this site allowed practical engineering and regulatory conclusions to be made in a reasonable amount of time. The analysis for this site enabled us to demonstrate convincingly that mining practices needed to be modified to reduce impacts on the hydrogeologic system. Multi-dimensional analyses have proven to be an invaluable planning tool for predicting environmental consequences related to coal mining.

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SECTION 6

HYDROLOGIC MODELING SYSTEMS

Page

Modeling for Water Supply Forecasting in the West
David C. Garen 6-1
Computer Modeling of Alpine Stream Diversions
T.M. Brady, and L.A. Martin 6-9
Automating Detailed System Regulation Studies
Douglas D. Speers, Gary R. Flightner, and Peter F. Brooks 6-18
NEXGEN-HEC's Next Generation Software Development Project
Arthur F. Pabst 6-26

Figures and Tables

Computer Modeling of Alpine Stream Diversions 6-9

Figures: 1. Stream blow-out caused by anchor icing 6-10
2. Proposed final diversion with vegetation 6-12
3. Wetland area for stream diversion 6-12
4. Plot of channel design characteristics 6-15

Table: 1. Manning's Equation (French, 1985, table 4.8) 6-14

Automating Detailed System Regulation Studies 6-18

Figure: 1. Schematic of the Columbia River System 6-21

NEXGEN HEC's Next Generation Software Project 6-26

Figures: 1. NexGen Hydrologic Modeling System 6-31
2. Hydrologic Component-Class Hierarchy 6-32
3. Hydrologic Modeling System-Object relationships 6-33

MODELING FOR WATER SUPPLY FORECASTING IN THE WEST

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ABSTRACT

The USDA Soil Conservation Service (SCS) is one of several federal agencies providing seasonal streamflow volume forecasts in the western United States. In an effort to improve its services and offer additional forecast products, the SCS has been improving regression forecasting techniques and has begun developing the capability to use conceptual hydrologic models. The new regression techniques can give significantly greater forecast accuracy than past practice, especially early in the forecast season. Conceptual modeling capability has begun with the development of a mean areal precipitation and temperature procedure based on an explicit accounting for orographic effects and optimal interpolation (kriging). Model comparison studies and experiments are currently underway to identify a model to implement that is appropriately conceptualized for this application and can be easily and robustly calibrated. The model will be used in a workstation-based, windowing computer environment. Future work will involve the development of stochastic precipitation and temperature models that will provide the future climate scenarios to use as input to the hydrologic model for the forecast period, and the development of decision support tools to enhance agricultural water management based on streamflow forecasts.

INTRODUCTION

Most of the streamflow in Western streams originates as snow accumulated during the winter. Measurements of the snowpack make it possible to forecast the amount of streamflow that will occur when the snow melts during the spring and summer. This type of forecasting, usually called water supply forecasting, is the prediction of the volume of water passing a given point on a stream for a specified season of the year. The season is a period of months during which the bulk of the streamflow usually occurs.

Water supply forecasting in the West is done by a number of federal and state agencies. Most water supply forecasts issued to the public are produced by a cooperative effort of two agencies: the USDA Soil Conservation Service (SCS) and the National Weather Service (NWS). Other agencies involved include the U. S. Bureau of Reclamation, U. S. Army Corps of Engineers, Bonneville Power Administration, and California Department of Water Resources.

Water supply forecasts are a key ingredient in the management of surface water resources in the West. The SCS is involved in streamflow forecasting primarily to aid agricultural water management. The SCS's principal client base includes irrigation districts, reservoir managers, and individual farmers, although many others also use the data and forecasts. As demands on Western water resources continue to grow, the value of accurate forecasts increases, and the need for more detailed hydrologic information than just the

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seasonal streamflow volume increases. In an effort to provide better services to its customers, the SCS has been developing improved forecasting techniques in two arenas: better seasonal volume forecasting techniques, and the use of conceptual hydrologic models. The SCS's activities in these areas are described below.

IMPROVED SEASONAL VOLUME FORECASTING TECHNIQUES

Most seasonal streamflow volume forecasts are produced using multiple linear regression equations. Input data for these equations include snow water equivalent, precipitation, and antecedent streamflow. Standard practice (Soil Conservation Service 1972) has been to aggregate like data types for several stations and/or measurement dates into weighted sums to produce indexes, which became the independent variables in the regression. A single equation was calibrated using observed data through the end of the forecast period, and this equation was used in all months that forecasts were made. For many forecasts, particularly early in the season, some of the input data were unknown because they were in the future, necessitating the substitution of long-term averages for the future variables.

Recent research has shown that this traditional approach has not realized the maximum forecast accuracy obtainable from regression (Garen 1992a). Seeking maximum accuracy in regression-based forecasts is useful because: (1) regression is still the primary method used for water supply forecasting; (2) the use of conceptual hydrologic models on a widespread basis is still several years away; and (3) regression forecasts provide a baseline level of accuracy against which to test conceptual models.

Several techniques can help provide superior forecast accuracy using regression models: (1) basing the regression model only on data known at forecast time (no future data); (2) principal components regression to deal with intercorrelation among independent variables and to eliminate the need to build indexes; (3) cross-validation to test the forecasting ability of regression models; and (4) systematic searching for optimal or near-optimal combinations of variables. Garen (1992a) has shown that these techniques can give substantial improvements in forecast accuracy over traditional procedures, especially early in the forecast season. These regression techniques are now being used by the SCS for all new forecast equation development.

Another way regression models have been improved is by using the Southern Oscillation Index (SOI), an index of large-scale atmospheric circulation associated with the El Niño, as a predictor variable. Recent work has shown that there exists a relationship between the SOI and weather and streamflow in the Northwest and Southwest (Cayan and Peterson 1989; Koch et al. 1991; Redmond and Koch 1991). SOI values from the previous summer and fall have a moderate, but significant, relationship to spring and summer streamflow (correlation coefficients in the approximate range 0.3 - 0.6). By providing an index of future weather, the use of the SOI as a regression variable affords an opportunity to increase forecast accuracy, particularly early in the forecast season.

HYDROLOGIC MODELING

Goals of Modeling

The potential for the use of conceptual hydrologic models in water supply and long-range streamflow forecasting has been suggested by a number of authors (e.g., Day 1985). The SCS's goals in using such models include: (1) improve the accuracy of seasonal streamflow volume forecasts; (2) produce streamflow forecasts with a finer time resolution than seasonal, i.e., daily and/or monthly; (3) produce additional forecast products, such as peak flow, low flow, and flow duration forecasts; (4) produce streamflow scenarios for reservoir and irrigation system simulations; and (5) demonstrate the use of forecasts of differing time resolution and accuracy in reservoir operations and water management decision making. Again, the SCS's main focus is to provide this information to facilitate improved agricultural water management, but certainly others can also benefit.

Modeling Prerequisites

There are three immediate prerequisites to achieving the aforementioned modeling goals. First is a technique to provide mean areal precipitation and temperature model inputs, in which observed elevation effects and spatial correlations are explicitly incorporated. Second is a hydrologic model that is appropriately conceptualized and can be calibrated robustly and with a reasonable amount of effort. Third, a convenient computer hardware/software environment is needed for rapid execution of the model and display of its results. These topics are discussed below.

Mean Areal Precipitation

Whether a watershed is modeled as a single unit, divided into elevation zones, or divided into homogeneous hydrologic units, mean areal precipitation (MAP) over all or sub-areas of the watershed is required. The classical techniques of estimating precipitation at a point include the normal-ratio method and inverse-distance-squared weighting method; the classical techniques for estimating MAP include Thiessen polygons and the isohyetal method (Linsley et al. 1975). While these techniques are relatively simple and straightforward, they have simplistic assumptions about the spatial correlation and variability of precipitation, do not handle orographic effects well, can be subjective, and are not necessarily optimal.

A more recent technique for estimating MAP is the use of detrended kriging. Kriging is an optimal spatial interpolation procedure for estimating the values of a variable at unmeasured points from nearby measurements. It can be used to estimate precipitation at numerous points on a rectangular grid throughout the watershed, and these values can be arithmetically averaged to obtain MAP. The grid is most conveniently established using a geographic information system, although it can also be done manually using maps. Each grid point is characterized by its location (latitude and longitude or rectangular coordinates) and elevation.

Kriging has been applied to the estimation of MAP by number of authors; Chua and Bras (1982), Dingman et al. (1988), and Phillips et al. (1992) used it in mountainous areas, where orographic effects are important, as in the West.

All of these previous applications, however, dealt with estimating MAP for a single storm or for annual totals, and none attempted to develop a daily time series of MAP. With the additional considerations required for daily MAP (Garen 1992b), the basic procedure is described below.

First, time-varying linear precipitation-elevation relationships are calculated using data from the available gages in or near the watershed of interest. The SCS's SNOTEL network is the main source of high elevation data in the West; low elevation data are usually supplied by NWS cooperative network sites. It was felt that daily precipitation-elevation relationships might be subject to large fluctuations and instability, so to ensure that the relationships are robustly estimated, the precipitation data are aggregated into consecutive periods of 7, 14, or 28 days in length, or aggregated into storm periods. The same relationship is applied to all days within each period. The choice of an aggregation period depends on the precipitation regime (frequency and amount of precipitation, consistency of storm tracks, etc.). Preliminary results using data from the Agricultural Research Service's Reynolds Creek experimental watershed in southwestern Idaho indicate little difference among the aggregation periods. This aspect is still under investigation.

Another nuance concerning the precipitation-elevation relationships is that the basin may need to be divided into regions if the orographic effects vary within the basin. For example, Hanson (1982) found that different precipitation-elevation relationships hold for the windward and leeward sides of topographic barriers in the Reynolds Creek watershed. In many watersheds, however, there are insufficient precipitation gages to define such differences very well, so spatial groupings are not warranted.

After the precipitation-elevation relationships are calculated, the residuals are obtained by subtracting these trends from the observed daily precipitation data. This results in detrended precipitation values, which are the data used by the kriging algorithm.

The spatial correlation structure of precipitation is modeled in kriging by the variogram. This is an empirically-derived function describing the dependence of the variable of interest with distance. In this work, a linear variogram is used, denoting a general decrease in the correlation of precipitation residuals with increasing distance between gages, within the spatial scale of a watershed.

In kriging, the quantity at an unmeasured point is estimated as a weighted sum of the measured values, where the sum of the weights is unity. The weights to be used on each measurement to estimate the quantity at an unmeasured point are determined by solving a system of linear equations, the coefficients of which are derived from the variogram and the distances among the locations of the gages and the location of the unmeasured point. In this work, each grid point has a different set of weights to be applied to the precipitation measurements.

The weights are used to calculate an estimated precipitation residual at each grid point for each day from the residuals at the gages. Using the grid point elevations, the linear trend is then added back in to give the estimated precipitation at the grid points. The arithmetic average of the grid point precipitation values for each day gives the daily MAP time series. If the watershed has been divided into elevation bands or other subunits, this process is done separately for each sub-area, using only those grid points that fall within the area. Each sub-area, then, has its own MAP time series.

Mean Areal Temperature

The estimation of mean areal temperature (MAT) is entirely analogous to the estimation of mean areal precipitation, hence the same procedure can also be used for temperature. These two are the primary inputs for hydrologic models. A similar procedure, however, could also be used for other quantities if desired.

Model Conceptualization, Parameterization, Calibration, and Forecast Accuracy

Conceptual hydrologic models have been used successfully for many years to produce streamflow foreasts for water management and flood warning purposes. Until recently, however, the SCS has only dabbled in the application of these models. An initial step for the SCS, then, has been to review models currently used by others. Two models widely used in the West are: the National Weather Service River Forecast System (NWSRFS) snow and soil moisture accounting modules (Anderson 1973; Burnash et al. 1973), and the Streamflow Synthesis and Reservoir Regulation (SSARR) model (U. S. Army Corps of Engineers 1987). Another model, used for similar purposes in Sweden, is the HBV model, developed by the Swedish Meteorological and Hydrological Institute (Bergström 1992). These models, plus experimental ones developed by the SCS, are being reviewed with respect to their conceptualizations, the ease with which they can be calibrated, and their forecast accuracy.

Model conceptualization and parameterization are related to the ability to calibrate the model and obtain robust parameter values. This is a critical issue both for theoretical and practical reasons. Theoretically, if a model is overparameterized or its conceptualization is overly complex, it is not possible to obtain unique parameter values; many sets of parameter values give equally good calibration fits to observed streamflow. The difficulties in calibrating hydrologic models have been discussed in the literature and are well-recognized (Johnston and Pilgrim 1976; Gupta and Sorooshian 1983; Sorooshian and Gupta 1983; Hendrickson et al. 1988; Duan et al. 1992). If a model cannot be robustly calibrated, it calls into question the validity of the model structure and the ability of the model to produce accurate forecasts. One must be realistic in how many parameters one can expect to estimate in the standard forecasting situation of using precipitation and temperature as input and matching the model results with streamflow at the watershed outlet. From a practical viewpoint, it is necessary to have a model that can be calibrated relatively quickly and easily, so that a model calibration does not have to involve a major expenditure of time. This necessitates an automated parameter optimization capability that can find parameter values requiring little, if any, adjustment; manual calibrations are too time consuming as well as non-optimal.

To explore these issues, model comparison studies have been and will continue to be conducted. One study compared monthly and seasonal streamflow forecasts from regression, a simple monthly streamflow model, and two daily conceptual hydrologic models for three watersheds in Idaho and Montana (Garen 1992b).

For these basins, regression still provided the most accurate forecasts, followed by the monthly model, then the daily models. There are several possible explanations for these results, but the study pointed out the need for further investigation into the models used and the conditions under which each forecasting method is most appropriate. A study currently underway, conducted jointly by the Agricultural Research Service and the SCS, involves the application of hydrologic models to the Big Wood River in central Idaho. The first step is a conventional application of the NWSRFS models using valley precipitation and temperature stations and manual model calibration. A second step will be to recalibrate the models using the MAP and MAT input data developed by the techniques described herein. A third step will be to use the HBV model and a simple experimental daily hydrologic model developed by the SCS. This study will help verify the MAP and MAT procedure and will help identify the forecasting abilities of the relatively complex NWSRFS models and the simpler HBV and SCS models.

These model studies are necessary to establish which model(s) to implement and under what circumstances conceptual modeling (as opposed to regression) is appropriate. If there are trade-offs between forecast accuracy and time resolution of streamflow, these need to be elucidated so that the forecast information provided to the user is properly matched with the decision making process to effect optimal water management.

Computer Environment

To use hydrologic models effectively in streamflow forecasting, it is necessary to have a computer hardware/software system that facilitates rapid execution of the model and graphical display of the results. Two such systems developed by federal agencies currently exist: the Modular Hydrologic Modeling System (MHMS), developed by the U. S. Geological Survey, and the Interactive Forecast Program (IFP), developed by the National Weather Service. These systems operate on a UNIX workstation in a windowing environment, allowing for multiple graphical displays of data and model results. The SCS will use one of these systems as the basis for its forecasting system, enhancing it as necessary. The modular structure of the software allows new functions to be added easily, making it flexible and enabling it to be tailored to any needs unique to SCS's mission.

FUTURE WORK

To forecast with conceptual hydrologic models, the standard practice is to use historically observed sequences of model inputs (principally precipitation and temperature) to produce numerous possible streamflow scenarios for the forecast period, as in the Extended Streamflow Prediction (ESP) procedure developed by the NWS (Day 1985). An alternative to using historically observed sequences is to use stochastically generated sequences. The advantage to the latter is that the parameters of the stochastic models can be conditioned on the value of the Southern Oscillation Index to introduce some knowledge of future weather patterns into the precipitation and temperature model inputs. An initial step in developing such models was taken by Koch and Garen (1992); the SCS anticipates continuing the development of these models.

It is envisioned that once the modeling system is operational, work will turn to developing decision support tools for small reservoir operation, irrigation water deliveries, and crop planning. This is done now, but only on a very limited basis. These tools will use streamflow forecasts as one of the inputs to assist reservoir operators, irrigation companies, and individual farmers improve their planning and operational decisions by explicitly describing the risk associated with alternative decisions.

CONCLUSION

The SCS is committed to providing the information needed to support wise management of Western water resources, particularly with respect to agricultural uses. As the demands on those resources increase, the need for hydrologic information and decision support tools also increases. An expansion of the SCS's capabilities in streamflow forecasting is an integral part of the ability to provide the needed information. In accomplishing these objectives, a careful, technically sound, state-of-the-art approach is being taken so that the forecast products will conform to high standards of quality and be appropriate for optimal decision making by the forecast users.

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COMPUTER MODELING OF ALPINE STREAM DIVERSIONS

by T. M. Brady[1] and L. A. Martin[2]

ABSTRACT

Researchers at the U.S. Bureau of Mines are demonstrating the use of computer-generated, three-dimensional topographic plots as design tools for planning permanent stream diversions and contours in an alpine placer mine environment. A model using computer-aided design (CAD) programs were coupled to hydrologic calculations to establish correct water flow at normal and flood stages. Regulatory and review agency personnel can then visualize the final product in three dimensions, giving them the opportunity to recommend design changes to fit permitting requirements before any earth is moved. The computer-aided design assisted the mine operators by decreasing the permit processing time, and, in this case, allowed the necessary earth-moving to be completed during the fall when the soil was dry. The success of this procedure resulted from allowing permitting and reviewing agencies to visualize the future appearance of the stream diversion.

INTRODUCTION

Problems of placer mine reclamation in mountainous areas at high altitudes are in many ways similar to problems encountered at high latitudes, including frozen ground, ice, snow, and fluvial processes. However, mountainous areas have the added problems of steep slopes and high relief, resulting in gravity-related problems of runoff and erosion (Cooke, 1990).

The continued existence of placer gold mining is a result of the high specific gravity of gold and gold's resistance to weathering, which causes its accumulation in alluvial gravels. Most gold-bearing gravels are lightly covered with fine clays, and during washing, these clay particles are freed, which affects water turbidity. Most regulatory attention has been placed on the effects of suspended clay particles in water; however, the release of suspended sediments has more far-reaching effects. Increased sedimentation results in the interstitial filling of the gravels, which affects surface-to-groundwater interrelationships, lessens the roughness factor of a stream, increases water velocity, and disrupts fish spawning beds. It has been reported that the mining of Birch Creek in Alaska has dramatically altered the surface-to-groundwater interface by lowering the groundwater table and leaving the stream perched above the phreatic water surface (Kelly, 1988).

During the course of mining, channelization occurs, which forces a stream into an unnaturally straight alignment. In terms of habitat, channelization reduces structural diversity by eliminating meanders, pools, steps, and riffles, and channel straightening leads to increased flow velocities and thus higher erosive forces (Gordon, 1992). As a result, a channel will erode.

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Erosion upstream is called head cutting. To control or eliminate head cutting, stream velocity needs to be slowed by establishing pools, riffles, pools, and steps, and by replicating stream sinuosity. In terms of habitat, bigger fish go to pools, and small benthic organisms and small fish populate the riffles (Bovee, 1974).

Researchers at the U.S. Bureau of Mines are engaged in studies that will assist mine operators to reclaim and close placer mine lands in environmentally sensitive areas in an economic and acceptable manner. One task has involved designing a permanent stream diversion for Deep Creek through a gold placer mine in eastern Oregon. The operator of the mine was having difficulty in obtaining the required state and federal permits for the diversion.

The mine operator wished to reestablish a permanent stream diversion. The first diversion attempt had been unsuccessful and had blown out from icing and high water flows (fig. 1). The operator had been providing the permitting authorities with only two-dimensional plots of topography and cross sections; however, these two-dimensional plots did not present technical data in a format that allowed visualization of the final results. Neither had the mine operator provided drawings showing how the ground would look when the stream diversion was completed. Consequently, state regulators were very skeptical about the feasibility of the mine's design for restoration of the stream.

Bureau personnel proposed using a three-dimensional, computer-aided design (CAD) programs to plan the stream diversion, after which the physical work could proceed. The programs chosen were SURFER and LANDCADD.[3] Data to be entered into the programs were collected during an on-site survey and from previous information collected by the U.S. Geological Survey. The survey information was verified using aerial photos of the site before any design work began.

Figure 1.--Stream blow-out caused by anchor icing.

[3]Reference to specific products does not imply endorsement by the U.S. Bureau of Mines.

In addition to creating a stream diversion channel that would not be eroded by flooding and freeze-thaw cycles, personnel from the U.S. Forest Service and Oregon Fish and Wildlife wished to provide a suitable habitat for fish, particularly during periods of low water flow. Criteria for fish habitat were entered into the design.

SURVEY

The initial step was to identify what information the mine had gathered and what information the computer program required. Although the mine operation had aerial stereographic photos taken earlier that year, it was found that the computer program required points in three dimensions at 10-m spacings in order to provide smooth, flowing lines on a three-dimensional plot.

Fifteen-year-old U.S. Geological Survey (USGS) topographic maps were compared to aerial photos taken earlier that year to determine the total effects of mining on the mine site. Because of the large amounts of disturbed ground, it was decided that an on-site survey should be done on the mine site. The survey would include areas where the stream was to be diverted and the unmined upstream portion of the stream. A secondary benefit, recognized later, was that a visual on-the-ground inspection allowed for an intuitive feel for the proposed diversion during the computer design process; for example, what boulders and what stream sinuosity should be incorporated into the design and how the diversion should be constructed to match the unmined portion of the stream.

Fifty key points were taken with a transit and plotted on a plane table. A benchmark from a previous survey was included for verification. X and y coordinates and elevation data were entered into the SURFER program, which takes data points in x,y,z, row- and column-format and computes them utilizing an algorithm that generates a topographic map. This map was checked against the aerial photos to verify contour heights. A proposed location for the stream was sketched onto the computer-generated topography. As part of the design, the slope was never to exceed a grade of 9 pct (which was the maximum grade of the upper stream channel). The result was a meandering path in which the stream avoided the mine pit (fig. 2).

The computer-generated topographic maps were then sent to the mine operator, who forwarded copies to the proper regulatory personnel. The agency requested one change in the plan: that the lower portion of the stream north of the pit be moved to flow into a previously excavated test hole. This test hole would act as a catch basin and might be converted into a wetland or bog in the future (fig. 3).

This change was easily implemented on the computer. The new channel diversion was sketched in a manner that did not exceed the grade specified in the design criteria (fig. 2).

STREAM DIVERSION DESIGN

Stream diversions are fairly common in placer mining. Past practice has been to create a temporary diversion while mining is underway and a permanent one after mining has ceased. However, this practice can create problems. For example, in a temporary diversion, the tendency is to route the stream through areas that might be remined or mined later. Because these areas generally contain unstable gravels, they are susceptible to erosion by flooding in the spring and ice wedging in the winter.

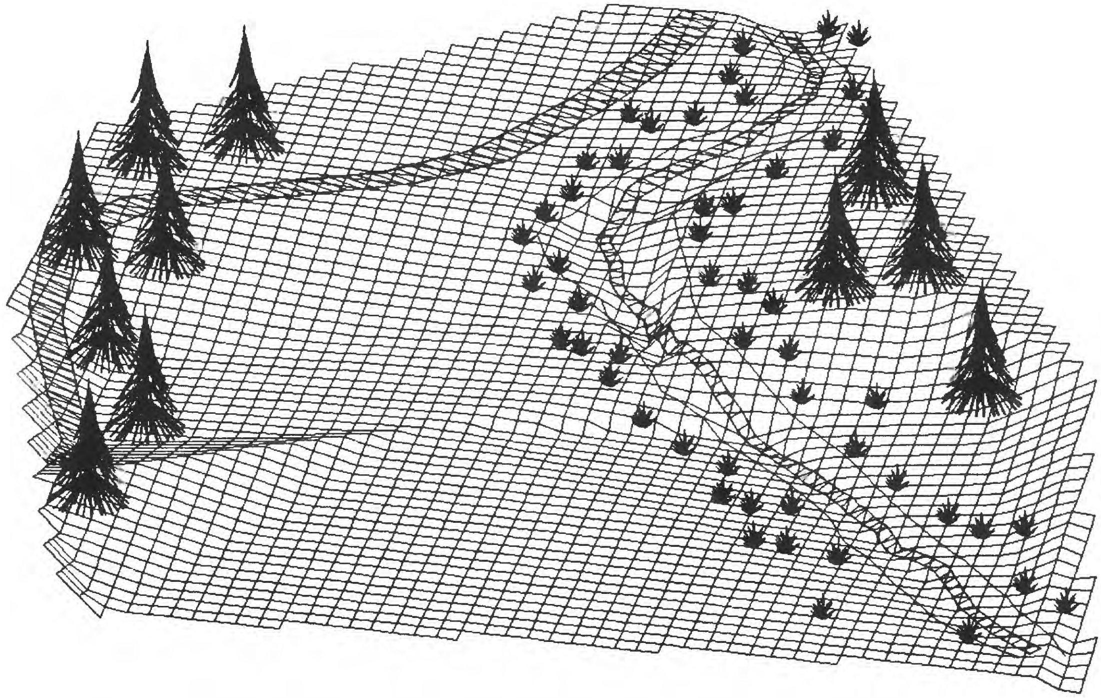

Figure 2.--Proposed final diversion with vegetation.

Figure 3.--Wetland area for stream diversion.

There are two approaches to the design and reclamation of streams: engineering or structural approaches and geomorphic or nonstructural approaches. An engineering or structural approach attempts to design and construct a water conveyance channel of such capacity to transport water and sediment from the drainage area and not have any alterations to the streambed or stream width. A geomorphic or nonstructural approach attempts to replicate channel characteristics such as gradient, sinuosity, and geometry and allow stream water to develop the final stream form. The one that works best for streams that have been mined is the geomorphic or nonstructural techniques; however, there are very few references addressing this approach for channel reconstruction on mined lands (Toy, 1987). A stream will not return to its former equilibrium but will rapidly adjust its morphology in order to achieve a new equilibrium compatible with new conditions (Touysinhthiphonexay, 1984). If channels are designed and quickly revegetated with riparian species, then structural types of stream control should not be necessary (Stillar, 1980).

There were five choices for a stream channel design: circular, parabolic, rectangular, triangular, and trapezoidal. A trapezoidal cross section was considered the best choice for this diversion because it would be the most stable in alluvial gravels. It would also be the easiest for the equipment on the site to excavate.

A method of designing active gravel bed streams, called the rational method, has been developed by Chang (1988). The rational method assumes a trapezoidal channel cross section consisting of a central mobile region and immobile banks. The bank slope is assumed to be at the angle of repose of the gravel. This method agreed with what we actually did at the mine site, except that semimobile banks were assumed to allow the banks to have some minor effect on modifying built-in sinuosity and bedform. Combining water discharge and sediment loads in the stream, the three unknowns of width, depth, and slope were determined using a flow resistance equation, a bed load equation, and the concept of minimum stream power.

The first equation in the process was to calculate Manning's equation for a trapezoidal channel:

$$Q_F = \frac{AR^{2/3}}{n}\sqrt{S},$$

where Q_F = flow rate, m^3/s,
A = area of trapezoid = $(b + zy)\ y$, m^2,
R = hydraulic radius, m,
n = Manning's roughness coefficient,
and S = slope of stream bed.

Manning's equation for roughness coefficients could easily be extracted from tables (table 1) to determine the proper base and side-slope roughness.

Table 1.--Manning's Equation (French, 1985, table 4.8)

Channel bottom description (1)	Minimum	Normal	Maximum
1. Gravels, cobbles, and a few boulders......................	0.030	0.040	0.050
2. Cobbles with large boulders....	.040	.050	.070

(1) Mountain streams, no vegetation in channel, banks usually steep, trees and brush along banks submerged at high-water stages.

The equation for a wetted perimeter of a trapezoid is:

$$P = b + 2y\sqrt{(1 + Z^2)}$$

where b = base
y = water flow height,
and z = side slope of channel.

USGS had already determined that a 25-year flood (Lidstone, personal communication, 1992) would result in a stream flow of 8 m^3/s, as compared to a normal flow of 0.25 m^3/s. Through trial-and-error using Manning's equation, it was determined that a 25-year flood would generate a base of 1.2 m and a critical flow height of 0.9 m with a side-slope ratio of 1. (fig. 4).

A stream channel is required to have freeboard for water containment and slope stability. To establish freeboard, the equation F = sqrt (Cy) (French, 1985) was used in which y = critical flow depth and C = an interpreted number. This number ranges from 1.5 at 0.57 m^3/s to 2.5 at 85 m^3/s. Therefore, C = 1.6, y = 0.9, and F = 1.2 m (fig. 4).

Use of the Straub approach to calculate summer and fall water flow allowed boulders to be factored in and increased pool-to-pool ratios throughout this portion of the stream channel during periods of low water. Therefore,

$$Y_c = 0.81\left(\frac{\psi}{Z^{0.75}b^{1.25}}\right)^{0.27} - \frac{b}{30Z},$$

for $0.1 < \frac{Q}{b^{2.5}} < 4,$ regime in which equation is valid,

where Y_c = critical flow,

and $\psi = \frac{\alpha Q^2}{g}$ = stream flow characteristics,

and, in this instance, α = 1 for parallel flow (French, 1985).

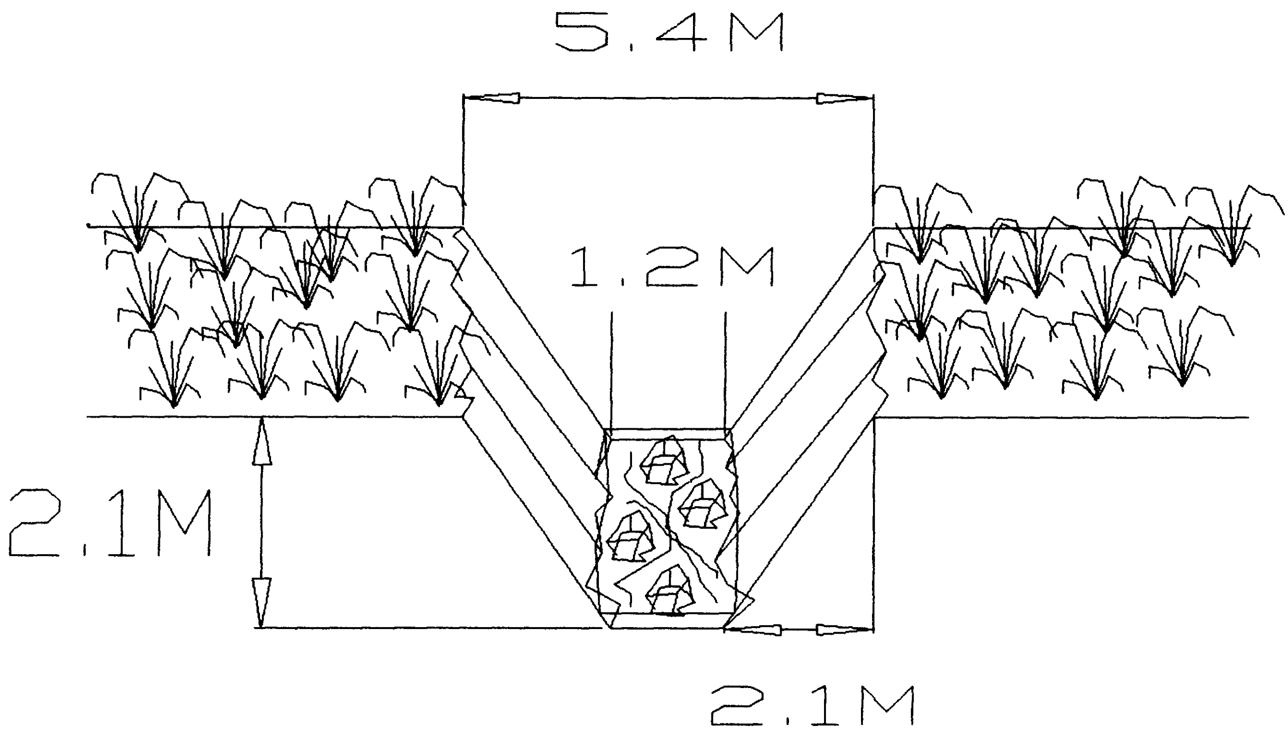

Figure 4.--Plot of channel design characteristics.

Using Q_n = 0.23 m^3/s, a critical flow of 0.15 m was obtained. In a mountain stream such as Deep Creek, the pool-to-riffle ratio is replaced by pool-to-step ratio where water tumbles over boulders into small scour pools. In Deep Creek, there is a combination of pool riffles and pool step functions up and down the undisturbed portion of the stream. Therefore, boulders greater than 0.15 m in diameter needed to be placed in the bottom of the stream, which would cause water to flow around them rather than over them, thus creating pools. Boulders of the size needed were found in the vicinity and were dug out of the diversion channel. Because the hydraulic radius and roughness were decreased, stream capacity was decreased. However, stream channel capacity was designed to handle flooding, and the stream has proven capable of stabilizing itself hydraulically.

After hydraulic flow was calculated, stream characteristics were sent to the mine operator along with the revised stream location. Final approval of the computer-generated stream diversion plan was granted in time to begin excavation in the fall, when soil moisture is at its lowest. Approximately 150 m of new channel were excavated and recontoured to the given dimensions. An interesting sidelight was that the mine operator placed his backhoe so that as the boom swung during excavation, it dug curves that added to the sinuosity of the new channel. This inhibited super-critical flow (when water flow height exceeds the design flow height) throughout the new diversion. This method saved both time and operation costs because the equipment did not have to be moved while excavating, thus keeping the number of equipment moves to a minimum.

The mine operator reported that the job took 80 hours of heavy machinery time. The excavator operator's general comment was that he got an intuitive feel for the final stream design after a couple of days of work, and looking at the plans, he could see where the stream should be heading and its general slope. The stream was introduced to its new channel during the first part of November. While the water flow was low, the stream was analyzed for pool-to-pool ratios and toe erosion so that the equipment was still available to correct any problems.

The stream diversion was reviewed during the following spring thaw by state regulators, Oregon Fish and Wildlife personnel, the mine operator, and U.S. Bureau of Mines personnel to determine if any additions to the stream were necessary before bonds were released. The contoured lands adjoining the diversions were also reviewed because if the stream flooded, the slopes could erode and it would cost a considerable amount to move equipment back to the area. After the visit, only two stipulations were incorporated into the partial bond release: that a 3-m section of the stream toe should be covered with riprap and that willow and alder seedlings should be planted immediately on the banks of the stream to control erosion during flood season.

CONCLUSION

Surface mining changes the hydrologic system that functioned before the land was disturbed. If the system has reached equilibrium following an earlier mining disturbance, then new mining will alter these conditions once again. Vegetative cover is removed, soil profiles are disturbed, and existing landforms are changed. Oregon is one of the few states that requires mining companies to restore both land and water affected by all types of mining.

Given the fact that the majority of placer mines are in alluvial gravels mixed with boulders and sand, a trapezoidal stream cross section is the most logical choice for a permanent stream diversion. This configuration is highly stable in both wide and narrow drainages. It is the most effective for a miner because no haulback is required. Computer-aided topographic mapping was shown to expedite the design of a stream diversion. The designer could see potential problems on a computer screen before any dirt was moved. Delays in permitting are very expensive to any mine operator. Computer-aided design can also reduce the time required to obtain permits, in this case from 1 to 2 years to less than 2 months which allowed a tremendous cost savings. The computer stream design allowed regulatory personnel to conceptualize the pre- and post-stream diversion plans in three-dimensional hard copy. In addition, the stream flow calculations can be easily done with the use of spreadsheets. New technology from computer-enhanced graphics can aid all persons in visualizing what numbers and text cannot explain.

The best channel design is one that incorporates all the expected hydrologic features of the disturbed surface rather than features of an undisturbed surface. Exact duplication of natural channels is costly and almost impossible to accomplish. Restoration of a channel is desirable and acknowledges that infiltration rates and topography have been modified by the mining process and will remain different for a long time. Even if previous mining completely altered the landscape, environmental damage can be repaired. It is apparent that surface mine reclamation is a combination of engineering and aesthetics. While it is not possible to guarantee success, it is possible to avoid serious or further environmental damage by using common sense and the natural resiliency of nature.

Placer mining operations should take an approach to reclamation that incorporates development of a mine plan that includes reclamation at the beginning. The mine in eastern Oregon took this planned reclamation approach in which the permanent diversion was designed, constructed, and monitored during active mining so that any problems could be taken care of and minor adjustments could be made to design and/or construction when equipment was on site. Also, from a regulator's point of view, it is beneficial to have a permanent diversion designed, constructed, and completed before the mine operators leave the area, so that the state's concerns can be incorporated into the plans and problems rectified immediately. Where costs must be minimized because of the finite financial resources of a small operator, emphasis must be placed on nonstructural techniques for stream restoration.

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AUTOMATING DETAILED SYSTEM REGULATION STUDIES

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ABSTRACT

A new computer program, AUTOREG, was developed with the goal of being able to complete a simulation of 50 years of Columbia River daily operations in the time it previously took to analyze one year of operation (about one week). Flood control analyses, in concert with other multiple-purpose reservoir operating polices on the Columbia River, have utilized the river module of the SSARR (Streamflow Synthesis and Reservoir Regulation) model. Despite numerous convenient features of this program, this analysis process requires almost constant manual interaction with the SSARR program to provide compliance with several operating rule curves at each of 15 reservoirs and 32 downstream control points. A current study, motivated to a large extent by the need to respond to the declaration that some salmon species in the basin are either in an endangered or threatened status, has necessitated a comprehensive system-wide evaluation of the Columbia River for 15-20 different system operating strategies.
AUTOREG, which interfaces with and controls SSARR, achieved its intended objectives by providing: (1) an efficient interface with the user under a UNIX/MOTIF processing environment; (2) an automated regulation simulation of reservoirs in compliance with at-site rule curves; and (3) semi-automated regulation simulation to meet requirements at downstream control points.

INTRODUCTION AND BACKGROUND

The Columbia River Treaty

In 1964, the U.S. and Canada signed the Columbia River Treaty (Treaty) which formed the basis for major hydropower-related developments on the Columbia River system. Under terms of the Treaty, four massive water storage projects were built: Mica, Keenlyside, and Duncan in Canada; and Libby in the U.S. The combined active storage of these projects is 25 million acre-feet. The U.S. made a one-time payment of $64 million for the flood control benefits the Treaty projects were expected to provide downstream in the U.S. The additional amount of power generated in the U.S. by the water stored in the Canadian Treaty projects was divided equally between the U.S. and Canada. Canada, in turn, chose to sell its half of this power benefit (approximately 600 average annual megawatts) to a group of 41 utilities in the U.S. for the first 30 years of each dam's operation. The utilities formed the Columbia Storage Power Exchange to purchase the Canadian entitlement. The Canadian Entitlement Allocation Agreements specify at which projects the power for the Columbia Storage Power Exchange is generated. The Allocation Agreements cover the same time period as the Power Exchange purchase contracts which will begin to terminate in 1998 and end by 2003. New Allocation Agreements will be needed to accommodate the delivery of the Canadian power share of the Treaty back to Canada.

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The Pacific Northwest Coordination Agreement

The Treaty also spawned the Pacific Northwest Coordination Agreement (PNCA) which enables coordination of power generation among many project owners in the Northwest. The PNCA calls for developing annual operating plans for power production that aim to maximize energy production while meeting the requirements for other river uses. The PNCA also expires in 2003.

The Endangered Species Act

It is recognized that the dams and reservoirs have impacted the fishery of the northwest, despite substantial mitigation efforts, including hatchery construction; a significant investment in structural facilities such as fish ladders and by-passes that have been constructed at the dams; and, operational measures such as the barging of smolts and releasing stored water to aid downstream migration (water budget). Recently, the National Marine Fisheries have listed several runs of Columbia and Snake River chinook, coho, and sockeye salmon as endangered. Also Kootenay River (below Libby Dam) sturgeon are also under evaluation for listing. Placing more emphasis on endangered species for system operation will most likely change the way the river is operated for flood control, recreation, power, and irrigation.

System Operation Review

The impending renegotiation of the current Canadian Entitlement Allocation Agreements (beginning in 1998) and of the current PNCA in 2003 afforded the region the perfect opportunity to evaluate power operation in context with other uses. Senior management and staffs at the Bonneville Power Administration, Bureau of Reclamation, and Army Corps of Engineers determined that demands by river users are becoming increasingly conflicting and the listing of various anadromous fish species will place even more demand on the resource. Therefore, the potential for dramatic changes in how the Columbia system is operated is high, and an EIS under the NEPA process would be necessary as part of contract renegotiation. A three year System Operation Review (SOR) was authorized with an initial congressionally approved budget of $15 million. The SOR will provide a means to develop a strategy for future systemwide operation considering all uses.

DEVELOPMENT OF AUTOREG

The Need For AUTOREG

After a lengthy regional scoping process under SOR, six major and distinct categories of System Operating Strategies (SOS) were formed. Within each SOS there are two to three variations for a total of about 15 possible system configurations from which the most beneficial one will be recommended for adoption. Each SOS will receive monthly modelling for a 50 year historical period. Reservoir outflows and pool elevations will be made available for analysis to 10 technical work groups each of which represents a specific river use, e.g., hydropower, irrigation, recreation, cultural resources, etc. The flood control work group of SOR will use the monthly regulation as guidance and perform a daily flood control regulation of the entire system for the same 50 year period. The products will be a flow-frequency curve for each of seven damage centers. Without AUTOREG a typical system flood control regulation would take approximately one week to complete. Hence 50 years could conceivably take 50 weeks, or one year. If all 15 possible system configurations are modelled, then the flood control work group could spend the better part of a career doing SOR work. In addition, outside of SOR, system managers are becoming more creative and prolific in concocting new operation schemes to try and squeeze more water out of the Columbia - schemes which must be evaluated for flood control impacts. An automated process was obviously necessary to meet the SOR schedule as well as provide a timely response to other routine requests for system evaluation.

Strategy of AUTOREG

AUTOREG was envisioned to interface with an existing computer simulation model called SSARR (Synthetic Streamflow and Reservoir Regulation). The SSARR program is a general-purpose, hydrologic simulation model which contains both watershed (basin) and river/reservoir (river) simulation capabilities (SSARR User's Manual, 1986). AUTOREG interfaces with the river component of SSARR only. While SSARR is generalized and can be applied to any river basin, the target for AUTOREG development was the Columbia River basin. Many different concepts of AUTOREG were discussed prior to its going out for bid. A primary consideration was if AUTOREG should be embedded within existing SSARR code. In other words, should the input structure of SSARR be modified to include the capability of incorporating the AUTOREG components? The SSARR model is very complex and it was felt that too much time would be spent by the contractor to learn SSARR first before AUTOREG development could even begin. Another item for debate was the extent to which AUTOREG would automate the project regulation process. Should AUTOREG go as far as being an expert system, helping the user with regulation decisions, or be able to provide regulation optimization? Also should AUTOREG be written such that basins other than the Columbia could be regulated? Ultimately the reality of budget and timely delivery of the product led to AUTOREG's current form which provides control and background calculations necessary to execute repeated simulations of portions of the SSARR program. AUTOREG is comprised of a series of menus which allows the user to prescribe the system configuration and how each project is to be regulated for any period of record. Based on the user input, AUTOREG then prepares an input stream, interfaces with a new database, executes the SSARR river model, and then performs a series of checks on the output and lists violations of basic system operation criteria.

COLUMBIA RIVER FLOOD CONTROL REGULATION

System Description

The U.S. Army Corps of Engineers has, through various authorities enacted by Congress, the responsibility for flood control regulation of both Federal and non-federal flood control reservoirs in the United States (see Figure 1). The Corps also serves, along with Bonneville Power Administration, as the United States Entity in the implementation of the Columbia River Treaty. Another major federal entity involved in the reservoir operations for flood control is the Bureau of Reclamation, which is responsible for the regulation of several of the reservoirs making up the flood control projects in the basin. The Corps has the responsibility of regulating the Bureau projects through Section 7 of the 1944 Flood Control Act.

Within the Columbia River Basin, flood runoff can be the result of spring snowmelt, sometimes augmented by spring rains, or by intense winter rainstorms augmented by snowmelt. The upper Columbia and Snake River basins are the predominate source of runoff during spring-summer flood events while the lower Columbia, lower Snake, and Willamette River basins produce the most significant pattern of winter runoff. The Portland-Vancouver area is subject to potential flooding and accompanying high hazards and economic loss in either season. Major storage projects in the upper Columbia Basin are most effective in controlling the spring-summer flood events while storage projects in the lower Snake and Willamette basin have the major role in controlling winter flood events. Of the 100 or so dams in the basin upstream from The Dalles (the system control point), only 14 projects are considered significant system flood control projects. The total storage capacity of the 14 flood control reservoirs is 39.7 million acre-feet, or 86% of the total storage capacity of the system of 46 million acre-feet. This also represents 41% of the average annual runoff of the river at The Dalles and 30% of the runoff of the major flood of April-August 1974, indicating that complete control of flooding in the basin is impossible with reservoirs alone.

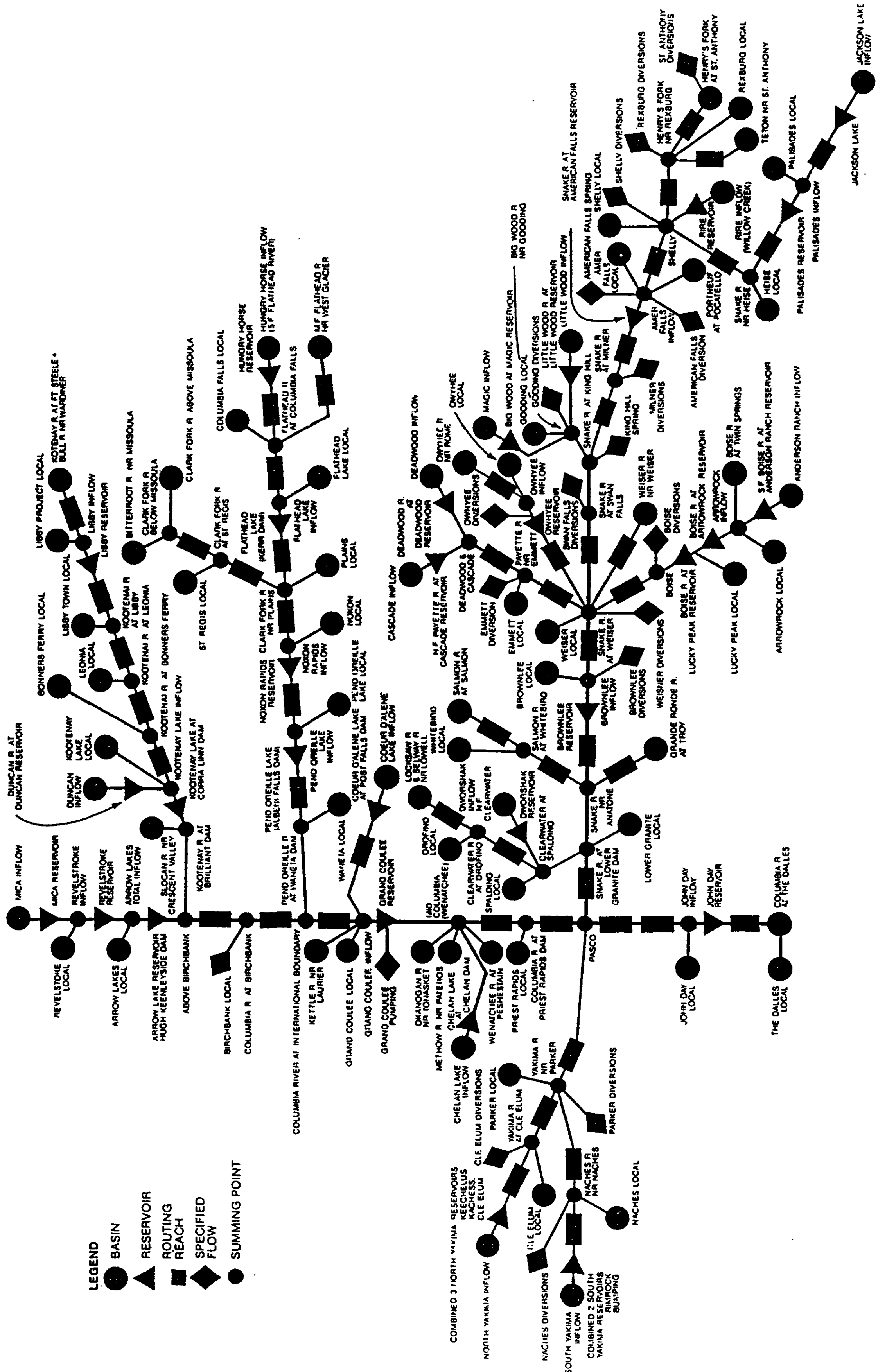

Figure 1. Schematic of the Columbia River System

Flood Control Criteria

Hydrologic studies, in most cases made during the planning and design phases of project development, lead to the derivation of seasonal flood control storage reservation diagrams (SRD) which specify the amount of drawdown needed at a specified time of year in order to regulate potential future flooding adequately. In the Columbia River basin, where the primary source of flooding is from snow melt, long-term forecasts of runoff are possible, which permits a variable specification of drawdown depending upon the volume of runoff forecasted.
Prior to the construction of the Columbia River Treaty storage in the late 1960's, flood control criteria were limited to project rule curves designed primarily for tributary protection. Because flood control storage capacity amounted to less than 10 million acre-feet before Treaty development, its regulation as a system was also relatively insensitive and non-complex. These studies led to an interim operating plan in 1968 and then to the document "Columbia River Treaty Flood Control Operating Plan". The Treaty flood control studies featured detailed daily routings of over 30 years of record to develop and test the principles that were to be set forth in the Operating Plan, and they incorporated not only Treaty storage but other developments planned or under construction at that time. Further details regarding the Treaty flood control studies can be found in the paper by Nelson and Rockwood(1971).

The Treaty Flood Control Operating Plan (1972) contains the following basic principles of operation, which are not only applicable to Treaty storage but all flood control projects in the basin as well:

1. Two distinct periods of operations are recognized: (1) the winter drawdown period in which flood control storage space is attained in accordance with storage reservation diagrams; (2) the spring refill period during which flood regulation is implemented.

2. For purposes of regulation during the refill period, two main categories of reservoir projects are: (1) headwater reservoirs operated with fixed (usually minimum) releases; and (2) reservoirs operated with variable releases for downstream flood control. These two categories are the most important for system regulation, and the variable release reservoirs (Arrow, Grand Coulee, and John Day) represent those that require continual adjustment during the spring runoff to achieve the flood control regulation in the lower river.

3. A variable controlled flow objective at The Dalles is utilized, in which years with higher runoff are regulated to a higher controlled flow to account for the inability to complete regulate all flood events and to make the most effective use of storage. Further, the controlled flow objectives can change during the course of a flood, as storage space is depleted in Category IV reservoirs.

Other Operating Criteria

Reservoir regulation involves to a large extent the interpretation and following of operation "rule curves". The Upper Rule Curve (URC), representing the flood control requirement, is determined from the flood control storage reservation diagram for the project in question. Since the URC restricts refill of the reservoir (until flood runoff begins), and the other rule curves - particularly the Variable Energy Content Curve (VECC) - exist in order to insure refill, conflict in operating guidance occurs if these two criteria are reversed (URC lower than VECC). An analysis has shown that the URC controls primarily in the high runoff years when flood control is of greatest concern, but in the lowest years reservoirs are likely to be below the URC due to power drafts. However, with additional water being requested for fish migrations (i.e., the Water Budget), VECC's will be raised, thus increasing the likelihood of conflict with flood control criteria.

HOW AUTOREG WORKS

~~Overview/~~Menu System

AUTOREG's three major functions are: (1) for a variety of regulation objectives, to automate input to the SSARR program; (2) after SSARR has executed, to perform a multitude of checks (presented graphically and in tabular form) to report any violations of rule curves, minimum flow, maximum flow, and maximum stage; and, (3) to evaluate some of the violations, modify the SSARR input appropriately, and re-run SSARR. The menu system of AUTOREG is arranged hierarchically into three classes: rule curve development and inspection, basic reservoir information (maximum and minimum elevation, outlet capacity, etc.), and a regulation prescription portion. The regulation menu is where the user specifies the time window for simulation, how much and what portion of the Columbia system will be regulated, and on a project by project basis what is the regulation objective. The information on how the system is to be regulated can come from one of two sources: from the regulation menu (specifically, run control) or from a "Master Control File" (MCF). The MCF is a sequential file of card image records each of which contains a starting and ending date and time, a reservoir identifier, and an operation code (opcode) which tells the reservoir how to operate for each time step. AUTOREG takes the project regulation information from the MCF, local inflows, river routing information, and project characteristics and builds an input dataset for SSARR. Locations of all necessary files are user specified, but defaults are available. A complete system regulation for one opcode for the 50-year historical period can be specified on one MCF record.

Database

The Corps of Engineers' Hydrologic Engineering Center (HEC) has developed a fully documented system of programs called DSS (Data Storage System) which lends itself to highly efficient storage and retrieval of time series and paired data. DSS provides a means for: (1) storing and maintaining data in a centralized location; (2) providing input to and storing output from applications programs; (3) transferring data between applications programs; and (4) displaying the data in graphs or tables. The user may also interact with the database through FORTRAN library routines which can be incorporated in any program. An important part of the AUTOREG-SSARR package is a new database in which all input, output, characteristic files, etc. are stored. All Columbia River local inflows, reservoir outflow characteristics, and storage elevation tables are initially available in DSS. In addition, AUTOREG writes to DSS any data which is needed by SSARR, which was recently modified to be able to read and write from DSS. Typically, a system daily flood control regulation begins by taking project outflows from another model which regulates the system on a monthly time step for an objective other than flood control (hydropower, navigation, etc.). The outflows from this type of simulation are termed MPOs (Monthly Power Outflows) and can be stored directly in DSS for immediate retrieval into AUTOREG and SSARR.

Utilization Of AUTOREG

By April of any year, the "Initial Controlled Flow" (ICF) and spring regulation guidance form the basis for determining reservoir outflows for flood control. The ICF is the unregulated flow at the Dalles above which flood control regulation (i.e. storing water) at the upstream projects must occur and is based on the water supply forecast (WSF) and available upstream storage. When the ICF is exceeded the headwater projects' outflows are usually reduced to minimum outflow. In contrast, Arrow and Grand Coulee reservoirs are refilled using a technique termed the "synthetic reservoir" in which outflows are increased as storage is filled. After May, the Flood Control Refill Curve (FCRC), Filling Transition Curve (FTC) which is a special operation to "top off" the reservoirs at the end of refill), and other guidance are used. A year-to-year variation in runoff magnitude results in some years, particularly those with high runoff, requiring more guidance (daily outflow adjustment) than low years. Prior to AUTOREG a simulation run was made one year at a time and typically involved the following steps:

(1) Given that new SRD's are to be evaluated, compute corresponding URCs for each reservoir, given WSFs (FORTRAN program).

(2) Obtain MPOs for each project. Convert to SSARR input format for use as initial outflow specification.

(3) Compute VECC's based upon WSF's (spreadsheet).

(4) Set initial conditions. These may be based upon the computed values from the last period in a previous year's simulation.

(5) Make an initial simulation for the year using MPOs as outflow specification.

(6) Review output. Redo outflows using VECC and URC criteria as guidance. Modify outflows by stipulating daily outflows. This might be a partial-year run. Repeat runs until satisfactory regulation is achieved.

(7) Refine the spring flood control regulation using the "synthetic reservoir" or intuitive guidance.

(8) Complete the year's run by creating output files, plots, and tabulating statistical results.

(9) Repeat for the next year.

The above process takes an experienced regulator about one week to fully analyze one year of data. All checks have to be done manually. The intent of AUTOREG is to replace the above manual process by automating most of the peripheral manual calculations, providing control over SSARR, permitting automatic iterative runs; and streamlining input and output display. With AUTOREG we are able to complete a 50-year simulation in one week. The following summarizes the steps that are required using AUTOREG for a 50-year study:

(1) Initiate an AUTOREG session, setting up controls, defining file names and locations of files, etc.

(2) Given a new SRD to evaluate, enter this via AUTOREG.

(3) AUTOREG computes URCs. Display and print out for check.

(4) Review VECCs and project data on screen.

(5) Set run controls for 50-year run, first pass.

(6) Display/print month-end elevations at projects and mean monthly flows. Check for validity.

(7) Display plot of daily hydrographs for spring period for selected years. Check for validity of flood regulation.

(8) Set up Master Control File for re-simulation (daily time step) of specified portions of years for selected years. Execute.

(9) Review new runs and repeat as necessary.

(10) Final output display of entire 50-year run.

A particularly powerful part of AUTOREG is its ability to perform Downstream Control (DSC) which was also manually done prior to AUTOREG. DSC makes a full 50-year simulation and, when necessary, reduces reservoir outflows to meet flow guidelines at downstream control points.

Summary

AUTOREG operates on a UNIX platform in an XWINDOWS environment, contains 50,000 lines of "C" (menus) and FORTRAN (regulation) code and was developed from scratch in one year by an independent contractor team of an engineer consultant familiar with Columbia River operations and two programmers. Currently, no amount of computer programming can replace the skill of an experienced regulator. But many of the tasks involved in a complex system regulation can be automated. The most time consuming part of this type of multi-reservoir regulation is the myriad of pre- and post-run checks which must be performed for every year of simulation and the computation of various rule curves. Each check consists of comparing a computed value against a limiting value, noting the violations, and adjusting input for the subsequent iteration. Prior to AUTOREG, all rule curve and ICF computations for 50 years were done via a spreadsheet and the results then manually entered into the SSARR input stream. AUTOREG now computes pre-run information such as: URCs, VECCs, FCRCs, FTCs, and ICF. SSARR was developed with rather crude graphics and no violation reporting. AUTOREG itself does no graphics but has menu items which when selected prepares input to DSPLAY (HEC's graphics utility for DSS) and plots the data on the screen. Plots can also be redirected to several output devices. AUTOREG automates certain reservoir operations by simply specifying a single operation code in the MCF. For example, specifying the URC operation code in the MCF directs AUTOREG/SSARR to not only operate to URCs but also checks to make sure that minimum and maximum reservoir releases are not violated. These are the kinds of checks which were formerly done manually. This type of primary and secondary checking for many of the operation codes is where AUTOREG's benefits are reaped.

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NEXGEN
HEC'S NEXT GENERATION SOFTWARE PROJECT

ARTHUR F. PABST[1]

ABSTRACT

HEC software in wide spread use around the world has evolved in its implementation and technical capabilities over the last decade. Significant changes in engineering needs, and computer capabilities have created an opportunity to provide a new generation of hydrologic and hydraulic software to meet current requirements and extend capabilities for performing hydrologic analysis. The HEC project to field new products will be described, with emphasis on the object oriented Hydrologic Modeling System (HEC-HMS).

BACKGROUND

The first generalized hydrologic engineering computer programs were published by HEC in 1966. Since that time the programs have undergone a gradual evolution as they migrated to the mainframe machines of the 1970's, the minicomputers of the later 1970's and early 1980's and most recently the microcomputers of the later 1980's. Over this time engineering methods were extended from original implementation of hand computation methods to many solutions that are based on forms of the basic equations of energy, momentum and mass. The current tools for hydrologic and hydraulic analysis that are available from HEC are a mix of batch computer oriented programs with editors, shells, and other wrappers to reduce the unfriendliness that betrays their ancestry.

NEW CHOICES

Hardware and Operating Systems

The continual rather rapid changes in computer hardware and software offers challenges to computer users, and computer product developers alike. In most cases the development of software lags behind the capabilities of the currently available hardware. In the hardware realm the latest CISC and RISC CPU chips have performance levels that are many times that of just three or four years ago. The CISC chips with the Intel family the dominate leader most commonly utilizes PC-DOS or its follow on systems of OS\2, MS-Windows or Windows NT. In the RISC line many more chip manufactures are involved, but the dominate leader in operating systems is UNIX. At this point in time it appears that from the available hardware and software choices two directions will continue.

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Complex Instruction Set Chip (CISC)

The CISC Intel chip will continue to dominate in number of units with Window NT becoming the prevalent operating system. In the RISC line the fastest chip changes daily, but most all machines use the UNIX operating system. HEC is currently struggling with issues related to what of the two future lines to develop software around. For many applications either choice would be acceptable. The Windows NT direction is attractive because of its lower cost, more widely available hardware. There are uncertainties about delivery of the system, multi-user capabilities, networking functionality, and the implicit reliance on a single supplier.

Reduced Instruction Set Chip (RISC)

The UNIX direction is attractive because it is a proven system, it supports multiple users, it has a well defined windowing system, and is available from many sources. The current RISC hardware is higher performance, but at a higher price tag. Ideally developing software that could be fielded on both systems would be most desirable.

Graphical User Interface/Graphics

The basic compute engine can easily be made transportable between these two systems. The difficulty lies in the graphically user interface (GUI) and in presentation graphics. Each of these areas tend to be specialized for each of the separate computer platforms. Some solutions can be used that directly produce a GUI for both systems, however, they tend to produce less desirable products in each of the systems. Using each systems native GUI capabilities produces a higher quality more consistent solution for each platform. A well engineered GUI is critical because if not properly done it will frustrate the user by not permitting him or her to easily perform the desired model interactions. A well done GUI will facilitate making changes to the model to accomplish the study objectives smoothly.

A key element for new software is how model information is presented in graphic form. It is essential to present to the model user a clear visual depiction of the way the user has described the entity being modeled, (i.e. the watershed, the river channel system), the input that is being operated on by the model, and the output response simulated by the model. To satisfactorily convey information the graphics must show both temporal and spatial aspects of the problem and of the models solution. The visualization may entail combinations of static and dynamically changing graphics.

Programming Choices

Procedural

One choice that is pertinent to all platforms is the choice of programming approach and programming language. Previous HEC software was developed with an orientation to procedural solutions. In this approach the problem is broken down into a series of procedural steps that were usually implemented in Fortran routines. The defined procedural steps are then carried out on the data by the routines.

Object Oriented

Another approach to defining problems and programming their solutions called "object oriented analysis" (OOA) has been receiving increasing attention in recent years. This view of developing solutions allows the problem to be analyzed much more closely to the problem in the real world. That is, the terminology used to describe the problem and how subject matter professionals talk about it is used directly to define "objects" that behave as their real world counter parts do. The software objects are created as needed and interact with each other to achieve a solution. Several computer languages support the concepts of object oriented analysis. The language in most widespread use is C++. C++ is available for both the UNIX and the Windows NT environments. This makes the use of object oriented approaches very attractive for newly developed software. Object oriented analysis supports the concept of a hierarchy of objects, or more correctly classes, that share inherited information and/or behavior. An example of a class structure used in a hydrologic model is given later. If the classes that are developed for a specific model are defined with a generalized view in mind these classes may be reused in other models.

NEXGEN SOFTWARE DEVELOPMENT

The scope of the NexGen project at HEC includes all of the technical areas that HEC has been active in over its 25 year history. However, do to budget and manpower constraints, the main efforts are focused on the two areas of a River Analysis System (HEC-RAS) and a Hydrologic Modeling System (HEC-HMS). The River Analysis System will only be referred to briefly in this paper. The Hydrologic Modeling System will be presented and illustrated.

River Analysis System (HEC-RAS)

The scope of the River Analysis System includes 1 dimensional steady state and unsteady state river hydraulics, and steady state sediment transport solutions. The design is to develop a database of the geometric information necessary to perform each of these solutions. The database would provide a common data representation that would be the base for model computations, data editing, and graphical display. The initial development accomplished to date includes a Fortran 90 library of hydraulic modeling routines for the steady state solution, and a GUI to allow the user to enter and edit data, execute multi-reach river networks, and display graphics of river geometry and computed profiles.

Hydrologic Modeling System (HEC-HMS)

The scope of the Hydrologic Modeling System includes event and continuous simulation of the runoff from a watershed. Figure 1 shows some of the windows that are associated with the HMS. Included are a schematic of the watershed, a data editor, tabular output, and various graphical displays.

Hydrologic Components

The watershed may be comprised of any number of hydrologic components. Hydrologic components include subbasins, reaches, conduits, junctions, diversions, and fixed geometry reservoirs. By configuring these components and size watershed may be represented. All hydrologic components have some things in common, but also have specialized attributes provide their unique behavior. Figure 2 shows the class hierarchy of the hydrologic components. All hydrologic components have a name, description and location, so these attributes are defined once in the block labelled "HydrologicElement". A junction is a point element that inherits the attributes that are defined in its parent blocks above it and then it defines the specific functionality of combining all flows coming into it. A reach is an element that provides the functionality of routing flow along a channel. Likewise, a subbasin is an element that knows how to take precipitation and produce a flow hydrograph at its outlet. Each of these components or objects perform their functions by carrying out the behavior they are programmed to have, or by using other objects to assist them.

Model Object Relationships

Figure 3 shows in greater detail some of the objects that exist when a model becomes defined for a watershed. The main program is initiated by the user. The main program uses the "ReadParam" object to read a preserved description of a particular basin being modeled. Based on the configuration desired the "ModelManager" object is requested to create one or more "Subbasin", "Reach", and "Junction" objects. Each "Subbasin" object in turn uses a lossrate object, "InitConst" in the case shown in the figure, a transform object, "Snyder", and a baseflow object, "Recession", to actually perform the modeling calculations. Each object that needs to read or write time series data uses "TimeSeriesIn" and "TimeSeriesOut" objects as appropriate. The modular structure of the C++ object oriented language and the interactions possible between the objects provides a highly functional and reusable modeling solution. It is very easy to extend the model to include soil moisture accounting algorithms, non-linear transform functions, or other desired features. Key to the design is the future extension of the engineering functionality of the model to processing spatially distributed precipitation, process user controlled moving storms, parameter optimization, and other higher level capabilities.

Model Component Interactions

The schematic shown in the upper left of Figure 1 shows that a subbasin object like "SLMN" is linked to a downstream junction "Salamanca". The configuration of the hydrologic components into such a network provides a visual depiction of the watershed being modeled, but it also is the actual linkage between the component objects. This allows the components in the model to interact with one another. For instance, if it is desired to find the outlet of the basin from any component, the component need only ask the component downstream where the outlet is. If that component is not the outlet it in turn will ask its downstream component where the outlet is. Thus, component by component the outlet can easily be found. In a similar fashion, if an object needs to know the total drainage area above it, it can ask each object above it for its drainage area and obtain the result. The model can compute itself, provide status information, generate statistics, write reports and display graphics by simple requests to its components. Because the model components always know about their neighbors these operations work even if the model configuration is changed from run to run.

SUMMARY

The HEC is actively developing next generation software to replace its existing suite of hydrologic and hydraulic products. Many issues regarding hardware platforms, operating systems, graphical user interfaces, visualization graphics, and databases must be dealt with to provide products to Corps and non-Corps users. Keeping to government and industry wide standards is critical to producing software that will be available and supportable for the next decade.

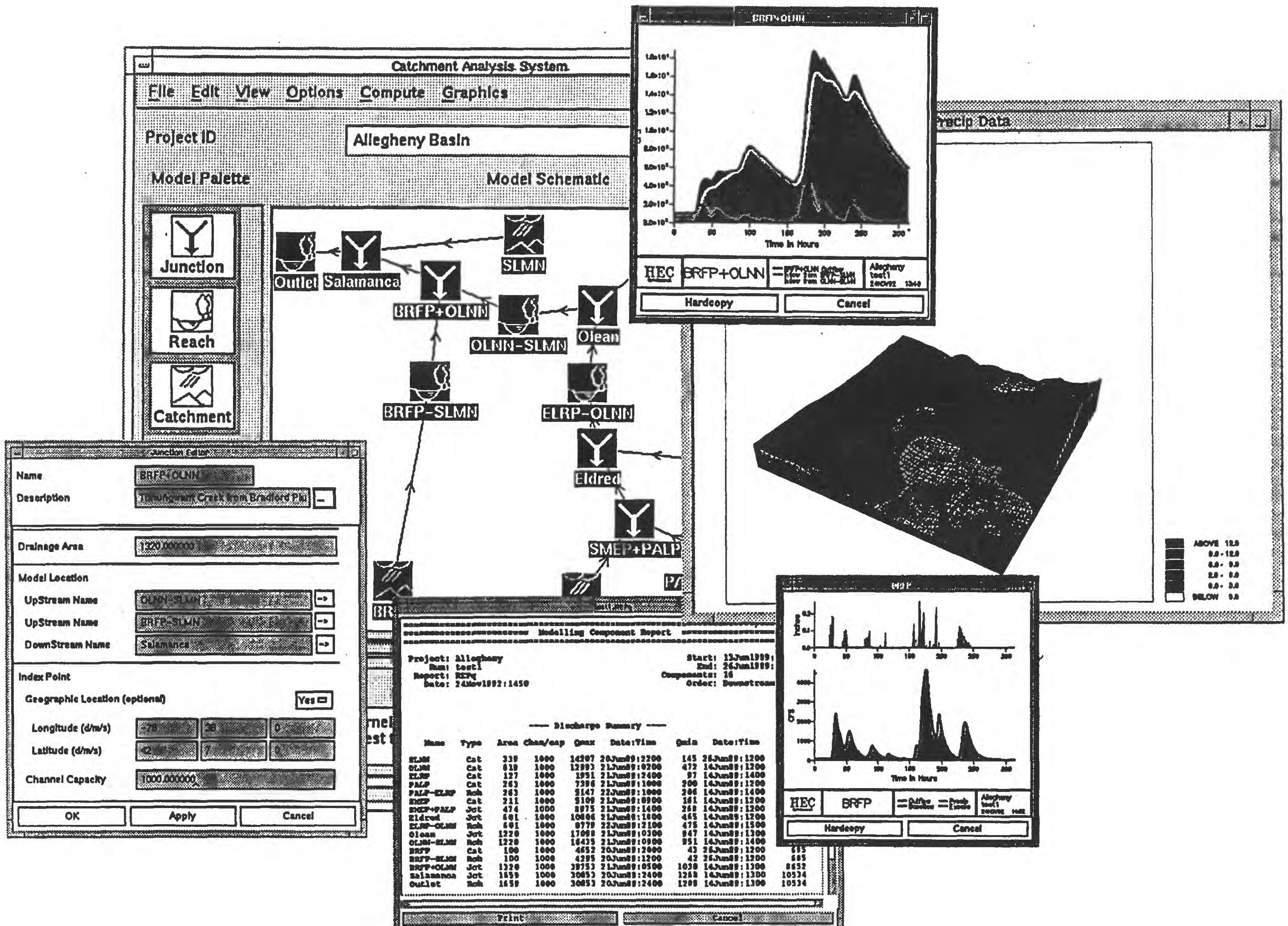

Figure 1 NexGen Hydrologic Modeling System

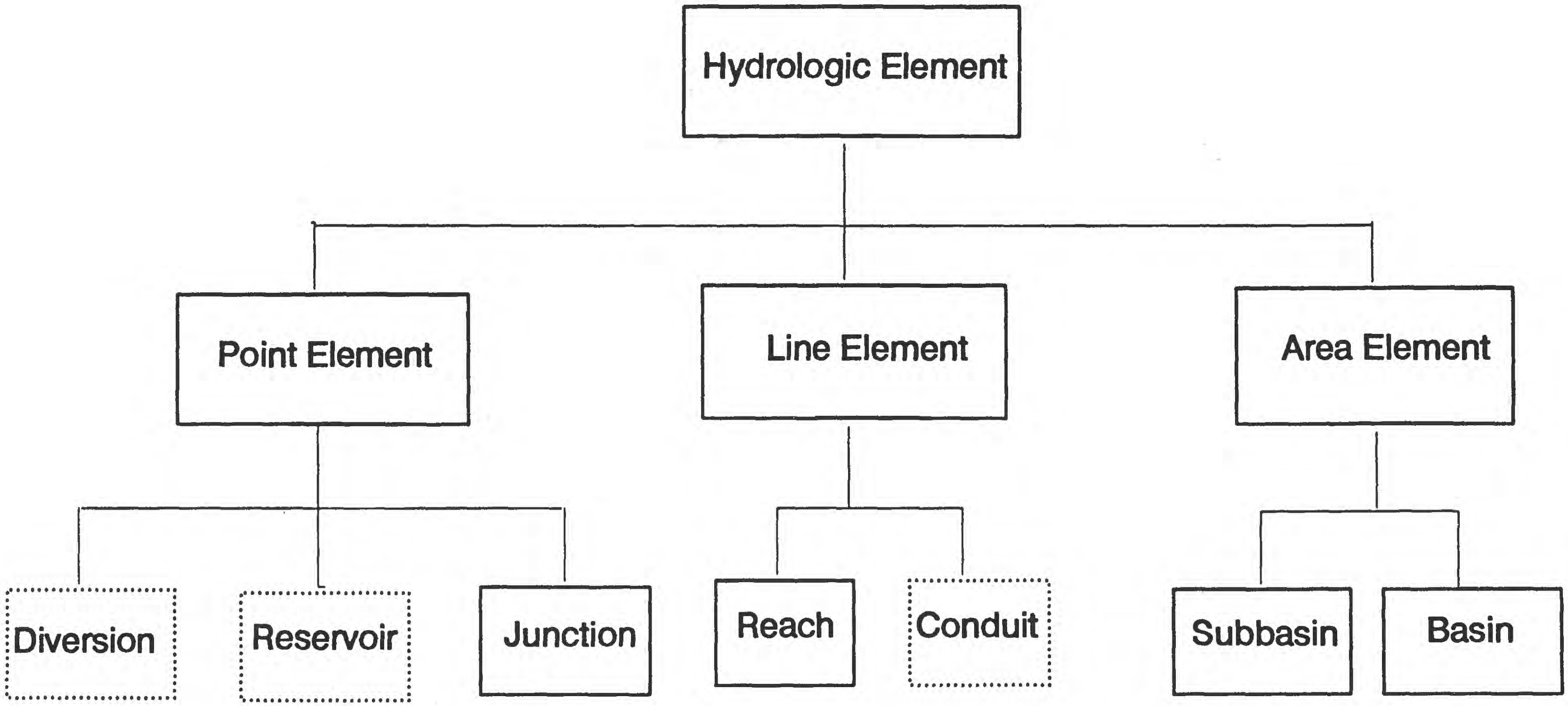

Figure 2 Hydrologic Component - Class Hierarchy

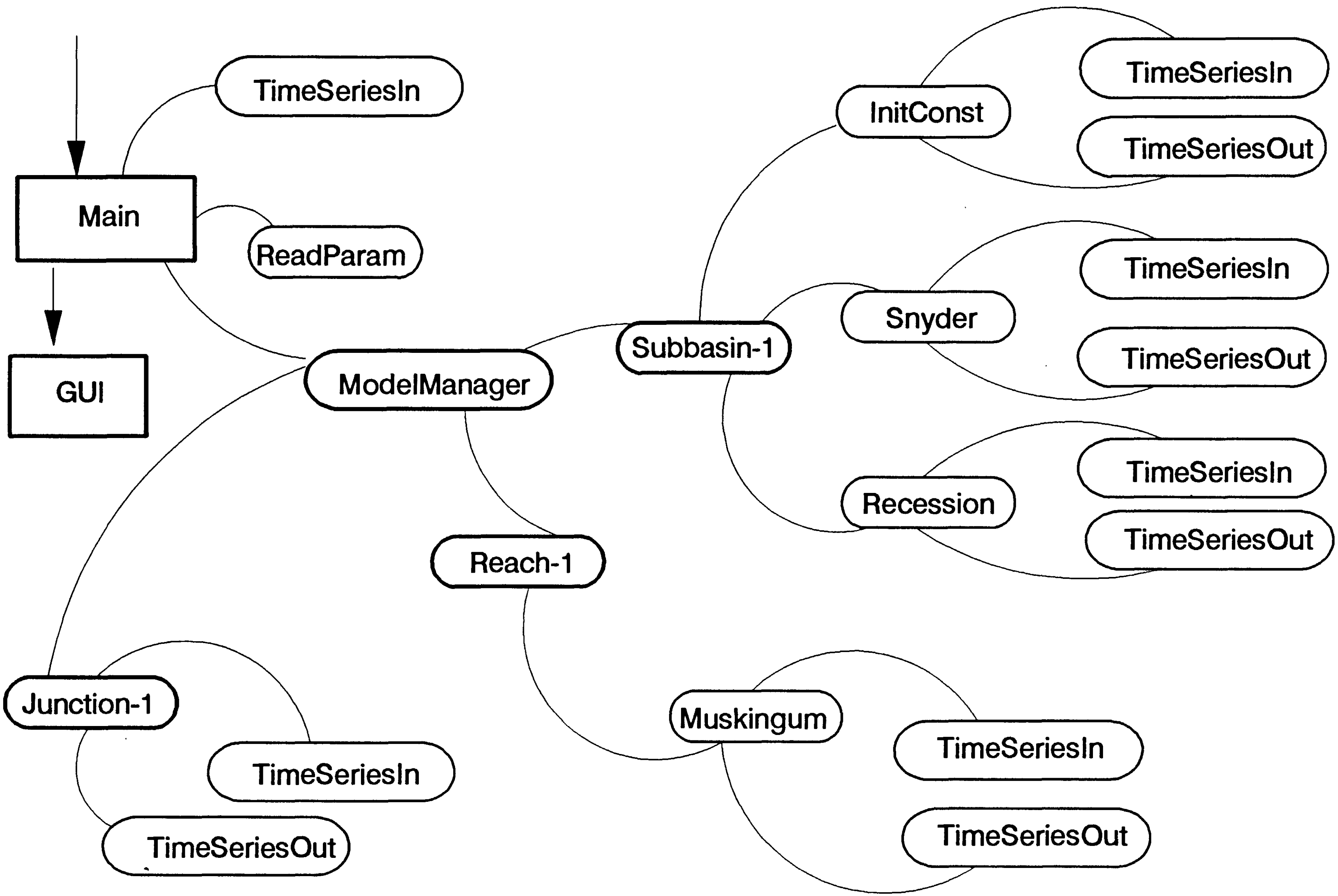

Figure 3 Hydrologic Modeling System - Object relationships

SECTION 7

STOCHASTIC HYDROLOGY - RISK AND UNCERTAINTY

Page

Advances on the Last Stochastic Hydrology Package
Donald K. Frevert 7-1
Upper Colorado River Simulation/Optimization Model
Leslie C. Stillwater 7-7
Using CLIGEN to Stochastically Generate Climate Data Inputs to WEPP and Other Water Resource Models
Arlin D. Nicks and Gene A. Gander 7-14
Muskingum Basin Reservoir Frequency Analysis
Dr. Surya Bhamidipaty and Jerry W. Webb 7-22
Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast
Donald P. Laurine and Larry E. Brazil 7-30

Figures and Tables

Upper Colorado River Simulation/Optimization Model 7-7

Figure: 1. Schematic of the Upper Colorado River System 7-8

Using Cligen to Stochastically Generate Climate Data Inputs to WEPP and Other Water Resource Models 7-14

Figures: 1. Precipitation and temperature stations selected for parameterization 7-19
2. Solar radiation and dew point temperature stations 7-19
3. Wind speed and direction stations 7-19
4. CLIGEN generated average annual rainfall erosion index 7-20

Muskingum Basin Reservoir Frequency Analysis 7-22

Plate: 1. Project Map Muskingum River Reservoirs 7-29

Table: 1. A summary comparison of the frequency of filling curves resulting from previous studies and the current analysis 7-28

Pilot Project Results from a Probability Based Long Range Water Management/Supply Forecast 7-30

Figure: 1. WARFS Colorado demonstration project area 7-33

ADVANCES ON THE LAST STOCHASTIC HYDROLOGY PACKAGE

Donald K. Frevert [1]

ABSTRACT

The Lane's Applied Stochastic Techniques (LAST) computer package was developed for the Bureau of Reclamation by Dr. William Lane in the late 1970's - primarily for use by hydrologists and engineers in planning and operation studies. Subsequent advances in stochastic hydrology theory and the evolution of personal computers and work stations have created the need for improved versions of the program. Descriptions of present capabilities, ongoing efforts to improve the model and recent applications are presented.

INTRODUCTION

The Bureau of Reclamation's LAST computer program has utilized disaggregation procedures to generate hydrologic data sets which are statistically consistent with the historically based data sets and are considered equally likely to occur in the future. These generated data sets are used in planning, operation and other types of hydrologic studies.

Since Dr. William Lane developed LAST between 1977 and 1979, the need to continually improve the package's capabilities has been recognized. Lane (1979) provides a description of the package as originally developed. Because of limited research budgets and competing workload commitments, progress on improving the program has been slow. Nevertheless, in recent years, some improvements have been made and other improvements are in progress.

As originally developed, the program relied on disaggregation techniques patterned after those of Valencia and Schaake (1973) and Mejia and Rouselle (1976) for spatial and temporal disaggregation. In 1984 and 1985, these capabilities were expanded to allow two level spatial disaggregation as described in Frevert and Lane (1985).

During the first ten years of the package's existence, it could be used only in a main frame computer environment. In the late 1980's the need was recognized for converting the package to run in a Personal Computer environment.

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RECENTLY COMPLETED IMPROVEMENTS

Work began on developing a Personal Computer (PC) version of the package in 1989. The source code used for the main frame was used as the basis for development of the PC version. This effort focused on two main areas:

1. Conversion of the source code from FORTRAN IV to FORTRAN V, and

2. Changes required to adapt to accessory software available for the personal computer.

The personal computer version was put into experimental use on a preliminary basis in the fall of 1989. Some substantial problems had been experienced in converting the source code to FORTRAN V and limitations in program capability (particularly plotting capabilities) resulted from the cost and availability of accessory software for personal computers. Other difficulties resulted from the need to create a new random number generator for use on personal computers which could duplicate random numbers generated in the main frame environment.

The effort to create a formatted parameter file (as opposed to the unformatted parameter file used in the main frame version of the package) resulted in additional difficulties. Although it was felt that there would be substantial advantages resulting from a formatted parameter file, some loss in precision of parameters resulted and this, in turn, caused an impaired capability to reproduce stochastic traces which had been generated on the main frame computer.

Over the next 12 months, an extensive effort was made to test, correct and enhance the personal computer version. In December, 1990 this improved version was made available for general use. Informal discussions with users indicate that the personal computer version is in good working order although the graphical capabilities remain limited. The current capabilities of the package are described in Lane and Frevert (1990).

Efforts are currently underway to enhance the program's capabilities in a variety of areas through the services of consulting specialists.

ONGOING IMPROVEMENTS

Through discussions with colleagues at professional conferences as well as on a more informal basis, a number of necessary improvements have been initiated.

It is anticipated that conducting this improvement effort in a workstation environment could be equally efficient or more so than conducting the effort in a personal computer environment. Furthermore, it would allow use of the improved version in a new and expanded environment while still making the same improvements in the personal computer version.

Key features which are being added as part of this developmental effort are discussed in the following sections.

Autoregressive Modeling Capabilities

The Autoregressive Moving Average (ARMA) methodology in generating annual data and Periodic Autoregressive Moving Average (PARMA) methodology in generating seasonal or monthly data is presently being added. The ARMA model has the form:

$$Q_t = \mathbf{A}\, Q_{t-1} + \mathbf{B}\, \epsilon_t - \mathbf{C}\, \epsilon_{t-1} \qquad (1)$$

for the annual ARMA (1,1) model where **A**, **B** and **C** are coefficient matrices, Q_t and Q_{t-1} are the discharges for years t and t-1 respectively and ϵ_t and ϵ_{t-1} are the corresponding random terms.

Likewise, the periodic PARMA (1,1) model has the general form:

$$Q_{\mu\tau} = \mathbf{A}_\tau\, Q_{\mu\tau-1} + \mathbf{B}_\tau\, \epsilon_{\mu\tau} + \mathbf{C}_\tau\, \epsilon_{\mu\tau-1} \qquad (2)$$

where $Q_{\mu\tau}$ is the discharge in year μ, month τ and $\mathbf{A}_\tau$, $\mathbf{B}_\tau$ and $\mathbf{C}_\tau$ are the parameters for month τ. Presently only Autoregressive (AR) capabilities are available.

Multivariate Autoregressive (MAR) and contemporaneous ARMA (CARMA) models are being considered as potential options for multisite modeling.

Parallel efforts will be made to develop Gamma Distribution based modeling capabilities. These include a Gamma Autoregressive (GAR) model for annual data and a Periodic Gamma Autoregressive (PGAR) model for seasonal modeling.

Product Model Capabilities

The capability to use Product Models on an annual and seasonal basis is also being added. It is anticipated that this will be particularly useful in generating stochastic data for intermittent streams. This is a very important issue which is presently not handled in the program due to limited transformation capabilities. Presently available transformation capabilities are the logarithmic and power methods which are stated as:

$$T = \ln\,(Q + c) \qquad (3)$$

and

$$T = (Q + c)^a \qquad (4)$$

where Q is the actual discharge, T is the transformed discharge, and c and a are constants which are arbitrarily selected by the user.

Both of these methods handle repeated zero discharges poorly and it is anticipated that the product model approach will help relax this limitation.

New Disaggregation Methods

In addition to the presently available Valencia Schaake and Mejia Rouselle approaches, these methods will include the Santos and Salas (1983) step method and perhaps the method presented by Stedinger, Pei and Cohn (1985). It is felt that some of these alternative approaches can lead to improvements for preserving seasonal variation in the generated data. This was known to be a limitation when the program was first developed and has become a more critical need in recent years as the state of the art has advanced.

Improved Transformation Capabilities

Enhanced transformation capabilities are being developed including more options and more help in transformation selection. The feasibility of adding automatic transform fitting through the method of least squares or the method of moments is also being evaluated.

Testing of Residuals

Testing procedures are being added to evaluate normality of residuals, autocorrelation of residuals and to compare the various modeling techniques.

Improved Capabilities in Accessory Package

Development of improved accessory packages is presently underway to assist users in the analysis of the generated data and in its' application to water resources planning and operation studies.

Improved Guidance for Beginning Users

Interactive messages in the program will be developed to provide users with background information on general principles of stochastic hydrology, suggestions as to situations where it would be most useful, improved guidance on grouping of stations, identification of key and substations and ways to avoid problems in the disaggregation process.

RECENT APPLICATIONS

Recent applications of the package include fish habitat studies on the Truckee - Carson river system of California and Nevada, analyses of the potential impacts of global climate change on operations of Bureau of Reclamation projects and evaluation of Colorado River Water Management issues.

The Truckee - Carson application was used to provide hydrologic information to an interdisciplinary and interagency team set up to assess the probability of survival of the Cui-Ui, an endangered fish species found in the lower reaches of the Truckee River. A set of 200 hydrologic traces covering key locations in the basin was generated for use by biologists in their population projection models. It was hoped that, through this type of approach, an objective estimate of the probability of survival of the Cui-Ui could be obtained. The final report containing results of this study is being reviewed internally by the respective agencies and has not yet been released to the public.

The global climate change study focused on Reclamation's Colorado Big Thompson project and how this project might be impacted by various possible climate change scenarios. The scenarios considered included changes in precipitation of -10%, 0 and +10% combined with increases in temperature of 0, +2 and +4 degrees celsius. The PRMS model supported by the US Geological Survey and described in Leavesley, et al (1983) was used to estimate what levels of impacts these hypothetical climatic changes could have on runoff in the project's water supply area. By use of these estimated impacts, an adjusted set of historically based runoff traces, one corresponding to each climate change scenario, was developed. The historically based runoff traces, in turn, served as the basis for a series of stochastically generated traces which were used in a project operations model. Results of this application are detailed in a soon to be published U.S. Bureau of Reclamation (1993) report.

A stochastic data base has been developed to be used on the Colorado River System for management and operations decisions. This data base allows for consideration of a wider variety of equally likely hydrologic scenarios than can be found in the historical hydrologic data set.

FUTURE AVAILABILITY AND POTENTIAL APPLICATIONS

It is anticipated that the improvements outlined in this presentation will be accomplished through an Interagency Personnel Agreement with Dr. Jose D. Salas of Colorado State University and will be completed in the spring of 1994. The improved model, with an updated user's manual, will be made available for general use when Dr. Salas' work is completed.

In addition to the more traditional applications to planning and operation studies, it is expected that the model will be useable in conjunction with dynamic programming algorithms to evaluate optimal reservoir management under present level hydrologic conditions as well as under climate change scenarios which could evolve in the future. Potentially, the package could be adapted into an Advanced Decision Support System (ADSS) environment.

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UPPER COLORADO RIVER SIMULATION/OPTIMIZATION MODEL

LESLIE C. STILLWATER[1]

INTRODUCTION

Purpose and Scope

Reclamation has traditionally managed river systems to achieve the full potential economic benefits of hydropower production while meeting project water commitments. The practice not only made good economic sense by covering project costs and allowing for the inexpensive and liberal delivery of water, but was motivated by an interpretation of the authorizations described in public law.

Public values now recognize the merit of the multiple use of water and in response, Reclamation is re-evaluating system operations. Proposed (and in some cases, existing) operations consider water uses which include instream flows for the maintenance of fish, riparian bird and wildlife habitats, recreation, and channel conditions. When water- use objectives compete, the decision process becomes functionally complex.

To evaluate current operations and to assist in the development of improved operations when competing water-use objectives exist, a monthly simulation/optimization model of the Upper Colorado River System was developed (Peterson and Stillwater, 1992). The model was originally applied to an analysis of the frequency of spills under traditional or "normal" operations and alternative operations in support of the Glen Canyon Dam Draft Environmental Impact Statement (1993).

In this paper the author discusses the decision support the model provides to an operator who is required to schedule monthly releases based on inflow forecasts when limited competing water-use objectives exist. The optimization algorithm and priority system which drive the decision procedure and the simulation are described. The model is applied to monthly historic inflow and forecast data for the years 1966 through 1989.

Model Summary

The model simulates real-time monthly release decisions for the five major reservoirs and four major power plants of the Upper Colorado River Basin. The term real-time is used in the context

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of this paper to describe the limited ability of the decision maker to forecast and interpret future events. The reservoirs modelled are Fontenelle, Flaming Gorge, Blue Mesa, Navajo and Lake Powell (Glen Canyon Dam). Navajo does not produce hydropower. A schematic of the system is shown in Figure 1.

Release decisions are determined each month based on inflows forecasted for the following months and the water-use objectives listed below:

- achieve a preferred release hydrograph specified by the user,
- when the preferred release hydrograph can not be achieved, perturb it as necessary according to a temporal distribution of "excess" water defined by the user,
- release within the efficient operating range of powerplants,
- meet end-of-month target reservoir contents for July and December, and
- do not release quantities of water greater than powerplant capacity (do not spill).

Preferred monthly release hydrographs may reflect any number of criteria, including desired instream flow conditions for the maintenance of habitat for fish, riparian birds, and wildlife; recreation; channel conditions; or hydropower scheduling. Necessary perturbations to the preferred release hydrographs are controlled through the optimization procedure described in the following sections.

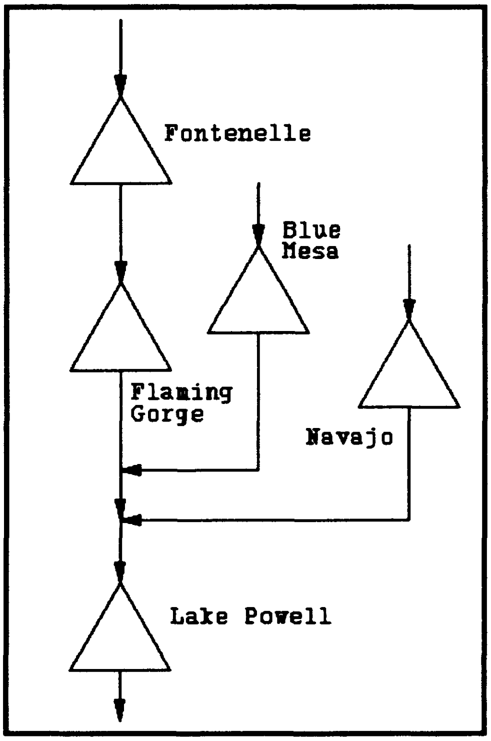

Figure 1. Schematic of the Upper Colorado River System.

DESCRIPTION OF THE MODEL

Model Input and Output

Model input includes weighting factors which define priorities for each water-use objective, historic forecasted inflows, historic actual inflows, target end-of-month storage contents for July and December, and preferred release hydrographs for each reservoir.

Model output includes the total monthly releases, power releases, spills, and end-of-month storage volumes for the period of record, as each would have occurred under the operating priorities specified by the user.

Simulation of the Reservoir System

The preferred hydrograph of monthly release volumes for each reservoir, provided by the user, serves as a "first cut" solution to the water distribution problem. Due to the influences of other water-use objectives and constraints, the preferred release hydrograph may not be achieved. A perturbation to the hydrograph is determined during the optimization phase of the model according to a prioritized distribution of excess water defined by the user.

Target end-of-month reservoir contents, referred to as target volumes, are provided by the user for the months of July and December. These months are referred to as target months. Target volumes are not necessarily a firm constraint, but are met according to the priority set by the user. The target volumes can be used to represent the preference to have reservoirs full by the end of July and ready to fill by the end of December.

Forecasted inflow volumes are revised at the beginning of each month during simulation for the months January through July. If the current month in simulation is January, forecasted inflow volumes for January through the next target month (July) are used to determine release decisions for all reservoirs in January. This simulates the real-time requirement for an operator to make release decisions for the current month based on imperfect knowledge of future inflows. Similarly, if the current month is February, forecasts for February through the next target month (July) are used to determine the releases for February, and so on.

Release decisions are made at the beginning of each month during simulation by the optimization algorithm. Actual inflow volumes are used to determine end-of-month reservoir contents for each reservoir. If actual inflow volumes differ significantly from the forecasted volumes (in other words, the forecast error was significant), the end-of-month reservoir contents for the current month may violate maximum or minimum storage constraints. In this case, adjustments are made to the current month's release so that these violations do not occur.

Actual inflow volumes are used in lieu of forecasted inflow volumes for the months August through December due to the predictable nature of the inflows for these months.

Current Month Water Balance

A volumetric water balance is performed at the beginning of the current month in simulation for each reservoir. The water balance determines the difference between the total preferred monthly release volumes and the total forecasted inflow volumes from the current month through the next target month (July or December):

$$\Delta V = \sum_{k=1}^{M} I_k - \sum_{k=1}^{M} R_k - \sum_{k=1}^{M} E_k - S_M + S_1 \qquad (1)$$

where, the summations are over the current month, 1, to the target month M,

I_i is the forecasted inflow volume during month k,

R_k is the preferred release volume during month k,

E_k is the estimated evaporation during month k,

S_M is the target storage volume at the end of the target month M,

S_1 is the storage volume at the beginning of the current month, and

ΔV is the total excess water (volume difference).

The excess water (ΔV) is the volume of water which must be released in *excess* of the preferred release hydrograph from the beginning of the current month to the end of the next target month. It may have a positive or negative value.

Perturbation of the Preferred Hydrograph as Forecasts are Revised

Because forecasted inflow volumes are revised at the end of each month, excess water ΔV is calculated at the beginning of each month during simulation. The user specifies how to perturb the preferred release hydrograph to accommodate the excess water via monthly distribution factors. These distribution factors indicate the percentage of the excess water for each of the months remaining to the end of the target month which will be added to (or subtracted from) the preferred release hydrograph.

This approach gives the user some control over the temporal redistribution of water as inflow forecasts are updated and actual inflows occur or when higher priority water-use objectives or constraints govern the release of water. For example, a strategy to distribute positive excess water ΔV, yet reduce the likelihood of future spills, is to release most of the excess in the earlier months. The priority given to matching the preferred distribution of excess water is set by the user.

DESCRIPTION OF THE OPTIMIZATION ALGORITHM

At each month of simulation a dynamic programming (DP) algorithm is called to determine the monthly release volumes for the current month through the next target month. The DP algorithm optimally distributes the excess water ΔV according to the penalty value accumulated due to violations of the weighted objectives.

Objectives and Weighting Factors

Release decisions are made for each month of simulation based on different and perhaps competing objectives. A weighting factor is assigned to each objective by the user, so that if a release decision violates the user's highest priority objective, the largest penalty is accumulated for each month of violation. Release decisions which violate lesser priority objectives, accumulate lesser penalties accordingly. When the maximum weighting factor is assigned to an objective, the objective becomes a system constraint. A system constraint is never violated.

Objective List

Each objective is prioritized by the user. Although other objectives may be formulated, the current objective list is as follows:

- The preferred hydrograph is perturbed by the total amount of excess water (ΔV in equation 1) which resulted from forecast revisions, according to the user-specified distribution factors. Penalties are accumulated for each month throughout the simulation based on the difference between the distribution factor for the current month and the actual percentage of ΔV added to (or subtracted from) the release for that month. The penalties reflect the user's priority on distributing excess water throughout the remaining months, set through the assignment of a weighting factor.

- Target volumes are met, if possible, at the end of the corresponding target months. Penalties are accumulated during target months when target volumes are not met. The penalties are based on the absolute value of the difference between the volume of water in storage and the target volume. The penalties reflect the user's priority on meeting target volumes, set through the assignment of a weighting factor.

- Spills are avoided so that maximum hydropower benefits are realized. Penalties are accumulated throughout the simulation period based on the total volume of water spilled for each reservoir for all months. The penalties reflect the user's priority on spill avoidance, which is set through the assignment of a weighting factor.

- Release volumes are maintained within the range of practical maximum and minimum release limits at each reservoir whenever possible. Practical release limits are the preferred maximum and minimum release volumes, but not the absolute maximum and minimum release volumes that can be allowed through the power plant each month. Penalties are accumulated throughout the simulation period based on the volume of water released which surpasses the practical release limits. The penalties reflect the user's priority on releasing within the practical limits. This priority is set through the assignment of a weighting factor.

- Maximum and minimum storage levels for each reservoir are formulated as system constraints. In other words, a violation of a maximum or minimum storage constraint accumulates the maximum penalty and the corresponding release decisions are flagged as infeasible.

For most objectives which are not system constraints, the penalty applied at each month is the product of the normalized volume of water which creates the violation and the corresponding weighting factor. A normalized volume of 1.0 indicates the objective has been violated in the current month to the greatest conceivable extent. A normalized volume of 0. indicates no violation has occurred. Normalized volumes permit similar priorities for different objectives when identical weighting factors are assigned.

MODEL PERFORMANCE AND RESULTS

In most years simulated, relatively small changes in the magnitude and shape of the monthly release hydrographs can be directed by the manipulation of the priorities described above. The accuracy of monthly forecasted inflows determines the degree to which a preferred hydrograph can be matched, and then only if the hydrograph does not violate the physical constraints of the system. The user exercises the most control over the general shape and total volume of the release hydrographs through priorities assigned to the redistribution of water in excess of the preferred hydrographs.

The computational density of the model can be extreme, because the dynamic programming algorithm may be called at every month of the simulation. Even so, the model executes in less than 2 minutes on an 80486/50 MHz IBM-compatible PC.

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USING CLIGEN TO STOCHASTICALLY GENERATE CLIMATE DATA INPUTS TO WEPP AND OTHER WATER RESOURCE MODELS.

Arlin D. Nicks [1] and Gene A. Gander [1]

ABSTRACT

Often climate data are not available or are difficult and expensive for hydrologic model users to obtain. Availability of climate data can limit the use of continuous simulation water resource models such as those now being used to estimate erosion, water quality, and environmental impacts. When such data are available they must be edited for missing and spurious data and are usually of a fixed record length which may not be applicable to the user needs. Development of stochastic weather generators and climate parameter databases that these generators utilize has greatly expanded the use of simulation models. CLIGEN, the climate data generator developed for the WEPP (Water Erosion Prediction Project) has a database of over 1100 stations in the U.S., Puerto Rico, and the Pacific Islands. CLIGEN provides daily values of precipitation amounts, durations, and intensity characteristics; maximum, minimum, and dew point temperatures; solar radiation; and wind speed and direction. Data which are required for many hydrologic, erosion, and plant growth models. Consequently, CLIGEN and its databases have been adapted to use by models other than WEPP such as CREAMS/GLEAMS, EPIC, SWRRB, AGNPS and others. The interactive operation of the model will be presented, as well as application with both hydrologic process models and other application of the generator and database.

INTRODUCTION

Several weather generator have been developed in the past decade to simulate weather inputs to various types of models. Three existing hydrologic and erosion simulation models EPIC (Erosion Productivity Impact Calculator) (Williams, et al., 1984), SWRRB (Simulator of Water Resources in Rural Basin) (Williams, et al., 1985), and SPUR (Simulator of Production and Utilization of Rangelands) (Wight, et al., 1983), use synthetic weather generators for climate data inputs. The outputs from these generators consist of the occurrence of precipitation, the daily amount, maximum and minimum temperature, and solar radiation. In the case of the EPIC model where wind erosion is estimated, average daily wind speed is also generated. Common to all of these models is the SCS curve number method partitioning precipitation into runoff and infiltration. Thus, only a daily estimate of precipitation is needed. However for more advanced water resource models for simulating erosion and surface and subsurface chemical movement utilizing incremental infiltration partitioning, some measure of disaggregated rainfall is required.

In 1985, a USDA - Water Erosion Prediction Project (WEPP) was started to develop new generation water erosion prediction technology (Lane and Nearing, 1989). Prediction

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requirements for federal and state user agencies, private industry, and individuals were increasing because of environmental concerns. These concerns require that not only sheet and rill erosion be estimated, but also the estimation of transport and deposition of the resulting sediments on the landscape by concentrated flow and in off-site locations such as stream channels and waterways. A part of the overall requirement was the need for climate inputs to drive portions of the processes and model components. Furthermore, climate data inputs would be required at every location that the model was to be applied, requiring a extensive climate database.

The user requirements (Foster, 1987) specified the following for
Climatic (Weather) Inputs:

> "Climate (weather) inputs can be, but not limited to values: (a) generated by a stochastic (random) weather generator, (b) obtained from historical weather records, or (c) derived from design storms characteristics including additions of water by sprinkler or surface irrigation. In any case, the climatic inputs shall be retrievable from a prerecorded record that can be directly accessed by the computer program implementing the procedure, and use of the procedure shall require no action by the user when the procedure is applied within specified geographic regions. . . . In the case of design storms, the maximum information that should be expected from the user is : (a) storm amount, (b) average intensity, (c) ratio of peak intensity to average intensity and (d) time to peak."

From these requirements, a weather generator, CLIGEN, (Nicks and Lane, 1989) was developed which supplies the following weather elements required by the WEPP models on a daily time step: 1) precipitation amount, duration, maximum intensity, and time to peak; 2) maximum, minimum, and dew point temperature; 3) solar radiation; and 4) wind speed and direction. To provide the necessary parameters for the generator, a database with approximately 1100 stations was developed for the conterminous 48 U.S. states, Alaska, Hawaii, Puerto Rico, and nine U.S. pacific islands. The techniques, procedures, and various data used in CLIGEN are given in the following sections.

PRECIPITATION OCCURRENCE

The method used for generating the number and distribution of precipitations events is a two-state Markov chain. This method involves the calculation of two conditional probabilities: a, the probability of a wet day following a dry day, and b, the probability of a dry day following a wet day. The combination of conditional probabilities is

$$P(W|D) = a \tag{1}$$
$$P(D|D) = 1 - a \tag{2}$$
$$P(D|W) = b \tag{3}$$
$$P(W|W) = 1 - b \tag{4}$$

where P(W|D), P(D|D), P(D|W), and P(W|W) are probabilities of a wet given a dry, dry given a dry, dry given a wet, and a wet given a wet previous day, respectively. Twelve monthly values of these probabilities are calculated and used to provide some transition from one season to another. Random sampling of the monthly distribution is then used to determine the occurrence of a wet or dry day. The mean daily temperature for the day is used to determine the liquid or solid state of the precipitation. The precipitation is assumed to be snow if the generated average daily air temperature is at or below freezing. Shown in figure 1 is the distribution of National Weather Service (NWS) precipitation and temperature climate stations used to calculate the parameters required by the generator. Other climate element parameters such as solar radiation, dew point temperature, and wind speed and direction are derived from other data sources with fewer observation stations. Parameters for these elements are calculated and distributed to each of the stations shown in figure 1 by interpolation procedures.

PRECIPITATION AMOUNT

A skewed normal distribution is used to represent the daily precipitation amounts for each month. The form of the distribution is

$$x = 6/g((g/2((X-u)/s) + 1)^{(1/3)} - 1) + g/6 \tag{5}$$

where x is the standard normal variate, X is the raw variate, and u, s, and g, the mean, standard deviation, and skew coefficient of the raw variate, respectively. The mean, standard deviation, and skew coefficient are calculated for each month. Then to generate a daily amount for each wet day occurrence, a random normal deviate is drawn and the raw variate, x (daily amount), is calculated using equation (5).

STORM DURATION

The method used to estimate the duration of generated precipitation is that proposed by Arnold et al., 1990. It is assumed that the duration of storm events is exponentially related to mean monthly duration of events given by

$$D = 4.607/(-2\ln(1-rl)) \tag{6}$$

where D is the event duration in hours and rl a dimensionless parameter from a gamma distribution of the half-hour monthly average precipitation amounts.

PEAK STORM INTENSITY

The maximum storm intensity is estimated by a method proposed by Arnold and Williams, 1989 as

$$r_p = -2P(\ln(1-rl)) \tag{7}$$

where r_p is the maximum storm intensity, P is the total storm amount, and rl is as described previously.

Time from the beginning of the storm to the peak intensity is estimated by calculating the upper limit of storm duration by

$$D_u = 24.0(1-e^{(-0.3/rl)}) \tag{8}$$

and

$$D_p = 0.4D_u \tag{9}$$

where D_u is the upper limit of storm duration varying from 0 to 24 h, and D_p is the time to peak intensity.

TEMPERATURE

Temperature values are generated from a normal distribution of the form given as

$$Tmax = Tmx + (STmx)(v)(B) \tag{10}$$
$$Tmin = Tmn + (STmn)(v)(B) \tag{11}$$

where Tmax and Tmin are generated maximum and minimum daily temperatures, Tmx and Tmn are the mean daily maximum and minimum temperature for a given month, STmx and STmn are the standard deviations of maximum and minimum temperature for the month, v is a random normal deviate, and B is a weighting function based on the wet-dry day probabilities. Values for B for a given month are

$$B(W|D) = 1 - P(W|D)\ /PF \tag{12}$$
$$B(W|W) = 1 - P(W|W)\ /PF \tag{13}$$
$$B(D|D) = P(D|D) \tag{14}$$
$$B(D|W) = P(D|W) \tag{15}$$

where PF is a probability factor based on the wet - dry day probabilities given by

$$PF = P(W|D)(1 - P(W|D)) + P(W|W)(1 - P(W|W) \tag{16}$$

The weighting function B is used to adjust generated temperatures for the dependency on precipitation state of the previous day.

Dew point temperature is simulated using the same methods as for maximum and minimum temperature. Dew point is generated by

$$Tdp = Tdpo + Stmn(v)(B) \tag{17}$$

where Tdp is the generated daily dew point temperature, Tdpo is the mean dew point temperature, and v is a standard normal deviate.

SOLAR RADIATION

Daily solar radiation is generated by

$$RA = (RAm) + (Ura)(x)(B) \tag{18}$$

where RA is the generated daily solar radiation, RAm is mean monthly solar radiation, Ura is the standard deviation for solar radiation, and x is a standard normal variate. The generated solar radiation is constrained between a maximum value possible for the day of the year, RAmax, and a minimum value set at 5% of the maximum value. The maximum radiation possible is computed from the station location and the sun angle on the day to be generated. The standard deviation is estimated by

$$Ura = (RAmax) - (RAm)/4 \tag{19}$$

WIND SPEED AND DIRECTION

Wind speed and direction are required in the WEPP models for the calculation of snow accumulation and melt and evapotranspiration of crops. The method used to generate wind direction is based on the division of historical wind data into 16 cardinal direction by percent of time the wind is blowing from that direction. A uniform random number between 0 and 1 is drawn to sample the accumulated distribution of wind directions. After the direction is calculated, the wind speed for that direction is generated using equation (5). But in this case, the mean, standard deviation, and skew coefficients of daily wind speed are used as the parameters.

DATABASE

Daily, hourly, and 15-minute data were obtained from the NWS National Climatic Data Center. These data were inventoried and approximately 7000 station were found with precipitation or precipitation and temperature with 25 years or more of record lengths. A sub-set of approximately 1100 stations based on a grid 1- by 1- degree of latitude and longitude were selected for parameterization. The distribution of these stations are shown in figure 1. At each station of this grid, parameters of all other climate elements were also calculated. Similarly, stations were selected in Alaska, Hawaii, Puerto Rico, and the U.S. pacific islands, resulting in a generator parameter database for each of the 50 U.S. states and territories.
Distribution of the solar radiation and dew point data station are shown in figure 2. Wind speed and direction stations used are shown in figure 3.

Users of the WEPP models generate a climate file using the parameters of the station nearest the model application site and input this file to the model. For models such as EPIC and SWRRB, the parameters required have been incorporated into the climate data bases of these models. CLIGEN has an option to generate the precipitation and temperature files for the GLEAMS/CREAMS model. Other models under development such as a continuous version of AGNPS (Young, et al., 1987) also uses CLIGEN to provide inputs. The database of daily precipitation and maximum and minimum temperature have been processed to develop a monthly time series database useful in Global Change studies. Using CLIGEN and a two-pass method of reading the data, generator parameters are calculated and missing data estimated and monthly mean temperatures and mean monthly total precipitation calculated.

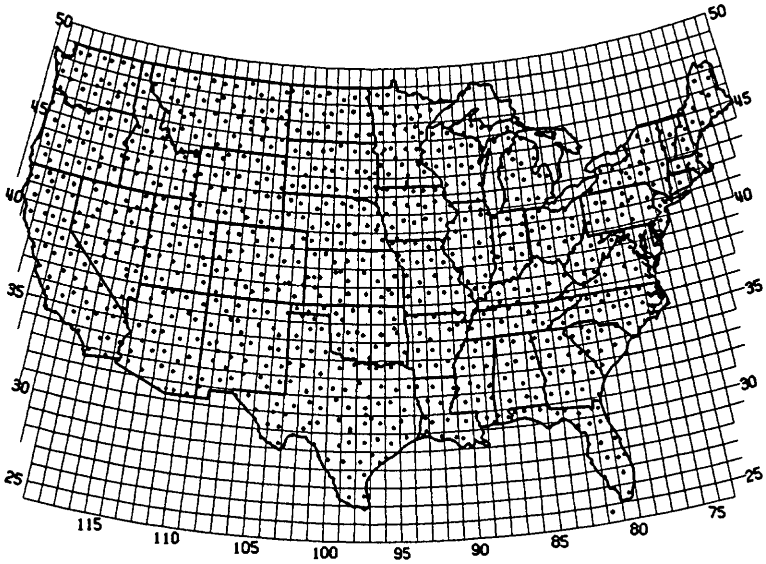

Figure 1 Precipitation and temperature stations selected for parameterization.

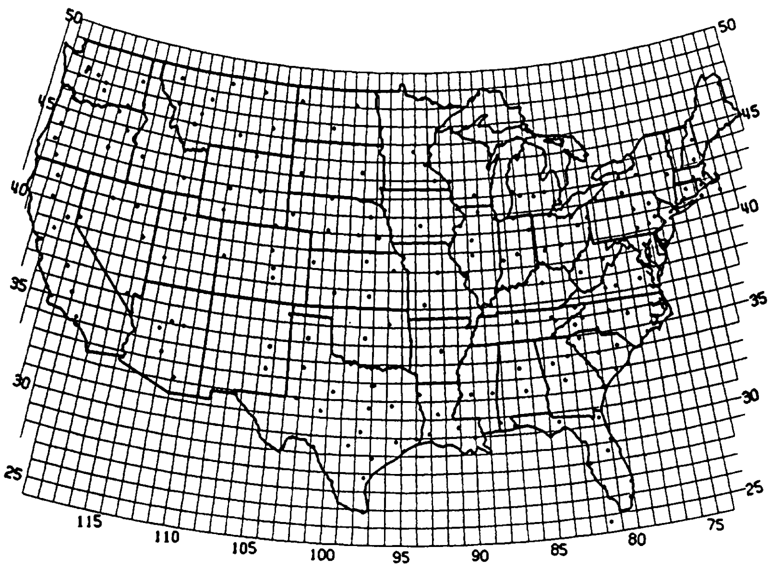

Figure 2. Solar radiation and dew point temperature stations.

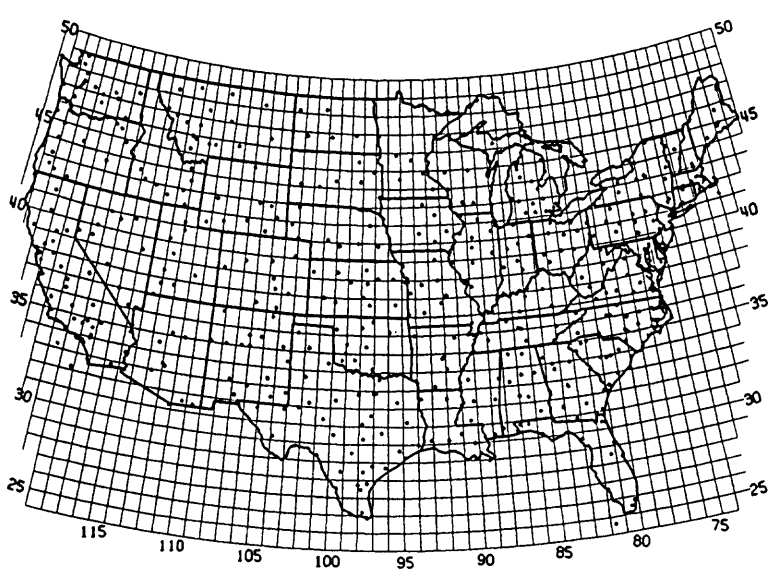

Figure 3. Wind speed and direction stations.

OTHER USES OF THE GENERATOR AND DATABASE

CLIGEN has been used in other application besides continuous simulation of inputs to water resources models. The parameter database was used to calculate regional and seasonal potential root zone recharge for the U.S. Monthly parameters of precipitation, temperature, solar radiation, and wind were used to calculate the monthly and seasonal potential evaporation, at each of the station in figure 1, using the Penman evaporation model (Penman, 1948). Differences between monthly precipitation and potential evaporation was calculated and contour mapped to delineate regions and seasons where precipitation exceeded potential evaporation. Thus, providing a measure of the precipitation available for root zone recharge that could be used to select methods of soil profile modification (Kemper, et al., 1993)

To check the validity of the climate data generated by CLIGEN, we generated 30 year records at each of the station in the eastern half of the U.S. (east of the 105th meridian). These records were then used to calculated USLE (Universal Soil Loss Equation) average annual rainfall erosion index, R, at each station. Using the rainfall amount, duration , time to peak, and the ratio of average intensity to maximum storm intensity and the disaggregation routine used in the WEPP model, distribution of storm intensities for each day of rainfall were calculated. From these distributions, the average annual R values were computed using the procedures outlined by Wischmeier (Wischmeier and Smith, 1978). Contours of the R values were constructed by computer programs and plotted as shown in figure 4. While there is not exact agreement between those contour lines constructed using CLIGEN and those given in the USLE handbook, the pattern is quite similar, indicating that the intensities generated are close to those of the observed data across the U.S.

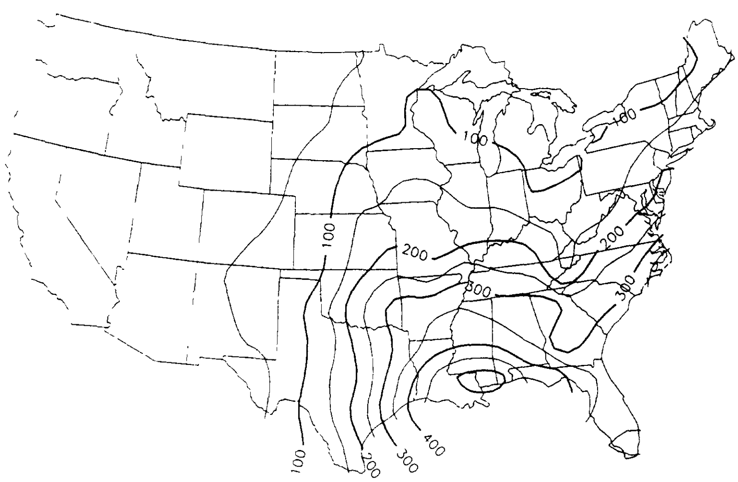

Figure 4. CLIGEN generated average annual rainfall erosion index.

SUMMARY

A weather generator, CLIGEN, and an extensive database of generator parameters have been developed that are being used in a number of water resource models. Weather elements generated included storm precipitation amount, duration, time to peak, average intensity and maximum intensity, daily maximum, minimum, and dew point, temperatures, solar radiation, and wind speed and direction. The data output by the generator supplies the data for a variety of environmental models. Also, the daily precipitation and temperature database developed may prove useful for other purposes such as Global Change research. The database and the generator are being updated as new data and procedures become available.

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MUSKINGUM BASIN RESERVOIR FREQUENCY ANALYSIS

DR. SURYA BHAMIDIPATY[1] AND JERRY W. WEBB[2]

ABSTRACT

The purpose of the study was to develop a consistent and defendable elevation frequency analysis of pool elevations for the fourteen (14) original reservoirs built in the 1930's within the basin. A significant level of interest has been expressed over encroachments over time into the easements of reservoirs within the basin. Current policies have resulted in the movement of some dwellings and additional sites will be moved unless constraints on pool usage can be developed that will allow dwellings to remain in the flood control pool. The procedure required a systematic design storm approach involving generation of hypothetical rainfall events for each project in the Muskingum Basin; graphical extrapolation for extreme storm events from generally accepted synthetic all season point rainfall frequencies; and evaluation of representative antecedent precipitation conditions through a review of historical storm infiltration rates for each project site. Maximum emphasis was placed on utilizing historic frequency data for developing the 5 to 50-year component of the curve. All parameters used in the extrapolation of the curves were calibrated to the observed statistics associated with the historic operations. This study represents a systematic, consistent traditional approach to a problem that could be analyzed using more state-of-the-art sophisticated techniques involving stochastic hydrology. The limitations and lessons learned through the traditional approach and absence of reliability studies for the stochastic methods pose a challenge to today's hydrologic engineer in the assessment of the "best" approach to a regional frequency analysis.

INTRODUCTION

Special Considerations.

The methodology that was applied in this study was the subject of considerable discussion within the Corps technical community. The initial proposal involved use of a stochastic rainfall approach of derived distributions. It was determined that the approach would be appealing from the research and development perspective, but it posed several technical obstacles and would exceed time and funding limitations. The consensus recommendation of the Corps hydrology community involved a more traditional design storm approach which would utilize historical data for calibration purposes. This study was funded by HQUSACE and represents a systematic, consistent traditional approach that would provide the necessary elevation frequency analysis. The limitations and absence of reliability studies for determining rare flood volumes given the broad range of operational scenarios, lack of data, and accepted methodologies were acknowledged during the initial scoping of the plan of study.

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General Basin Information.

The Muskingum River basin, situated in the east central part of Ohio, occupies 8051 square miles and comprises about 20 percent of the land area of the state. The drainage pattern is highly irregular. The basin has been divided into two portions by the continental ice sheet. The line of glaciation runs in a generally northward direction from Perry County to Ashland County and from there eastward, leaving the basin near the Carroll-Columbiana county line. The glaciated portion to the north is characterized by gently rolling topography whereas the unglaciated area to the south and east is generally rough and well dissected, the only departure from this pattern being the broad valleys of the major streams. The Muskingum River, formed by the junction of Tuscarawas and Walhonding Rivers at Coshocton, in the center of the basin, is 112 miles in length, following a generally southerly but irregular course to Marietta, where it joins the Ohio River 172 miles below Pittsburgh. Principal tributaries include the Walhonding, Tuscarawas and Licking Rivers and Wills Creek.

The original fourteen Muskingum River Reservoirs control a drainage area of 4,267 square miles. As shown on the basin map (Plate #1), there are three tandem reservoir systems in the Muskingum River basin. The Dover reservoir system in the Tuscarawas River basin consists of Dover reservoir and three upstream reservoirs - Atwood, Bolivar and Leesville. The Mohawk reservoir system in the Walhonding basin includes Charles Mill, Mohicanville and Pleasant Hill, and North Branch Reservoir. North Branch reservoir which is located on the North Branch of the Kokosing River has a drainage area of 44.5 square miles and was completed in 1973, using current spillway design criteria. The Wills Creek reservoir system in the Wills Creek basin includes only one of the original group of 14, namely Senecaville, plus Salt Fork reservoir. Salt Fork Reservoir was constructed by the State of Ohio in 1967 and has a drainage area of 160 square miles (Note, frequency-of-filling curves were not developed for this reservoir). The total drainage areas for the Dover, Mohawk and Wills Creek tandem systems are 1,397, 1,501 and 844 square miles, respectively. Additional reservoirs include Tappan, Clendening, Piedmont, Beach City, and Dillon which operate independently and have drainage areas of 71, 69, 86, 300 and 743 square miles, respectively. Dillon and North Branch Kokosing were not among the original fourteen projects.

Regional Natural Discharge Frequency Analysis.

The original fourteen reservoirs were constructed in the 1930's. Therefore, there exists a significant database of hydrologic data upon which several studies have been performed. A regional natural discharge frequency analysis for the entire basin was performed in 1982. The regional analysis used methods set forth in Bulletin 17B, "Guidelines for Determining Flood Flow Frequency," dated September 1981, and published by the United States Water Resources Council. A Log-Pearson type III distribution was fitted to the annual event series at 54 gaging stations with an average of approximately 40 years of record throughout the Muskingum River Basin to derive generalized relationships which relate frequency curve factors such as mean, standard deviation and skew to the individual basin factors. A map of the entire region was drawn to delineate isolines showing areas of equal skew. Supporting documentation and results of this earlier study are available in Huntington District. Peak discharges from this regional study were used in this study for initial calibration of runoff parameters associated with the design storms.

Real-Time Flood Forecasting and Reservoir Control Analysis.

A detailed study of the basin was performed by HEC in 1986 for the purpose of establishing real time forecast capability for water control purposes. The procedures and analysis were documented in HEC's Special Projects Memorandum No. 86-1, dated February 1986. The unit hydrographs and maximum routing times that HEC presented in Memorandum No. 86-1 were used as a basis for the hydrologic model used with the design storm approach. HEC's Memorandum goes into great detail as to how the Muskingum Basin was broken down to determine loss rates, infiltration, routing times, and other parameters associated with real time forecasting. The report was published as documentation of the development and testing of real-time water control models for flood forecasting and reservoir operations in the Muskingum River Basin.

ANALYSIS METHODOLOGY

General Background Analysis.

The basic approach used in this study required that estimates for reservoir inflow volumes and their correlating pool elevations be determined for a full range of frequency events. Reservoir inflow volume frequencies could be estimated using several techniques including graphical plotting position analysis of annual peak storage values, annual frequency analysis of peak storage volumes using Bulletin 17B techniques, frequency analysis of observed inflow gaging stations, and use of an HEC-1 watershed model (Flood Hydrograph Package developed by HEC, Davis, CA) with hypothetical storms. All of these techniques only approximate inflow volumes associated with rare storm events and are only as good as the extrapolation techniques used.

Graphical Frequency Analysis.

A graphical plotting position approach was employed to analyze the actual peak annual storage values at each project. The results of this procedure provide meaningful results up to the highest plotting position, which in this case utilizing the Median plotting formula is equivalent to approximately a 75-year storm event. The upper end of the graphical plots were sensitive to potential high outliers and assignment of plotting positions to the largest five events in the historic record produced inconsistencies in skewness associated with the graphical plot between the 10-year and 75-year event.

Bulletin 17B Annual Frequency Analysis.

This analysis was performed as a check against the graphical plotting position analysis. Standard procedures were applied to annual peak storage volumes to produce a frequency relationship. Problems were experienced in the evaluation of high outliers and inconsistent shape of the curves for rare storm events.

Observed Inflow Station Frequency Analysis.

This analysis was performed subsequent to the majority of work performed by Huntington District. The intent of the analysis was to ascertain the validity of calibrated storage values and runoff parameters produced by the hypothetical hydrologic model with actual parameters determined from several uncontrolled inflow gaging stations.

Hypothetical Design Storm Approach.

As previously discussed, the plan of study recommended a design storm approach to the subject analysis. It was assumed that this approach would provide the basis for determining the stage frequency relationships for all reservoirs within the system. Considerable effort was devoted to establishing a working hydrologic model that could be operated in a system mode to determine the response of the basin to the design storms. As the study progressed, additional techniques utilizing historic data were used to determine the sensitivity of the computed reservoir responses to the initial assumptions.

Rainfall Data and Distribution.

The National Weather Service (NWS) has developed statistical data on historical rainfall amounts for most of the United States. This information is available in U.S. Weather Bureau Technical Paper No. 49 and Technical Paper No. 40 and National Oceanic and Atmospheric Administration (NOAA), Technical Memorandum NWS Hydro-35. This data was extracted to generate a hypothetical rainfall hydrograph. HECIFH (Interior Flood Hydrology Package developed by HEC, Davis, CA) was used to develop the 2-, 5-, 10-, 25-, 50-, 100- and 500-year events in the Muskingum Basin. Total rainfall amounts from the 100-year and 500-year events were used to interpolate the appropriate amount for the 200-year all season point rainfall. Final results from this calculation allowed the manipulation of the 100-year storm distribution amounts to generate the 200-year event. Sensitivity of the frequency curves to duration was considered in the analysis.
The NWS rainfall data provided historically related frequencies of depth-duration rainfall amounts for the Muskingum Basin. These rainfall amounts were entered in the computer program HECIFH to generate hypothetical storm distributions for the Muskingum Basin. A sensitivity analysis of duration was performed resulting in the decision to utilize a 4-day storm for purposes of this study. It should be noted that other durations including 1-day, 2-day, 7-day, and 10-day were considered in this study.

Infiltration.

In order to establish initial assumptions for use in the hydrologic simulation of the design storm events, the peak discharges associated with the regional natural discharge frequency analysis were used to calibrate the rainfall losses associated with the 10-, 25-, 50-, 100-, 200-, and 500-year events. Loss rates were estimated for each frequency until the natural discharges were reproduced within reasonable error limits. The basis for this procedure was outlined in the 1986 study completed by HEC in which several historic events were analyzed to develop "Unit Graphs" for each smaller basin within the Muskingum Basin.

Antecedent Conditions

The original scope of work proposed determining antecedent conditions from historical storm infiltration rates and starting pools at each project. A review of the historic data indicated that the design assumptions to be used in this study would have to be established based on reasonable engineering judgement and consistent policy. Due to lack of historic data for extreme events, a method consistent with the synthetic design storm approach was necessary. It was determined that an antecedent event proportional to the design storm would precede the main event. Starting pools and channel flows throughout the basin would be established based on the response to the antecedent event and then the design storm would follow. This concept acknowledges the potential for antecedent conditions to impact flood control pools prior to a major storm event. The similarity between these assumptions and the generally accepted, standard procedure for developing antecedent conditions for a PMP storm (30% with 3-day dry conditions or 39% with 5-days dry conditions) provides a consistent procedure that maintains a relationship with the frequency storm events. As previously discussed natural condition computer models were developed to calibrate the synthetic storms to the natural peak discharge condition. Infiltration rates for the entire storm were derived from this process. Runoff for the antecedent condition utilized these infiltration rates on a 50% rainfall event over the basin prior to the actual synthetic storm event with a 2-day dry period between storm events. In other words, for a 100-year storm event, the synthetic rainfall associated with a 100-year event was reduced by 50% and applied to the basin with a 2-day no-rain condition between the storms. For a 200-year event, the 200-year rainfall was reduced by 50% and then subsequently each frequency event was established in the same consistent manner. Most of the reservoirs were able to operate in such a manner as to pass flows associated with the antecedent storm event and return to normal pool prior to the main event for all but infrequent rare storm events.

EVALUATION OF RESULTS

Initial Evaluation.

The initial phase of this study provided results from the design storm approach. These results were analyzed based on calibrated natural condition rainfall losses. When these preliminary results were compared to the results of the graphical plotting position analysis and the Bulletin 17B analysis, it appeared that the calibrated losses for rare storm events were inconsistent with extrapolated values from the other methods. The resulting disparities indicated the need for a study into the historical duration of runoff volumes associated with the Muskingum Basin. As previously discussed, a volume frequency analysis for various uncontrolled inflow gaging stations was performed. The resulting volume frequency analysis indicated that there were inconsistencies in the skewness and extrapolation of the curves beyond the 50 year storm event. Since the basin can experience frozen, snow-covered conditions and antecedent conditions can fluctuate dramatically, it was decided that more conservative loss rates should be used for extreme events. Utilizing some degree of engineering judgement, losses were estimated and applied to a basinwide hydrologic model. An initial loss rate of 1.25 inches was used for the 100-, 200-, and 500-year events with uniform loss rates of 0.05, 0.025, and 0.00 inches per hour, respectively.

Final Evaluation.

Review of the results of the rare storm simulation with the revised loss rates indicated that a combination of techniques / results would be the best approach to representing a complete pool elevation frequency relationship for each reservoir. The consistency of these relationships relative to the different reservoirs was maintained through development of a ranking factor and plotting procedure for combining the results from the different analyses.

Ranking Procedure.

The ranking of reservoirs was performed to assure that a consistent frequency of filling curve would be developed when comparing reservoirs within the basin. The criteria that was used in the ranking was supported by a volume sensitivity analysis based on the 200-year frequency storm with 100% runoff. The initial loss of 1.25 inches was computed and deducted from the volume associated with the antecedent and design storm. The outflow volumes were based on percent outflow versus inflow relationships that were run for the 200 year event reservoir simulation analysis. This analysis assumed uniform losses of 0.025 inches. The overall factor shown on the table was developed by dividing the resulting storm volumes by the total flood control storage available at each reservoir site. This produced a range from 0.95 for Pleasant Hill to 1.62 for Beach City. The factor represented a relative ratio of percentage flood control storage utilized by a 200 year storm event. The ranking factors were utilized in establishing the plotting position for the frequency at which the spillway would be overtopped.

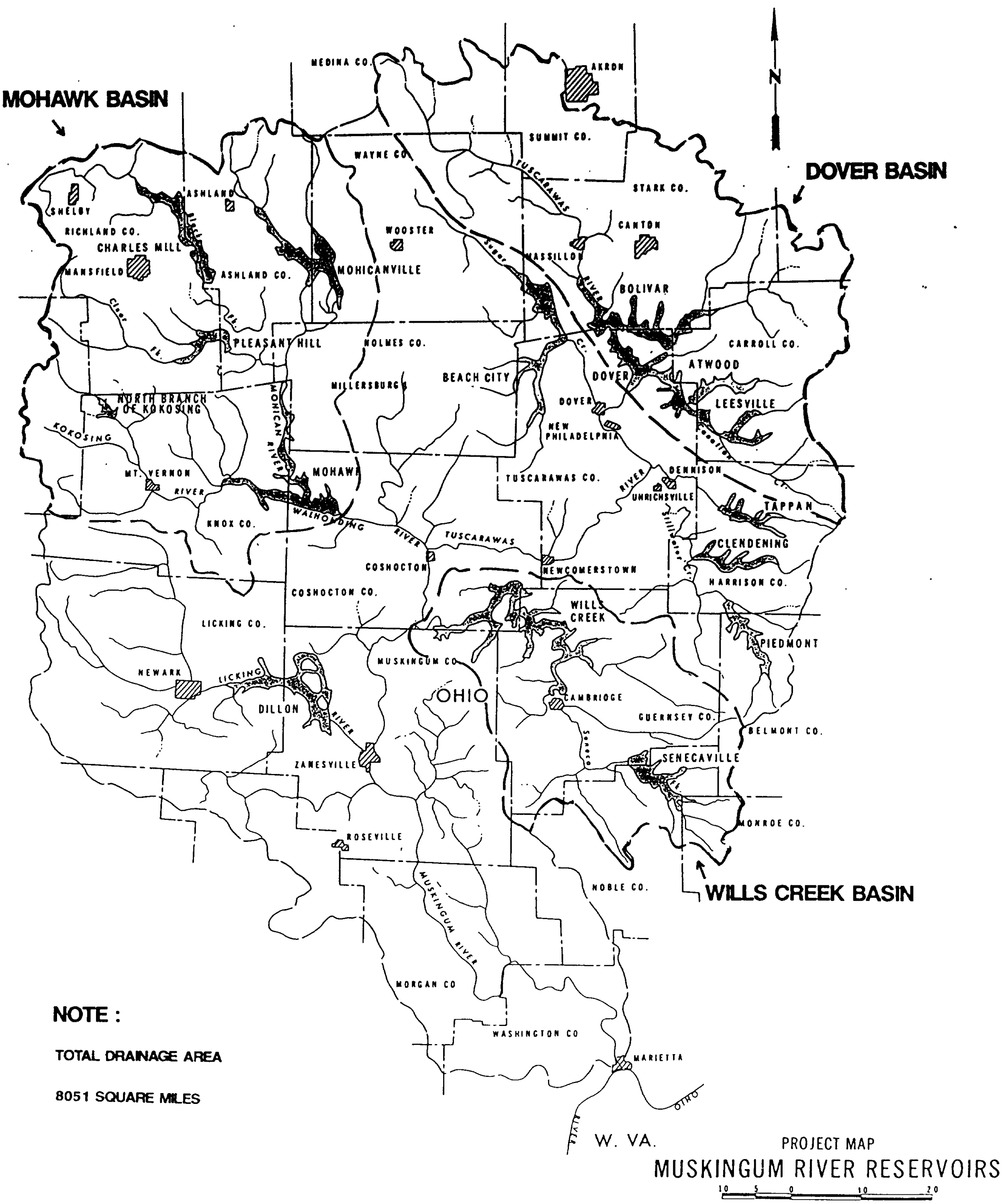
Plotting Procedure.

All analysis and curve plotting was performed on reservoir volumes and then the final curves were converted to elevation frequency. The graphical plotting position analysis of the historic annual peak storage volumes was used to define the lower portion of the curves. This determination was made based on the fact that this analysis maximized use of the historic information and best represents the actual historic operations and basin response. Plotting positions were determined for this data by using both the Weibull and Median approach to graphical frequency analysis. The District currently uses Bulletin 17B guidelines based on Median plotting position to analyze flow frequency data. It was this criteria that resulted in the decision to use the Median plotting position procedure for the final plotting position of peak storage data. Results from this analysis were plotted and considered accurate to approximately the 50-year frequency. The upper component of the curve was defined through a comparison / combination of an extrapolation of the graphical plotting position analysis and the hypothetical reservoir simulation results. A straight-line extrapolation of the curves was produced to the 100-year frequency. Actual results of the reservoir simulation of the 100-year event with 1.25 inch initial loss and 0.05 inch uniform loss were performed. If the results of the reservoir simulation were lower than the straight line extrapolation, the values from the reservoir simulation were ignored. If the simulation values were above the straight line extrapolation, a curve fitting procedure was applied between the 50-year and 200-year events. It was concluded that the historic information should be dependable up to the 50-year and in absence of better information would exhibit a straight line extrapolation to the 100-year. The 200-year storm event with 1.25 inch initial loss and 0.025 inch uniform loss ended up being the governing design storm event. The resulting pool volumes from the reservoir simulation analysis was plotted and used in all 16 curves. The 500-year event with 1.25 inch initial and zero uniform losses was also run but it only produced meaningful results for Pleasant Hill where the spillway was not overtopped and some of the uncontrolled reservoirs that had a high level of protection such as Clendening and Senecaville.

FINAL RESULTS AND CONCLUSIONS

The results from these procedures were graphically plotted for each of the projects. The final shapes of the curves are not consistent between reservoirs due to disparities resulting from several components involved in the curve development. In some cases, the shape of the stage volume relationship causes the elevation frequency curve to look totally different from the volume frequency relationship. Another major factor is the computed plotting positions applied to the largest five storm events in the historic record. Anomalies in the shape of the curves, which appear predominantly between the 10-year and 75-year event, are directly related to the plotting position formula which establishes this portion of the curve based on the largest five storm events. High outliers which could exceed a 75-year event or events of essentially equal magnitude introduce a strong influence on the skewness of the curve. The operational scenarios for storm events within this range may also influence the shape of the curve. The original purpose of this study emphasized determination of the magnitude of storm required to fill the reservoirs. The shape of the lower portion of the curve could be refined, based on additional sensitivity analysis and more detailed evaluation of the above considerations. A summary comparison of the frequency of filling curves resulting from previous studies and the current analysis is provided in the following table.

PROJECT	SPILLWAY ELEVATION (in feet)	FREQUENCY OF FILLING AT SPILLWAY (in years)	
		PREVIOUS	CURRENT
Bolivar	962	250	210
Wills Creek	779	100	210
Charles Mill	1020	300	300
Mohawk	890	190	200
Pleasant Hill	1065	575	540
Dover	916	205	180
Atwood	941	500	330
Beach City	976.5	74	180
Clendening	910.5	300	370
Dillon	790	100	250
Leesville	977.5	390	350
Mohicanville	963	90	300
Piedmont	924.6	300	330
Senecaville	942.5	300	370
N. Branch Kokosing	1146	240	300
Tappan	909	300	320



NOTE :

TOTAL DRAINAGE AREA

8051 SQUARE MILES

PROJECT MAP

MUSKINGUM RIVER RESERVOIRS

SCALE IN MILES

HUNTINGTON DISTRICT, HUNTINGTON, W. VA

Revised 30 JUNE 1968

PLATE 1

PILOT PROJECT RESULTS FROM A PROBABILITY BASED LONG RANGE WATER MANAGEMENT/SUPPLY FORECAST

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ABSTRACT

A pilot project sponsored by the National Oceanic and Atmospheric Administration/National Weather Service (NOAA/NWS), Riverside Technology, inc. (RTi), Denver Water Department (DW) and Colorado State University (CSU) and carried out with cooperation from the Bureau of Reclamation (BOR) was established to demonstrate the value of long range forecasting for the purpose of improving water management of complex reservoir systems. The project objectives are to define a methodology of incorporating long range probabilistic forecasts into reservoir operations and quantify the benefits of the forecast information. The Denver Water Department has the primary responsibility to provide adequate water to subscribers in the Denver Metropolitan area. In doing so it diverts water from the Colorado River Basin to Eastern Colorado, sells hydroelectric power, while complying with other competing water rights and commitments in the water supply network. The Extended Streamflow Prediction System (ESP) developed by NOAA/NWS was used to supply probabilities of equaling or exceeding weekly, monthly, or seasonal flows. Strategies based upon these probabilities and modeling techniques developed at Colorado State University were applied to the water supply system. Initial results show how a reliable water supply was assured and overall usable water yields from the reservoir system were increased while optimizing benefits from other competing demands, such as, hydropower and recreation.

INTRODUCTION

Proper management of water resources is vital to the Nation's economy, the quality of our environment, and our overall social well-being. Water management decisions that affect water resources systems are a daily routine. In most cases, these water management decisions are based on localized ad-hoc information systems that cause inefficient and wasteful utilization of the Nation's water resources. The science of real-time hydrologic forecasting, and potential computer and telecommunications resources to support the associated data processing, has reached the point that significant advances can now be made in river forecasting to provide improved flood warnings and information for water managers. A NOAA initiative, Water Resources

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Forecasting Services (WARFS) provides improved hydrologic forecast models that produce probabilistic forecasts for water management decisions makers.

In the fall of 1991, a cooperative project was initiated to demonstrate the value of WARFS, integrating new technologies for the purpose of improving water resource forecasting services in the Colorado Basin, and in particular, the Blue and Williams Fork River Basins. It will provide the basis for planning and preparation of a national program.

This approach will be based on a reconstitution of historical events at a site where ESP information is now available. The site consists of three reservoirs on adjacent rivers, Williams Fork, Dillon, and Green Mountain Reservoirs. A period of water years 1986 through 1991 will be used to make an assessment on how operations would occur with and without the ESP forecasts. An analysis will be performed to determine the benefits of having the additional information provided by ESP. The NWS River Forecast System will be used to provide short-, and long-range streamflow and volume predictions and associated probabilities, so that water managers can portray various operational strategies.

The project objectives will define a methodology of incorporating long range probabilistic forecasts into reservoir operations and quantify the benefits of the forecast information.

NATIONAL WEATHER SERVICE RIVER FORECAST SYSTEM (NWSRFS)

Advanced observations, enhanced data integration techniques, improved models, and expanded historical and real-time hydrometeorological data bases provide a strong technical base for comprehensive water resource forecast information. The key element of WARFS is NWSRFS. The system consists of many computer models and procedures to simulate important meteorological, hydrologic, and hydraulic processes. The system is made up of three components; the Calibration System (CS), the Operational Forecast System (OFS), and the Extended Streamflow Prediction System (ESP). All these components share the same models and processes.

Calibration System -- The CS performs tasks needed to process historical hydrometeorological data and to estimate model parameters for a specific basin.

Operational Forecast System -- The OFS uses real-time hydrometeorological data in conjunction with short term meteorological forecasts to generate streamflow forecasts for hours or a few days into the future. It maintains an accounting of the current models states. These state values describe the hydrologic condition of the basin, including the snow cover, soil moisture, and channel storage.

Extended Streamflow Prediction System -- ESP enables the hydrologist to make extended probabilistic forecasts of streamflow and other hydrological variables. ESP assumes that historical meteorological data are representative of possible future conditions and uses these as input data to hydrologic models along with the current states obtained from the OFS component. A separate streamflow time series is simulated for each year of historical data using the current conditions as the starting point for each simulation. The streamflow time series can be analyzed for peak flows, minimum flows, flow volumes, etc., for any period in the future. A statistical analysis is performed using the values obtained from each year's simulation to produce a probabilistic forecast for the streamflow variable. This analysis can be repeated for different forecast periods and additional streamflow variables of interest. Short-term quantitative forecasts of precipitation and temperature can be blended with the historical time series to take advantage of any skill in short-term meteorological forecasting. In addition, knowledge of the current climatology can be used to weight the years of simulated streamflow based on the similarity between the climatological conditions of each historical year and the current year.

ESP's flexibility and conceptual basis allows it to have many applications, including water supply forecasts, flood control planning, drought analysis, hydropower planning, and navigation forecasts. The ESP probabilistic forecasts provide uncertainty information needed by water managers for risk-based decisions. As in the project, the streamflow time series generated by ESP can be output as products, so that they can be used in reservoir simulation/optimization models to investigate how operations might be improved.

PROJECT AREA DESCRIPTION

The project is located on the western slopes of the Rocky Mountains in Colorado. It comprises a drainage area of 828-square miles (2145 km^2) including most of the areas encompassing the Blue and Williams Fork Rivers. The basins are divided into a set of collection systems, the Moffat and Roberts Tunnel, Williams Fork, Dillon, and Green Mountain Reservoirs.

The primary function of these systems is to provide a reliable water supply to the east side of the Continental Divide, specifically, the metropolitan area of Denver. A second role is to produce power which is used to offset delivery costs and lost power production due to diverting water outside the basins. A number of critical decisions must be made on a daily basis. The reservoirs are operated in an attempt to meet competing goals, such as water supply, flood control, power production, maintenance of instream inflows for aquatic life, and recreation. Operational decisions must consider water supply demands, water requirements of more senior water users, power interference, and most importantly, providing a reliable water supply.

The Williams Fork System consists of a collection system, the Gumlick Tunnel, and Williams Fork Reservoir. The collection system and Gumlick Tunnel convey water collected in the head waters of the Williams Fork River on the west side of the Divide to the Fraser River Basin. From the Fraser River, water is conveyed through the Moffat Tunnel to the east side of the Divide. Williams Fork Reservoir is used to supply replacement water when the "call" comes on the Colorado River and the Gumlick Tunnel is diverting out of priority. Hydropower is generated at

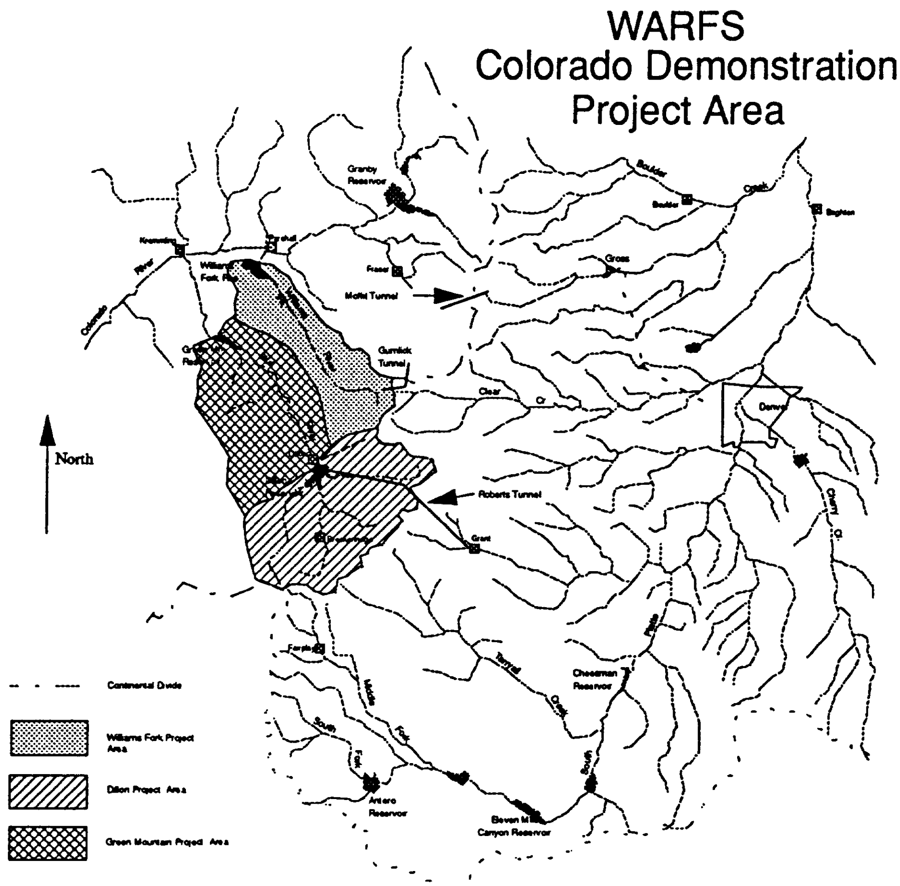

Figure 1. Project Area

Williams Fork Reservoir as replacement power lost by DW operations.

The Roberts Tunnel System consists of the Robert Tunnel and Dillon Reservoir. Dillon Reservoir collects runoff from the Blue River and then conveys the water over the Continental Divide through the Roberts Tunnel. Power is generated at both the Roberts Tunnel and Dillon Reservoir. Green Mountain Reservoir is downstream of Dillon and is used to generate power and provide replacement water for water diverted east through the Big-Thompson Project. Recreation is an important local activity on

Dillon Reservoir, so high water levels are maintained as long as possible during the summer season. A Blue Ribbon trout fishery is located between Dillon and Green Mountain and Dillon Reservoir releases are made to support this fishery.

TECHNICAL APPROACH

Two major steps were required to incorporate ESP forecast information into reservoir operations and then perform an initial estimate of the benefits; (1) the verification of ESP forecast information and (2) the modeling of reservoir operations at the three demonstration area reservoirs.

The purpose of the first effort is to assess the accuracy of the forecasts for the period of record to be used in the modeling tasks. The second effort will consist of the adaptation and implementation of operational models for use at DW.

ESP verification selected a suitable period of historical record for reconstitution of operations. The period selected was based on adequacy of records of operations, data quality, and hydrologic variation. The project period is the 1986 through 1991 water years. ESP verification was performed by generating and statistically analyzing ESP forecast traces for the verification period. The verification information will be used to determine the accuracy of the forecasts and how representative the results of the project will be for other locations.

The modeling effort consisted primarily of tasks to incorporate ESP forecast information into DW operations in the Blue and Williams Fork River Basins. Green Mountain Reservoir was included because of integral relationships of that operation to the Dillon Reservoir operation. Emphasis was placed on the use of existing models to simulate DW operations. MODSIM was selected as the reservoir simulation model. One criterion for model selection was its suitability for use with ESP inputs. After selection of MODSIM, rules were defined to represent operations of the DW systems. The model was verified and recalibrated using historical releases made during the selected reconstitution period.

Once the model adequately represents DW operations, tasks will be performed to optimize the operational rules using the historical calibration period. Optimization will be made using CSUDP, a generalized dynamic programming code. The optimization procedure will consider operational constraints, such as water supply targets that must always be met and trade-offs of reservoir uses.

Modifications will be made to allow the reservoir model to use ESP forecast information. Runs will be made to simulate operations in the reconstitution period. ESP information will be evaluated along with optimization techniques. Benefits associated with the optimization and the additional ESP information will be computed. Calculation of these benefits will be aided by discussions with DW personnel defining the value of water for various uses such as water supply, hydropower, and recreation.

The results of the benefits analysis will be used to modify the operational reservoir model for use in real-time by DW operations personnel. The project will result in the development of state-of-the-art decision support tools that can be used to improve the management of DW reservoirs. The tools will allow decision makers to assess risk as part of the decision process. Completion of this project is expected at the end of calendar year 1993.

PRELIMINARY RESULTS

In the early stages of this project, ESP information was made available to DW operations personnel for analysis. Their first attempt to utilize the probabilistic information obtained through ESP was applied to a simple spread sheet, allowing the managers to look at different operating scenarios. One scenario looked at a construction project at Williams Fork Reservoir during the spring of 1992. The project involved drawing the reservoir down to allow reconstruction of boat ramps. DW needed to evaluate the risk of not refilling the reservoir prior to the end of spring runoff. The penalties for not filling the reservoir were smaller hydropower revenues and limitations in their operations during releases at the time the "call" on the Colorado River arrives. The streamflow volumes and exceedance probabilities were used to consciously weigh the risks of the proposed project and then make an informed decision

Water managers interested in ESP forecasts usually want to know the accuracy of this information. ESP forecast performance is evaluated on how accurate the probability distribution of the variables represent the true statistical distribution. It is not possible to judge the procedures significance using the forecast value. By monitoring the performance of a model over a number of events, error statistics can be complied to give an understanding of the forecast skill. An ESP Verification System has been developed to help quantify the forecast skill of the particular calibrated ESP model. The system is comprised of two parts: a trace generation component and a trace analysis component. The generation program generates historical traces for one year in length and at weekly or monthly intervals throughout the historical period. These represent an individual forecast. The trace analysis component makes a statistical verification of these sets of historical hydrologic traces. The verification program answers the following considerations: are the probabilistic statements from ESP correct and is there skill in the value of the forecasts. The forecast skill is assessed using the forecasts and looking at the percent reduction of the root mean square error. To verify the exceedance probability values, the forecast was transformed to a standardized deviate and tested for normal distribution with a mean of zero (using t-statistic). Even when the conditional distribution is not normal, the test is valid for large n.

ESP verification results showed significant skill in forecasting seasonal (April-July) snow-melt volumes. The monthly forecast's in root-mean-square errors exhibited the following reductions: December (-11.5%), January (-29.8%), February (-35.5%), March (-33.1%), and April (-36.2%). Verification also indicated the ESP procedure reasonably estimates the conditional probability distribution of the streamflow variable.

MODSIM is a network simulation model developed at Colorado State University. It has been extensively utilized throughout the State of Colorado for many major water projects. The model requires strict bounds on each network link and satisfaction of the mass balance at each node. Unlike most network models, MODSIM uses an optimization technique to find the optimal network solution. The Lagrangian relaxation algorithm calculations uses integer numbers, allowing for high computational speeds and the ability to execute on a desk top computer.

Calibration is a two step process: (1) a hydrologic calibration that verifies the water balance in the system and (2) an administration calibration that verifies release priorities and operating policy assumptions.

MODSIM has demonstrated it can accurately represent complex river and operational priority systems. It is excellent for utilizing the ESP hydrologic forecasts, especially the uncertainty information. The project area river system and operational constraints have been successfully calibrated. Work is continuing on evaluating the significance and benefits of the ESP information.

CONCLUSIONS

An ESP verification system was developed to described the skill (both statistically and quantitatively) and develop confidence among the water management community in the abilities of the NWSRFS technology. The verification results were presented for Dillon. The procedure exhibited significant skill in forecasting the seasonal volume. In the future, the ESP Verification system may be used routinely to estimate the forecast skill after calibration but before it is brought on-line operationally.

Preliminary results show that the information available through ESP can be extremely useful in the decision process by providing DW personnel with timely probabilistic information about future hydrologic events. This information has been used for daily operations, long-term planning and risk analysis. For the first time, DW personnel have the benefit of using all available ESP information without having to maintain any hydrologic models. The NWS will continuously run the models and make the forecast data available for DW analysis.

The project has produced a framework for understanding how probabilistic hydrologic information can be used to improve water management activities. MODSIM was demonstrated as a useful tool to fully integrate management schemes for monitoring water supply reliability and related operational priorities. It provides a useful platform to integrate ESP probabilistic information with the management scenarios required of today's water managers. The final step in this project is to quantify the benefits obtained by incorporating the ESP risk information with network and optimization modelling techniques.

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SECTION 8

MODEL VERIFICATION

Page

Validation Strategies Based on Model Application Objectives
David C. Goodrich, Jeffry J. Stone, and Richard van der Zweep 8-1
Verification of Hydrologic Modeling Systems
Billy E. Johnson, Nolan K. Raphelt, and Joe C. Willis 8-9
A System Response Approach for Verifying Surface and Groundwater Models
Bernard H. Hsieh 8-21
Urban Runoff Model Calibration and Validation
R.S. Dinicola 8-29
Wetland Identification SCS, Missouri
Jerry P. Edwards 8-35
Determining Design Unit Hydrographs for Small Watersheds
Joseph M. Sheridan and William H. Merkel 8-42
TOPMODEL, A Topography-Based Watershed Model
David M. Wolock 8-50

Figures and Tables

Validation Strategies based on Model Application Objectives 8-1

Figures: 1. Lucky Hills Watersheds location map and maximum number of overland and channel elements used by KINEROS and WEPPWV 8-7
2. Scatter plots for KINEROS validation for runoff volume and peak discharge for LH-4 8-8
3. WEPPWV Validation efficiencies for runoff volume and peak discharge for LH-5 8-8

Tables: 1. Sequential validation steps for the WEPPWV 8-4
2. KINEROS calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge using optimum multipliers 8-4
3. WEPPWV calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge 8-5

Verification of Hydrologic Modeling Systems 8-9

Figures: 1. Goodwin Creek Watershed Site Map 8-14
2. Goodwin Creek Watershed-Event No. 1 8-15
3. Goodwin Creek Watershed-Event No. 2 8-16
4. Goodwin Creek Watershed-Event No. 3 8-17
5. Goodwin Creek Watershed-Event No. 4 8-18
6. Goodwin Creek Watershed-Event No. 5 8-19

A System Response Approach for Verifying Surface and Groundwater Models 8-21

Figures: 1. Moving response function with fixed input structure 8-22
2. Frequency response coefficients of the numerical model simulation for a nonlinear MISO system 8-24

Page

A System Response Approach for Verifying Surface and Groundwater Models-continued

Figures: 3. Tidal current comparisons near bottom layer (33 ft depth) at Summit Bridge, C&D Canal 8-25
4. System simulated results versus field observations for a water well near Wichita, Kansas 8-27

Table: 1. Frequency response coefficients of tidal current verification at the Summit Bridge, C&D Canal 8-26

Wetland Identification, SCS, Missouri 8-35

Figure: 1. Drainage Area vs. Discharge: 2-Year Frequency, 7- and 15-Day Duration 8-40

Plate: 1. Wetland identification by SCS in Missouri 8-41

Table: 1. Log-Pearson Type III duration frequency analysis Grand River near Sumner, Missouri, Drainage Area = 6,880 Square Miles 8-38

Determining Design Unit Hydrographs for Small Watersheds 8-42

Table: 1. Selected regional watershed UH parameters 8-45

TOPMODEL, A Topography-Based Watershed Model 8-50

Figures: 1. Diagrams of streamflow-generation mechanisms during high-flow periods 8-51
2. Diagram of water fluxes in TOPMODEL 8-52
3. Plan view of grids of (a) elevation, (b) steepest downhill direction, (c) number of upslope nodes, (d) tanB values, and (e) In(a/tanB) values. The data shown are a subsection of a larger uniform 10x10 grid 8-55
4. Maps of (a) elevation, and (b) In(a/tanB) values for Sleepers River watershed in Vermont. Higher values are indicated by darker shades of gray 8-56

VALIDATION STRATEGIES BASED ON MODEL APPLICATION OBJECTIVES

DAVID C. GOODRICH, JEFFRY J. STONE, AND RICHARD VAN DER ZWEEP[1]

ABSTRACT

Validation methodologies which are based on specific modeling objectives are presented for an event based, unsteady state, research model, KINEROS, and a continuous, quasi-steady state, management model, Water Erosion Prediction Project Watershed Version (WEPPWV). The modeling objectives for KINEROS are to investigate the effect of geometric model simplification and spatial variability of input parameters on performance over a wide range of events. The methodology for KINEROS includes sensitivity analysis over a range of events to minimize the set of calibration parameters. The procedure, coupled with using distributed parameter multipliers alleviates the problems associated with parameter interaction and identifiability. The modeling objectives for WEPPWV are to investigate the effects of simplifications of the rainfall-infiltration-runoff process on model performance in terms of management applications. The methodology includes parameter calibration of a complex model to be used as a benchmark for comparison and using those parameter values in validation of increasingly simpler representations of the hydrologic process. Results of this study indicate that model validation should be performed in a multi-stage fashion when the model is complex in terms of geometric or hydrologic sub-process representation. Systematic and careful analysis of interim calibration and validation results must be carried out to avoid the modeling bane of hidden, but compensating errors. This is particularly true when models are being constructed from sub-components which may synergistically affect the final output.

INTRODUCTION

The objectives of the development of hydrologic research and management models are complementary, but have different emphases. The researcher is interested in both understanding and explaining the hydrologic process while the manager is interested in using a model to arrive at a decision. In both cases, validation is an important part of model development. For the researcher, it is necessary as part of the scientific method; for the manager, it is necessary for confidence in any decision based on the model because these decisions have policy, economic, human and environmental ramifications.

This study examines two validation strategies using the research model KINEROS (Woolhiser et al., 1990) and the management model WEPPWV (Lane and Nearing, 1989). KINEROS is a distributed event rainfall-runoff model which uses a four point finite difference scheme to solve the kinematic wave equations for overland and channel flow. The overland flow supply rate is computed by solving the Smith-Parlange (1978) infiltration equation given one or more rainfall time-intensity distributions. The model is distributed in that a watershed can be represented by a number of overland and channel elements but also that within an overland flow element infiltration parameters can be represented by a probability distribution (Woolhiser and Goodrich, 1988).

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The WEPPWV model overland flow hydrologic components are composed of a climate generator, rainfall disaggregation scheme which represents the rainfall intensity distribution by a double exponential function, the Green-Ampt Mien-Larson infiltration equation, and peak flow regression equations based on the kinematic wave model for a single plane. The channel hydrology components consist of a transmission loss equation and a regression relationship for peak flow for the channel elements. In contrast to KINEROS, WEPPWV simplifies how the geometry of the watershed and the hydrologic sub-processes are represented. In addition, because the operational mode of the WEPPWV model is continuous simulation, parameters which control the hydrologic components are updated to account for the effects of temporal changes of plant growth, water balance, soil, and management practices.

The objectives of this paper are to illustrate the interpretation and expectations of model validation results by 1) validating the KINEROS model with emphasis on minimizing the set of calibration parameters, verifying the model response within sub-areas of the watershed, and assessing the impact of input rainfall representation of model validation; and 2) extending the KINEROS study using the WEPPWV model with emphasis on the relative sensitivity of model process simplification on model output.

METHODOLOGY

Two important steps in the validation process are identification of sensitive parameters and verification to insure that the calibrated model can simulate the processes being modeled. Including only the most sensitive parameters in calibration is equivalent to increasing the number of observed data used in the calibration process (Beck, 1987). Studies specific to the models used in this analysis (Goodrich, 1991: Tiscareno et al., 1992) have shown that model output is most sensitive to the rainfall intensity distribution, effective saturated conductivity (K_e), and the hydraulic roughness coefficient. The latter two are used in this study as calibration parameters. In the case of distributed models or models which are made up of several components, validation of the internal model output and component model output are also necessary. Internal and component model validation are important in order to ensure that the final model output is not a result of compensating errors.

The subwatersheds of the USDA-ARS Walnut Gulch Experimental Watershed used for the KINEROS validation are the LH-6 (0.4 ha), LH-2 (1.4 ha), and LH-4 (4.4 ha) and for the WEPPWV validation LH-5 (0.2 ha), LH-1 (1.3 ha), and LH-3 (3.68 ha) (Renard, 1970 and Figure 1). Note that by using the nested watersheds LH-6 and LH-2 for watershed LH-4 and LH-1 for LH-3, internal model validation is possible and some degree of interior model confidence can be established. The watersheds are characterized by desert brush vegetation, sandy loam soils with significant rock content, high amounts of soil surface erosion pavement, and are subject to high intensity precipitation from air-mass thunderstorms of limited spatial extent. Model performance for both calibration and validation is evaluated by the coefficient of efficiency, E (Nash and Sutcliffe, 1970) and visual examination of scatter plots of measured versus simulated. If the model predicts observed runoff with perfection, $E = 1$. If $E < 0$, the model's predictive power is worse than simply using the average of observed values.

KINEROS - The input rainfall data are derived from two raingages about 300 m apart and are weighted using a space-time rainfall interpolation scheme described by Goodrich (1991). This study also investigated the level of geometric model complexity (basin discretization) required for distributed rainfall-runoff modeling using KINEROS and therefore employed large scale maps to derive a very detailed representation (large number of model elements) of the LH-6, 2, and 4 watersheds (Figure 1). Geometric model element parameters are derived from the large scale topographic maps and field measurements of channels. Infiltration parameters (K_e) were derived from soil texture from 17 soil samples distributed in LH-4. For KINEROS the validation process consists of a calibration phase in which observed data is used to alter field estimated parameters and verification in which an independent set of runoff events is used to assess 1) model performance by visual means and the efficiency statistic, and 2) assessment of model performance on subwatersheds internal to the primary watershed to insure internal model performance.

For calibration and verification it is unrealistic to consider adjustment of parameters on a large number of individual model elements. Beven (1989) concluded that, for modeling continuous flow, more than four or five parameters will result in identifiability problems. Therefore, a scalar multiplier approach is taken in which a multiplier for each major element parameter is employed. To visualize this concept, imagine a catchment made up of two overland flow elements, one with a field estimated Manning's roughness of 0.05 and the other with 0.08. With a roughness multiplier of 2 the respective roughness become 0.1 and 0.16 so the relative ratio between the two field estimated roughnesses is maintained. This concept becomes more advantageous when the catchment is represented by many elements when only a single multiplier is used for each main element parameter (such as hydraulic roughness) to reduce the overall adjustable parameter space a small dimension. Using the multiplier approach, univariate sensitivity analysis of model runoff, peak flow, and time to peak to multiplier changes is used to identify the most sensitive parameters. This knowledge, coupled with modeler knowledge of which parameters are most uncertain (subjectively derived) results in selection of a parsimonious calibration parameter space of three multipliers. They were uniform basin multipliers for K_e, the coefficient of variation of K_e (C_v), and hydraulic roughness. The resulting small number of calibration parameters largely satisfies the concerns regarding overparameterization while minimizing parameter interaction and identifiability problems.

An acceptable multiplier for each watershed is found by using E as an objective function for a common set of ten calibration events on each of the three watersheds. When final multipliers are applied to initial field estimated parameters, the resulting values are checked to insure that they are physically realistic and are not acting as mere fitting parameters. These calibrated parameter multipliers are used to model runoff response for an independent verification event set. The validated model is also used to the assess effects of geometric model simplification on model performance as each watershed is also modeled as a single overland flow plane element using a simplification methodology described by Goodrich (1991).

WEPPWV - The watershed geometric representation used for WEPPWV is shown in Figure 1 and is similar to the simplified geometry used for KINEROS. The calibration and validation procedure begins with an evaluation of how well the calibrated Green-Ampt and kinematic wave equations can reproduce observed runoff characteristics using the observed rainfall intensity distribution from a single raingage. The next step is to sequentially simplify the rainfall input and peak flow calculation (Table 1) until the model structure is the WEPPWV model as will be applied by the end users. Step one is a test of the best possible model response; step two examines the effect of approximating the event rainfall by the disaggregation scheme; step three examines the effect of approximating the kinematic wave equation; and step four is a test of model parameter estimation and updating. For steps one, two, and three, the model is run in a single event mode; for step four the model is run in continuous daily simulation mode.

Table 1. Sequential validation steps for the WEPPWV.

Step	Process		
	Rainfall	Peak Discharge	Parameter Estimation
1	Observed event	Kinematic wave	Calibration
2	Disaggregated event	Kinematic wave	Calibration
3	Disaggregated event	Approximate method	Calibration
4	Disaggregated daily	Approximate method	Model computed

RESULTS AND DISCUSSION

KINEROS - For the optimum multipliers the KINEROS model performs very well as judged by the efficiency statistic (E) for both the calibration and validation event sets for the three watersheds used in the analysis (Table 2). Extrapolation capability is demonstrated as the model simulated runoff from events well outside the calibration range (observed runoff volume from 0.4 to 12.3 mm; validation range 0.08 to 47.8 mm). The large drop in E for Qp for the LH-6 validation event set was largely due to poor model performance on the largest event in the validation set. Typical scatter plots for the validation results of observed versus simulated runoff volume and peak runoff rate are shown in Figure 2 for LH-4.

Table 2. KINEROS calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge using optimum multipliers.

Basin	Calibration efficiency						Validation efficiency			
	Volume			Peak			Volume		Peak	
	1	2	3	1	2	3	1	2	1	2
LH-6	.98	.97	.81	.95	.94	.86	.98	.98	.79	.77
LH-2	.97	.88	.88	.97	.93	.93	.93	.92	.93	.89
LH-4	.97	.96	.89	.98	.88	.88	.99	.99	.92	.96

1 - two raingages, maximum number of overland and channel flow elements
2 - two raingages, one overland flow element, no channel elements
3 - one raingage, maximum number of overland and channel flow elements

An overall assessment of internal model accuracy using the nested LH-6 and LH-2 is obtained by using the parameter multipliers of LH-4 on the internal model representations of LH-2 and LH-6 for catchment runoff simulations. When this is done for LH-6, E equals 0.91 and 0.86 for runoff volume and peak rate, respectively and for LH-2 comparable E values are 0.96 and 0.97. The good efficiencies obtained by using LH-4 multipliers for the internal watersheds suggests a good deal of internal model accuracy.

To test the sensitivity of model response to the rainfall intensity distribution, one raingage is used as input with the calibrated parameter multipliers (see 1 RG rows in Table 2). For the calibration event set, the efficiency statistic E for runoff volume drops substantially. Simulation comparison also points out that runoff variations induced by rainfall variability far outweigh parameter perturbations used in the sensitivity analysis. The uncertainty in rainfall input due to small- and large-scale spatial variability suggests that the confidence in the calibration can only be equal to or less than the certainty of rainfall input data. This has been pointed out by numerous investigators (for example, see Troutman, 1983) but not at the scale of 300 m. As many models are tested on small research watersheds it is important to recognize the limitations imposed by the assumption of spatially uniform rainfall on parameter identification and model validation, particularly when runoff is a result of thunderstorm rainfall.

A parallel conclusion can be drawn by examining the model response when 1 overland flow plane model element (1 Elem rows in Table 2) and 2 raingages are used as input. Comparing these results to the one raingage results indicates that the error introduced by simplifying the geometry of these watersheds to a single element is less than or equal to the error from using one raingage for the calibration set. Therefore, unless there are major differences in land use, basin discretization should not exceed the ability to resolve input rainfall variability.

WEPPWV - The model efficiencies for calibrated runoff volume are similar in magnitude to those of KINEROS when a single raingage is used as input (Table 3). The lower efficiencies for calibrated peak discharge can be attributed to the fact that peak discharge is computed by a generalized regression relationship which obviously does not represent the hydrologic processes on these watersheds. The lower efficiencies for the validation of LH-3 are the combination of more small events in the validation set of LH-1 (calibration mean runoff volume=4.1 mm, validation runoff volume=2.8 mm) and problems in parameter identification due to physical changes in LH-1 (Van Der Zweep, 1991). The lower efficiencies for peak discharge for LH-5 are indicative that the roughness value was poorly identified in calibration.

Table 3. WEPPWV calibration and validation coefficient of efficiency (E) for runoff volume and peak discharge.

Basin	Calibration efficiency		Validation efficiency	
	Volume	Peak	Volume	Peak
LH-5	.79	.65	.75	.27
LH-1	.91	.81	.22	-1.02
LH-3	.85	.76	.57	.06

The sequential validation results are illustrated using LH-5 as an example. Referring to Figure 3, note that while the efficiency for runoff volume decreases as the model is simplified, the efficiency for peak discharge increases. The decrease in efficiency for runoff volume from step one to steps two and three is due the disaggregation model structure which always underestimates the observed peak rainfall intensity. The decrease in step four is due to the parameter estimation component which in this case estimated a value for K_e=2.03 mm/hr significantly lower that the calibrated value of 7.7 mm/hr. The increase in efficiency of peak discharge is a result of compensating errors within the model including the underestimation of peak rainfall, under estimation of K_e, and overestimation of the hydraulic roughness.

This study suggests that validation of a complex model, whether it is complex in the manner in which it represents a watershed (geometric complexity) or in the manner in which it represents the hydrologic sub-processes (process complexity), cannot be a one step analysis. The peak discharge efficiency in step 4 above would indicate that the model is doing a good job when in reality the output is a consequence of compensating errors in the peak discharge sub-processes.

The trend in recent years among Agricultural Research Service's and other agency's modeling efforts has been to incorporate modules from previously written models into the current model, particularly for management application models. For example, the WEPP model use the water balance routines from the SWRRB model (Williams et al., 1985) and the crop growth routines from the EPIC model (Williams et al., 1983). The Soil Conservation Service is amassing a suite of models under broad categories such as hydrology, plant growth, and earth science with the ultimate goal of linking these components together depending on a given management objective (SCS, 1992). Given the results of this study, model validation becomes a multi-stage process for geometrically and hydrologically (sub-process) complex models. Systematic and careful analysis of interim calibration and validation results must be carried out, particularly when models are being constructed from sub-components which may synergistically affect the final output.

CONCLUSIONS

Analysis of the study watersheds with the research model KINEROS with a multiplier applied to a small set of the most sensitive parameters offers a method to achieve a parsimonious calibration-validation parameter set to avoid identification and interaction problems. Additionally, if one is to apply a distributed watershed model, model response in interior subwatershed must be verified before any conclusions can be drawn regarding interior watershed dynamics. The importance of identifying the dominant processes controlling catchment response was also demonstrated by illustrating that excessive catchment discretization is unwarranted if rainfall variability is not described on a comparable scale. The WEPPWV results demonstrate the importance of component model validation and the role of compensating errors in producing the model output. The comparison of the KINEROS and WEPPWV results demonstrates that the validation expectations of the researcher can be high, but those of the manager will be lower because of the approximations and simplifications necessary to implement a management model under the constraints of time and money. To understand and interpret validation results of a model's output necessitates a systematic analysis of the model components and their interactions.

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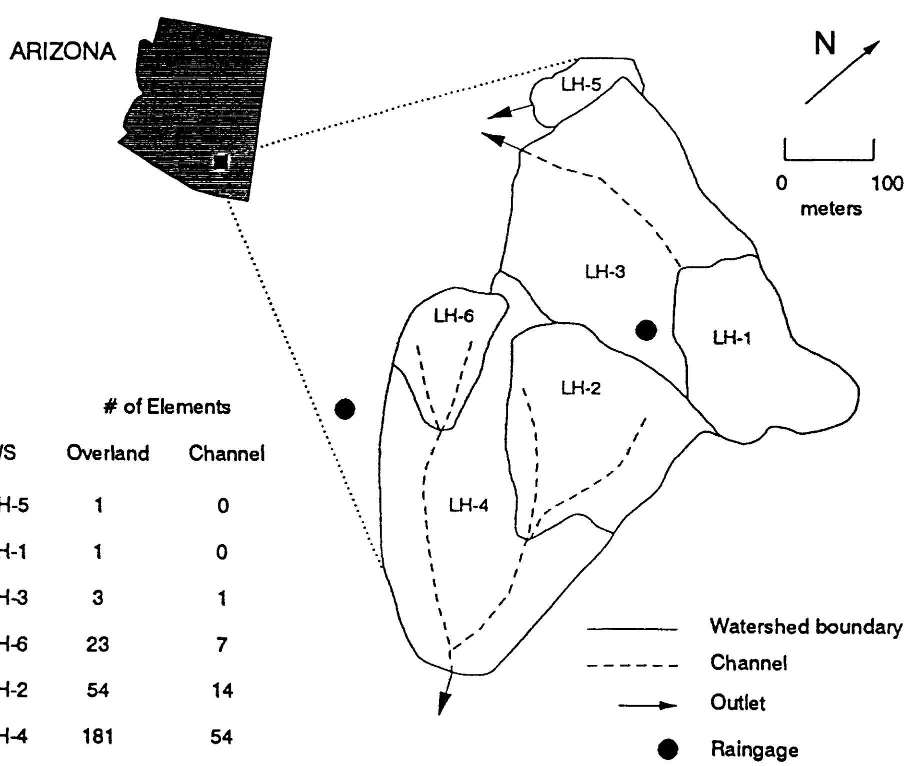

# of Elements

WS	Overland	Channel
LH-5	1	0
LH-1	1	0
LH-3	3	1
LH-6	23	7
LH-2	54	14
LH-4	181	54

Figure 1. Lucky Hills Watersheds location map and maximum number of overland and channel elements used by KINEROS and WEPPWV.

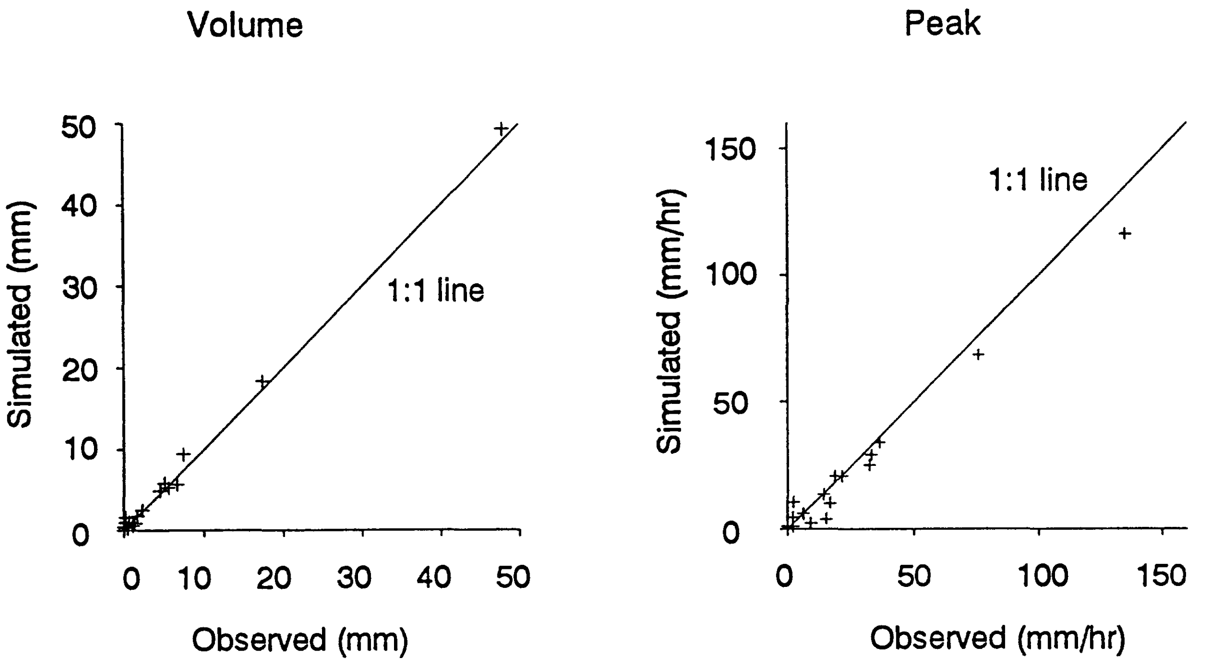

Figure 2. Scatter plots for KINEROS validation for runoff volume and peak discharge for LH-4.

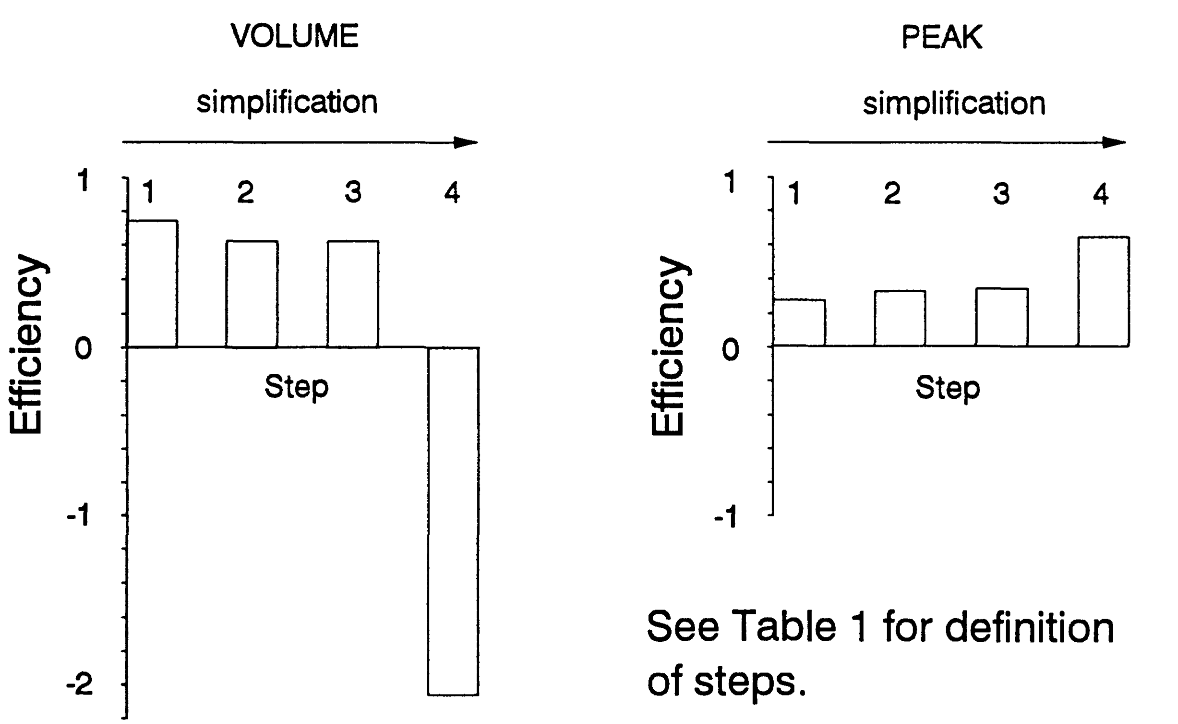

Figure 3. WEPPWV Validation efficiencies for runoff volume and peak discharge for LH-5.

VERIFICATION OF HYDROLOGIC MODELING SYSTEMS

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ABSTRACT

The purpose of this paper is to discuss the availability of hydrologic data from the Goodwin Creek Watershed. The Goodwin Creek Watershed is an area of approximately 8.5 square miles with 14 comprehensive gaging stations. The gaging stations gages areas from 0.6 square miles to 8.5 square miles on a continuous basis for stage, discharge, and sediment concentrations. These data are an excellent source of observed hydrologic data for development of hydrologic models. The paper will present the application of three hydrologic modeling systems to the Goodwin Creek Watershed. The three methods that will be presented are HEC-1 Snyder Unit Hydrograph approach, the SCS Curve Number approach, and a two-dimensional rainfall-runoff model. The results of the modeling efforts will be to compare the ease of calibration of the model, the stability of the calibration, and the ability to physically determine required input parameters.

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INTRODUCTION

Purposes and Scope

In many hydrologic applications obtaining a design peak flow is the goal of a study. However, in other applications, being able to simulate the peak flow and the general shape of a storm hydrograph is important to the study. Along these lines, being able to simulate a period of record using historical rainfall can be a very valuable tool in performing sediment studies. These issues were the catalyst behind doing the following study.

The purpose of this study was to use different hydrology models on a watershed that has numereous gages, both rainfall and discharge, to determine which model performed the best in simulating the peak flow and the shape of the observed hydrograph.

This study describes calibration of three hydrologic models to observed data. The first hydrologic model used was an HEC-1 model using the Snyder's Unit Hydrograph Method for overland flow and a Normal-Depth Channel Routing Routine, the second hydrologic model used was an HEC-1 model using the Soil Conservation Service Curve Number Method for overland flow and a Normal-Depth Channel Routing Routing. The third hydrologic model was a 2D hydrologic model, CASC2D, developed by Dr. Pierre Julien at Colorado State University. This model uses a 2D diffusive wave equation to simulate overland flow and a 1D diffusive wave equation to simulate channel flow.

The goals of this study were to try and use physical data such as landuse, soil type, elevation, channel cross-sections, and rainfall to simulate the runoff events. The scope of this study was to determine the best procedure to use on ungaged watersheds for the purpose of simulating runoff events.

Description of the Study Site

The watershed used in this study was the Goodwin Creek Watershed located in the southwestern part of Panola County in North-Central Mississippi. The watershed covers approximately 8.5 square miles (Figure 1). The predominate soil type is silt loam. The landuse is pasture, crop land, and forrest.

STUDY RESULTS

In this study, there were five rainfall events simulated. The events covered the time between 1981 and 1988. The following is a list of tables for each event and plots of the data.

Event No. 1
Start Time and Date : 21:30 October 17, 1981
End Time and Date : 01:00 October 18, 1981

	Time to Peak (Minutes)	Peak Flow (CFS)
Observed	267	1405
Snyder	234	1458
SCS	235	1350
CASC2D	232	1396

Figure 2 shows all three of the hydrologic models calibrating fairly well to the observed data. The timing of the peak flows were off, but the peak flows themselves were close to what was observed. This storm has very little rainfall preceeding it, so there was a fair amount of infiltration that occured before runoff could begin.

Event No. 2
Start Time and Date : 19:00 February 8, 1982
End Time and Date : 01:00 February 9, 1982

	Time to Peak (Minutes)	Peak Flow (CFS)
Observed	300	1000
Snyder	237	863
SCS	231	843
CASC2D	339	1046

Figure 3 shows CASCS2D calibrating to the observed, however the Snyder and SCS methods did not seem to calibrate to the observed data. This storm was preceeded by rainfall and as such the soil was saturated. All three hydrologic models had very little infiltration before overland flow began. In the Snyder and SCS models, all infiltration was turned off and as we see, the peak flows still did not reach the observed peak flow.

Event No. 3
Start Time and Date : 00:00 September 30, 1985
End Time and Date : 13:20 September 30, 1985

	Time to Peak (Minutes)	Peak Flow (CFS)
Observed	350	158
Snyder	450	161
SCS	300	159
CASC2D	380	162

Figure 4 shows a rather small event. The goal in simulating this event was to try and calculate a low flow condition, less than one year frequency, in this watershed. From the plot, CASC2D once again seemed to calibrate to the observed data fairly well. However, Snyder and SCS method had trouble. The SCS method seemed to want to oscillate up and down, while the Snyder method would not reproduce the rapid rise and fall of the flow.

Event No. 4
Start Time and Date : 20:31 December 27, 1988
End Time and Date : 16:31 December 28, 1988

	Time to Peak (Minutes)	Peak Flow (CFS)
Observed	328	1218
Snyder	170	1211
SCS	140	1229
CASC2D	253	1220

Figure 5 shows all three models calibrating to the observed data, except that the timing was off on all three. As for the shapes of the hydrographs, Snyder and SCS seemed to want to stay high for a longer period of time than did the observed flow. CASC2D followed the general shape of the observed, however it seemed to want to fall quicker that the observed flow.

Event No. 5
Start Time and Date : 12:52 December 2, 1983
End Time and Date : 24:00 December 4, 1983

	Time to Peak (Minutes)	Peak Flow (CFS)
Observed	1364	3383
Snyder	1344	1969
SCS	1344	1879
CASC2D	1324	3086

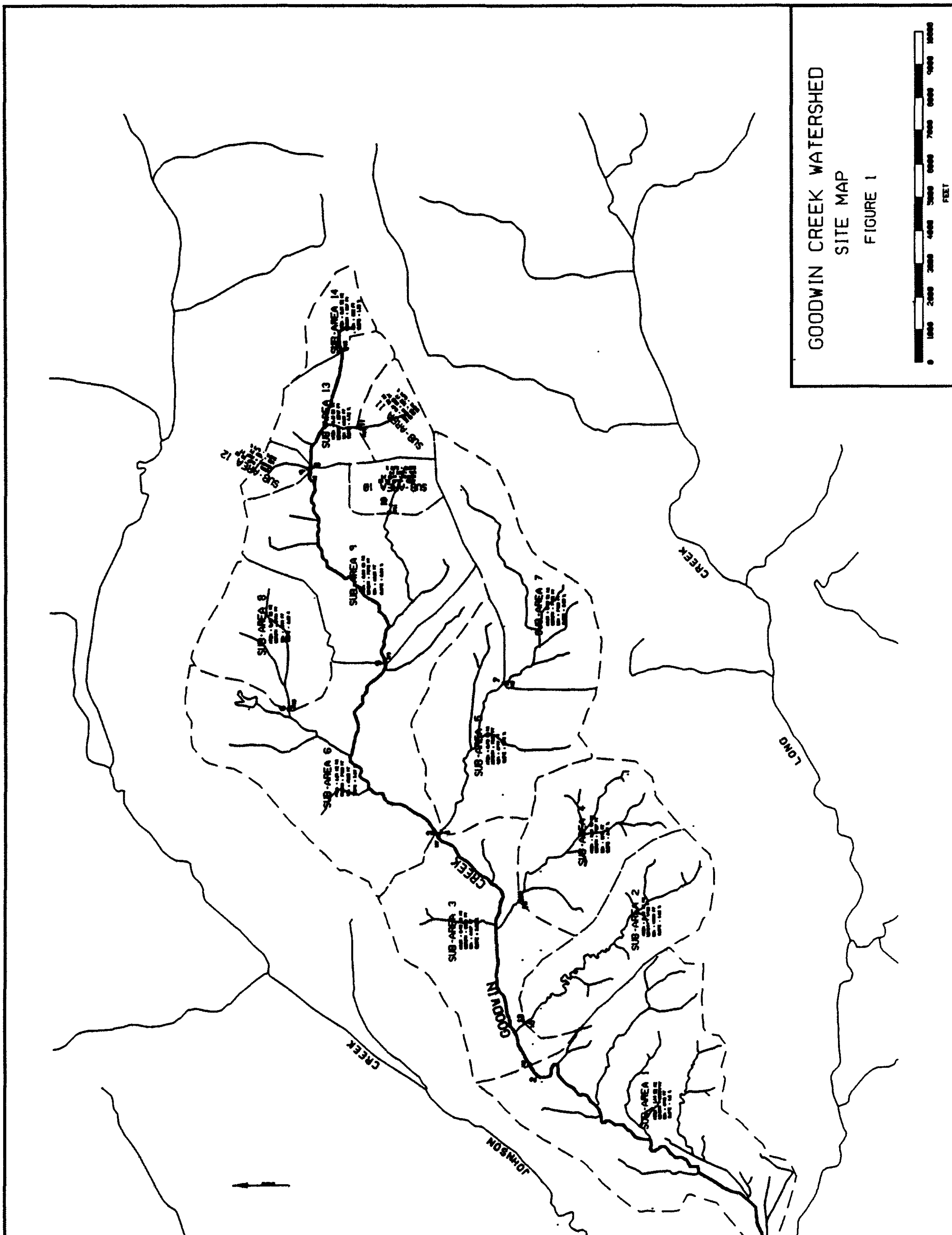
Figure 6 shows an attempt to simulate two storms back to back. All three models did well in timing the peak flows for both storms. Howver, Snyder and SCS did not reach the observed peak flow. CASC2D was a little high on the first storm and a little low on the second storm, but overall it did a good job of simulating the observed hydrograph.

CONCLUSIONS

The goal of this study was to simulate different hydrologic models with the purpose of comparing the peak flow, the timing of the peak flow, and the general shape of the hydrograph to observed data. In performing sediment studies, it is important to be able to calculate the full hydrograph for watersheds in order to calculate sediment movement. Also, one may be modeling watersheds where gaged data is limited. Therefore, one is limited to using physical data to model.

With these issues in mind, we chose the three models presented in this paper. From the tables and the plots, we feel that the CASC2D model developed by Colorado State University shows a lot of promise. This model seemed to consistantly calculate the shape and peak flow of the observed data fairly well. The timing of the peaks were off, but with better representation of the physical terrain and better cross-section definition, timing should improve.

In conclusion, CASCS2D performed well for these storm events. Howver, more tests need to be run and also different infiltration and channel routing routines need to be added and tested in order to develop a robust model.


GOODWIN CREEK WATERSHED
SITE MAP
FIGURE 1
FEET
SUB-AREA 1
SUB-AREA 2
SUB-AREA 3
SUB-AREA 4
SUB-AREA 5
SUB-AREA 6
SUB-AREA 7
SUB-AREA 8
SUB-AREA 9
SUB-AREA 10
SUB-AREA 11
SUB-AREA 12
SUB-AREA 13
SUB-AREA 14
GOODWIN CREEK
LONG CREEK
JOHNSON CREEK

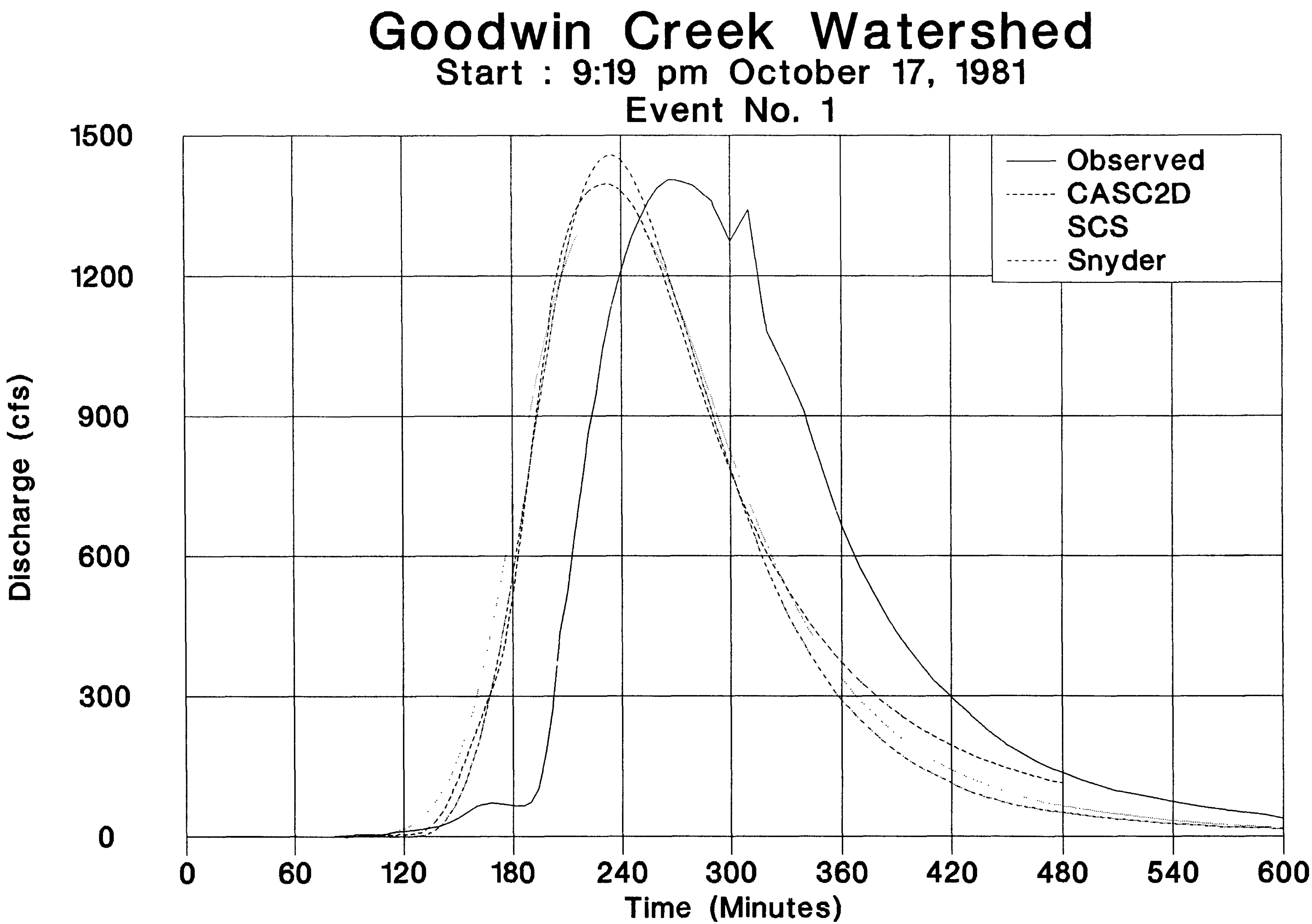
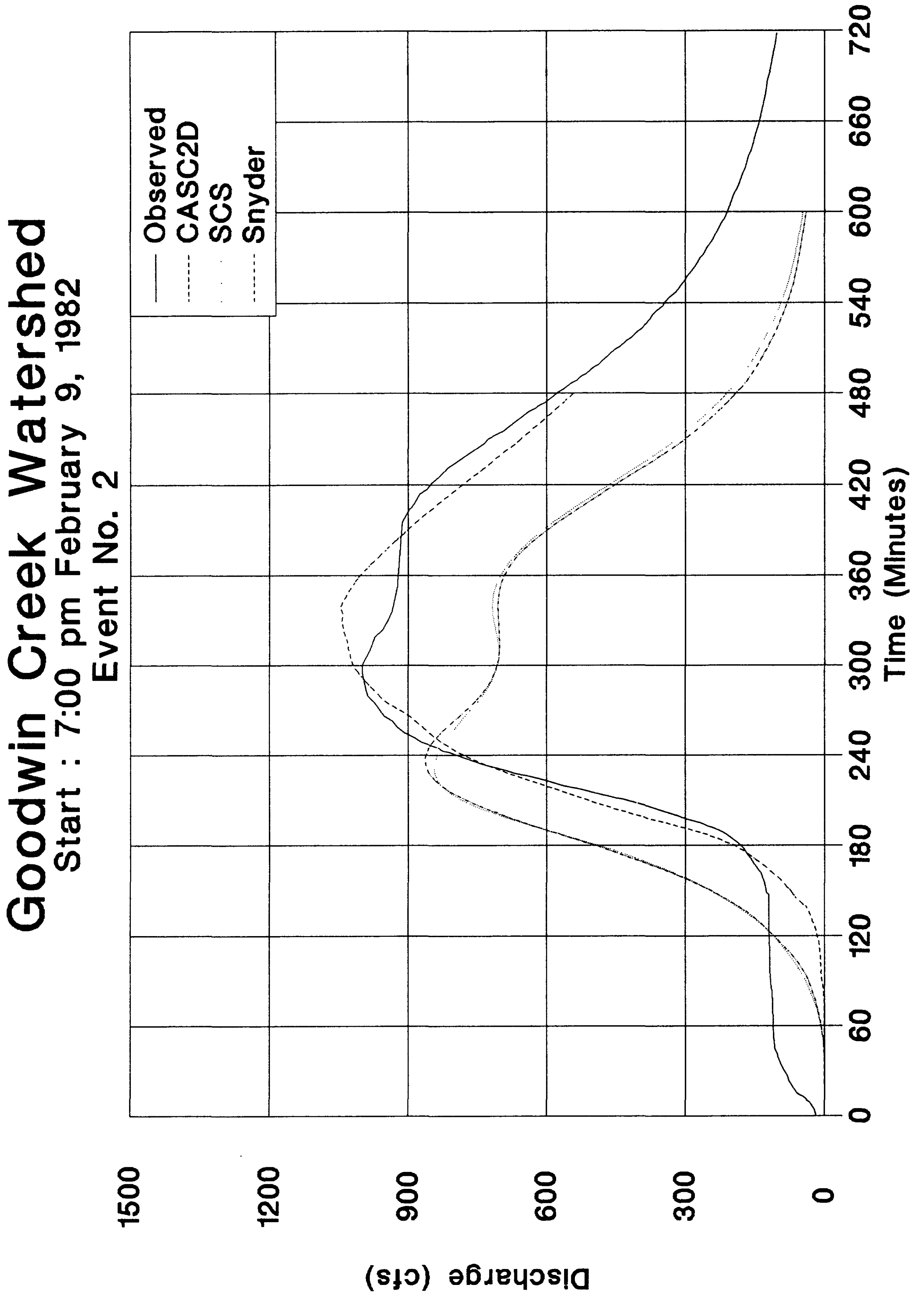

Goodwin Creek Watershed
Start : 9:19 pm October 17, 1981
Event No. 1
Observed
CASC2D
SCS
Snyder
Discharge (cfs)
1500
1200
900
600
300
0
0
60
120
180
240
300
360
420
480
540
600
Time (Minutes)

Figure 2



Goodwin Creek Watershed
Start : 7:00 pm February 9, 1982
Event No. 2
Observed
CASC2D
SCS
Snyder
Discharge (cfs)
0
300
600
900
1200
1500
Time (Minutes)
0
60
120
180
240
300
360
420
480
540
600
660
720

Figure 3

Goodwin Creek Watershed

Start : 12:00 am September 30, 1985

Event No. 3

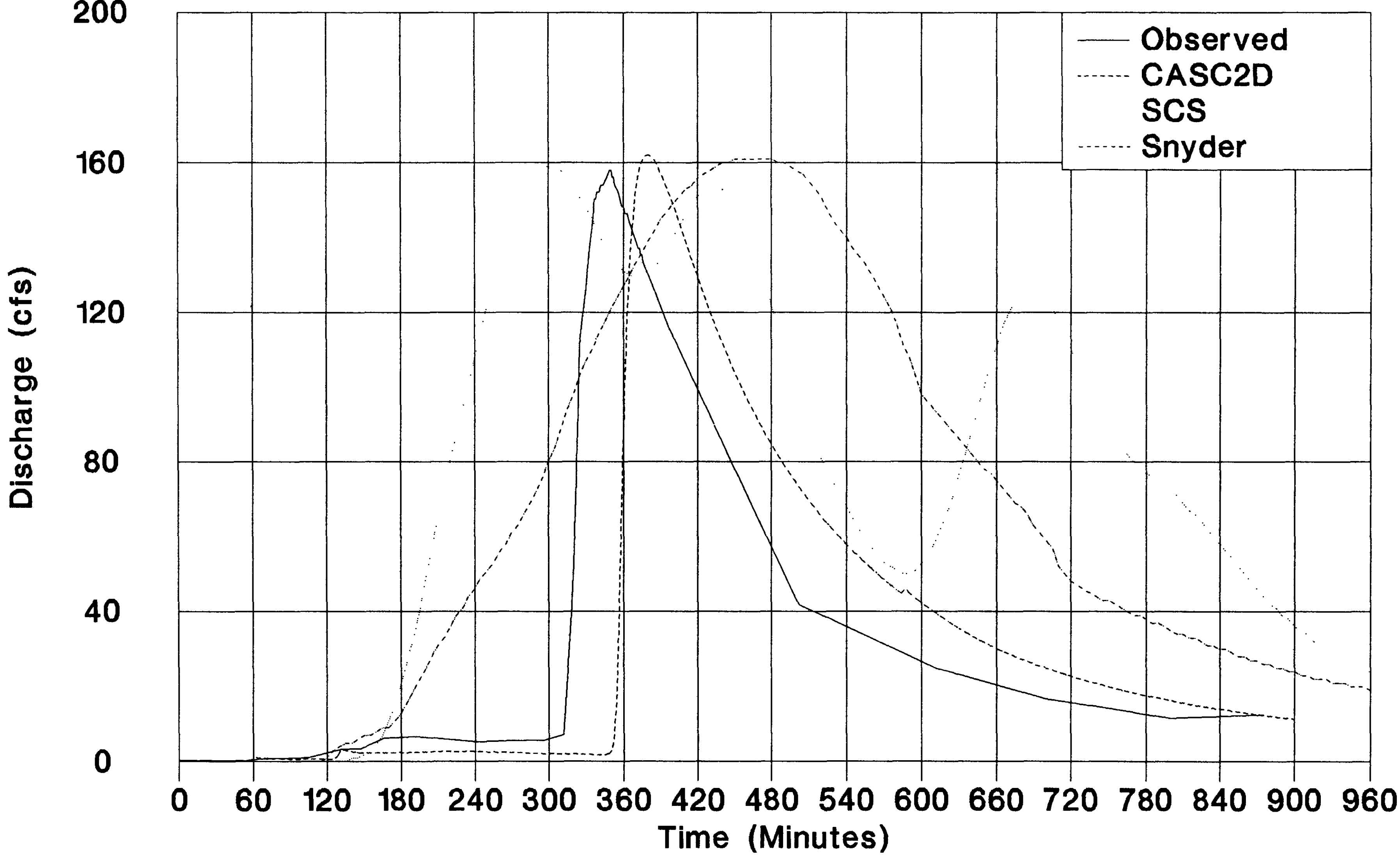


Figure 4

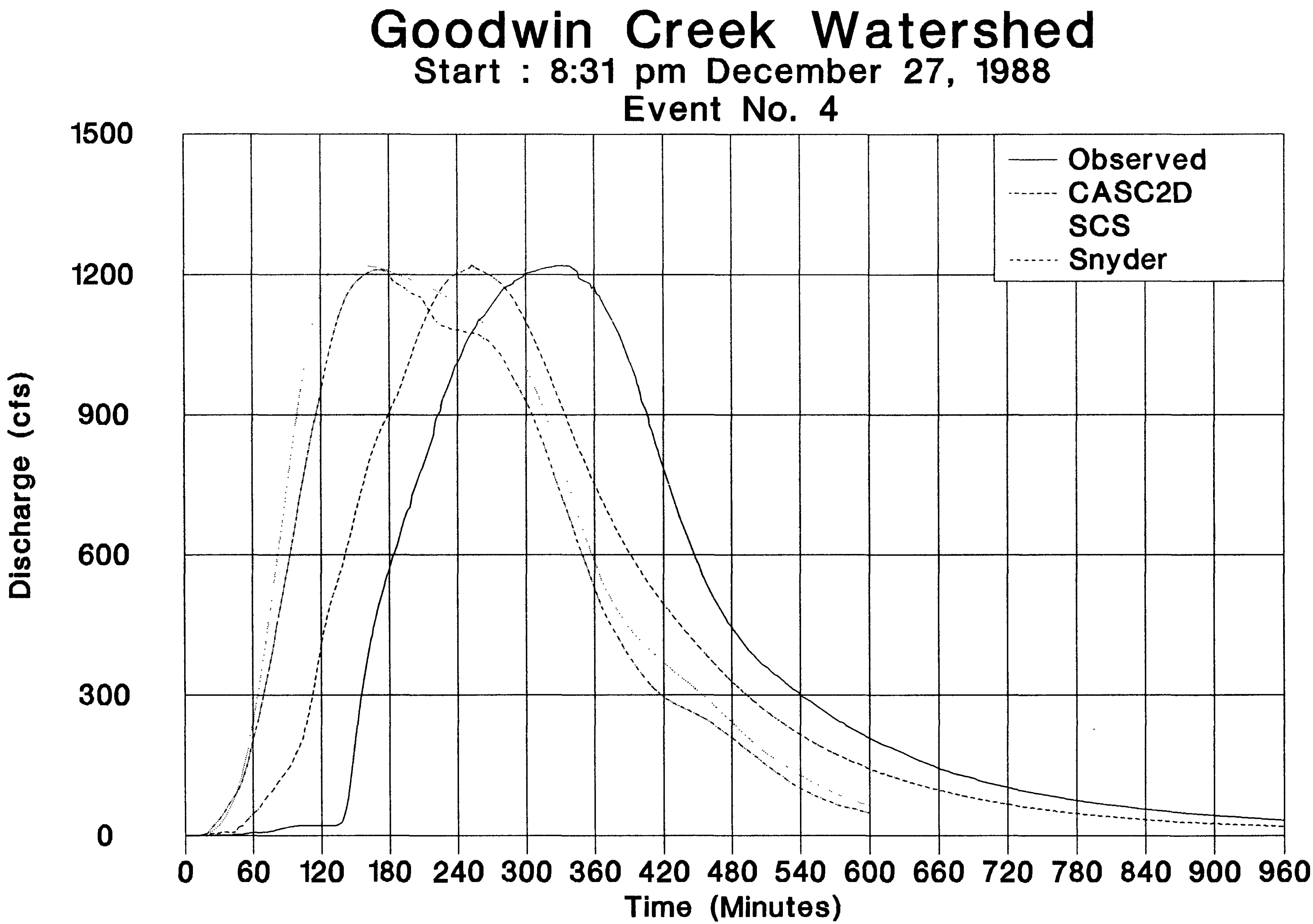

Goodwin Creek Watershed
Start : 8:31 pm December 27, 1988
Event No. 4
Observed
CASC2D
SCS
Snyder
Discharge (cfs)
1500
1200
900
600
300
0
0 60 120 180 240 300 360 420 480 540 600 660 720 780 840 900 960
Time (Minutes)

Figure 5

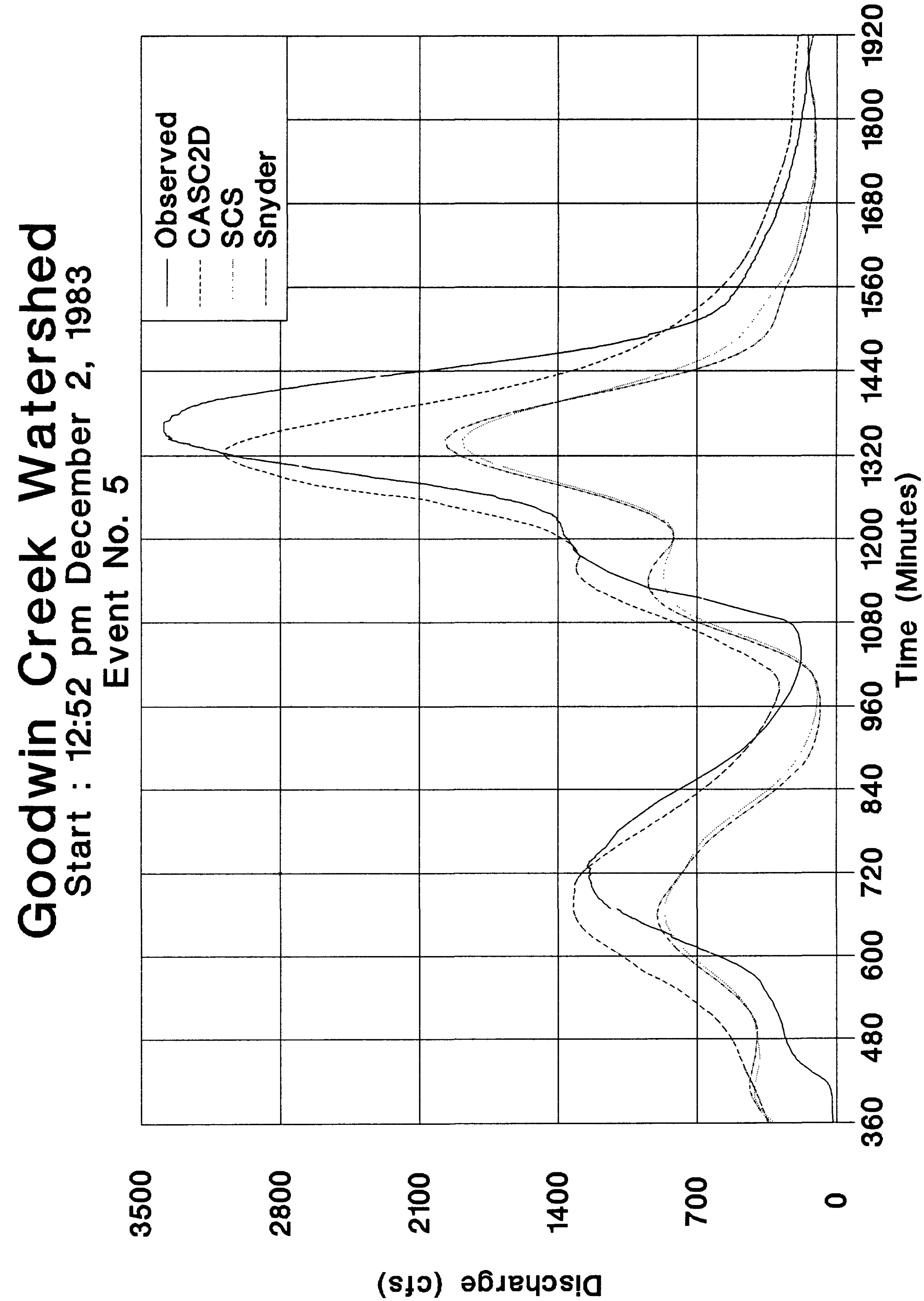

Goodwin Creek Watershed
Start : 12:52 pm December 2, 1983
Event No. 5
Observed
CASC2D
SCS
Snyder
Discharge (cfs)
0
700
1400
2100
2800
3500
360
480
600
720
840
960
1080
1200
1320
1440
1560
1680
1800
1920
Time (Minutes)

Figure 6

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Julien, Pierre Y., and Saghafian Bahram, 1991, A Two-Dimensional Watershed Rainfall-Runoff Model - CASC2D User's Manual.

A SYSTEM RESPONSE APPROACH FOR VERIFYING SURFACE AND GROUNDWATER MODELS

BERNARD B. HSIEH[1]

ABSTRACT

The frequency response coefficients, which are based on the ratio of numerical response system to measurement response system, are defined and used as an indication of model performance. These response systems are conducted by the dynamic transformation through a multiple input/single output (MISO) system analysis between prototype data and results from numerical simulation to identify the physical presentation of the critical target area within the computational domain. This new technique is demonstrated on one three-dimensional surface model of Chesapeake Bay-C&D Canal-Delaware Bay and one two-dimensional groundwater flow model near Wichita, Kansas. It shows that this method can capture more physical insights that many traditional statistical procedures might miss.

INTRODUCTION

With multidimensional surface and groundwater model advancement, verification to obtain a satisfactory model become much more complicated and time-consuming. The evaluation of model performance has not developed as fast as computational facilities and numerical techniques. In most studies conducted so far, verification has consisted of simple statistical comparisions between model predictions and field observations. The comparable parameters are also often limited to simple variable evaluation. Performance criteria that involve system response and express actual physical contents can definitely make these comparison more meaningful.

The nonlinear behavior resulting from natural fluctuations, such as hydrological processes, is very difficult to be examined by such a purely stochastic point of view. Generally, the selection of either time domain or frequency domain approach depends on the needs of the application. However, the time domain approach fails to present long-term overall pictures unless many insignficant terms are included as model components. In addition, since the numerical model has the capability of describing the nonlinear terms in the governing equations, the system model must be able to

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solve the nonlinearity problem simultaneously. Obviously, this needs the solution of a multiple nonlinear system with frequency domain approach.

The multiple nonlinear system analysis (Bendat 1990) is not a very new topic in the hydrological field. However, because of its complicted procedures of computation and the difficulties of nonlinear system identification, its applicability is somewhat limited. In general, a model output is the result of input forcings through physical processes. In order to incorporate the system model with the numerical model input/output structure, a moving response function with fixed input design for the system model was proposed. Each system output corresponds to one computational cell (i.e., verification station) from the numerical model. In this case, when the output station is changed, the input functions still remain the same. This provides a relative index to examine the response variation over comutational domain. The diagram (Figure 1) shows two different response functions derived from three input sources.

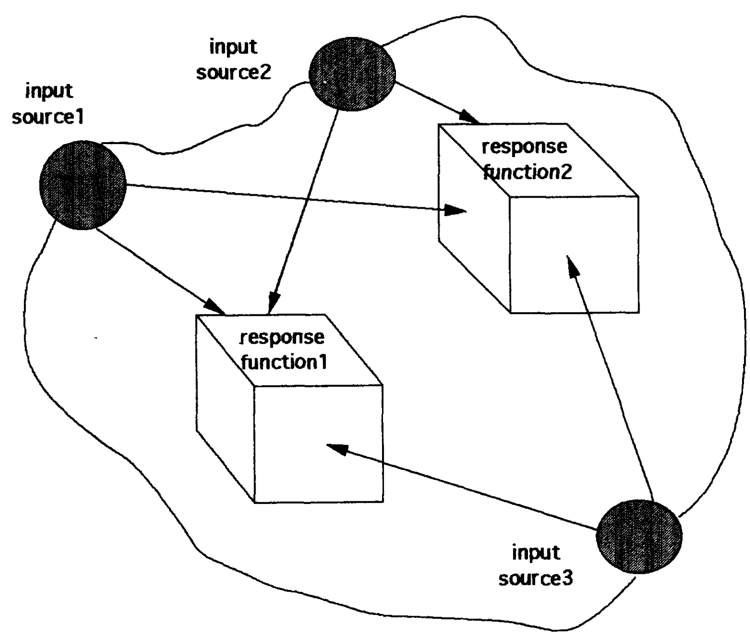

Figure 1. Moving response function with fixed input structure

In this paper, a MISO nonlinear system was solved by the computer software -MISOF4. It has been developed by the U.S. Army Engineer Waterways Experiment Station (WES) for identifying the multiple linear system with frequency domain approach and time domain simulation option, dual frequency band combination, and correlated input separation features.

In order to demonstrate this new system response approach, monthly simulation results from a three-dimensional multiple-opening estuary salt transport model (Hsieh, Johnson, and Richards 1991) were used to determine the performance in a selected critical location. A two-dimensional unconfined aquifer numerical model was used to examine the water table fluctuations due to natural recharge and stream-aquifer interactions from the literature (Gelhar et al. 1974) for a site in Kansas. This provides a variety of data to understand the deterministic forcing and stochastic phenonema related to the model performance.

MULTIPLE NONLINEAR SYSTEM AND FREQUENCY RESPONSE COEFFICIENTS

A multiple linear system with frequency domain approach transfers input/output from time domain to frequency domain using Fourier transformation technique. The multiple-frequency response function is obtained from each frequency band through the transformation. The multiple coherence functions (or square multiple coherence functions) are then computed to check how these input series exert on the output function. For a perfect transformation, this function has a value of one compare to the value of zero for a totally uncorrelated system.

For a multiple nonlinear system, the transformation from input series to ouput function no longer can be directly solved by a traditional multiple linear system. The time delays from each input/output (or subinput/suboutput) path cause big bias errors for the spectral analysis (Schmidt 1985), and the nonlinear effects curtail its capability. While this problem is still under research, one of the best alternative solution(Hsieh 1993) is to decompose input/output series into a series of parallel subsystems for each significant band. A finite-memory nonlinear system is inserted between the input series and subtransfer function. It means that the multiple frequency response function is the summation of each subfrequency response function. Any time delay of each subsystem can be corrected individually.

Under these considerations, two response systems were constructed. The first system presents a nonlinear system between input series and observed output. The multiple coherence in this series indicates the measurement response. The computation response, which correlates the numerical model output and input series, is shown by the second system. The ratio of multiple frequency response functions between these two systems for each frequency band is defined as the frequency response coefficients. This process is illustrated by Figure 2. It should be noted that any measurement errors causing input/output uncertainties will not be accounted for in this computation.

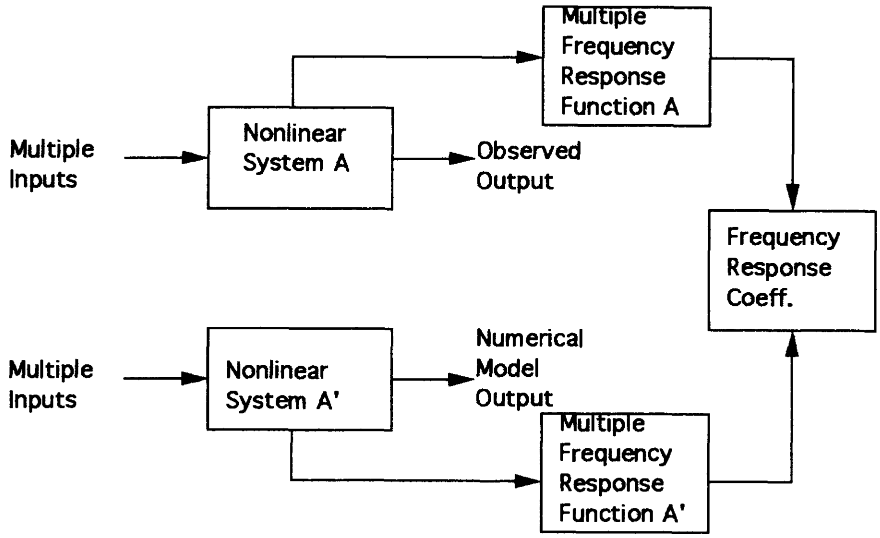

Figure 2. Frequency response coefficients of the numerical model simulation for a nonlinear MISO system

EXAMPLE OF SURFACE WATER MODEL

A three-dimensional hydrodynamic model has been developed for addressing the flow and salt transport through the C&D Canal due to tidal forcings, riverflow discharges from major tributaries, and wind-driven water surface (Hsieh, Johnson, and Richards 1991). A month-long current verification of the model has been conducted by the observed stations. The excellent agreement between field measurements and numerical computation results for the near-bottom layer at the Summit Bridge, C&D Canal, is shown in Figure 3. However, the reliability of the model has to be evaluated by better methods in order to perform further investigations.

Three forcings with five different sources (tides from Delaware Bay mouth and Upper Chesapeake Bay, riverflow discharges from the Susquehanna River and Delaware River, and wind stress from the gauge of Wilmington, Delaware) are considered as inputs; and the tidal current at the Summit Bridge is regarded as output. This MISO nonlinear system is extremely difficult to solve because of siginificant time delays between each input/output series, tidal energy distribution over several narrow-frequency bands, and complicated bathymetry.

One easy way to determine the performance of model verification is to calculate the transfer function between numerical model results and field measurements. The perfect match will be unity or high coherence functions with zero phase over the frequency band. The

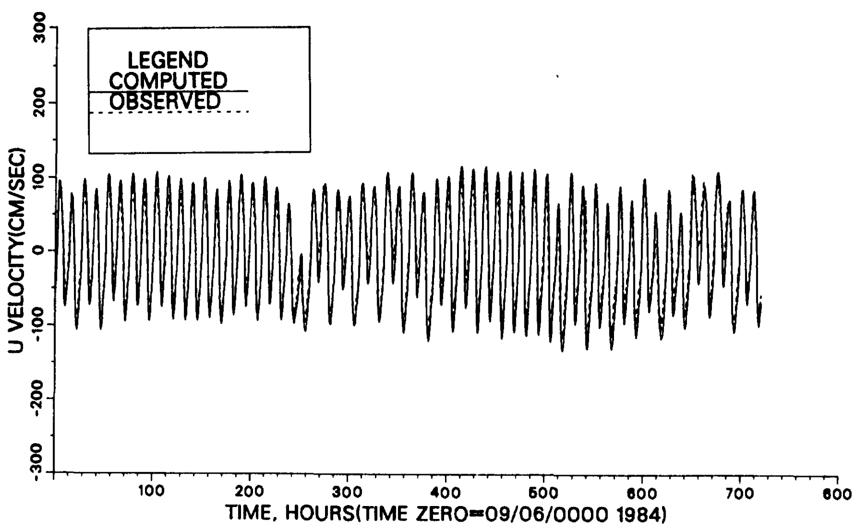

Figure 3. Tidal current comparisons near bottom layer (33-ft depth) at Summit Bridge, C&D Canal

drawbacks from this approach are that too many insignificant bands also need to be computed and nothing is related to the model inputs. The best approach is to identify the significant bands and time delays from spectral analysis and then to use the decomposition technique (Hsieh 1993) converting a MISO non-linear system to a series of equivalent single input/single output (SISO) nonlinear systems. This involves the ordering process of conditioned inputs and a finite-memory non-linear inserting procedure.

The preliminary analysis shows that the river inflows and wind stress have weak correlation to tidal currents for this target station within a monthly period. Five significant tidal forcing frequencies (S2, M2, N2, K1, and O1) from two boundaries with different phases are chosen as system inputs. The multiple response functions for both response structures are obtained after computing the simulated system output from the MISOF4 package for an inverse Fourier trnasformation option. The repeating procedure stops when the residuals of output are close to white noise series. The frequency response coefficients for this verification point are presented in Table 1. Another parameter, phase difference between these two systems, is also calculated. The results show that this numerical model is undershooting the semidiurnal band and is overshooting the diurnal band. The field measurement leads the numerical result about 24 deg for the major component M2, for example. Since the Summit Bridge receives stronger tidal propagation from the Delaware side, the physical causes and effects must be further investigated in order to improve the verification of the numerical model.

Table 1. Frequency Response Coefficients of Tidal Current Verification at the Summit Bridge, C&D Canal

Significant Frequency	Frequency Response Cofficient	Phase Difference
S2	1.222	0.347
M2	1.208	0.414
N2	1.209	0.003
K1	0.843	0.338
O1	0.856	0.239

EXAMPLE OF GROUNDWATER MODEL

Hydrologic phenomena are generally recognized as being affected by complex natural events. Natural variability, such as temporal fluctuations in groundwater recharge/discharge or water level in adjacent bodies of water and spatial variations in recharge and hydraulic conductivity, usually deal with aquifer properities. This example study uses a phreatic aquifer, which is regarded as a transformation system with two inputs and one output. The two inputs are the accretion rate and the stream stages. The output of the system is the piezometric head in the aquifer. The study area, near Wichita, Kansas, is chosen from the Gelhar et al.(1974) report. The data are based on long-term (33 years) monthly data from the report including the water level in a well.

A two-dimensional aquifer simulation model was used to generate water table conditions. However, because this program cannot incorporate time-varying inputs, the results are not satisfying. Currently, another two-dimensional finite-element groundwater flow model is used to conduct this simulation. The model boundary is prescribed by the river stages from Arkansas River and Little Arkansas River,and no flux boundary at the upper side. The numerical model consisted of 150 nodes and 278 elements.

While the numerical model was under verification, the system model was constructed to identify the transformation system. Three significant frequencies (annual cycle, 40 months cycle, and 110 months cycle) are selected as the candidates. The system simulation model (solid line) versus field obervation (dashed line) from 33-year water well is presented in Figure 4. Further study to relate extreme events is needed to improve this model identification problem.

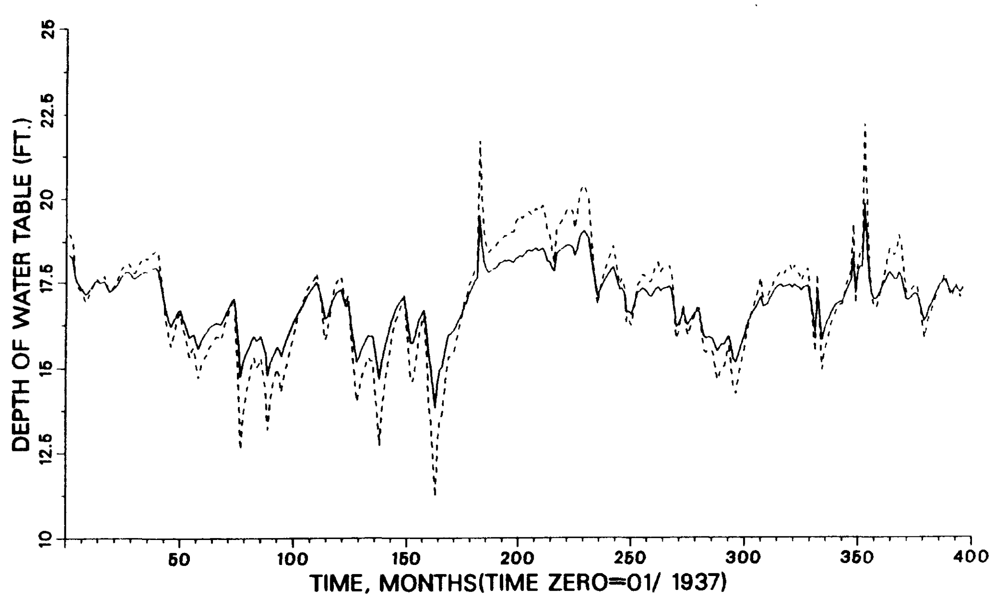

Figure 4. System simulated results versus field observations for a water well near Wichita, Kansas

CONCLUSIONS

The calculation of the frequency response coefficients from a MISO nonlinear system can assist in improving the understanding of physical phenonema for verifying the surface and groundwater models. Further investigation requires the knowledge of stochastic response other than deterministic response only. The development of a MISO nonlinear system solver without the converting process can overcome much more complicted natural systems problem and can improve the modeling efficiency.

ACKNOWLEDGEMENTS

The tests described and the resulting data presented herein, unless otherwise noted, were obtained from research supported by the Civil Works Program of the United States Army Corps of Engineers and conducted at the U.S. Army Engineer Waterways Experiemnt Station, Vicksburg, MS. Permission was granted by the Chief of Engineers to publish this information.

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URBAN RUNOFF MODEL CALIBRATION AND VALIDATION

R.S. DINICOLA

INTRODUCTION

Predicting the effects of urbanization on drainage basin hydrology requires an understanding of the relations between rainfall and runoff under both natural and urbanized conditions. A qualitative understanding of rainfall-runoff relations, presented in the form of a conceptual model, can be postulated from readily obtainable information about soils, climate, topography, and land-use, and from existing theories concerning runoff generation processes. A quantitative expression of rainfall-runoff relations, the necessary basis for a tool designed to predict hydrologic effects, is more difficult to formulate. The relations can sometimes be quantified by analyzing long-term records of measured precipitation and streamflow at multiple sites, but such data are rarely available for the headwater drainage-basins that are commonly most affected by urbanization. Therefore, an approach commonly used to quantify the relations of short-term records with observed data involves using a numerical rainfall-runoff simulation model to extract the maximum amount of understanding from limited data.

The quantification of rainfall-runoff relations with numerical simulation models is a not a straightforward task. Numerical models represent the individual hydrologic processes in a watershed, such as interception or infiltration, with mathematical equations. Many of these equations include parameters, such as interception storage capacity or infiltration capacity index, which represent spatially averaged values of the true physical attributes of an area, and such values are difficult or impossible to directly measure in the field. The values for many model parameters are, therefore, most often determined through calibration of the numerical model with observed hydrologic data. Streamflow data from one or two sites within a basin are the most commonly available data for calibration, but the use of these streamflow records leads to a major shortcoming of this calibration process. Streamflow represents a basin-integrated response of many processes that are related to streamflow generation, so the role that each individual process plays in the generation of streamflow is not always clear. Hence,

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the calibrated values for the individual model parameters may not be representative of actual conditions, even if the numerical model as a whole does adequately simulate the observed streamflow used for calibration. If the model parameters are not representative of actual conditions related to all of the individual processes, then it is unlikely that the resulting numerical model will be useful as a predictive tool. Thus, even though a calibrated numerical model may 'work', it must 'work' for the right reasons in order for it to have value as a predictive tool.

A recent study in the unincorporated areas around the Seattle metropolitan region was designed to provide a tool to local planners and engineers for predicting the effects that urbanization may have on rainfall-runoff relations (Dinicola, 1990). The prediction tool consisted of some guidelines for constructing numerical simulation models using the Hydrologic Simulation Program - FORTRAN (HSPF; U.S. Environmental Protection Agency, 1984), and a set of calibrated HSPF parameter values that were determined for the physiographic region as whole. The guidelines and parameters could be used, in combination with readily measurable physical characteristics of specific drainage basins, to construct numerical simulation models for most headwater drainage basins in the study area. The numerical models could then be used with existing climate data and existing and projected land-use information to obtain reasonable simulations of both pre- and post-development rainfall-runoff relations for the basins. The primary benefit of such an application is that long-term streamflow records would not be required for constructing the numerical models because the critical model parameters had already been calibrated for the region as a whole. Although the results of the parameter calibration phase of the study suggested that such an application may be feasible, a great deal of uncertainty existed about the accuracy of numerical simulation models for drainage basins not included in the original calibration study. The accuracy was assessed by performing a subsequent validation study.

A validation study (referred to as verification in some reports) is a systematic procedure designed to test the basic assumptions inherent in numerical simulation models, and to demonstrate their ability to perform the tasks that are expected of them. There were four critical assumptions in the simulation models that required validation. The first was that the conceptual model that forms the basis of the numerical model is correct. The second assumption was that the computer program itself is adequate for quantifying the rainfall-runoff relations. The third assumption was that the approach used for constructing a numerical simulation model for a specific basin results in a model that adequately represents the significant features of the conceptual model. The final assumption was that the calibrated parameter values are adequate for quantifying the rainfall-runoff relations.

PURPOSE AND SCOPE

The purpose of this paper is to describe the approach used to quantify rainfall-runoff relations in headwater drainage basins around the Seattle metropolitan area of Washington state, and to present a few examples of the results that can be obtained by using such an approach. The formulation of a generalized conceptual model of rainfall-runoff relations for the study area is briefly described, followed by descriptions of the model construction and parameter calibration process, and of the validation process used to test the four critical assumptions inherent in the simulation models.

CONCEPTUAL MODEL

A conceptual model describing the qualitative features of rainfall-runoff processes in the study area as a whole was formulated using information from soils, geologic, topographic, and land-use maps, from historic climate records, and from results of other hydrologic investigations in humid, temperate areas. The conceptual model was formulated to be applicable to most, if not all, headwater basins in the study area, and it describes the runoff mechanisms thought to be most important in the region as a whole. The conceptual model provides a framework to construct numerical models that contain enough detail to adequately simulate the predominant runoff mechanisms in the area, but are simple enough to be realistically calibrated and validated with somewhat limited observed streamflow data.

The conceptual model formulated for the Seattle metropolitan area can be summarized as follows. The important runoff mechanisms in undisturbed, forested areas are shallow-subsurface flow from hillslopes mantled with glacial till; ground-water flow from glacial outwash deposits; and saturation overland-flow from depressions, valley bottoms, and till-capped hilltops. In disturbed areas, primarily urban, most of the same runoff mechanisms are important for pervious parcels within the urban areas, but Horton overland-flow is an additional important runoff mechanism during larger storms. Overland flow from impervious surfaces within the urban areas is also important in the urban areas.

MODEL CONSTRUCTION AND PARAMETER CALIBRATION

Numerical simulation models were constructed for 21 gaged drainage basins in the study area. The conceptual model was used as the basis for how model parameters were 'distributed' across a basin, and for determining the relative values of model parameters for different soils, slope, and land-use types. The distributed parameter approach that was used for model construction required division of a drainage basin into land-segments, each with relatively uniform physical and hydrologic characteristics. Twelve land-segment types were defined for this investigation. All of the area of a particular land-segment type need not be contiguous, so it was possible to represent complex mosaics of soil types, vegetative cover, topography, and land use by using only the twelve land-segment types.

The HSPF parameters in the simulation models--such as the infiltration index, interception storage capacity, or the subsurface flow index--were calibrated concurrently for the 21 gaged basins using precipitation, evapotranspiration, and streamflow data collected during the 1985-86 water years. During calibration, a given set of parameter values representing a given land-segment type were varied consistently in all basins where the land-segment type was present. The calibration effort resulted in 12 sets of generalized HSPF parameter values, one set for each land-segment type with a unique hydrologic response. The magnitude of the simulation errors that remained after calibration was not large enough to reject the postulated conceptual model on which the models were based (see Dinicola, 1990, for details). The storm-runoff mechanisms presented in the conceptual model appeared to be well supported by these initial simulation results, although interstorm and dry-period streamflow generation were not as well represented.

VALIDATION

The final phase of the Seattle metropolitan area study involved assessing the accuracy of applying the model construction and calibration results to other drainage basins within the region. This was done by assessing the validity of the conceptual model on which the numerical models are based, of the HSPF program, of the approach used to construct numerical models, and of the generalized HSPF parameter values. The validity of these four components of the prediction tool was evaluated using a proxy-basin test, wherein numerical models were constructed for drainage basins other than those used for the calibration exercise, and the ability of the numerical models to simulate streamflow in the proxy basins was tested.

Numerical simulation models were constructed for eleven additional Seattle area drainage basins for which hydrologic data from the 1987-88 water years were collected. The models were initially constructed using the previously determined approach and generalized HSPF parameter values, and the simulation results were compared with observed streamflow data. If the simulation errors--the differences between observed and simulated streamflow--for one of the validation basins were comparable to those errors reported for the calibration exercise, then all four components of the prediction tool were considered to be valid for the conditions found in that basin. If the simulation errors were found to be much greater than the calibration errors, then various components of the numerical model, such as model parameter values, were manipulated and additional simulations were performed. The goal of these additional simulations was not to tailor each numerical model to get the best possible simulation for each of the validation basins; rather, the goal was to identify those simulation errors that occurred consistently in the validation basins. For example, the models for most of the validation basins simulated baseflow poorly. Subsequent manipulation of those models showed that the approach used to determine ground-water discharge zones, and the generalized parameter values related to the timing of ground-water discharge, were invalid for the study area.

The validation exercise allowed the following conclusions to be made regarding the quantified rainfall-runoff relations. The initial conceptual model for rainfall-runoff relations in the study area is valid, although results suggest that the phenomenon of upslope runoff draining into the ground-water system of outwash deposits was not fully recognized. The HSPF program is a valid tool for computer simulation of rainfall-runoff relations in the study area in nearly all cases, although the program does not adequately simulate the timing of runoff pulses and peaks in basins where the runoff is affected by particularly complex ground-water surface-water interactions. The initial approach used for constructing the numerical simulation models was not adequate for all basins, but the modifications made to that approach in this investigation identified the major shortcomings of the initial approach. The modifications to the approach were related to: (1) the quantity of ground-water allowed to discharge into a basin, and to (2) the phenomenon of upslope runoff draining into the ground-water system of outwash deposits. The generalized HSPF parameter values appear to be valid for simulating most components of the rainfall-runoff relations in the study area. The simulation of the timing of ground-water discharge is an exception; no values for the parameters representing that process were found to be generally valid across the study area.

Given the above results from the validation assessment, guidelines for constructing reasonably accurate numerical simulation models for other drainage basins in the study area were made. These guidelines focused on the particular type of streamflow data that is required for model construction for drainage basins with particular physiographic characteristics. For example, a few baseflow measurements of streamflow are needed for most basins, but more frequent storm-period streamflow measurements are required for basins with extensive glacial-outwash deposits.

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WETLAND IDENTIFICATION, SCS, MISSOURI

JERRY P. EDWARDS [1]

ABSTRACT

Wetland identification is critical in administering the swampbuster provisions of the 1985 and 1990 farm bills. The SCS in Missouri, found it necessary to address the seasonally flooded portion of wetland identification, particularly along the two major rivers, the Mississippi and the Missouri. The 2-year, 15-day frequency flows and the 2-year, 7-day frequency flows were identified to meet FSA requirements.

INTRODUCTION

This discussion describes the procedures and methods used by Missouri SCS to identify wetland areas resulting from long duration flooding. Missouri has a number of rivers that have drainage areas exceeding 1000 square miles. The most prominent ones are the Mississippi and Missouri Rivers.

One of the 1985 and 1990 farm bills goals is to insure protection of the wetland and aquatic environment while allowing for environmentally sustainable flood plain use and development, and also not to put undue hardship on the land user.

It is recognized that the definition of a wetland may change with new legislation, but the procedures and methods shown here will still apply.

In Missouri, each area office established a wetland team to prepare the wetland inventory maps. Maps of the areas concerning seasonal flooding for extended periods were developed for each stream in the state by the hydrologist.

WETLAND IDENTIFICATION

Wetlands are defined as areas that have a predominance of hydric soils and that are inundated or saturated by surface or ground water at a frequency and duration sufficient to support, and under normal circumstances do support, a prevalence of hydrophytic vegetation typically adapted for life in saturated soil conditions.

This definition was first stated in the 1985 farm bill and later restated in the 1990 farm bill.

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To be considered a wetland the following three conditions must exist:

1. Hydric Soils are those that meet the criteria set forth in the publication "Hydric Soils of the United States."
   a. These include saturated soils with water tables at or near the surface during the growing season.
   b. Soils that are ponded for long periods during the growing season.
   c. Soils that are seasonally flooded for extended periods during the growing season.

2. Hydrophytic vegetation is made up of the plants that grow in water or in a substraite that is periodically deficient in oxygen during the growing season. This determination may be made by visual observation of vegetation.

3. Wetland Hydrology exists when an area is saturated to the surface or inundated at some point in time during an average rainfall year during the growing season.

The wetland hydrology criteria and the hydrologic part of the hydric soils criteria are identical.

Water supply is not a factor in identifying a wetland or hydric soil. However, To create an artifical wetland, it is necessary to provide adequate water supply to support the wetland.

SEASONAL FLOODING

Seasonal flooding is defined as an area along major streams and rivers where surface water exists for extended periods during the growing season under average conditions.

Surface water must be present for extended periods in the growing season to qualify as seasonally flooded or ponded. According to the farm bill "Extended periods" is defined as the continued presence of surface water for at least 15 consecutive days or 10 percent of the growing season, which ever is less under average conditions (50 percent chance of occurrence using all existing precipitation or stream gage records).

The remainder of this discussion pertains to seasonal flooding and its determination. The farm bill specifies seasonal flooding on CROPLAND, as that area flooded by the 2-year frequency 15-day duration flood event occurring during the growing season. In Missouri this type of flooding usually occurs in the early part of the growing season. For NON CROPLAND flooding, a 2-year frequency 7-day duration flood is used to protect wetland areas and other aquatic environments.

Determining and delineating the areas flooded along streams and rivers by the 2-year frequency 7-day and 15-day duration floods becomes quite important and is the objective of this analysis.

HYDROLOGIC ANALYSIS OF STREAM GAGE DATA

In Missouri, average daily flows were used to determine the average flow over the extended periods of, 7- and 15-day durations for these analysis.

Another option for selection of discharge-duration values would have been to use daily hydrographs and measure actual out of bank flow durations and depths on a daily basis. This method is much more time consuming and harder to analyze.

The average flows are much easier to explain, defend and illustrate so that it can be understood by the public. The Missouri and Mississippi Rivers rise and fall very slow because the drainage areas are large and upstream reservoirs are intended to level out downstream flows by controlled releases. Also flow in the channel rises and falls much faster than flood plain flows. In fact much of the overbank flows are slow to drain from the fields. It is the opinion of the Missouri wetland team that this should be the recommended procedure.

The first objective was to develop flow-frequency data using average flow for 7-day and 15-day durations, by use of procedures in SCS, National Engineering Handbook, Section-4, Chapter 18, or Water Resource Council bulletin 17B.

To make this analysis the following steps were followed:

1. Obtain USGS daily flow data for the stream gages to be analyzed.

2. Select the period of record. Decision may be effected by installation of an upstream dam or quality of data. For example, an upstream reservoir was built in 1965, only data after that date was used.

3. Determine the growing season. For Missouri, Mid-March through the last of September was considered to be the growing season. The growing season is defined in publication, "Hydric Soils of the United States,SCS, June 1991".

4. This analysis can be done using either the USGS flow duration computer program or the SCS volume duration program (VDP). Both programs determine average discharge values for the selected return period.

5. Using the average discharge rate for 7- and 15-day durations we determined the percent chance of occurrence and corresponding flow rate from the frequency curve for each duration. These discharges were then used to develop the profiles. An example of the discharge analysis in cubic feet per second is shown below.(Table 1)

Table 1

LOG-PEARSON TYPE III DURATION FREQUENCY ANALYSIS
GRAND RIVER NEAR SUMNER, MISSOURI
DRAINAGE AREA = 6,880 SQUARE MILES

Exceedence Probability	Recurrence Interval	7-day Parameter Value	15-day Parameter Value
0.90	1.11	9,000 cfs	5,550 cfs
0.50	2.00	26,960 cfs	17,450 cfs
0.20	5.00	45,500 cfs	36,570 cfs
0.10	10.00	56,580 cfs	38,800 cfs
0.01	100.00	83,030 cfs	59,780 cfs

6. By using USGS stream gage rating tables, determine the gage height and convert to National Geodetic Vertical Datum (NGVD). These elevations were used at the stream gages to plot watersurface profiles.

DEVELOP FLOOD PROFILES

Local, State and federal agencies usually have Stream and flood profiles available for most of the larger Rivers. These may be available through the Corps of Engineers or FEMA, for example. In cases where no stream profiles are available it was necessary to develop our own profiles from 7.5-minute USGS topographic maps.

Using the 2-year frequency, 7-day and 15-day duration average daily discharges, plot the corresponding elevation profiles. After the profiles were plotted, it was necessary to compare the results to known high water marks and/or projected flood profiles. These previously developed profiles and elevations were used to guide us between stream gages.

If the stream had no gaging stations to make frequency discharge determinations, it was necessary to estimate these values from regionalized data and also estimate the channel capacities to determine if the frequent flooding part of wetland determination has been met.

Upon completion of these profiles, they were coordinated with local, state and federal agencies to insure agreement with any existing data.

When working with limited data, field trips may be necessary to observe physical features and estimate channel capacities.

PREPARE MAPS

The areas inundated by the 2-year frequency 7- and 15-day duration floods were outlined on USGS 7.5-minute topographic quadrangle maps covering the stream reaches for which we developed profiles. The area inundated was mapped to the next higher contour based on elevations at each river mile interpolated from the elevation profiles. A majority of the surface water elevations for the 7- and 15-day floods were typically within a USGS mapped contour interval. Most of the maps had 10-ft contour intervals, while some had 5- or 20-foot intervals. The mapping procedure followed these steps:

1. USGS topographic maps covering the profiled stream sections were assembled. River miles were manually measured and marked on the maps from the profile starting point. A line representing the midpoint of the river was followed in measuring all channel distances. (Map 1)

2. At each river mile, the 7 and 15 day elevations were recorded on the maps. A master list of elevations by stream and river mile was prepared as part of the documentation process. Elevations were interpolated to the nearest foot from the elevation profile plots.

3. After marking the river miles and recording the 7- and 15-day elevations, the area inundated was delineated to the next higher contour line. If an area was contested, we then would use the elevation from the profiles along with actual surveyed field elevations to establish a more exact area on the maps. The field information had to be provided by the producer using the services of a reqistered professional land surveyor or a professional engineer.

Only inundated areas between the stream channel and a levee were identified when delineating areas having extended seasonal flooding. Those areas on the land side of the levee were protected from frequent flooding.

We provided each field office with maps showing the extent of average 7 and 15 day duration flooding for each county.

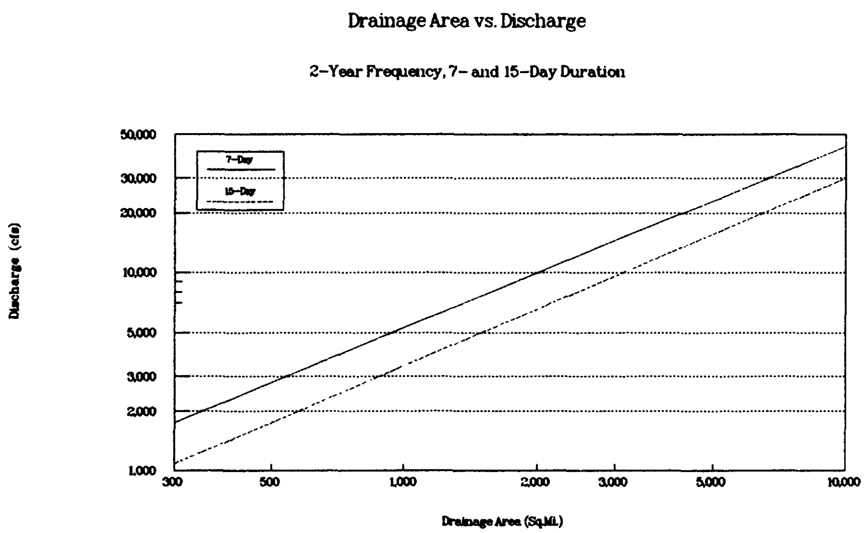
DISCUSSION OF RESULTS

Examination of stream gage data, indicated that 400- to 500-square mile drainage areas were about the size that could be expected to produce enough average daily discharge to exceed bank full capacity for a 7- or 15-days period. Corresponding discharges varied but generally ranged from between 3,000 cfs and 4,000 cfs.

The following chart shows the regression of the average discharge in cubic feet per second vs drainage area in square miles for all the stream gages studied in Missouri.(Figure 1)

It was found that in most cases, the 15-day average discharge was about 2/3 of the 7-day.

Figure 1

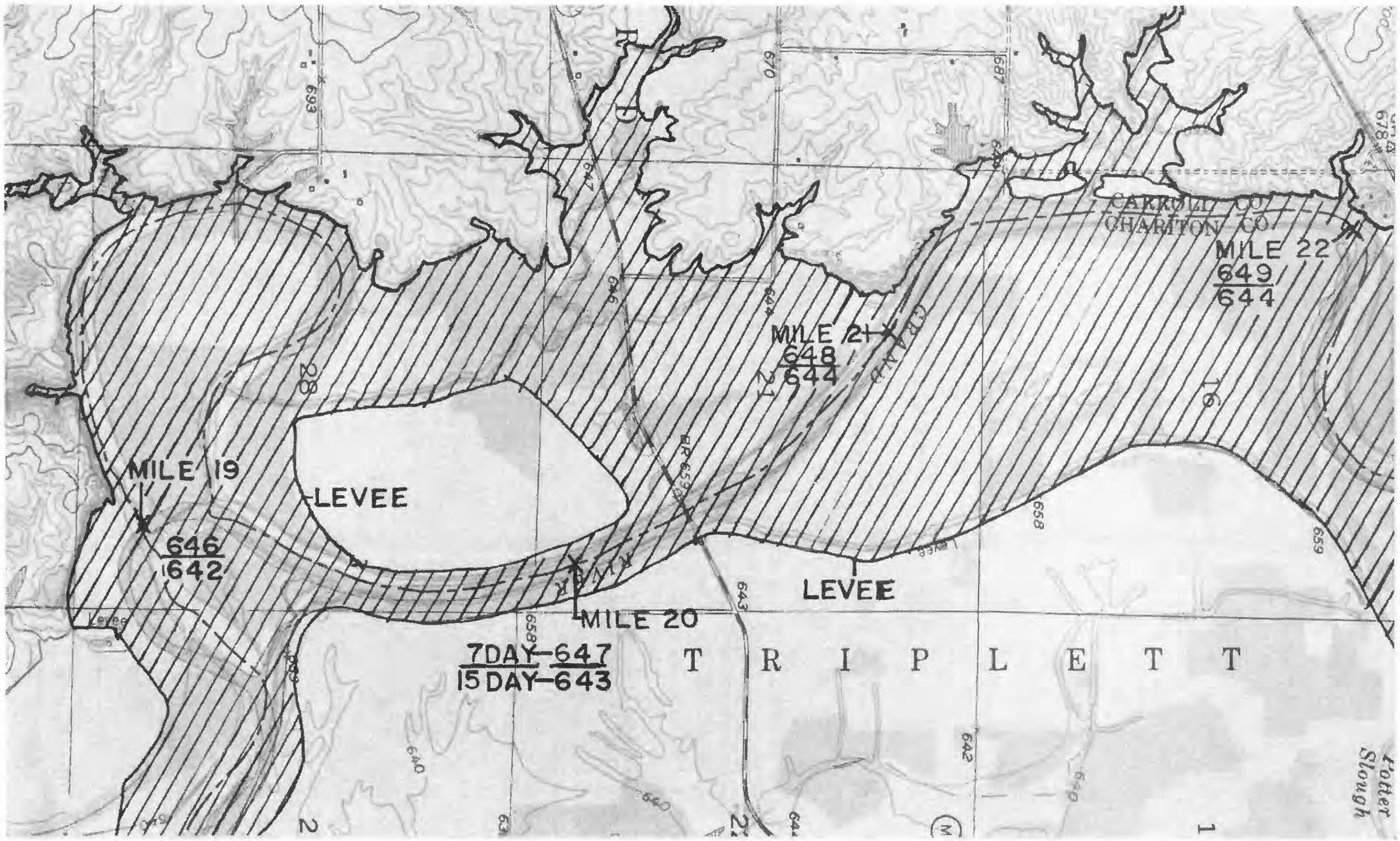


One observation made was when flooding of cropland became more frequent than about once every other year, we would see a levee along the stream to protect the adjacent field.

This proceedure has resulted in no problems because it is easy to explain how and why each item was developed. Only on one occasion were the results questioned, and the reason was the individual had some other data and misused the statistics. That was solved easily with a short explanation.

WETLAND IDENTIFICATION BY SCS IN MISSOURI

ELEVATION AND AREA INUNDATED BY 7- AND 15-DAY DURATION 2-YEAR FREQUENCY FLOOD.



DETERMINING DESIGN UNIT HYDROGRAPHS FOR SMALL WATERSHEDS

JOSEPH M. SHERIDAN[1] AND WILLIAM H. MERKEL[2]

INTRODUCTION

The USDA Soil Conservation Service (SCS) has previously recommended a single standard design unit hydrograph (UH) to convert storm runoff volume to a storm hydrograph. The SCS, recognizing that a single UH may not be adequate for applications in all physiographic regions, has expressed a need for alternative design hydrograph shapes. In April 1989, the SCS along with the USDA Agricultural Research Service (ARS) held a National Hydrology Workshop in Tucson, AZ to discuss hydrologic topics of mutual interest. One of the primary needs expressed by the SCS at the 1989 workshop was for development of alternative unit hydrographs for use in design applications in ungaged areas, particularly in regions of low topographic relief.

The 1989 National Hydrology Workshop resulted in the subsequent formation of two work groups, one of which was the ARS-SCS Interagency Work Group on Unit Hydrographs. This paper briefly details activities of the Unit Hydrograph Work Group including goals, objectives, and progress to date in developing alternative UH shapes for use by the SCS in design applications on ungaged watersheds.

BACKGROUND

Unit Hydrograph Concept

The unit hydrograph (UH) concept advanced by Sherman (1932) presumes that a characteristic storm hydrograph represents the direct runoff from a unit volume of rainfall excess occurring in a unit time and distributed uniformly over a given catchment. The UH concept contains the premise of a linear, time-invariant system. The development of the UH concept has been cited by Dooge (1973) as one of the highlights of the classical period of hydrology (circa 1930 to 1945). Dooge also indicates that, while the assumptions of linearity and time-invariance are not strictly correct, hydrologists continue to utilize the concept for two reasons: linear methods are (1) simple and easy to use, and (2) results obtained are generally acceptable for engineering applications.

Procedures for generating synthetic unit hydrographs for applications on ungaged watersheds have been a primary pursuit of practicing hydrologists since the development of the UH concept (Dooge, 1973). Synthetic UH methods have been proposed by Snyder (1938), Clark (1945), and the SCS (1964), among others. These methods provide simplified, empirical relationships for development of synthetic unit hydrographs for applications on ungaged areas, with the shape of the UH typically based on one or two hydrograph parameters, such as watershed time lag, time-to-peak, or peak discharge rate.

Nash (1958) later suggested the gamma function as having the general shape required for representing the UH. The gamma function can be considered conceptually as being the impulse response for a cascade of equal linear reservoirs and requires only two parameters (n, the number of reservoirs and K, the storage delay time of each of the reservoirs). More recently, the works of DeCoursey (1966) and Williams (1968, 1973) led to refinements in the gamma UH approach, culminating in the development of a gamma-exponential UH technique, which provided superior results when fitting observed storm hydrographs.

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Dooge (1973) and Hjelmfelt (1992) have cited the need for establishing predictive relationships between UH parameters and catchment characteristics in order for the UH technique to become an adequate tool for developing synthetic design hydrographs for ungaged watersheds.

The SCS Design Unit Hydrographs

A special case of the synthetic UH has been an integral part of the peak discharge and storm runoff hydrograph generation procedures used by SCS in the design of conservation measures and structures. The SCS standard UH is currently one of the most commonly cited and used design hydrograph procedures. The SCS standard UH (of either triangular or dimensionless form) was developed by Mockus (1957) from rainfall and runoff records on small agricultural watersheds and is characterized by several empirically based assumptions.

Field applications of the SCS standard UH by personnel in the SCS state offices and national technical centers have indicated that a single UH may not be adequate for applications in all physiographic regions. SCS personnel at the Northeast National Technical Center, realizing the particular difficulties in applying the standard UH to watersheds with very flat topography, developed an alternative design UH from limited data on four watersheds in the Delmarva peninsula of the eastern U.S. (Welle, et al. 1980). This alternative UH (referred to as the Delmarva UH) has also been used for selected design applications in other regions of the U.S., limited primarily to low relief areas of the southeastern U.S.

Recognizing the need for developing improved hydrologic design procedures for use under a wide range of physiographic conditions, the SCS has expressed a need for alternative synthetic design hydrographs. Improved design UH procedures would result in improved storm runoff peak flow estimates, thereby creating more cost-effective design of conservation measures and structures. Further, improved capabilities for estimating storm runoff hydrographs would also result in improved accuracy and reliability of estimates of sediment and agricultural chemical transport in runoff from rural areas required for SCS environmental and water quality programs. Benefits cited by the SCS for development of improved hydrologic design procedures would extend to all SCS programs in water quality.

1989 National Hydrology Workshop

In April 1989, a National Hydrology Workshop was held by SCS and ARS in Tucson, AZ to discuss topics of mutual interest to soil and water engineering personnel of both agencies. Two of the specific problem areas identified by the SCS at the 1989 National Hydrology Workshop were the need for (1) further evaluation of the SCS Runoff Curve Number (RCN) procedure with possible development of regional curve numbers, and (2) development of regional or alternative design unit hydrographs for use on ungaged watersheds. Each of these topic areas was deemed critical to improving existing SCS design procedures. As a result of the 1989 National Hydrology Workshop, two interagency work groups were formed to develop improved design procedures for the two specific problem areas identified by the SCS: the Runoff Curve Number Work Group and the Unit Hydrograph Work Group. This paper focuses specifically on activities of the ARS-SCS Interagency Work Group on Unit Hydrographs.

UNIT HYDROGRAPH WORK GROUP

Interested soil and water professionals in ARS and SCS identified during the 1989 National Hydrology Workshop were included on the ARS-SCS Interagency Work Group on Unit Hydrographs. Membership was divided approximately equally between ARS research engineering personnel and SCS state, regional and national technical staff. Representation in the Work Group was also distributed somewhat geographically over the U.S.

The first meeting of the UH Work Group was in Washington, DC in September 1990. The charge to the Work Group was to: (1) outline strategies for developing regional or alternative unit hydrographs for SCS design applications in regions of diverse topography; (2) develop standard methodologies for developing regional or alternative design hydrographs based on actual watershed storm data; and (3) properly and adequately document technical findings and recommendations.

The agenda for the initial meeting of the UH Work Group focused on the following general objectives: (1) definition of the nature and magnitude of problems encountered using current standard design UH, (2) identification of primary physiographic regions where design application problems exist, and (3) formulation of strategies to permit development of alternative UH procedures.

Discussions relating to primary problem areas at the initial UH Work Group meeting as well as previous comments made by participants at the special UH session of the 1989 National Hydrology Workshop cited numerous cases or field applications where the standard SCS UH (peak factor = 484 and time-of-recession/time-to-peak [Tr/Tp] = 1.67) was believed to be inadequate. Most of the cases cited by SCS design personnel related to applications in regions of flatter terrain, although some concerns were also expressed for steeper, mountainous terrain. In general, however, the consensus was that hydrologic design procedures would benefit from more extensive, well-documented evaluations of unit hydrographs derived from actual watershed storm data. The existing SCS standard UH (peak factor of 484, Tr/Tp = 1.67 with 37.5% of flow on the rising side of the hydrograph) was based upon rather limited storm runoff data, and despite substantial literature related to the UH concept, additional scientific documentation regarding appropriate synthetic UH design parameters needed for design applications on ungaged watersheds remains rather limited.

Specific problem regions identified by the Work Group included: (1) flatlands regions of the southeastern U.S. (Coastal Plain and Flatwoods physiographic regions), (2) steeper, mountainous regions of western U.S., and (3) the "pothole" regions of Minnesota. Specific goals set at the initial UH Work Group meeting for developing regional or alternative design UH were to:

(1) Evaluate available procedures for obtaining individual event UH from actual rainfall-runoff records. Test procedures initially on limited number of locations using available quality hydrologic data bases.

(2) Determine regional variability in UH parameters and whether regional UH parameters (tied perhaps to Major Land Resource Area) are adequate, or if UH parameters can be related to watershed physical characteristics.

(3) Remain cognizant of possibility for future changes in either SCS design runoff generation procedures (i.e., either RCN or Green and Ampt) or synthetic hydrograph procedures (either current dimensionless-type UH or gamma-distribution based UH).

(4) Be aware of need for design procedures to be fully compatible and integratable into SCS design procedures, programs, and software, such as TR55, TR20, EFM2, FOCS and water quality models.

In September 1991, a second meeting of the ARS-SCS Interagency Work Group on Unit Hydrographs was held at Ft. Worth, TX at the USDA-SCS Southern National Technical Center. At this meeting several specific items of progress accomplished by members of the Work Group consistent with goals and objectives previously identified were discussed, including:

(1) Evaluation of synthetic UH procedures -- In an evaluation of commonly used synthetic design UH procedures, Hjelmfelt (1992) concluded that the available synthetic procedures have many similarities and a common basis of development. The various UH procedures are each limited, or constrained, by certain simplifying assumptions made by the originators. The commonly used UH procedures will give similar results if similar simplifying assumptions are made. Also, the potential of the gamma-exponential distribution for representing design UH shapes was examined. Hjelmfelt's paper provides

an excellent background and theoretical basis for development of regional or alternative synthetic design UH procedures.

(2) Hydrograph optimization program -- An optimization program developed in earlier UH studies by Williams (1968, 1973) for fitting observed storm hydrographs was modified for use on personal computers. This program contains features consistent with Work Group goals and objectives, such as user-specified options of several rainfall partitioning techniques and also of both SCS-type synthetic UH and gamma-exponential UH approaches.

(3) A report by two members regarding testing of the U.S. Army Corps of Engineers, HEC-1 model in the optimization mode with the SCS hydrology option on the Reisel, Texas watersheds and on steeper, mountainous watersheds of the western states indicated difficulty in fitting observed storm hydrographs. Optimized peak factors for the SCS hydrograph were hypothesized to be constrained internally in the optimization mode of HEC-1, forcing the peak factor to remain very near the standard SCS design value (484) and thereby limiting flexibility of this model for the Work Group optimization case studies, particularly for applications on extreme terrains. Further testing and evaluation was recommended.

(4) Limited testing of the existing unit hydrograph optimization program of J.R. Williams on storm data from selected flatland watersheds of the southeastern U.S., showed good results in fitting observed storm hydrographs. The program generally fit both peaks and recessions of observed storm events, producing excellent overall fit to observed runoff hydrographs.

Specific tasks outlined at the second UH Work Group meeting included refinements to prior goals as well as greater specificity regarding strategies for selection of initial watershed data sets for optimization. Criteria for selection of watersheds for the initial phase of the regional testing included: (a) a goal of approximately 6-8 storm events per watershed, (b) selected storms limited to single peak events approximately equalling or exceeding mean annual flow, (c) use of high quality rainfall and runoff data with raingage networks adequate to determine areal distribution of rainfall and recording time resolutions adequate for size of drainage basin.

Initial comprehensive hydrograph optimization tests were proposed for the flatlands watersheds of the Coastal Plain and Flatwoods regions of the southeastern U.S., and the more moderate topography of the Texas Blacklands watersheds. The quality of available watershed data and familiarity of two principal investigators involved in case studies with these watersheds and with general watershed hydrologic response characteristics contributed to selection for initial optimization test phase. Concurrent with the initial phase of testing was the compiling/archiving of watershed data for other physiographic regions for use in the eventual more inclusive regional testing. This effort includes not only rainfall-runoff data for selected events, but also soils, topographic, geomorphic, and climatic data; watershed peak flow frequency distributions; hydrologic instrumentation information (location, recording frequency, depth increments, etc.); and antecedent conditions for selected storm events.

Also, further modifications to the Williams hydrograph optimization program were indicated to provide additional options for Work Group users. These changes included user-specified options for either the 2-parameter or 3-parameter gamma UH, and a user-specified option for weighting of the hydrograph fitting toward either hydrograph peak or overall shape, as well as for increased program documentation.

Subsequent to the second Work Group meeting, further testing and evaluation of the HEC-1 model in the optimization mode was made using storm data from 10 experimental watersheds. HEC-1 Version 4.0.1E was utilized in these evaluations. Tests confirmed that when optimizing within the SCS option for a given storm event, the standard peak factor (484) is used by HEC-1 and only the watershed lag is optimized. This means that even within the HEC-1 optimization mode the standard SCS peak factor and hydrograph shape are essentially retained. Therefore, the HEC-1 model's optimization capabilities are limited in regard to the specific needs of the UH Work Group.

WATERSHED CASE STUDIES

Specific progress to date on testing of optimization procedures on specific watershed case studies may be summarized as follows:

(1) Southeastern watersheds -- Evaluation of UH parameters on flatland watersheds of the Coastal Plain and Flatwoods physiographic regions has progressed via the following activities:

(a) A selected storm event data set was developed for six Coastal Plain and one Florida Flatwoods watersheds (drainage area < 20 mi^2). Events were restricted to single peak events, approximately equal to or exceeding the 2-yr return frequency, and having relatively uniform rainfall distribution over the gaged area. Four to 10 events per watershed were selected for UH optimization analyses.

(b) Existing commonly used empirical hydrograph time parameter design relationships were evaluated for estimating hydrograph time parameters on flatland watersheds.

(c) Flatland selected storm data were evaluated using the Williams hydrograph optimization program with both the Green and Ampt and the SCS RCN (2 options) rainfall-partitioning schemes. Optimized UH parameters were obtained for both the SCS-type synthetic UH and the gamma-exponential UH. Selected mean UH parameters are shown for Coastal Plain and Flatwoods watersheds in Table 1.

(d) A comprehensive compilation of watershed physical characteristic and geomorphic information for flatland test watersheds was completed for use in UH parameter-watershed characteristic evaluations. This compilation (Sheridan and Ferreira, 1992) includes standard measured and computed geomorphic indices.

(2) Texas Blacklands watersheds -- A selected storm data set has been assembled for four Texas Blacklands experimental watersheds (0.5 to 6.8 mi^2). Initial storm hydrograph optimizations have been completed and evaluation of optimized hydrograph parameters is underway. Complete watershed descriptive and geomorphic information is currently being assembled for use in hydrograph parameter regression analyses. Mean UH parameters obtained for the Blacklands watersheds selected storm events are also shown in Table 1.

Conclusions to date

1. For flatland watersheds of the southeastern U.S., existing commonly used empirical relationships for estimating design hydrograph time parameters greatly underestimated those time parameters needed for best comparison with observed hydrograph times. Results indicate that significant errors in estimating hydrograph time parameters on flatland watersheds and, therefore, in developing appropriate synthetic design UH's for watersheds of this region may be attributable to available time parameter design relationships. Measured hydrograph time parameters (time-to-peak and time-of-concentration) for nine flatland watersheds were highly correlated with the watershed main channel length and drainage area. More complex combinations of watershed physical and geomorphic characteristics did not improve estimates of observed hydrograph times over those from simple watershed characteristics. A manuscript describing these findings (Sheridan, 1992) has been submitted for publication.

2. It was the consensus among those attending the 1989 National Hydrology Workshop and of the UH Work Group that peak rate factors for low topograph-

ic relief watersheds would likely be much lower than the 484 peak rate factor currently used in the SCS standard design UH. Preliminary results based on analyses of selected storm events for seven flatland watersheds in the southeastern U.S. indicate, however, that this premise may not be entirely correct. Mean peak rate factors determined for design storm events on the flatland watersheds ranged from approximately 130 to over 500. Observed percentage of flow volume on the rising side of the hydrograph values ranged from 16 to 30%, compared to the standard SCS UH of 37.5%. While a low peak rate factor of approximately 100 was anticipated for watersheds of the Florida Flatwood region based on limited previous UH work in that physiographic region, the range of peak rate factors observed for the Coastal Plain watersheds was somewhat surprising. The six Coastal Plain watersheds, which are located in close proximity (near Tifton, GA), showed a significant range in optimized hydrograph parameter values (peak rate factors ≈ 280-510) despite apparently similar physical characteristics. Results of these tests indicate that single regional design UH may not be a readily achievable goal.

3. Preliminary regression analyses on optimized flatland UH parameters and watershed physical characteristic/geomorphic information indicates that the mean watershed UH peak factor, as well as the watershed gamma-exponential synthetic UH parameters are highly correlated with readily measured watershed geomorphic characteristics. Upon completion of flatlands UH parameter regression analyses, a technical paper will be submitted to an engineering journal.

FUTURE EFFORTS AND DISCUSSION

After the initial case studies on southeastern flatland and Texas watersheds have been completed, the results will be evaluated by the Work Group. After the Work Group has reached a consensus on the approaches and procedures for developing regional or alternative design hydrographs, the agreed upon analytical methods will be applied to other regional data sets.

Relationships for predicting design UH parameters for applications on ungaged flatland watersheds are being developed for use with either of three alternative rainfall partitioning schemes: (1) standard SCS RCN (single watershed weighted CN), (2) zonal SCS RCN (suited to applications in regions of partial-area hydrologic conditions), and (3) Green and Ampt infiltration procedure. The relationships being developed also include UH parameters for either the current SCS-type design UH, or for the alternative of a gamma-exponential design UH. This approach, while somewhat cumbersome, provides maximum flexibility for future decisions regarding SCS hydrologic design procedures, and will hopefully ensure the utility of the UH Work Group findings.

While the flatland storm UH data shows promise for developing design UH parameter relationships based on watershed characteristics, results of other regional watershed/storm UH parameter analyses must be evaluated independently. Ideally, predictive relationships would be developed for each region or for multiregion zones. However, it is possible that different watershed physical characteristics would be the primary predictors for different physiographic regimes. Identification or definition of various regional divisions is one of the remaining topics for resolution by the Work Group. However, results to date on the flatlands watersheds do raise hopes that predictive relationships based on watershed physical characteristics will minimize the number of regional subdivisions required.

We feel that the ARS-SCS Work Group on Unit Hydrographs has the opportunity to make significant contributions toward meeting the current needs of SCS regarding hydrologic design procedures, but also to make significant contributions in the field of hydrology through improved understanding of factors controlling storm runoff response from small watersheds. Many of the current UH empirical design relations were developed from rather limited watershed data, often with limited statistical testing to identify definitive causal relationships. Several of the design procedures that are now commonly applied to a wide range of topographic conditions were developed from rather unique data sets. For instance, Snyder's (1938) empirical relationships, which form one of the more commonly used and cited synthetic design UH procedures, were developed based on storm data from watersheds in the Appalachian Mountains.

Acknowledgment: The authors wish to acknowledge the efforts and contributions of the following ARS-SCS Interagency Work Group on Unit Hydrographs committee members: Allen Hjelmfelt, Jr. and Jimmy Williams of the USDA-ARS; and Gary Conaway, Sonia Jacobsen, Helen Moody, and Fred Theurer of the USDA-SCS.

Table 1. Selected Regional Watershed UH Parameters

Physio-graphic Region	Watershed	Drainage Area (mi^2)	Number of Selected Storm Events	Mean Peak Factor	% of Flow on Rising Side
Coastal Plain	M	1.0	6	282	25
	N	6.0	9	509	32
	O	6.2	9	404	30
	K	6.5	10	299	27
	J	8.5	7	342	29
	I	19.3	5	379	30
Flatwoods	T	15.7	4	129	16
Blacklands	C	0.9	6	460	30
	D	1.7	8	387	29
	G	6.8	6	331	28
	Y	0.5	6	376	28

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TOPMODEL, A TOPOGRAPHY-BASED WATERSHED MODEL

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ABSTRACT

TOPMODEL is a watershed model that simulates the variable-source-area concept of streamflow generation. The important model parameters are computed from topographic data in a manner that simulates the hydrologic effects of topography on streamflow generation. This paper describes the basic concepts of TOPMODEL, gives the fundamental equations that relate hydrologic variables to topography, and outlines the method used to compute the topographic parameters for the model.

BACKGROUND

TOPMODEL is a physically based watershed model that simulates the variable-source-area concept of streamflow generation. The model has been used in a variety of hydrologic research areas including synthetic flood-frequency derivation (Beven, 1987), model-parameter calibration (Hornberger and others, 1985), spatial-scale effects on hydrologic processes (Wood and others, 1990), topographic effects on water quality (Wolock and others, 1989; 1990), climate-change effects on hydrologic processes (Wolock and Hornberger, 1991), and the geomorphic evolution of basins (Ijjasz-Vasquez and others, 1992). The model has evolved into numerous forms with varying levels of complexity since it first appeared in the literature (Beven and Kirkby, 1979).

The version of TOPMODEL described in this paper is derived from the one used in Hornberger and others (1985). This particular version of TOPMODEL was developed to study questions related to the estimation of model parameters from observable watershed characteristics and the calibration of parameters through optimization techniques (Wolock, 1988).

CONCEPTS OF STREAMFLOW GENERATION

Concepts of streamflow-generation mechanisms describe how streamflow is produced; for example, it is a widely accepted concept that during low-flow periods, streamflow is "generated" by the drainage of water from the saturated subsurface zone into the stream channel (Dunne and Leopold, 1978).

There are a number of concepts describing the generation of streamflow during high-flow periods, that is, during storms. The main concepts discussed in the literature are presented schematically in Figure 1. The first concept, called infiltration-excess overland flow (also called Horton overland flow) states that streamflow during storms is generated by overland flow, which is produced when precipitation rates exceed infiltration rates at the land-atmosphere interface. In the original concept of infiltration-excess overland flow, Horton (1933) assumed that streamflow during storms was produced by overland flow generated over the entire area of a watershed. Later, Betson (1964) proposed that in some watersheds, streamflow during storms was generated from infiltration-excess overland flow produced in only a small part of the watershed area, and this idea became known as the partial-area concept. Infiltration-excess overland flow occurs where infiltration rates are lower

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than precipitation rates; for example, in disturbed or poorly vegetated areas in subhumid and semiarid regions.

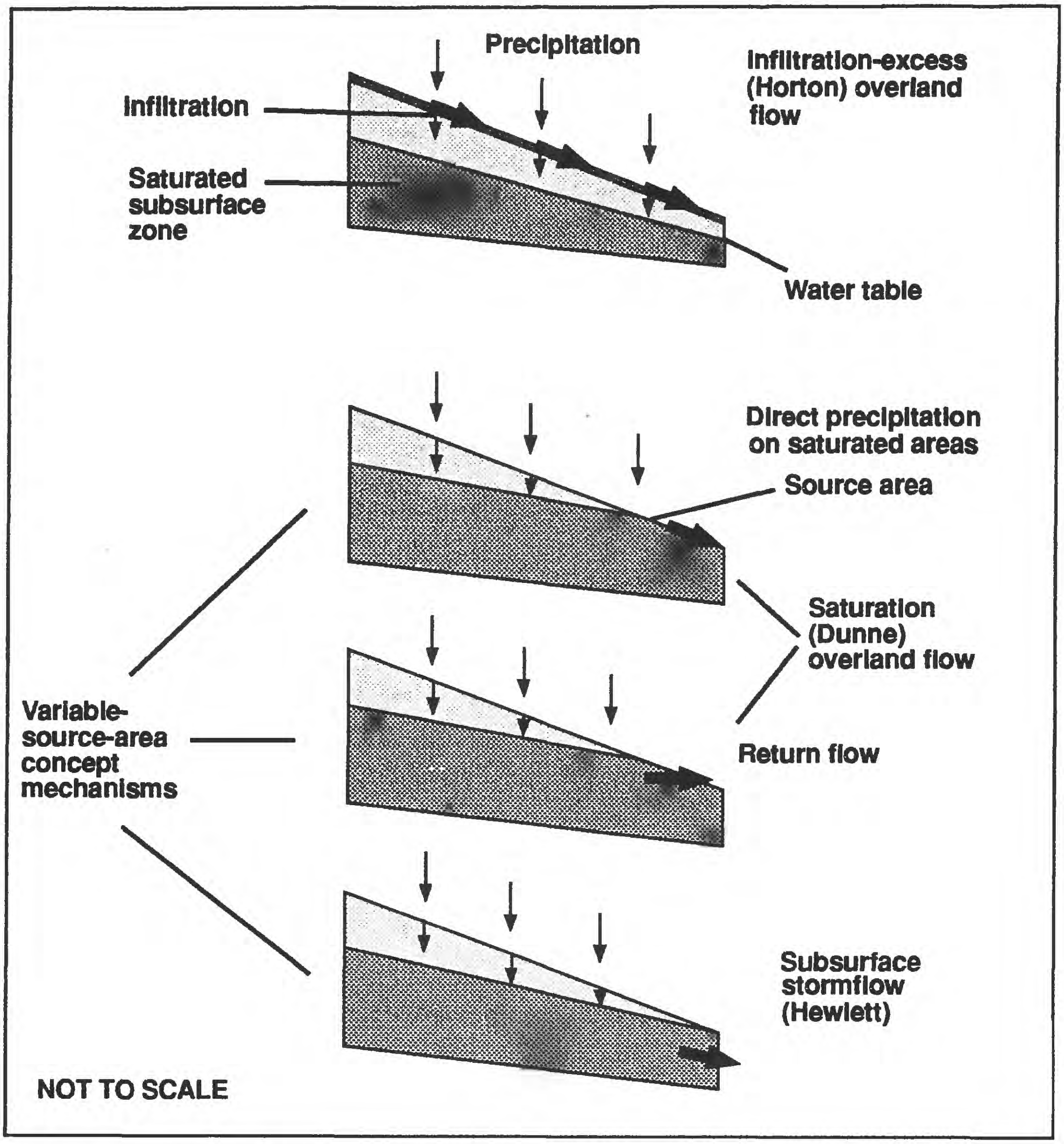

Figure 1. Diagrams of streamflow-generation mechanisms during high-flow periods.

Another concept of streamflow generation during storms is called the variable-source-area concept. The earliest published work that evolved into this concept was by Hursh (1936). In the variable-source-area concept, streamflow during storms is generated on saturated surface areas called "source areas", which occur in places where the water table rises to the land surface (Figure 1). The rise in the water table occurs because of infiltration of precipitation into the soil and down to the saturated subsurface zone, and then subsequent downslope movement of water in the saturated subsurface zone. Saturated land-surface areas usually develop near existing stream channels, and expand as more water enters the subsurface through infiltration and moves downhill as saturated subsurface flow. Variable-source-area concept flow occurs where infiltration rates are higher than precipitation rates; for example, in undisturbed vegetated areas in humid, temperate regions.

In the variable-source-area concept, saturated land-surface areas are sources of streamflow during storms in several ways (Figure 1). Saturation overland flow (also called Dunne overland flow) is generated if the subsurface hydraulic characteristics are not transmissive and if slopes are gentle and convergent. Saturation overland flow can arise from direct precipitation on the saturated land-surface areas or from return flow of subsurface water to the land surface in the saturated areas (Dunne and Black, 1970). Subsurface stormflow (Hewlett and Hibbert, 1967) is generated if the near-surface soil zone is very transmissive (high saturated hydraulic conductivity) and gravitational gradients are high (steep slopes).

The version of TOPMODEL described in this paper simulates the variable-source-area concept of streamflow generation, not the Horton (1933) concept of infiltration-excess overland flow or the partial-area concept of Betson (1964). [Other versions of TOPMODEL, such as the one in Wood and others (1990), simulate all of the concepts.] In the variable-source-area concept, rainfall (or snowmelt) infiltrates into the upper zone of the soil anywhere that the water table has not risen to the land surface (Figure 2). Water stored in the upper soil zone is available for evapotranspiration and evaporates at a rate dependent on the potential rate and the amount of moisture available in the upper soil zone. It is assumed that some rainfall (or snowmelt) can bypass the unsaturated subsurface zone and directly move into the saturated subsurface zone. This bypassing effect is attributed to macropores, which are large pores in the soil that conduct water downward before the soil is completely saturated (Beven and Germann, 1982).

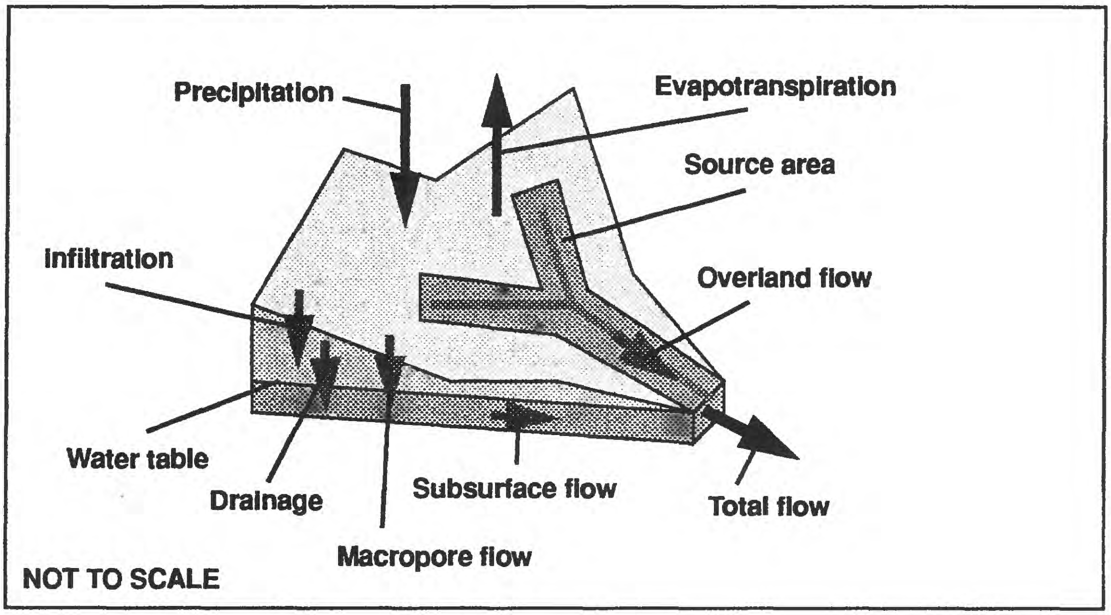

Figure 2. Diagram of water fluxes in TOPMODEL.

The depth to the water table is decreased by water draining down from above or by water draining laterally from other parts of the watershed. If the amount of water added to the saturated subsurface zone in a particular location in the watershed is large enough, the water table rises to the land surface, and the area becomes a saturated source area. If rain (or snowmelt) occurs on a saturated land-surface area, then saturation overland flow is produced by direct precipitation on saturated areas. The saturated land-surface area also can produce return flow if the water table rises above the land surface.

During all streamflow conditions, water stored in the saturated subsurface zone is assumed to move downslope towards the stream channel. Some amount of water, depending on the volume stored and model parameters, drains into the stream. TOPMODEL assumes that the rate of subsurface flow into the stream increases exponentially as the water table moves closer to the land surface. This assumption is based on the ideas that macropores can increase hydraulic transmissivity in the lateral direction and that macropores become increasingly abundant near the soil surface (Beven, 1984; Elsenbeer and others, 1992). Any drainage from the saturated subsurface zone into the stream increases the depth to the water table.

The location of source areas (the saturated land-surface areas) within the watershed are affected primarily by basin topography. Topography affects the location of source areas because it is the three-dimensional configuration of gravitational effects on drainage. This is consistent with observed spatial distributions of soil moisture and potentiometric surfaces (for example, Burt and Butcher, 1985; Dunne and others, 1975). Source areas are found where subsurface water collects; these are locations where large upslope areas drain and where the capacity is limited for farther downslope drainage. As subsurface water moves downhill it collects in topographically flat, convergent areas; the degree of convergence determines how much upslope-area subsurface water drains to a given location and the slope affects the "ability" of water to move farther downhill.

Running TOPMODEL requires the specification of topographic and soils characteristics, watershed latitude, and a time series of precipitation and air temperature. The watershed latitude is used to generate a time series of day lengths that, along with the daily time series of temperature, are used to calculate potential evapotranspiration.

The model predictions include, in addition to streamflow, estimates of overland and subsurface flow and the spatial distribution of the depth to the water table. Overland flow for a given time step is calculated knowing the areal extent of the saturated land-surface areas and the precipitation intensity. Subsurface flow is computed as a function of the maximum subsurface flow rate (determined by topographic and soils characteristics) and the watershed average depth to the water table. The watershed average depth to the water table is computed by water balance; that is, by keeping track of inputs (precipitation) and outputs (overland flow, subsurface flow, and evapotranspiration). By knowing the watershed average depth to water table and the topographic characteristics, the areal extent of the saturated source areas can be calculated.

TOPMODEL EQUATIONS

The mathematical starting points used to derive the fundamental TOPMODEL equations are: (1) the continuity equation, (2) Darcy's Law, and (3) the assumption that saturated hydraulic conductivity decreases exponentially as soil depth increases. [The validity of the third starting point is supported by data in Beven (1984) and Elsenbeer and others (1992).] These starting points lead to equations that show the relations of the model state variables to readily computed topographic characteristics.

One fundamental equation gives the relation of the depth to the water table at any location *x* [$z_{wt}(x)$] to the watershed average value of the depth to the water table ($\bar{z}_{wt}$), a scaling parameter related to soil properties (*f*), the watershed area upslope from location *x* (*a*), the gravitational gradient at location *x* (*tanB*), and the watershed average value of *ln*(*a/tanB*) (λ):

$$z_{wt}(x) = \bar{z}_{wt} + \frac{1}{f}[\lambda - ln(a/tanB)_x]. \qquad (1)$$

Equation (1) is applied to every location *x* in the watershed at every time step to determine the location and extent of saturated land-surface areas, indicated by locations where $z_{wt}(x) \leq 0$. [A value for $z_{wt}(x)$ less than zero implies return flow.] The extent of the saturated area is multiplied by the precipitation intensity (an observed input) to compute the amount of overland flow. Equation (1) indicates that values of *ln*(*a/tanB*) relate directly to the topographic likelihood of development of saturated, overland-flow producing source areas--higher values of *ln*(*a/tanB*) indicate higher potential for development of saturation. High values of *ln*(*a/tanB*) occur at locations where large upslope areas are drained (high value of *a*) and the local gravitational gradient is low (low value of *tanB*).

Another fundamental equation shows the relation of subsurface flow ($q_{subsurface}$) to the watershed average value of the maximum saturated hydraulic transmissivity (T_0), the watershed average value of the depth to the water table ($\bar{z}_{wt}$), and the watershed average value of *ln*(*a/tanB*) (λ):

$$q_{subsurface} = T_0 e^{-\lambda} e^{-\bar{z}_{wt}}. \qquad (2)$$

Equation (2) shows that λ, the mean of the *ln*(*a/tanB*) distribution, is inversely related to the potential rate of subsurface flow; watersheds with high λ values have low potential subsurface-flow rates.

To reduce model computational time, all locations in the watershed with the same *ln*(*a/tanB*) value are assumed to have a hydrologically similar response. This assumption allows the aggregation of the *ln*(*a/tanB*) distribution from a spatially explicit description of the watershed into one of intervals in *ln*(*a/tanB*). The model equations do not change, but the calculations are performed using the *ln*(*a/tanB*) values of frequency-distribution interval midpoints instead of the individual spatially distributed values. By knowing the relative frequency (that is, the proportion of watershed area) corresponding to each interval midpoint, total watershed values for the model state variables can be calculated. TOPMODEL can be run in the true spatial domain (as in Wood and others, 1990) or in the frequency domain (as in Wolock and others, 1990).

COMPUTATION OF THE *ln*(*a/tanB*) SPATIAL DISTRIBUTION

The spatial distribution of *ln*(*a/tanB*) is computed from a uniform grid of elevations using algorithms based on those reported in Jenson and Domingue (1988), using the following steps (see Figure 3).

1. The elevation at each location is compared to the elevations of its

neighboring points, and the steepest downhill direction is assigned to each location in the grid.

2. The number of points upslope from each location (number of uphill points that drain into a given location) is calculated.

3. The magnitude of *tanB* in the steepest downhill direction is calculated.

4. The *ln(a/tanB)* values are calculated as:

$$ln(a/tanB) = ln\left[\frac{(number\ of\ upslope\ points+1)\times grid\ cell\ length}{tanB}\right]. \quad (3)$$

The value of *tanB* is reset to *0.5/(grid cell length)* at locations where the observed value of *tanB* equals 0.

(a) **Elevation (m)**

505	506	505	508	513	515	519	526
510	511	510	511	514	514	518	524
516	516	516	510	519	519	522	525
522	522	521	521	524	523	522	522
520	521	519	524	526	523	523	521
519	519	519	524	528	524	519	516

(b) **Steepest downhill direction**

↑	↑	↖	←	←	↖	←	←
↖	↑	↑	↖	↖	↖	←	←
↑	↑	↑	↖	←	↑	↖	↖
↑	↑	↗	↑	↖	↑	↖	↘
↙	↓	↓	←	↖	↘	↘	↓
←	←	←	←	↙	→	↘	↘

(c) **Number of upslope points**

0	3	20	10	8	2	1	0
2	2	7	0	0	7	2	0
1	1	0	5	0	2	0	0
0	0	0	1	0	0	0	0
0	0	1	0	0	0	0	0
10	9	3	0	0	0	2	2

(d) **tanB in the steepest downhill direction**

.20	.16	.10	.10	.16	.06	.13	.23
.20	.16	.16	.13	.13	.03	.13	.20
.20	16	.20	.00	.30	.16	.20	.16
.20	.20	.26	.36	.33	.13	.06	.03
.10	.06	.00	.16	.13	.10	.16	.16
.10	.00	.00	.16	.13	.16	.16	.13

(e) **ln(a/tanB)**

5.0	6.5	8.7	8.1	7.3	7.2	6.1	4.8
6.1	6.2	7.2	5.4	5.4	8.8	6.5	5.0
5.7	5.8	5.0	9.2	4.6	6.2	5.0	5.1
5.0	5.0	4.7	5.1	4.5	5.4	6.1	6.8
5.7	6.1	8.1	5.1	5.4	5.7	5.1	5.1
8.1	9.7	8.8	5.1	5.4	5.1	6.2	6.5

Figure 3. Plan view of grids of (a) elevation, (b) steepest downhill direction, (c) number of upslope nodes, (d) tanB values, and (e) ln(a/tanB) values. The data shown are a subsection of a larger uniform 10x10 grid.

The relation of *ln(a/tanB)* to saturated source-area development is evident when the spatial distribution is computed for a watershed of sufficient size to contain many grid points. Figure 4, for example, shows a graphical representation of the elevation and $ln(a/tanB)$ distribution for the Sleepers River watershed in Vermont. The watershed area is about 109 km^2, and the grid points are 30 m apart. The dark areas on the $ln(a/tanB)$ part of Figure 4 have the highest values and represent areas that are the most likely to become saturated.

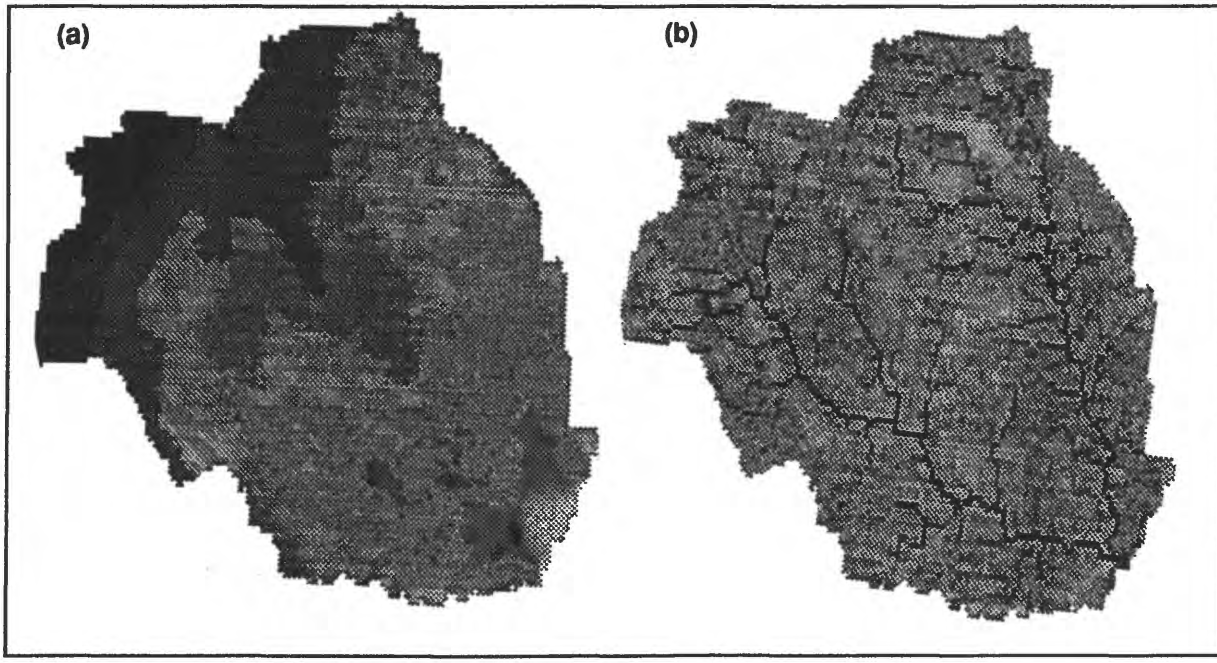

Figure 4. Maps of (a) elevation, and (b) ln(a/tanB) values for Sleepers River watershed in Vermont. Higher values are indicated by darker shades of gray.

SUMMARY

TOPMODEL is a watershed model that simulates the variable-source-area concept of streamflow generation. The model uses topographic information derived from elevation grids to compute parameters that relate hydrologic processes to important topographic characteristics.

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