SIMULATION OF RAINFALL-RUNOFF FOR BASINS IN THE ROLLA, MISSOURI, AREA

By ROBERT R. HOLMES, JR. *and* JEFFERY W. EAST

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CONTENTS

ILLUSTRATIONS

Page

TABLES

CONVERSION FACTORS AND VERTICAL DATUM

Multiply inch-pound unit	By	To obtain metric unit
inch (in.)	25.40	millimeter
foot (ft)	0.3048	meter
mile (mi)	1.609	kilometer
foot per foot (ft/ft)	1.00	meter per meter
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
acre	4,047	square meter
	0.4047	hectare
square mile (mi^2)	2.590	square kilometer
	259.0	hectare
acre-foot (acre-ft)	1,233	cubic meter

To convert degrees Fahrenheit (°F) to degrees Celsius (°C), use the following equation:

$$°C = 5/9 \times (°F - 32)$$

Sea level: In this report "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)--a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

GLOSSARY

Conceptual model (physically based model)--A model that has the form of the constitutive mathematical equations indicated by the physical, chemical, and biologic characteristics of the hydrologic system.

Continuous simulation--Model simulation over long periods, daily or hourly, taking into account soil moisture accumulation and depletion.

Depression storage--Precipitation that becomes trapped in small indentations on the land surface of the **drainage basin.**

Deterministic model--A model in which the parameters are free of probability distribution.

Discretization--A procedure by which mathematical abstraction of the physical **drainage system** is conducted for input into a **model.**

Distributed model--A model where the parameters and stimuli (rainfall and snow cover, for example) are apportioned throughout the drainage basin according to the discretion of the modeler.

Drainage basin--A part of the surface of the earth that is occupied by a **drainage system,** which consists of a surface stream or a body of impounded surface water together with all tributary surface streams and bodies of impounded surface water.

Drainage elements--The part of a **drainage basin** that takes the water routed from the **subcatchments** and hydraulically routes it through to the outlet. Elements include channels, manholes, detention ponds, storm sewers, pipes, or anything that affects the conveyance or conveys water once it is in the **drainage system.**

Drainage system (network)--The series of **drainage elements** in a basin that convey water once it has been routed off of the **subcatchments.**

Event simulation--Simulation over a single rainfall-runoff period, where no attempt at soil moisture accounting before the period is done by the **model.**

Floodplain--The lowland that borders a river, usually dry but subject to flooding.

Frequency--The relation between return period or recurrence interval, in years, and magnitude of a hydrologic event, such as a rainfall quantity or flood peak.

Hydrograph--A graph showing flow with respect to time.

Impervious area--Effective part (that which is hydraulically connected to the **drainage system**) of the contributing drainage area that will not allow water to pass through the soil/rock strata (usually because it is overlain with concrete, asphalt, or other material).

Initial moisture deficit--The difference between the antecedent water content of the soil and the soil porosity.

Interflow--Water that enters the stream by the process of infiltration and conveyance through the top part of the soil layer (top 2 to 5 feet).

Model--A simplified representation of a complex system.

Objective function--A calculated value based on the sum of the square of the differences of the log of the observed values and the log of the simulated values divided by the log of the observed values.

GLOSSARY--Continued

Parameter--A characteristic quantity of a system that does not vary with time but which may or may not be physically measurable.

Prototype--The actual physical system; what a **model** is trying to represent.

Subcatchment (subbasin)--The smallest defined areal unit in a simulation **model** where the runoff is generated as overland flow.

Time to peak--The time between the beginning of rainfall input and the peak of the ensuing runoff **hydrograph.**

Variable--A measurable quantity of a system that assumes different numerical values in time.

SIMULATION OF RAINFALL-RUNOFF FOR BASINS IN THE ROLLA, MISSOURI, AREA

By Robert R. Holmes, Jr. *and* Jeffery W. East

Abstract

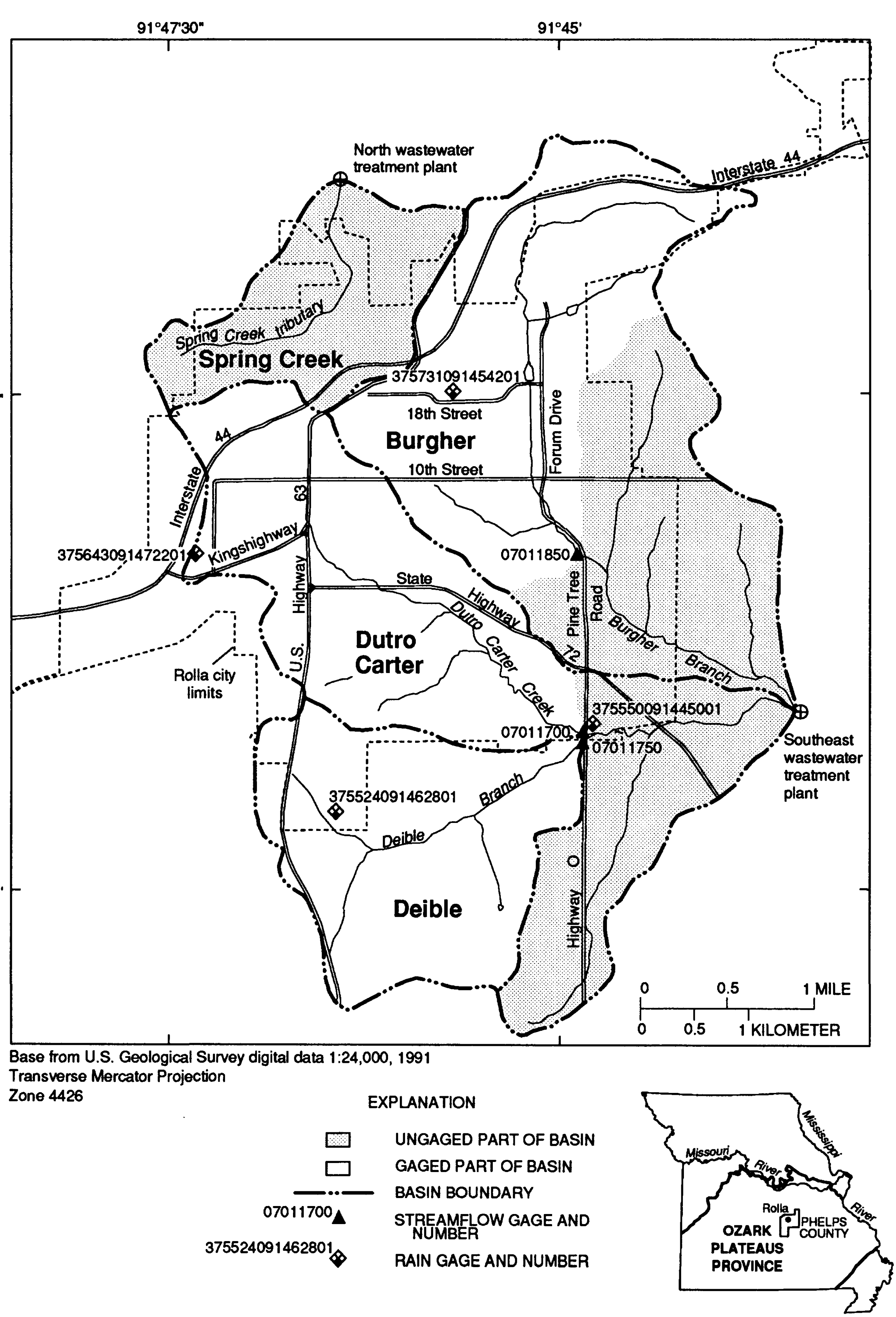
Important rainfall-runoff characteristics for basins in the Rolla, Missouri, study area were determined to be overland flow, interception storage, interception losses, evaporation, and infiltration. Using these important rainfall-runoff characteristics, the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) was configured and calibrated for basins in the study area. The data network for the study area consisted of four continuous rainfall gages and three continuous streamflow gages. These data were collected for purposes of calibrating the SWMM.

Calibration of the model, using observed data from three runoff events (ranging in frequency from less than the 2-year to the 10-year recurrence intervals), was performed by minimizing objective functions representing peak discharge, volume of runoff, and time to peak discharge from the beginning of simulation. The absolute mean percent difference between the simulated and observed data for peak discharge, volume of runoff, and time to peak discharge are 9.47, 10.8, and 19.6 percent. The ranges in percent difference for discharge are -26.2 to 20.4; for volume of runoff, -21.8 to 16.4; and for time to peak, -36.4 to 41.7. The percent differences between the observed and simulated data are thought to occur because of either inadequate representation of the rainfall spatial and temporal distribution in the model input data set, inability to represent the spatial and dynamic features of the basin, observed streamflow data errors, or some combination of these factors. In addition, potential errors in the delineation of the drainage system (stormsewer conduits, length, and geometry) exist because of limited information available. Additional data collection for calibration and validation efforts and more detailed discretization of the drainage basins would improve the accuracy of the model simulation.

Before the model was calibrated to the basins in the study area, a sensitivity analysis of SWMM parameters was performed on a simplified drainage basin. The output of runoff (peak volume and timing) in SWMM was determined to be most sensitive to subcatchment width, percentage of impervious area, saturated hydraulic conductivity, and initial moisture deficit. The volume of runoff was affected by percentage of impervious area, saturated hydraulic conductivity, and initial moisture deficit. The peak flow rate was affected by subcatchment width and percentage of impervious area, while the time to peak was affected by subcatchment width. The model also was determined to be sensitive to the magnitude of the time step in the streamflow routing segment of the SWMM.

INTRODUCTION

The city of Rolla (fig. 1) is a growing municipality in south-central Missouri. The increase in impervious area associated with urban development has resulted in an increase in stormwater runoff, which in some areas has, at times, overloaded the storm drainage system. The increased runoff, together with floodplain encroachments, exacerbates the frequency and magnitude of floods in low lying areas.



Base from U.S. Geological Survey digital data 1:24,000, 1991
Transverse Mercator Projection
Zone 4426

Figure 1. Location of study area, gages, and area of each basin that was gaged.

The city's approach to this stormwater management problem is to consider all the drainage basins within the city as a whole, rather than in parts, to allow the relative effects of a particular stormwater control structure on the complete system to be analyzed. Stormwater drainage system design is aided by the use of rainfall-runoff hydrologic simulation models. Because a simulation model mathematically represents a hydrologic system, the model can be used to predict runoff from the quantity of rainfall distributed over time and space. The U.S. Geological Survey and the city of Rolla, Public Works Department, initiated a cooperative study to construct a simulation model for the Rolla area. This simulation model was calibrated on basins in the Rolla area using rainfall-runoff data collected from October 1, 1990, to September 30, 1992. Storm events used for modeling in this period were short duration thunderstorms with high-intensity rainfall.

Purpose and Scope

This report describes the process used to determine the important rainfall-runoff characteristics and presents the results from configuration and calibration of the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM) for rainfall-runoff simulation in the Rolla area. This simulation model was configured to simulate single storm events around the 2-year or greater return frequency in small (less than 4 mi^2) urban drainage basins. Rainfall-runoff data were collected during three separate storms from October 1, 1990, to September 30, 1992, and used to calibrate the model to the basins in the Rolla area. These storms were brief (less than 3 hours), high-intensity rainfall thunderstorms with the resulting runoff having recurrence intervals ranging from less than 2 to 10 years.

Description of Study Area

Geographically, the study area is in central and western Phelps County in south-central Missouri (fig. 1). Physiographically, it is in the northeastern part of the Ozark Plateaus Province and lies on the surface-water drainage divide between the Missouri and the Mississippi Rivers (Lee, 1913). The Ozark Plateaus Province is characterized by steep slopes, sharp relief, and rocky, clayey soil. Elevation in the study area ranges from 900 to 1,150 ft above sea level. The predominant rock types in the Ozark Plateaus Province are limestone and dolomite (Fenneman, 1938). Land surfaces in the study area range from impervious surfaces of asphalt to undisturbed natural ground cover of forest and grassland with rock-clay-silt soil.

The climate of the study area includes occasional freezing weather during the winter months (December to February) and high humidity during summer months (June to September). Temperatures range from below freezing during the winter months to more than 90 °F during the summer. Average annual rainfall for the Rolla area from 1900 to 1988 was 40.98 in. (Pugh, 1992). High-frequency rainfall events are mainly generated by intense, convective thunderstorms during the summer and slower frontal thunderstorm systems during the winter.

The city of Rolla drainage area is about 12.75 mi^2. The surface-water drainage divide between the Missouri and the Mississippi Rivers is located through the northern edge of the city. Therefore, the Rolla area is characterized by small drainage basins, typically less than 3 mi^2, which are susceptible to flash flooding.

Rainfall-runoff in the vicinity of Rolla (fig. 1) drains predominately to the southeast through two streams, Dutro Carter Creek and Burgher Branch, which flow toward the Mississippi River. A third stream, Deible Branch, crosses the southern section of the drainage basin to the east where it joins Dutro Carter Creek. Dutro Carter Creek and Burgher Branch flow south until they combine at the Southeast wastewater treatment plant. All three creeks flow intermittently. The junction of Dutro Carter Creek and Burgher Branch is the downstream terminus for the study area on the east side. The extreme northwestern edge of the city (fig. 1) is drained by the intermittent Spring Creek tributary, which flows north. The North Rolla wastewater treatment plant is the downstream terminus for the study area on the northwest side.

Acknowledgments

Personnel from the city of Rolla, Public Works Department, assisted in installing data collection instrumentation, locating drainage conduits in the study area, and providing 2-ft elevation contour mapping. Special thanks to Jonathan Delano, Chester Patton, Marylee Sands, Rolla Public Schools, city of Rolla Fire Department, Rolla Municipal Utilities, and Missouri Department of Natural Resources, Division of Geology and Land Survey, for allowing installation of data collection equipment on their property.

METHODS OF STUDY

Simulation models range from simple empirical models in which all the hydrologic processes are lumped together to complex, distributed conceptual models that attempt to account for all the hydrologic processes occurring in the drainage basin. However, all simulation models, regardless of their complexity, are only approximations of actual hydraulic and hydrologic processes. Different models are applicable to different situations. Before any model is chosen for use, a complete understanding of the questions to be answered by the model and specifics concerning the drainage basin of interest are necessary. For example, magnitude of rainfall events, time scale, land use, hydraulic drainage system, and homogeneity of the drainage basin to be modeled are important considerations in choosing a model.

The usual approach to understanding rainfall-runoff processes for inclusion in simulation models has been to incorporate available knowledge about the processes into a conceptual model of the system, and then to compare model-simulated results with observed runoff data (Dinicola, 1990). This approach involves adjusting model parameters to minimize differences between the simulated and observed results. Because runoff is a basin-integrated response, an adequate understanding of all processes involved in generating the runoff is not possible (Dinicola, 1990). Therefore, parameters are adjusted on the basis of the relative sensitivity of the model output, making sure a particular parameter is within a reasonable range consistent with observed values.

The method used for this study consisted of collecting data for calibration and characterization of rainfall-runoff processes in the study area. A sensitivity analysis was performed to determine which parameters caused the model output to be most sensitive. Finally, simulation model parameter values were estimated and adjusted by calibrating the simulation model.

Data Collection

For model calibration purposes, a network of rainfall and streamflow gages was set up in the study area (table 1). Data from these gages were collected every 5 minutes. The rainfall gages had floats and recorders sensing total accumulation of rainfall with time. The four continuous recording rainfall gages were geographically distributed throughout the drainage basins (fig. 1). Criteria for selecting sites for rainfall gages included geographic distribution of gages, overhead clearance for rainfall collection, and site security to protect against vandalism.

Streamflow gages were stilling well float-type installations. The three continuous recording streamflow gages were located on the major streams draining the city, Dutro Carter Creek, Deible Branch, and Burgher Branch. Criteria for selecting the streamflow gage locations were based on hydraulic flow-rating characteristics and accessibility during high water. Elevation of the water surface (stage) was determined every 5 minutes to the nearest 0.01 ft and logged by an automated digital recorder in accordance with Buchanan and Somers (1968). A rating relation to convert stage to discharge was constructed for each gage by making discharge measurements at various stages according to Buchanan and Somers (1969). For extreme stages, the relation of stage to

Table 1--Data collection stations for the city of Rolla

[USGS, U.S. Geological Survey; --, no data]

USGS station number (fig. 1)	Station name and location	Drainage area, in square miles
	Rainfall gages	
375524091462801	Rolla Fire Training Center	--
375550091445001	Rolla Municipal Utilities Shop	--
375643091472201	Missouri Department of Natural Resources	--
375731091454201	USGS Warehouse	--
	Streamflow gages	
07011700	Dutro Carter Creek at Highway O	2.62
07011750	Deible Branch at Highway O	2.25
07011850	Burgher Branch at Pine Tree Road	2.94

discharge was determined by indirect methods as outlined in Bodhaine (1968). The location of the streamflow gages in relation to the drainage basins, indicating that some or part of the drainage basins of interest was ungaged, is shown in figure 1. The model streamflow output was calibrated using data collected at these locations.

Description of Simulation Model

The computer simulation model used was the SWMM (Huber and Dickinson, 1988). The SWMM was chosen because it is a conceptual, deterministic, rainfall-runoff model developed for the analysis of stormwater runoff in urban rainfall-runoff systems. The SWMM can be used in either continuous or event simulation mode.

The SWMM can account for rainfall, snowmelt, evaporation, depression storage, infiltration, interflow, percolation, evapotranspiration, and ground-water flow. However, as will be discussed later, all processes were not incorporated into the model configured for the study area.

The SWMM accounts for spatial variations by allowing the drainage basin to be discretized into idealized rectangular subcatchments joined into a link-node scheme with the drainage system. The SWMM generates runoff hydrographs for each of these subcatchments and systematically routes them through the drainage system. Runoff is generated by accounting for rainfall, evaporation, depression storage, and infiltration [using the Green-Ampt equation (Green and Ampt, 1911)]. Runoff is routed to the drainage system node by using a non-linear reservoir technique based on the kinematic wave approximation to the St. Venant equations (Huber and Dickinson, 1988). Once the runoff reaches the drainage system, the option exists to route the water through the drainage system by either kinematic wave, if backwater effects are negligible, or dynamic wave channel routing methods (Huber and Dickinson, 1988).

Mathematical equations and descriptive parameters are used in SWMM to conceptualize the rainfall-runoff processes. The names of the process-related parameters used in SWMM for this study and what they represent follows:

- HYDCON - Saturated hydraulic conductivity of soil (in. per hour) for use in the Green-Ampt infiltration equation;
- IDS - Impervious area depression storage (in.);
- IMD - Initial moisture deficit in the soil [volume air/volume voids (fraction)], which is used to define the antecedent moisture conditions in the event mode for use in the Green-Ampt infiltration equation;
- IMP - Percent impervious area of subcatchment;
- IMPN - Impervious area Manning's roughness;
- PDS - Pervious area depression storage (in.);
- PERVN - Pervious area Manning's roughness;
- ROUGH - Manning's roughness of conduits in the drainage system;
- SLP - Ground slope of subcatchment (ft/ft);
- SUCT - Average capillary suction (in.) of water for use in the Green-Ampt infiltration equation;
- VAP(i) - Evaporation (in. per day) for month i;
- W - Width (ft) of overland flow subcatchment (subarea) that, when specified, determines the length of overland flow (L_0); and
- WAREA - Area of subcatchment (acre).

Sensitivity Analysis using Model Parameters

To determine which parameters most affect the calibration of a rainfall-runoff simulation model in a particular study area, a sensitivity analysis is performed by varying one parameter at a time between the range of reasonable values and analyzing the effect of the parameter variation on the model output (discharge). If model output varies substantially from an observed or given value with variation of a certain parameter, then that parameter is deemed a sensitive or an important parameter.

The SWMM uses multiple subcatchments to account for spatial variation; therefore, each subcatchment is characterized with the parameters listed in the previous section. Because the gaged drainage basins have multiple subcatchments, proper sensitivity analysis on a gaged drainage basin was thought to be pointless because the same parameter in each subcatchment would have to be varied; therefore, the spatial effects would be difficult to separate from parametric effects. For this study, a simplified small homogeneous rectangular basin with only one subcatchment draining into one hydraulic transmission conduit was used to determine the sensitive parameters in SWMM and the effects of varying the time steps in the computational part of the model. The parameter values that were used in the sensitivity analysis using this simplified drainage basin were similar to those for the study area. The peak flow, volume, and time to peak were used as benchmarks for sensitivity.

From this sensitivity analysis the following was ascertained:

1. The model output was most sensitive to IMP, W, and two of the three variables that control infiltration, HYDCON and IMD. The runoff volume of the hydrograph was affected by HYDCON, IMD, and IMP. The peak flow rate of the hydrograph was affected by IMP and W, whereas the time to peak was affected by W.

2. IMPN, PERVN, and ROUGH were determined to cause slight sensitivity in model output and used to "fine-tune" the SWMM.

3. For the time step to route water off the subcatchment, the model output was determined to be insensitive to any differences in the time step as long as the time step was less than the time interval of rainfall observation (for example, 5 minutes).

4. For the time step to route flow down the drainage channel, the model output was determined to be sensitive to small differences in the time step. Therefore, the smallest capable time step (1 minute) was used.

Ellis and Alley (1979) document similar sensitivity results using SWMM in the Denver, Colorado, area.

Those parameters deemed "insensitive" in the model generally are assigned reasonable values and fixed for the duration of the modeling procedure. This approach has been done in other studies (Becker, 1986; Thompson, 1989).

Construction of Simulation Model

Once the areal rainfall-runoff characteristics, modeling objectives, model to be used, and the model sensitive parameters have been identified, construction of the model can begin. All rainfall-runoff models have basic components for mathematically transforming rainfall into runoff, but each model must be constructed or configured for the area of interest. The drainage basin and drainage system must be discretized for use in the model, which requires division of the drainage basin into land segments, each with relatively uniform physical and hydrologic characteristics (Leavesley and others, 1983). Once the physical drainage system has been discretized into subcatchments and drainage elements (storm inlets, detention ponds, pipes, and channels), the parameters of the conceptualized rainfall-runoff processes are determined for each subcatchment and drainage element.

Discretization of Drainage Basins and Element Grid

Discretization begins by determining the degree of drainage basin and element grid refinement (fig. 2) needed to sufficiently fulfill the modeling objective. If the model is for design purposes, as is the case in this study, Huber and Dickinson (1988) recommend a fine discretization, whereas for planning purposes, a coarse discretization is sufficient. However, it is desirable to represent the total catchment by as few subcatchments as possible (Huber and Dickinson, 1988), which usually is dictated by the type of hydraulic detail needed (backwater, pipe surcharging, routing, or storage effects). For each location in the drainage basin where a discharge hydrograph is needed for design, at least one subcatchment is needed upstream from the location. Subcatchment discretization is the only way to temporally and spatially represent rainfall variations, necessary for this study because of the short, convective thunderstorms that are highly variable in temporal and spatial aspects.

The SWMM represents each subcatchment as a rectangular basin with user specified geometric and hydrologic parameters. Each subcatchment empties into only one drainage element inlet, but each inlet can accept multiple subcatchment inflows. A more detailed explanation of how SWMM represents drainage basins is given in Huber and Dickinson (1988).

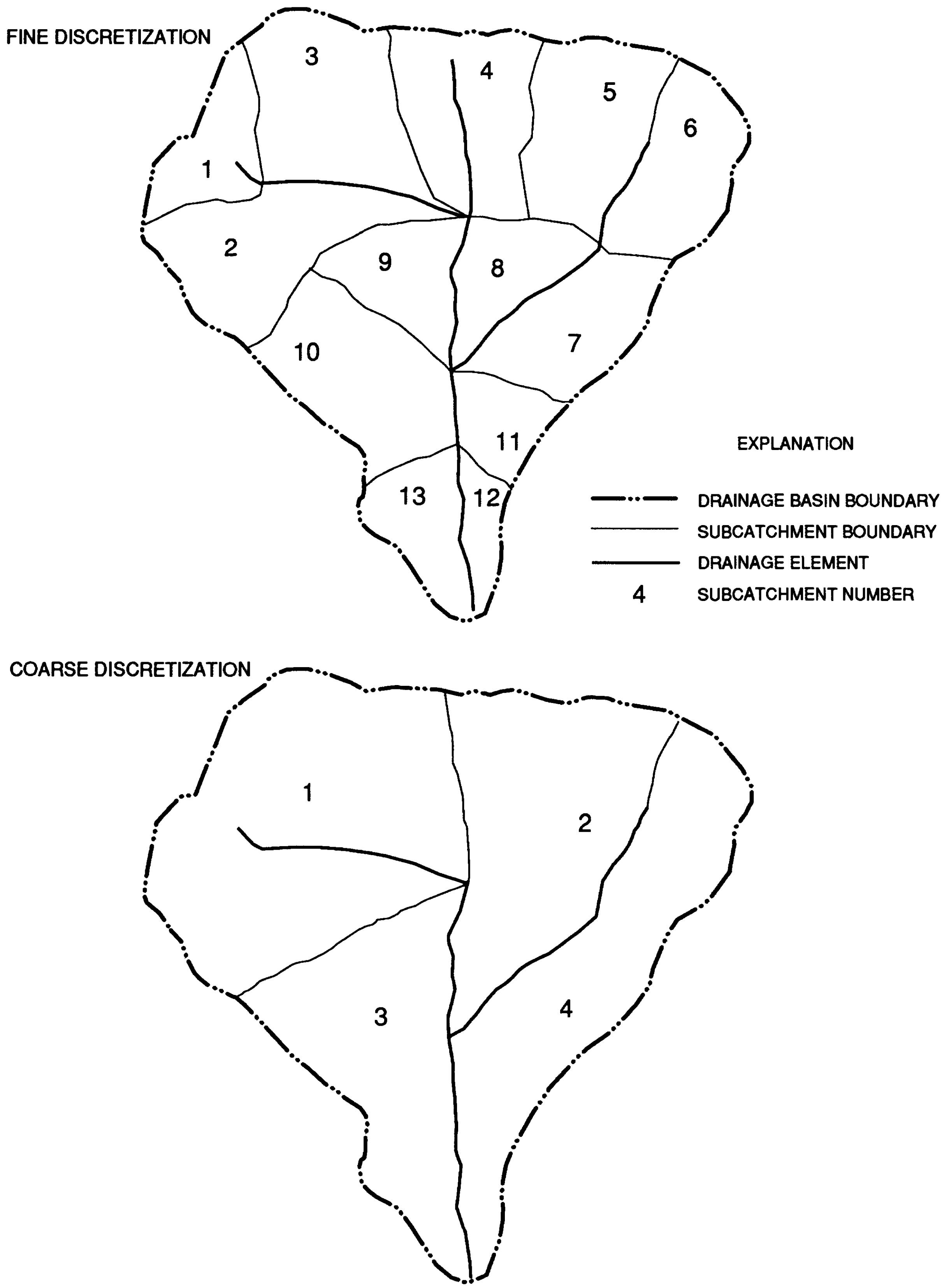


Figure 2. Example of drainage basin with fine and coarse discretization.

Parameter Estimation for Simulation Model

Parameters for each subcatchment and drainage element are specified to compute runoff from rainfall. Actual measurement of some SWMM parameters, such as IDS, IMD, IMP, PDS, PERVN, and SUCT, is difficult, if not impossible. Therefore, a reasonable estimate of these parameters is used based on both published literature and experience of the modeler, with some parameters (those determined to be "sensitive") adjusted later during calibration. Troutman (1985) states that parameters should be physically realistic and their values be selected so as to make the simulated peaks and volumes agree well with observed peaks and volumes (calibration process). Other parameters may be obtained from onsite visits, areal maps, or publications by local, State, or Federal agencies.

Calibration of Simulation Model

Once the model has been configured for the study area drainage basins and initial estimates for the model parameters have been completed, the process of calibrating the model begins. The immediate goal of calibration is to minimize the differences between the simulated runoff and the observed runoff (Thompson, 1989). This is done by selecting an objective function and minimizing (or maximizing, depending on the function) that function to arrive at the best simulation of the prototype. The prototype storms to be used as calibration data sets should be large enough so that the model calibration is not biased toward smaller runoff events that would result in underestimation of the larger rainfall-runoff events (2-year or greater return period) used in design. Generally, the period of record in most rainfall-runoff studies is relatively short; thus the chances of getting a large number of 2-year or greater frequency runoff events are small. Therefore, it usually becomes necessary for the modeler to use judgement in selecting enough runoff events to calibrate the model without biasing the results.

Because the SWMM currently (1992) does not have an optimization routine that automatically adjusts the parameters to minimize an objective function, a manual calibration procedure was followed patterned after the iterative procedure used by Baffaut and others (1987). Runoff was simulated for all storms with rainfall quantities large enough to adequately calibrate the model, and the output was compared to measured data for each of the three streamflow gages at the lower end of the gaged drainage basins (fig. 1). Three objective functions then were computed for all the storms. The objective functions are a measure of the level of agreement between the simulated results and the observed values. These objective functions are for the peak (OBJPEAK), total storm volume (OBJVOL), and the hydrograph time to peak from the beginning of simulation (OBJTP). The functions are calculated as follows:

$$\mathrm{OBJPEAK} = \left[\sum_{i=1}^{N}\sum_{j=1}^{3}\left(\left(\left(Pm_{ij} - Po_{ij}\right)/Po_{ij}\right)\times 100\right)\right]/(N\times 3) \quad (1)$$

$$\mathrm{OBJVOL} = \left[\sum_{i=1}^{N}\sum_{j=1}^{3}\left(\left(\left(Vm_{ij} - Vo_{ij}\right)/Vo_{ij}\right)\times 100\right)\right]/(N\times 3) \quad (2)$$

$$\mathrm{OBJTP} = \left[\sum_{i=1}^{N}\sum_{j=1}^{3}\left(\left(\left(Tm_{ij} - To_{ij}\right)/To_{ij}\right)\times 100\right)\right]/(N\times 3) \quad (3)$$

where N is the number of storms;
- i is the storm number;
- j is the gage;
- Pm_{ij} is the simulated peak flow rate (ft^3/s) for storm i at gage j;
- Po_{ij} is the observed peak flow rate (ft^3/s) for storm i at gage j;
- Vm_{ij} is the simulated volume of runoff (acre-ft) for storm i at gage j;
- Vo_{ij} is the observed volume of runoff (acre-ft) for storm i at gage j;
- Tm_{ij} is the simulated time to peak (hours) from the beginning of simulation for storm i at gage j; and
- To_{ij} is the observed time to peak (hours) from the beginning of simulation for storm i at gage j.

Calibration was conducted on the basis of matching peak flow, volume, and time to peak. However, because the predominant use of the model will be urban drainage design, Ibrahim and Liong (1992) recommend that "In urban drainage designs the most important criterion for runoff simulation is to achieve the least-prediction error in the peak flow." Therefore, all objective functions were used, but OBJPEAK was given more importance. Sensitive parameters were adjusted one at a time to improve the level of agreement between the model and the prototype. Each sensitive parameter was adjusted the same magnitude for each subcatchment. The objective functions again were computed to determine if they had decreased. The process of adjustment was continued until the objective functions were minimized and no parameters were adjusted to unreasonable values (Troutman, 1985).

After model calibration is complete, verification normally is conducted to determine if the model is valid for data sets other than the ones used for calibration. However, because the data collection program was short (2 years), the quantity of large magnitude storms available for this study was minimal; therefore, all runoff events approaching the 2-year flood frequency as determined from Becker (1986) were used.

SIMULATION OF RAINFALL-RUNOFF

After sufficient prototype data had been collected, rainfall-runoff for the gaged drainage basins in the Rolla area was simulated. Important rainfall-runoff characteristics were identified, and the simulation model was configured to match the Rolla prototype as closely as possible. The simulation model then was calibrated to the gaged basins, and the parameters used in the calibration process for the gaged basins were extrapolated to the ungaged basins.

Characterization Of Important Rainfall-Runoff Characteristics For Study Basins

Dingman (1984) identifies the components and processes of the land phase of the hydrologic cycle to be rainfall, snowmelt, interception storage, interception loss, evaporation, infiltration, interflow (percolation), evapotranspiration, overland flow, ground-water flow, and runoff. Snowmelt, percolation, evapotranspiration, and ground-water flow were not considered in configuring the SWMM for this study because they do not affect stormwater runoff for basins in the study area.

For this study, overland flow was observed to be the main mode of translating the water from the drainage basin to the stream. Overland flow is affected by interception storage, interception losses, evaporation, and infiltration. These processes were incorporated into the configuration of SWMM.

In the Green-Ampt infiltration accounting procedure in SWMM, IMD is considered to vary with antecedent moisture, SUCT varies with antecedent moisture and soil type, and HYDCON is independent of antecedent moisture and dependent on soil type. For purposes of this study, IMD and SUCT were variable in the simulation, depending on the classification of the basin as dry, normal, or wet. Criteria for these three classifications are discussed later.

Construction Of Simulation Model

The three gaged drainage basins were divided into subcatchments so the proper hydraulic detail needed for a system wide drainage design could be determined (fig. 3). The hydraulic detail needed was determined with the assistance of the city of Rolla, Public Works Department. Each subcatchment was simplified and represented in the model as a rectangular basin. Each subcatchment drained into a drainage element inlet. Each drainage element inlet emptied directly into the drainage element. Hydrologic similarity between the prototype system of subcatchments and hydraulic elements and the model system of rectangular subcatchments and hydraulic elements was maintained. For each subcatchment and hydraulic element, parameters were estimated based on physical measurements of the prototype, published values, and experience of the modeler.

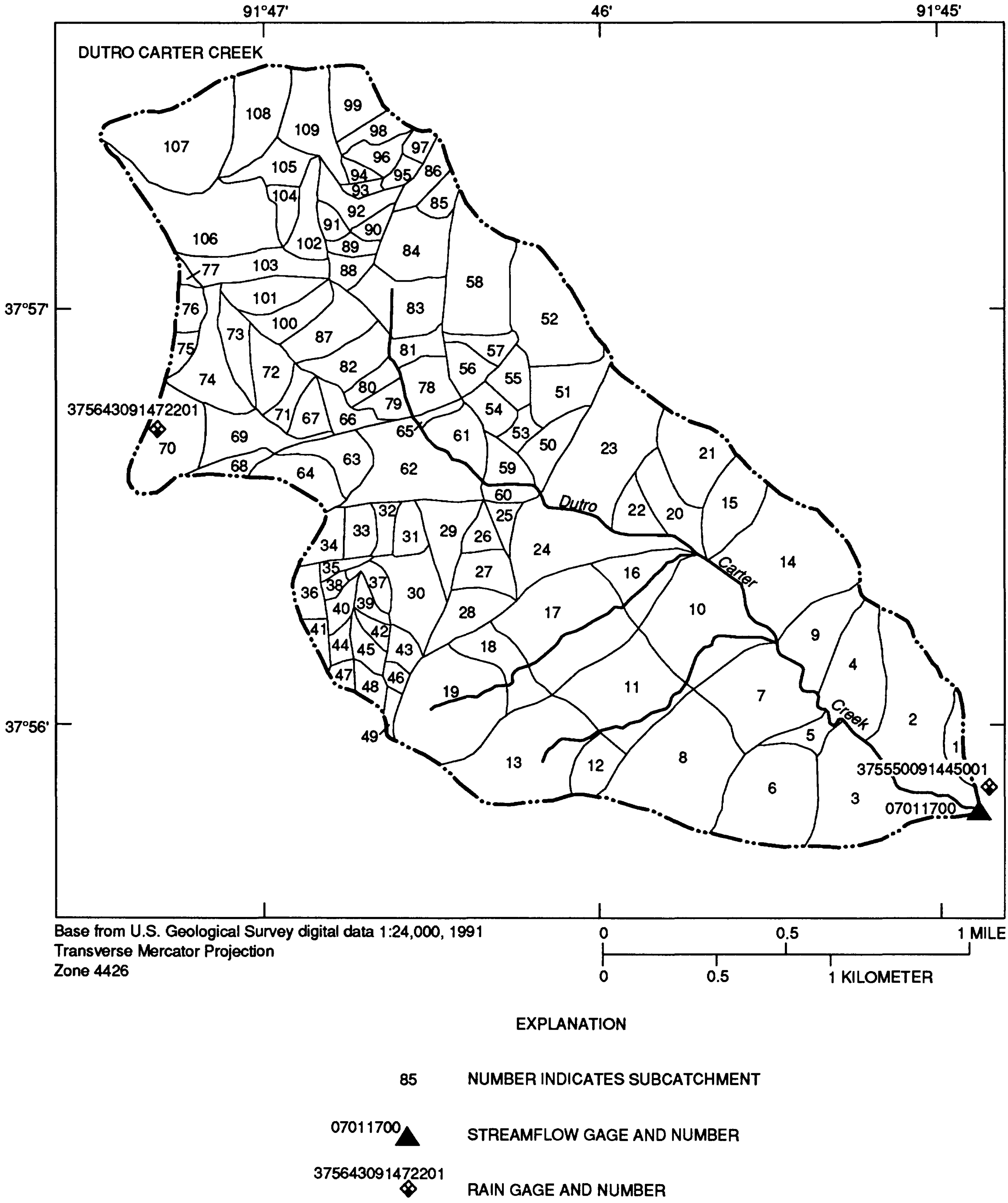
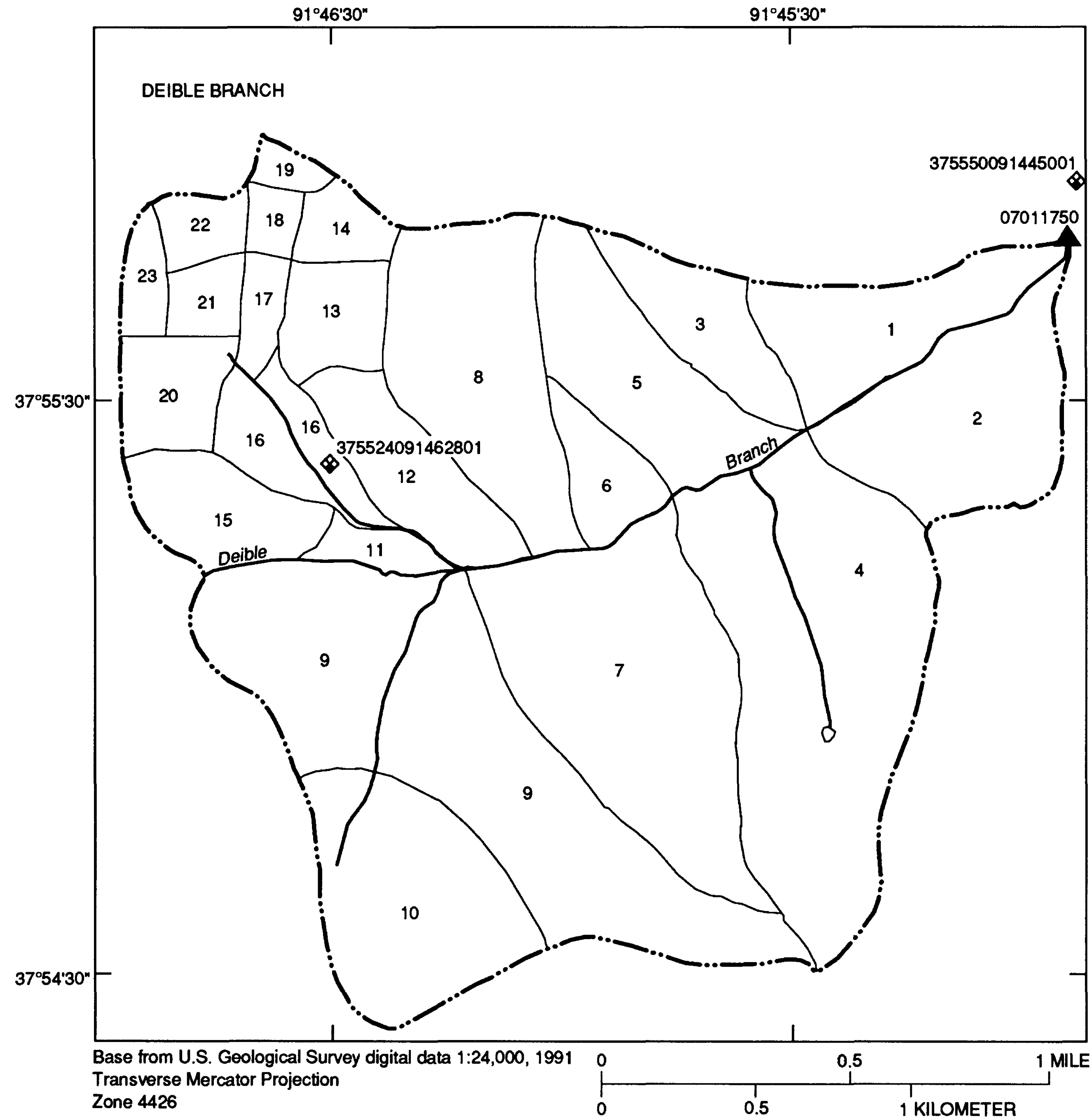


Figure 3. Discretization of the Dutro Carter Creek, Deible Branch, and Burgher Branch drainage basins.



EXPLANATION

8 NUMBER INDICATES SUBCATCHMENT

07011750 STREAMFLOW GAGE AND NUMBER

375550091445001 RAIN GAGE AND NUMBER

Figure 3. Discretization of the Dutro Carter Creek, Deible Branch, and Burgher Branch drainage basins--Continued.

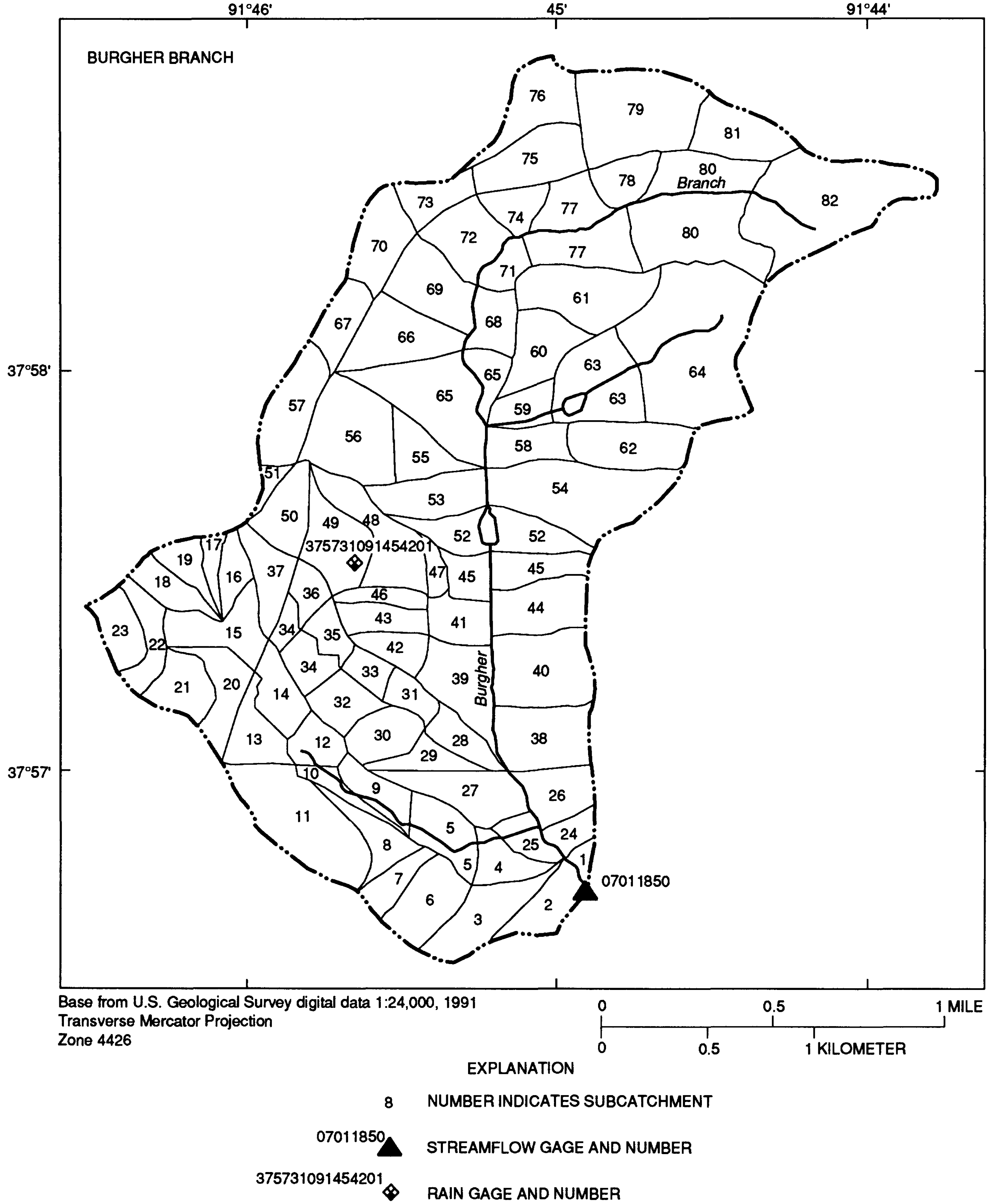


Figure 3. Discretization of the Dutro Carter Creek, Deible Branch, and Burgher Branch drainage basins--Continued.

The parameters that determine the volume and rate of runoff resulting from precipitation in the basin are divided into two categories--geometric and process-related parameters. The geometric parameters are SLP, W, and WAREA. For each subcatchment, both SLP and WAREA were determined from topographic maps of the study area. The SLP ranged from 0.03 to 0.10 ft/ft and WAREA ranged from 1 to 50 acres. Because W represents width of overland flow in an idealized rectangular representation of the actual subcatchment, W is not physically measurable. An initial estimate of W for each subcatchment was made based on methods contained in Huber and Dickinson (1988) and was later adjusted, within appropriate limits, during subsequent model calibration. The subcatchment W estimates ranged from 100 to 3,000 ft.

The process-related parameters are IMD, IMPN, PERVN, IDS, PDS, VAP(i), and the parameters specific to the Green-Ampt infiltration equation (HYDCON, IMD, and SUCT). Many of the process-related parameters are not physically measurable and were estimated from published literature (Southard, 1986; Chow and others, 1988; Huber and Dickinson, 1988; National Oceanic and Atmospheric Administration, 1991) and modeler experience.

As urbanization increases, the IMP increases because parking lots, houses, streets, and other structures replace pervious areas. Southard (1986) presents a method to determine impervious area from the percentage of developed area (PDA) on 7.5-minute U.S. Geological Survey topographic maps. Because of the level of basin discretization needed, many of the subcatchments in this study cover about 15 to 20 acres and make delineation of the PDA for each subcatchment tedious. Therefore, a combination of Southard's (1986) method and modeler judgement determined the estimation of initial IMP values. Because physical measurement of IMP was difficult and the relative sensitivity of model output to IMP was large, IMP was adjusted during calibration. Subcatchment ranges for IMP were from 3 to 40 percent.

For overland flow, IMPN and PERVN represent frictional resistance because of surface roughness and ground cover. Because overland flow depths are small compared to channel flow, the effects of vegetation on overland flow are more pronounced, effectively increasing roughness. Therefore, Manning's roughness coefficients for overland flow were larger than those for channel flow. Estimating IMPN and PERVN was difficult because of the ground cover variability. Huber and Dickinson (1988) report values ranging from 0.012 (IMPN value for asphalt) to 0.41 (PERVN value for dense shrubbery). Values for initial estimation were selected from published values in Bedient and Huber (1988) and Huber and Dickinson (1988). The pervious areas are dominated by lawns and dense turf, so a value of 0.30 for PERVN was selected for all subcatchments. The impervious areas are dominated by rough asphalt streets, so a value of 0.025 for IMPN was selected for all subcatchments.

Precipitation may infiltrate the ground, become trapped in small depressions (depression storage), or flow over the surface (runoff). Depression storage must conceptually be satisfied before the occurrence of runoff. The depression storage is subject to depletion by both evaporation and infiltration. Huber and Dickinson (1988) state "...depression storage may be treated as a calibration parameter, particularly to adjust runoff volumes. If so, extensive preliminary work to obtain an accurate a priori value may be pointless since the value will be changed during calibration anyway." As suggested, IDS and PDS were used as calibration parameters and ranged in value from 0.02 to 0.20 in. The values for VAP(i) were determined by applying pan coefficients to the average of three sites where pan evaporation data were collected by the National Oceanic and Atmospheric Administration (1991). These three sites (Lakeside, Mt. Vernon, and St. Louis, Missouri) are all within 120 mi of the study area. An average daily value in inches per day was determined for each month.

For this study, the Mein and Larson approximation (Huber and Dickinson, 1988) of the Green-Ampt equation was used to simulate infiltration. For the soil types in the study area, Chow and others (1988) estimate HYDCON is about 0.04 in. per hour, IMD ranges from 0.32 to 0.52, and SUCT ranges from 10 to 12 in. As previously mentioned, IMD and SUCT both vary with the antecedent moisture conditions, and because SUCT is hard to physically quantify, for this study SUCT is considered independent of soil type. Therefore, IMD and SUCT were assigned values based on antecedent moisture conditions (dry, normal, and wet) when the model was calibrated. Criteria for each of the three classifications (dry, normal, and wet) and the parameter values assigned for IMD and SUCT are given in table 2.

The drainage system in the model is characterized by geometric information about each hydraulic element, and a Manning's roughness coefficient is used to describe the frictional resistance of the hydraulic element. Characterization of storage elements (detention ponds) requires elevation-area-storage relations and a hydraulic rating for the outflow structure. All the geometric information was determined either from topographic maps or from onsite measurements of the hydraulic elements. To simplify model input, all natural channels were simulated as trapezoids or parabolas. The effect of using these shapes to represent the actual cross-sectional shape was deemed insignificant in relation to the overall drainage basin simulation. However, future use of the model for overbank flows and individual drainage element design may warrant inclusion of the natural cross sections into the model.

Manning's n values for all hydraulic elements were chosen based on literature (Barnes, 1967; Chow, 1959) and experience of the modeler. The storage element elevation-area-storage relation was determined from topographic maps. The ratings of outflow structures were determined either by standard U.S. Geological Survey current meter discharge rating techniques (Kennedy, 1984) or by indirect methods described in Hulsing (1967) and Bodhaine (1968).

Calibration Of Simulation Model

Calibration of the model was conducted by systematically changing the sensitive parameters to optimize the objective functions. Ideally, as many rainfall-runoff events as possible would be selected for calibration. However, Becker (1986) indicates that for urban rainfall-runoff simulation careful selection of smaller magnitude rainfall-runoff events, so that adequate emphasis could be given to the larger rainfall events (the type of event of interest in a design model), is warranted. Therefore, because larger rainfall events were desired and the data collection period was short, only rainfall-runoff events approaching the 2-year frequency or larger were selected for calibration, which resulted in only three rainfall-runoff events selected (table 3).

All physically measurable model parameters (ROUGH, SLP, and WAREA), were initially determined and held constant for the model calibration. The parameters HYDCON, IDS, IMD, IMP, IMPN, PDS, PERVN, SUCT, and W were adjusted (in the range of reasonable values) systematically during calibration to minimize the three objective functions defined in equations 1 to 3.

The ability of the calibrated model to match the observed peak flow, total volume of runoff, and time to peak of the three rainfall-runoff events at the three streamflow gages is shown in figure 4. The calibration results are listed in table 4. Typical storm hydrographs that compare simulated and observed runoff are shown in figure 5. All observed flood peaks (table 3) were less than a 10-year frequency.

Calibrated parameter values for IMD and SUCT were dependent on antecedent moisture condition (table 2) and independent of subcatchment. Calibration values for HYDCON, IMPN, and PERVN proved to be independent of subcatchment once the model was calibrated and were 0.04 in. per hour for HYDCON, 0.03 for IMPN, and 0.39 for PERVN. The IMP was not a constant for all subcatchments because of urbanization differences in each subcatchment.

Table 2--Antecedent moisture classification scheme for assignment of parameters in the U.S. Environmental Protection Agency's Storm Water Management Model

[>, greater than]

10-day antecedent rain, in inches	Season (growing[a] or dormant[b])	Classification	Initial moisture deficit (IMD)	Soil suction (SUCT), in inches
0	Growing	Dry	0.52	12
0	Dormant	Dry	.52	12
0 to 1	Growing	Dry	.52	12
0 to 1	Dormant	Normal	.43	11
1 to 2	Growing	Normal	.43	11
1 to 2	Dormant	Wet	.32	10
>2	Growing	Wet	.32	10
>2	Dormant	Wet	.32	10

[a] April 1 to September 30.
[b] October 1 to March 31.

Table 3--Frequency of flood peaks observed at gaging stations for the three rainfall-runoff events used in calibration of the U.S. Environmental Protection Agency's Storm Water Management Model

[<, less than]

Gaging station (fig. 1)	Observed peak discharge, in cubic feet per second	Frequency,[a] in years
	October 17, 1990	
Dutro Carter Creek	272	<2
Deible Branch	60.4	<2
Burgher Branch	149	<2
	November 27, 1990	
Dutro Carter Creek	1,140	5 - 10
Deible Branch	880	2 - 5
Burgher Branch	620	<2
	April 14, 1991	
Dutro Carter Creek	859	2 - 5
Deible Branch	726	2 - 5
Burgher Branch	537	<2

[a] Frequency determined from Becker (1986).

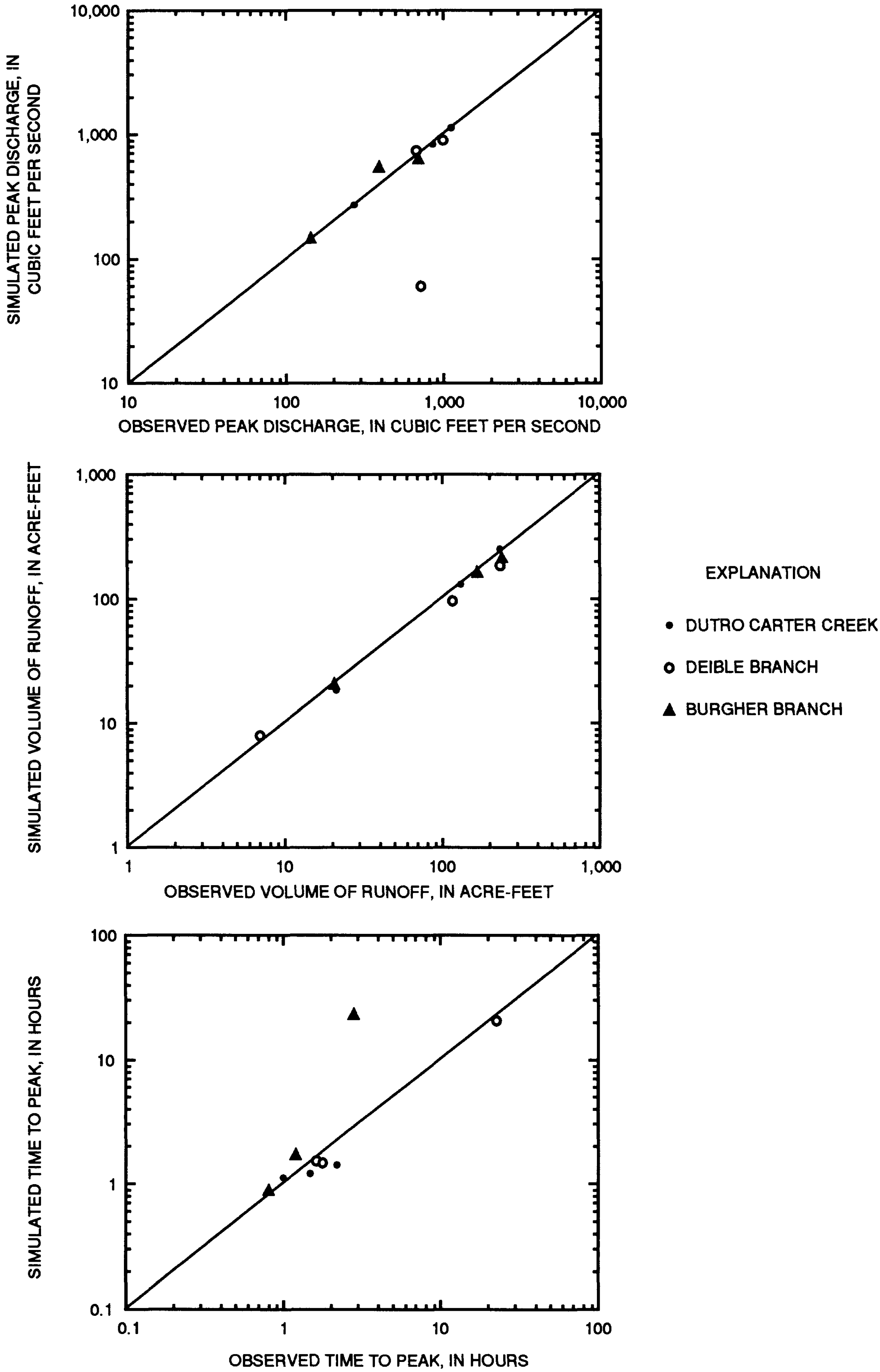


Figure 4. Observed and simulated peak discharge, volume of runoff, and time to peak data from model calibration from Dutro Carter Creek, Dieble Branch, and Burgher Branch.

Table 4--Observed and simulated rainfall-runoff event peak discharge, volume of runoff, and time to peak data for Dutro Carter Creek, Deible Branch, and Burgher Branch

[Observed, value, in cubic feet per second for peak discharge, in acre-feet for volume of runoff, and in hours for time to peak; simulated, value, in cubic feet per second for peak discharge, in acre-feet for volume of runoff, and in hours for time to peak; percent difference, [((Simulated - Observed)/Observed) x 100)]]

Gaging station (fig. 1)	Peak discharge[a]			Volume of runoff[b]			Time to peak[c]		
	Observed	Simulated	Percent difference	Observed	Simulated	Percent difference	Observed	Simulated	Percent difference
October 17, 1990									
Dutro Carter Creek	272	271	-0.37	21.6	18.8	-13.0	1.0	1.13	+13.0
Deible Branch	604	727	+20.4	6.89	8.02	+16.4	1.8	1.44	-20.0
Burgher Branch	149	146	-2.01	20.6	20.4	-0.97	.8	.9	+12.5
November 27, 1990									
Dutro Carter Creek	1,140	1,132	-0.70	130	129	-0.77	1.5	1.2	-20.0
Deible Branch	880	989	+12.4	116	97.2	-16.2	1.6	1.5	-6.25
Burgher Branch	620	687	+10.8	166	165	-.60	1.2	1.7	+41.7
April 14, 1991									
Dutro Carter Creek	859	819	-4.66	236	255	+8.05	2.2	1.4	-36.4
Deible Branch	726	670	-7.71	234	183	-21.8	2.3	2.1	-8.7
Burgher Branch	537	396	-26.2	244	219	-10.2	2.8	2.3	-17.9

[a] Peak discharge is the maximum discharge for the storm period.
[b] Volume of runoff is the volume of runoff for the period of each rainfall-runoff event.
[c] Time to peak is the time from the beginning of model simulation (corresponding to the beginning of rainfall) to the time corresponding to the peak discharge.

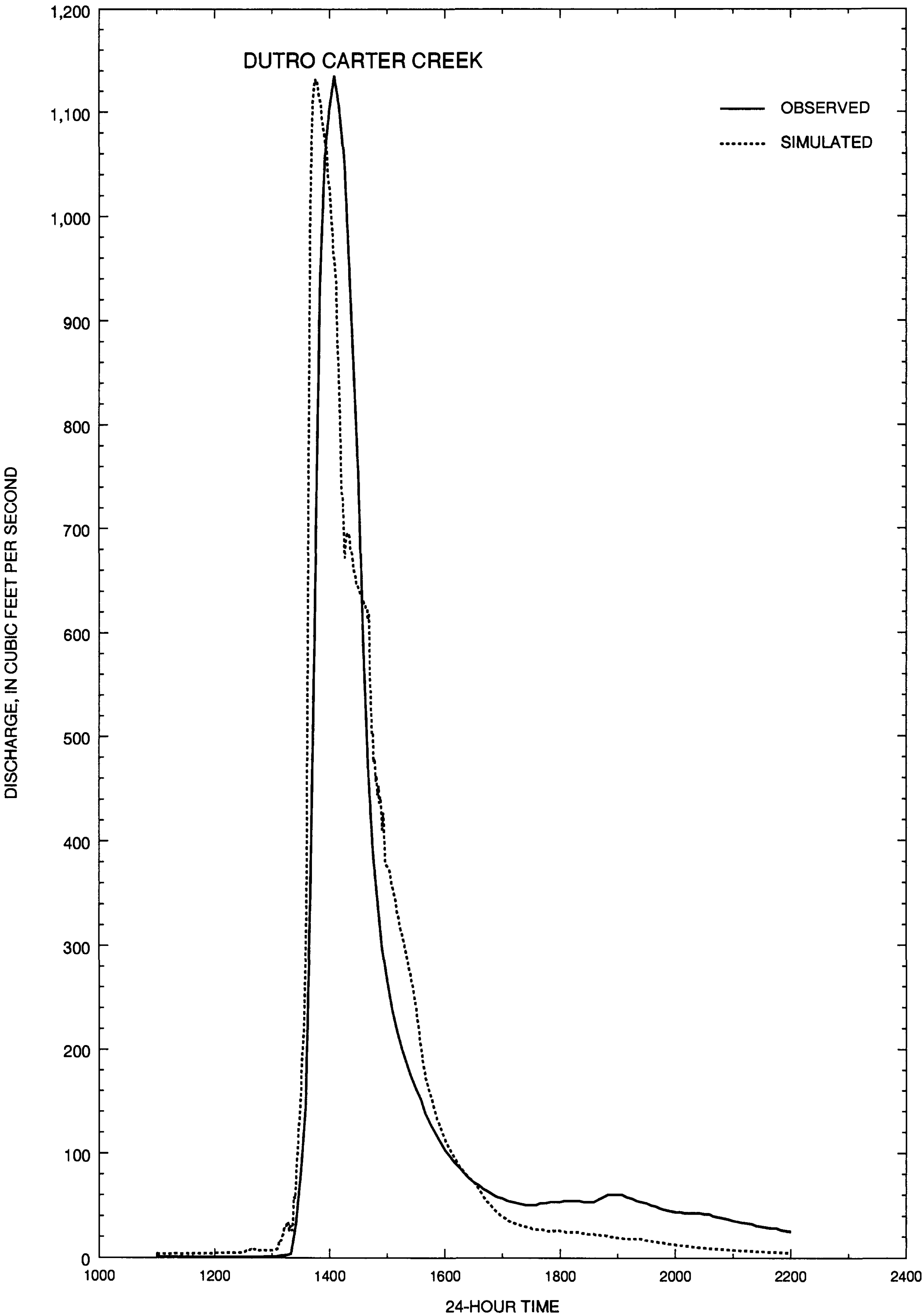


Figure 5. Observed and simulated discharge for Dutro Carter Creek, Deible Branch, and Burgher Branch gaging stations for the storm of November 27, 1990.

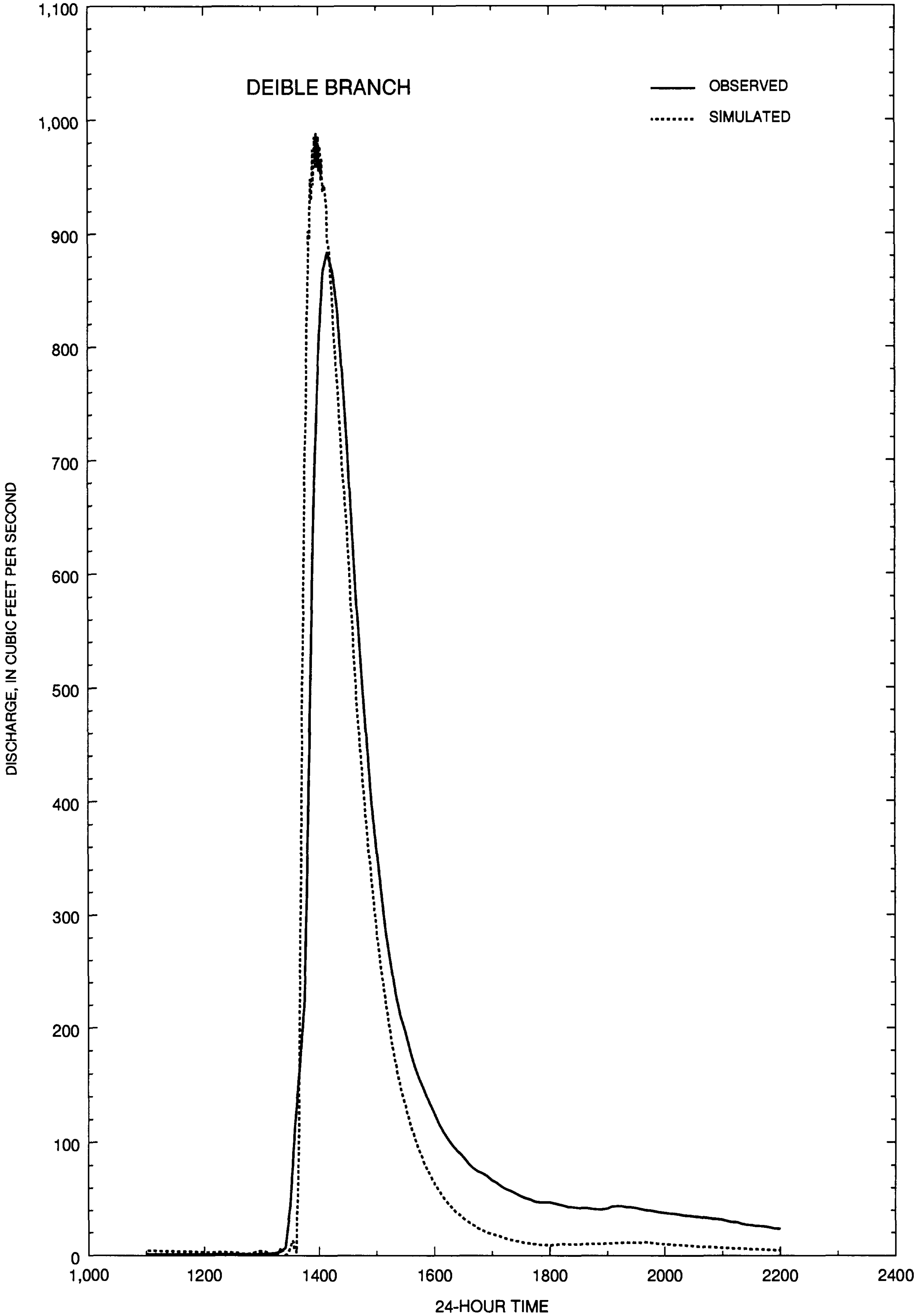


Figure 5. Observed and simulated discharge for Dutro Carter Creek, Deible Branch, and Burgher Branch gaging stations for the storm of November 27, 1990--Continued.

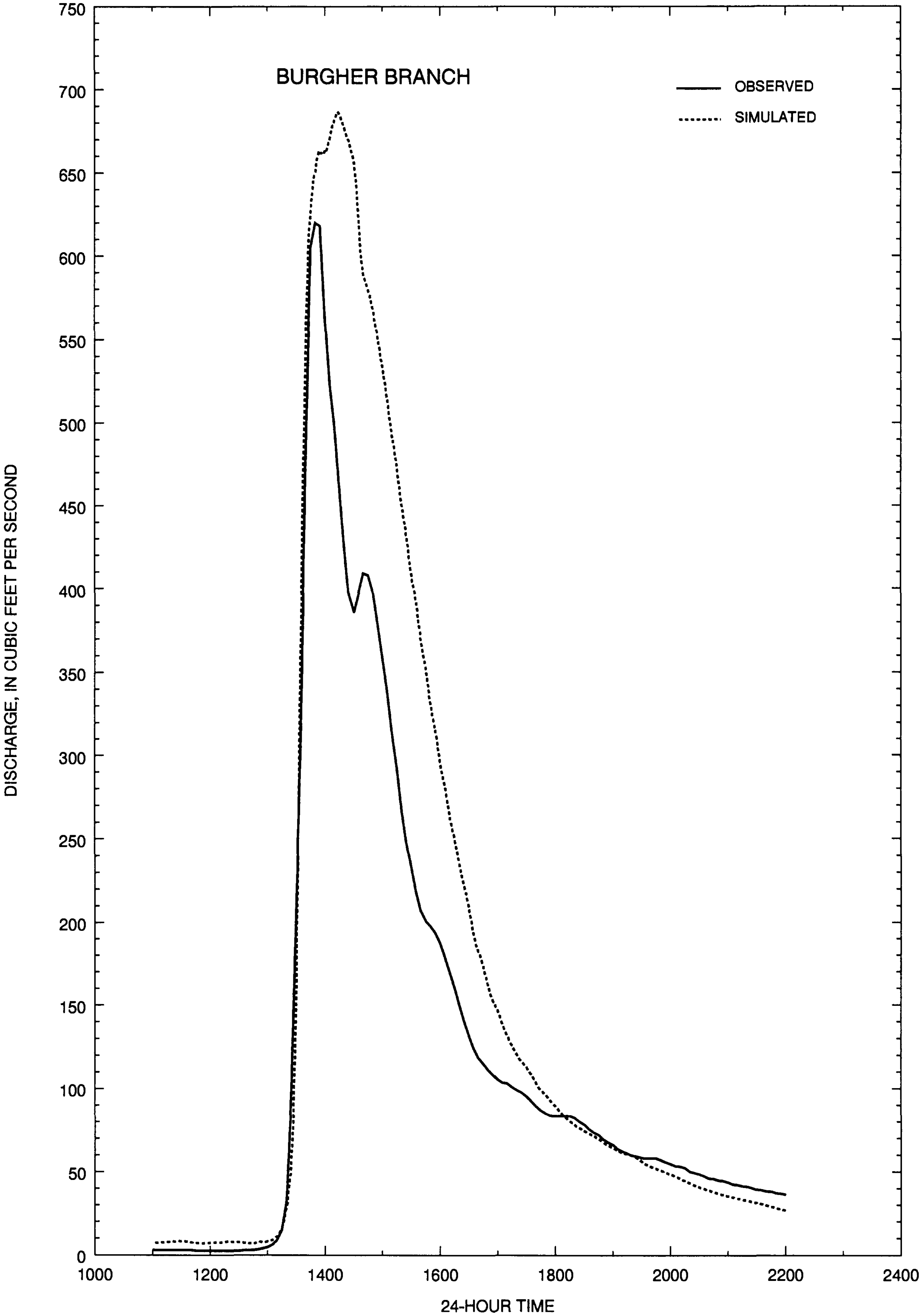


Figure 5. Observed and simulated discharge for Dutro Carter Creek, Deible Branch, and Burgher Branch gaging stations for the storm of November 27, 1990--Continued.

The calibrated SWMM input data sets from this study can be obtained from the U.S. Geological Survey office, Rolla, Missouri. In addition, the calibration rainfall-runoff data sets can be obtained from the same office.

Analysis of Errors in the Simulation Model

The failure to replicate the observed data with the simulated data is known as error. The errors in this model simulation have four possible sources: errant observed rainfall-runoff data, inadequate temporal and spatial representation of rainfall distribution in the model, error in rainfall volume, and inability (either because of time or model limitations) to represent the spatial and dynamic features of the drainage basin. The absolute mean percent differences between the simulated and observed data for peak discharge, volume of runoff, and time to peak were 9.47, 10.8, and 19.6 percent. The ranges in percent difference for discharge are -26.2 to 20.4; for volume of runoff, -21.8 to 16.4; and for time to peak, -36.4 to 41.7.

Each subcatchment in the drainage basins was assigned the nearest rainfall gage to represent the rainfall that fell on that subcatchment. The rainfall from these gages was then entered into the model as the stimulus for the calibration storm runoff. After the simulation was completed, the observed and simulated runoff were compared on the basis that both had the exact same stimulus (as measured by the rainfall gages), when in all likelihood they did not. The only way to accurately measure the true stimulus would be to have a rainfall gage for every square foot of the drainage basins; however, this is impossible. Huber and Dickinson (1988) report, "Without doubt, rainfall data are the single most important group of hydrologic data required by SWMM." Therefore, more rainfall gages would have better determined the true rainfall distribution of the calibration storms. This better determination would likely decrease some of the difference between the observed and simulated results.

The drainage basins were discretized into SWMM according to drainage system information currently (1992) available. This information consisted of maps outlining the major storm sewer trunk lines and open channel stream conduits, as well as some onsite verification. However, this information was not exhaustive in its representation of the true drainage system. The ability and accuracy of SWMM for the study area could greatly benefit from a data base of accurate information on all drainage system components, including location, type, size, and Manning's roughness characteristics.

To increase the reliability of the SWMM simulation, additional calibration data sets are necessary. Resuming the rainfall-runoff data collection for the study area would provide additional calibration data sets, which would improve the model accuracy. Furthermore, depending on the number of storms available from additional data collection, the data could be divided into two distinct data sets, thus allowing for both calibration and validation of the model.

Application of Simulation Model

Each rainfall-runoff simulation model constructed is intended for specific applications. Using the model for other applications may yield erroneous results.

In this study, the model was designed and calibrated for stormwater design (2-year or greater frequency rainfall with short duration). This model will perform poorly in the simulation of longer-duration and lower intensity rainfall, or in a continuous simulation mode.

For simulation of runoff based on hydraulic drainage system changes for a low- to medium-magnitude storm (1- to 2-year frequency), the SWMM model configured for this study will be adequate, on the basis of the data available for calibration (see table 3 for frequency of calibration storms). However, if more rainfall-runoff data became available, especially for 25- to 50-year frequency storms, recalibration would be required to adequately allow the model to simulate events of larger frequency (25 year or greater).

Hydrologic similarity allows extrapolation of the calibrated model parameters for the gaged subcatchments to subcatchments in the ungaged part of the drainage basins (lower Dutro Carter Creek, lower Burgher Branch, and the Spring Creek tributary basins; fig. 1) so that rainfall-runoff to the two wastewater treatment plants shown in figure 1 can be compared. The accuracy of the simulation would be expected to be slightly less than that provided for the gaged basins (see table 4 for differences in observed and simulated results).

SUMMARY AND CONCLUSIONS

Storm event rainfall-runoff in the Rolla, Missouri, area was simulated using the U.S. Environmental Protection Agency's Storm Water Management Model (SWMM). Rainfall and streamflow data were collected at selected locations within the study area to use as calibration data for the simulation model. Before the model for the drainage basins was calibrated, a sensitivity analysis of model parameters was done on a simplified representative drainage basin. Output from the SWMM was determined to be most sensitive to saturated hydraulic conductivity (HYDCON), initial moisture deficit (IMD), percentage of impervious area (IMP), and subcatchment width (W). The volume of runoff was affected by HYDCON, IMD, and IMP. The peak flow rate was affected by IMP and W, whereas the time to peak was affected by W. The model also was determined to be sensitive in the streamflow routing part of the model to time step, while the model was insensitive to time step in the subcatchment runoff generation part of the model.

Overland flow was determined to be the main mode of translating water from the basin to the stream. Overland flow was affected by interception storage, interception losses, evaporation, and infiltration. All of these processes were incorporated into the configuration of the SWMM model.

The model was calibrated, using observed data from three storms with recurrence intervals of less than 10 years, by minimizing objective functions representing peak discharge, volume of runoff, and time to peak discharge from beginning of simulation. The absolute mean percent differences between the simulated and observed data for peak discharge, volume of runoff, and time to peak discharge are 9.47, 10.8, and 19.6 percent. The ranges in percent difference for discharge are -26.2 to 20.4; for volume of runoff, -21.8 to 16.4; and for time to peak, -36.4 to 41.7. The percent differences between the observed and simulated data are thought to occur because of errant observed rainfall-runoff data, inadequate temporal and spatial representation of rainfall distribution in the model, error in rainfall volume, and inability (either because of time or model limitations) to represent the spatial and dynamic features of the drainage basin. In addition, some errors were likely in delineation of the drainage system (stormsewer conduits, lengths, and geometry) because of inadequate information available at the time of study. Additional data collection for calibration and validation efforts would improve the accuracy of the model simulation.

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