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Status of Surface-water Modeling in the U.S. Geological Survey

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By Marshall E. Jennings and Nobuhiro Yotsukura

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By Marshall E. Jennings and Nobuhiro Yotsukura

ABSTRACT

The U.S. Geological Survey is active in the development and use of models for the analysis of various types of surface-water problems. Types of problems for which models have been, or are being developed, include categories such as the following: (1) specialized hydraulics, (2) flow routing in streams, estuaries, lakes, and reservoirs, (3) sedimentation, (4) transport of physical, chemical, and biological constituents, (5) surface exchange of heat and mass, (6) coupled stream-aquifer flow systems, (7) physical hydrology for rainfall-runoff relations, stream-system simulations, channel geometry, and water quality, (8) statistical hydrology for synthetic streamflows, floods, droughts, storage, and water quality, (9) management and operation problems, and (10) miscellaneous hydrologic problems. Following a brief review of activities prior to 1970, the current status of surface-water modeling is given as being in a developmental, verification, operational, or continued improvement phase. A list of recently published selected references, provides useful details on the characteristics of models.

INTRODUCTION

One of the primary missions of the U.S. Geological Survey is to conduct basic and applied research in the problems related to land-water environments. The research is conducted to improve understanding of natural land-water system processes such that quantitative predictions of system response to stress, either natural or man-made, can eventually be accomplished.

Surface-water modeling based on a deterministic, statistical, or qualitative framework represents a large segment of continuing Survey research in land-water problems, although use of the terminology "surface-water problem" sometimes is arbitrary because of the integral nature of the hydrologic system involved. Surface-water models include not only those models which traditionally have been defined as rational representations of natural surface-water processes by use of hydraulic, hydrologic and geologic principles, but also those models which have recently been developed in order to cope with a rapidly expanding spectrum of surface-water problems. For example, systems-analysis models have become important tools for solving such problems as watershed management and gaging network design.

Surface-water models are used by researchers and field hydrologists alike; by researchers to advance scientific knowledge of natural processes and systems, and by field hydrologists to provide predictive information for managers and planners. As management tools, surface-water models are being increasingly relied upon by decision makers who must plan under an "alternative futures" concept.

The purpose of this report is to summarize the current status of surface-water modeling in the Geological Survey following a brief, but fairly complete, review of modeling activities before 1970. Two lists of references are attached for the reader interested in more details, namely, "Recently published selected references" including those published after 1970, and "References before 1970". The recently published references list the published work as of mid-1978. The references before 1970 list the work done through 1969; however, publication of a few reports was delayed as late as 1973.

SURFACE-WATER MODELING ACTIVITES BEFORE 1970

Surface-water research within the Survey prior to 1930 was rather limited. Examples include a rainfall-runoff relations study by Rafter (1903), weir experiments by Horton (1906, 1907), a study of ice effects on stream flow by Hoyt (1913), and sediment-transport experiments by Gilbert (1914). The period between 1900 and 1940, however, was significant in that the Survey was actively engaged in the task of establishing nation-wide gaging networks and of improving stream-gaging techniques (Corbett and others, 1943).

An expanded water-data base provided by the Survey contributed greatly to a solid growth of hydrologic knowledge; this growth was essential in assessing long term trends and in evaluating basin-wide characteristics for many surface-water problems. During the period between 1930 and 1950, statistics-based hydrology established itself as a distinct surface-water discipline, paralleling the more classic and deterministic hydraulics. Hydrologic models developed in this period include those for rainfall-runoff relation (Hoyt and others, 1936), flood hydrograph analysis (Jarvis and others, 1936; Langbein, 1940, 1944), and watershed characterization (Langbein and others, 1947).

Beginning in the early 1950's, unprecedented expansion and diversification took place in surface-water modeling. The summary of modeling work after 1950 may be conveniently presented by following each specialized field studied by a more or less cohesive group of researchers.

The study of evaporation and heat exchange in lakes and reservoirs is a field where mathematical models, successfully developed through an extensive study of Lake Hefner (U.S. Geological Survey, 1954), have had a long-standing impact on later activities within and without the Survey (Harbeck, 1955, 1962; Harbeck and others 1959; Koberg, 1964; Hughes, 1967).

Another field with notable modeling accomplishment in the early 1950's is that of the hydraulics of flow through weirs, culverts, and bridge constrictions (Kindsvater and others, 1953; Carter, 1957; Tracy, 1957; Davidian and others, 1962; Kindsvater, 1964). Models for channel boundary roughness and resistance were also developed by this group (Tracy and Lester, 1961; Barnes, 1967).

Sediment transport has long been the subject of interest at the USGS. Early efforts (Love and Benedict, 1948); Hains and others, 1952; Colby and others, 1953; Colby and Hembree, 1955) were succeeded after the late 1950's by extensive flume experiments and theoretical analyses of highly stochastic transport mechanics (Simons and Albertson, 1961; Colby, 1964; Nordin, 1963; Guy, 1964; Nordin and Beverage, 1965; Simons and others, 1965; Guy and others, 1966; and Williams, 1967). Note that the above listing represents a small portion of research outcomes in this particular field, which, in the last 20 years, grew to be almost independent of other surface-water hydraulics studies. Until the early 1970's, most sedimentation studies where carried out in Fort Collins, Colo., in cooperation with Colorado State University. The Fort Collins unit also conducted research in dispersion and reaeration problems and functioned as a focal point of surface-water research and training.

Channel morphology and watershed characteristics are very closely related to sediment transport as well as to extreme flows. Modeling of these processes expanded drastically since the early 1950's (Leopold and Maddock, 1953; Wolman, 1955; Leopold and others, 1960; Leopold and Miller, 1956; Leopold and Wolman, 1957; Bagnold, 1960, 1966; Brush, 1961; Wolman and Brush, 1961; Leopold and others, 1966; Kilpatrick and Barnes, 1964; Langbein and Leopold, 1966, 1968; Simons and Richardson, 1966; Leopold and Langbein, 1962; and Scheidegger and Langbein, 1966). Regionalized hydrologic and morphologic characteristics were reported by Troxell and others, 1954; Culler, 1961; Hadley and Schumm, 1961; Schumm, 1960, 1963; Kennon and Peterson, 1960; and Peterson, 1962. On reservoir storage problems, early works (Langbein and others, 1951; Culler and Peterson, 1953) were later succeeded by more probablistic models (Langbein, 1958; Riggs and Hardison, 1973; Hardison, 1968).

In view of current environmental concerns, it is also significant that concepts of ecology, conservation, and water management were introduced by Survey researchers in the late 1950's (Leopold, 1958, 1959, 1960a–b; Langbein, 1959; and Nace, 1960).

Analysis of flood and drought frequency and magnitude started in the late 1940's (Langbein, 1949; Dalrymple, 1950; Carter, 1951). Because of the perennial importance and high priority of this problem among surface-water problems, intensive efforts of the Geological Survey were invested in the analyses by means of statistical treatment of data and empirical correlation with watershed variables (Dalrymple, 1960; Benson, 1962, 1964; Mitchell, 1962; Hardison and Martin, 1963; Hardison, 1969; Reid and others, 1968; Cruff and Rantz, 1965; Riggs, 1965). Efforts were also directed toward close cooperation with other Federal, state, and local government agencies. The outcome of this cooperation was a series of Water Supply Papers, 1961-1689, published between 1963 and 1968 explaining regionalized flood frequency prediction methods (Green, 1964; Tice, 1968; Speer and Gamble, 1964, 1965; Barnes and Golden, 1966; Wiitala, 1965; Patterson, 19646, 1965, 1966; Patterson and Somers, 1966; Patterson and Gamble, 1968; Matthai, 1968; Butler and others, 1966; Young and Cruff, 1967; Bodhaine and Thomas, 1964; and Hulsing and Kallio, 1964). Introduction of probability theories and statistical information theory contributed substantially to the advancement of mathematical aspects of extreme flow statistics (Matalas, 1963; Matalas and Jacobs, 1964; and Fiering, 1963).

Use of high-speed digital computers by Survey researchers became popular in the early 1960's. A large number of old and new problems, which hitherto were unapproachable, became solvable by means of numerical simulations and experiments in both hydraulic and hydrologic specializations. In deterministic modeling, numerical techniques were developed for the solution of transient flow of estuaries (Baltzer and Shen, 1961; Lai, 1965; and Baltzer and Lai, 1968), for solutions of solute transport in upland streams (Yotsukura and Fiering, 1964), and for the simulation of rainfall-runoff processes on small watersheds (Dawdy and O'Donnell, 1965). In stochastic modeling, probabilistic numerical experiments became important tools for advancing synthetic hydrology and systems-analysis research (Matalas, 1967, 1968; Matalas and Gilroy, 1968; Kirby, 1969).

Awareness of new surface-water problems was probably as significant as the introduction of digital computers in inducing another marked expansion of Survey modeling activities in the early 1960's. Research efforts began in new problems such as estuarine discharges (Rantz, 1963; Dempster and Lutz, 1968; Cummings, 1968; Peterson and Carlson, 1968), transport and reaction of water-quality constituents (Sayre and others, 1963; Glover, 1964; Kennedy, 1965; Pickering and others, 1965; Fischer, 1967, 1968; Carrigan, 1968; Sayre and Chang, 1968; Pickering, 1969; and Godfrey and Frederick, 1970), statistical analysis of water-quality constituents (Dawdy and Feth, 1967; Moore, 1967; Steele, 1968; and Collings, 1969), stream reaeration (Langbein and Durum, 1967; Durum and Langbein, 1966), time-of-travel (Searcy and Davis, 1961; Bauer, 1968), flow under ice (Carey, 1967), urban hydrology (Harris and Rantz, 1964; Leopold, 1968; Dawdy, 1969; Vice and others, 1969), glacial hydrology (Meier, 1969), and gaging network design and error analysis (Leopold, 1962; Carter and others, 1963).

In concluding this brief summary of surface-water modeling before 1970, note that many modeling activities after 1970 are continuous and identifiable with those established earlier and previously described. With recent improvements in data transmission and computer utilization, however, modeling activities after 1970 have shifted substantially toward mathematical or quantitative descriptions.

Documentation and standardization of model utilization in field problems have been important activities of Geological Survey research. Earlier standardized procedures for general surface-water techniques were purblished as Water-Supply Paper 1541 (U.S. Geological Survey, 1960a) and those for flood-flow techniques as Water-Supply Paper 1543 (U.S. Geological Survey, 1960b). Starting in 1967, the TWRI (Techniques of Water-Resources Investigations) series has represented the most convenient form of publishing standardized techniques which were derived from models and tested for field and office applications.

RECENT DEVELOPMENTS

Several changes affecting the conduct of water research took place in the early 1970's. Nearly all Geological Survey field offices obtained access to Survey central computers through terminals. The field offices thus became equipped with the capability of handling data and models routinely and in close cooperation with research specialists. Another change was the opening of the GCHC (Gulf Coast Hydroscience Center) near Bay St. Louis, Miss., in 1971. The GCHC absorbed almost all of the research and instrumentation activities previously held at Colorado State University, Fort Collins, Colo., and at Columbus, Ohio. The GCHC facilities, including a 300-feet-wide outdoor flume and a modern instrument shop, became the Geological Survey national core for hydraulic experiments and instrumentation. The initiation of remote sensing activities in the Survey is also a notable recent development, in which application of earth-satellite technology is expected to provide a cost-effective means of automatic data collection and transmission from widely scattered gaging stations.

One major characteristic of recent surface-water modeling is the emphasis on water quality problems which arose in connection with environmental pollution. Problems such as deoxygenation, thermal loading, pesticide pollution, and aquatic eutrophication have begun to impose an unprecedented degree of interdisciplinary co-operation among various research specializations. Studies of water-quality assessment in major river basins were begun with the assessment of the Willamette River basin, Oregon. The success of this study lead to two subsequent projects, namely, the Yampa River basin, Colorado and Wyoming, and the Chattahoochee River basin, Georgia, and to a continuing program of such studies at field level. Specialized water-quality approaches such as tracer technology applied to reaeration determination and waste transport simulation in estuaries were developed and refined.

Some phases of research in water quantity were subjected to new evaluations. An extensive evaluation of the streamflow data collection program[1] indicated that the existing program was not providing homogeneous data for regulated streams. Mathematical models of stream systems were developed to reflect the effect of regulation, storage, diversion, and management practices on streamflow. The expansion and implementation of numerical rainfall-runoff models were started on a nationwide scale. In addition to providing tools for flood-frequency analysis on small, rural streams, rainfall-runoff modeling has been expanded to address problems of hydrologic consequences of land-use such as energy development and urbanization. Such models include both quantity and quality components.

Because of the preponderance of computer-based modeling in the 1970's, a series of computer-program user manuals was started as U.S. Geological Survey Computer Contributions. These are available through the National Technical Information Service, U.S. Department of Commerce, Springfield, Virginia 22151.

CURRENT SURFACE-WATER MODELING ACTIVITIES

The current status of surface-water modeling, a continuing research activity of U.S. Geological Survey, is summarized in table 1. Investigators listed in the table are those who have been actively engaged in research between 1970 and 1978, and publications include only those published after 1970. In order to facilitate comparative reference, table 1 is prepared in the same format as that in the companion report for ground-water modeling.[2]

Some comments are in order regarding the classification of phases of modeling activity. Models in the "developmental" phase are those in an active stage of conceptualization and formulation. To state that a model is in the "verification" phase means that tests are being made to determine how satisfactorily model output represents, quantitatively and qualitatively, a natural physical process. Verification involves direct comparison of observed and model-computed responses based on a few sets of input data. Data used in the calibration of a model normally is not included in observed response data for verification. Because of the above reason, statistics-based

[1]Benson, M. A., and Carter, R. W., 1973, A national study of the streamflow data-collection program: U.S. Geological Survey Water-Supply Paper 2028, 44 p.

[2]Appel, C. A., and Bredehoeft, J. D., 1976, Status of ground-water modeling in the U.S. Geological Survey: U.S. Geological Survey Circular 737, 9 p.

TABLE 1.—*Status of surface-water modeling, U.S. Geological Survey*

[Principal investigators can be located at U.S. Geological Survey, Water Resources Division, National Center, Reston, Virginia 22092]

	Phase of activity					
	Develop-mental	Verifi-cation	Opera-tional	Continued improve-ment	Principal U.S. Geological Survey investigators	Recently published selected references
Specialized Hydraulics						
Channel roughness	X	X	--	--	D. L. Collins, V. R. Schneider.	
Turbulence and diffision	X	X	X	X	N. Yotsukura, F. A. Kilpatrick R. S. McQuivey, T. N. Keefer.	Yotsukura and Cobb (1972), Nordin and Sabol (1974), Weiss (1971), McQuivey and Keefer (1976), Yotsukura and Sayre (1976).
Flow through bridges and culverts	--	X	X	--	V. R. Schneider, L. A. Druffel.	Schneider and others (1976), Schneider and Druffel (1975).
Conduit flow	--	--	X	X	J. Davidian.	Smoot, Davidian, and Billings (1974).
Time-of-travel	--	X	X	X	F. A. Kilpatrick, J. F. Wilson, Jr.	Eikenberry and Davis (1976), Martens (1974).
Flow over dams	--	--	X	X	D. L. Collins.	Collins (1976), Collins and Wires (1975).
Flow Routing						
Streams and estuaries—one dimensional						
Finite element	X	X	--	--	R. T. Cheng, J. K. Lee, R. L. Cooley, L. H. Smith.	Cooley and Syed Afaq Moui (1976), and Smith and Cheng (1976).
Finite difference	--	X	X	X	R. A. Baltzer, R. W. Schaffranek, C. Lai, J. P. Bennett, G. A. Lutz.	Bennett (1975), 1977), Lutz, Hubbell, and Stevens (1975).
Characteristics method	--	--	X	X	C. Lai, C. L. Chen.	Lai and Onions (1976).
Linearized equation	--	X	X	X	V. B. Sauer, T. N. Keefer.	Sauer (1973), Keefer and McQuivey (1974), Jennings and Keefer (1977), Keefer (1974).
Estuaries and bays—two dimensional						
Finite element	X	X	--	--	R. T. Cheng, W. G. Gray, D. P. Lynch, J. P. Bennett, R. A. Walters.	Gray (1976).
Finite difference	--	X	X	X	R. A. Baltzer, R. W. Schaffranek, R. T. Cheng.	Baltzer (1972), Leendertse (1970), Liu (1974), Schaffranek and Baltzer (1975).
Characteristic method	X	X	--	--	C. Lai, C. L. Chen.	Lai (1976), 1977).
Estuaries and bays—three dimensional						
Finite element	X	X	--	--	R. T. Cheng.	
Finite difference	X	X	--	--	R. A. Baltzer, R. T. Cheng,	Liu and Nelson (1977).
Stratified flows	--	X	X	--	E. R. Holley.	Holley and Waddell (1976).
Lakes and reservoirs						
Water balance	--	X	X	--	T. H. Thompson, K. M. Waddell.	Thompson (1972, 1974), Waddell and Fields (1976).
Circulation	X	X	--	--	R. T. Cheng.	Cheng (1977).
Dam break	--	X	X	--	L. A. Druffel, T. N. Keefer, C. L. Chen.	Glass, Keefer, and Rankl (1976), Keefer and McQuivey (1976), Chen and Druffel (1977).
Sedimentation						
Erosion	X	X	--	--	H. P. Guy, D. G. Frickel.	Guy (1976), Frickel, Shown, and Patton (1975).
Alluvial channels	X	X	--	--	T. Maccock, Jr., C. F. Nordin, J. P. Bennett, R. H. Meade, G. P. Williams.	Maddock (1976), Nordin and Rundquist (1973), Nordin (1971), Rathbun and Kennedy (1976).
Bedload	X	X	--	--	C. F. Nordin, R. H. Meade, W. W. Emmett, D. W. Hubbell.	Emmett and Seitz (1973), Nordin and Rathbun (1971).
Suspended load	--	X	X	--	W. W. Emmett, C. F. Nordin, J. P. Bennett.	Jennings and Land (1977), Bennett (1974), Nordin and McQuivey (1971).
Water Quality						
Water-quality parameters and processes						
Chemical	X	X	--	--	V. C. Kennedy, B. F. Jones, J. D. Hem, E. A. Jenne, H. V. Leland, E. Calander, I. K. Barnes.	Kennedy (1971), Brown (1976), Hem and Steele (1975), Jenne and Avotins (1975), Leland (1976), Jones, Kennedy, and Zellweger (1974).
Biological	X	X	X	X	M. E. Jennings, D. W. Stephens, H. V. Leland, J. G. Cloren, D. J. Schultz.	Jennings and Bauer (1976), Stephens and Jennings (1976).
Water quality transport						
Streams						
Dissolved oxygen, conservatives and nonconservatives	X	X	X	X	M. E. Jennings, J. P. Bennett, D. P. Bauer.	Bauer and Bennett (1976), Zand and Kennedy (1976), Bauer and Jennings (1975), Jennings and Bryant (1974).
Excess temperature	--	X	X	X	N. Yotsukura, H. E. Jobson, A. P. Jackman, D. P. Bauer.	Jobson (1973, 1977), Jobson and Yotsukura (1972), Jackman and Yotsukura (1977), Bauer and Yotsukura (1974), Bauer and MacKenroth (1974).
Natural temperature	--	X	X	--	E. J. Pluhowski, T. D. Steele.	Pluhowski (1970), Steele (1974).

TABLE 1.—*Status of surface-water modeling, U.S. Geological Survey*—Continued

	Phase of activity: Developmental	Phase of activity: Verification	Phase of activity: Operational	Phase of activity: Continued improvement	Principal U.S. Geological Survey investigators	Recently published selected references
Estuaries and bays—conservatives and nonconservatives	X	X	X	--	E. A. Prych, W. C. Haushild, D. H. Peterson, T. J. Conomos, N. Yotsukura, R. L. Cory, J. L. Glenn, J. P. Bennett.	Prych, Haushild, and Stoner (1976), Haushild and Prych (1976), Peterson and others (1971), Conomos and Peterson (1975), Yotsukura, Cory, and Murakami (1972).
Tracer simulation studies	X	X	X	--	N. Yotsukura, F. A. Kilpatrick	Yotsukura and Kilpatrick (1973), Kilpatrick and Cummings (1972).
Lakes	X	X	X	--	D. B. Adams.	Adams (1975).
Water-quality simulation						
Intensive river-quality investigations						
Willamette River Basin, Oregon	--	--	X	X	D. A. Rickert, W. G. Hines, S. W. McKenzie.	Rickert, Hines, and McKenzie (1976), Hines and others (1977).
Chattahoochee River Basin, Georgia	X	X	X	--	R. N. Cherry, R. L. Faye.	Jobson and Keefer (1978), Cherry and others (1978).
Urban stormwater quality	X	X	X	X	H. C. Mattraw, M. E. Jennings, S. W. McKenzie, R. A. Miller, T. Ross.	Miller, Mattraw, and Jennings (1978), Jennings and Doyle (1978), McKenzie and Miller (1976), Barnes and Jennings (1977).
Surface Exchange						
Evaporation and radiation	X	X	X	--	H. E. Jobson, A. M. Sturrock, A. P. Jackman, N. Yotsukura.	Sturrock (1977), Jobson (1973), Yotsukura, Jackman, and Faust (1973), Jobson (1972).
Evapotranspiration	X	X	X	--	R. L. Hanson, T. E. A. Van Hylckama, R. M. Myrick, F. A. Branson.	Hanson and Dawdy (1976), Van Hylckama (1975), Branson and Shown (1975).
Reaeration	X	X	X	--	R. E. Rathbun, D. W. Stephens, D. J. Shultz.	Bennett and Rathbun (1972), Essen and Rathbun (1976), Rathbun, Shultz and Stephens (1975).
Coupled Stream-Aquifer System						
Finite difference	--	X	X	--	T. J. Durbin, G. F. Pinder.	Durbin (1974), Pinder and Sauer (1971).
Finite element	X	--	--	--	E. A. Prych.	
Linearized equation	--	X	X	--	A. F. Moench, L. F. Land, R. R. Luckey.	Moench, Sauer, and Jennings (1974), Land (1977), Luckey and Livingston (1975).
Physical Hydrology						
Flood-way analysis	--	--	X	X	J. O. Shearman, G. W. Edelen, Jr., E. J. Kennedy.	Shearman (1976), map reports and analyses available for most states.
Unit hydrograph	--	X	X	--	V. B. Sauer.	Sauer (1970).
Rainfall-runoff simulation	--	X	X	--	G. H. Leavesley, R. W. Lichty, J. M. Knott, K. W. Lee, T. J. Durbin.	Boning (1974), Lee, Kapple, and Dawdy (1975), Durbin (1974), Dawdy, Lichty, and Bergman (1972), Hauth (1974), Wibben (1976), Carrigan (1973).
Stream systems simulation	--	--	X	X	J. O. Shearman, J. T. Armbruster, W. Harry Doyle, Jr., I. C. James, II.	Burns and James, II (1972), Shearman and Swisshelm (1973), Armbruster (1977), Jeffcoat and others (1976), Krug (1976).
Statistical Hydrology						
Synthetic streamflows						
Markov processes	--	--	X	X	N. C. Matalas, J. R. Slack.	Mejia, Dawdy and Nordin (1974).
Fractional Gaussian Noise	--	--	X	X	J. R. Slack.	
ARIMA processes	X	X	--	--	J. T. Armbruster.	
Flood-flow frequency						
Flood frequency methods—large and small streams	--	--	X	X	W. H. Kirby, W. O. Thomas, Jr., R. W. Lichty, P. H. Carrigan, Jr., E. E. Schroeder.	Schroeder (1974), Thomas and Corley (1977), Kirby (1973).
Urban flood frequency	--	--	X	X	S. L. Johnson, D. G. Anderson, M. E. Jennings, V. B. Sauer, G. R. Dempster, Jr., H. G. Golden.	Johnson and Sayre (1973), Anderson (1970), Jennings and Mattraw (1976), Sauer (1974), Dempster (1974).
Low-flow frequency	--	--	X	X	H. C. Riggs, J. T. Armbruster, M. E. Moss.	Riggs (1972), Armbruster (1976), Hardison and Moss (1972).
Storage potential	--	--	X	--	H. C. Riggs, C. H. Hardison.	Riggs and Hardison (1973).
Channel geometry and flow—regionalized	--	X	X	--	E. R. Hedman, H. C. Riggs, D. O. Moore, A. G. Scott.	Hedman and Kastner (1974), Riggs and Harenberg (1976), Scott and Kunkler (1976).
Regionalized streamflow characteristics	--	X	X	X	D. M. Thomas, H. C. Riggs, M. E. Moss.	Thomas and Benson (1970), Riggs (1973), Flippo (1976).
Water-quality statistical analysis	--	--	X	X	T. D. Steele, E. J. Gilroy, N. C. Matalas, R. O. Hawkinson, D. J. Lystrom.	Steele and Matalas (1974), Steele, Gilroy and Hawkinson (1974), Blakey, Hawkinson, and Steele (1972), Steele (1972, 1973).

TABLE 1.—*Status of surface-water modeling, U.S. Geological Survey*—Continued

	Phase of activity					
	Developmental	Verification	Operational	Continued improvement	Principal U.S. Geological Survey investigators	Recently published selected references
Management and Operations						
Gaging network design						
Network analysis	--	--	X	--	M. E. Moss, D. E. Burkham, N. C. Matalas, E. J. Gilroy, P. H. Carrigan, Jr.	Moss and Dawdy (1973), Carrigan and Golden (1975), Moss Moss (1976).
Socioeconomic analysis	--	--	X	X	I. C. James, II, M. E. Moss, M. R. Karlinger, E. D. Attanasi.	Moody (1973), James (1973), Attanasi (1973), Attanasi, Close and Lopez (1975).
National stream quality accounting network	--	X	X	--	J. F. Ficke, R. O. Hawkinson, T. D. Steele, J. C. Briggs.	Hawkinson, Ficke, and Saindon (1977).
River-basin assessment, Yampa River, Colorado and Wyoming	X	--	--	--	T. D. Steele, D. P. Bauer, D. A. Wentz.	Bauer, Steele, and Anderson (1978).
Satellite data relay	X	X	--	--	R. W. Paulson, W. G. Shope.	Paulson (1976).
Miscellaneous Hydrologic Studies						
Remote sensing						
Water management and ecologic prediction	X	X	X	--	A. L. Higer, V. P. Carter, M. E. Jennings.	Higer, Coker, and Cordes (1976), Higer, Cordes, and Coker (1976), Jennings and O'Neil (1976).
Snow hydrology	X	X	X	--	G. H. Leavesley, W. V. Tangborn, M. F. Meier, L. A. Rasmussen.	Meier (1975), Tangborn and Rasmussen (1977).
Isotope hydrology	X	--	--	--	T. B. Coplen.	
Fishery studies	--	X	X	--	R. P. Novitzki.	Novitzki (1976).
Strip mining effects	X	X	X	--	G. C. Lusby, G. H. Leavesley, G. L. Feder.	Lusby and Toy (1976), Leavesley (1977).
Glacial hydrology	X	X	X	--	M. F. Meier, S. M. Hodge, R. M. Krimmel, W. V. Tangborn, L. R. Mayo.	Rasmussen and Campbell (1973), Hodge (1976), Krimmel, Tangborn, and Meier (1972), Meier and others (1971).

models, which generally make use of all available data, cannot be subjected to verification.

Models listed in the "operational" phase are ready to be applied to field problems and are documented in some form. In many "operational" models, additional efforts are being made to improve accuracy, flexibility, or convenience of application. This phase is defined as "continued improvement."

Many investigators other than those listed in table 1 are, or have been, involved in the particular modeling activity. The investigators listed in table 1 can be located through the U.S. Geological Survey, Water Resources Division, National Center, Reston, Virginia 22092.

The "recently published" references in table 1 provide useful details on the characteristics and capabilities of the subject model. These as well as additional references are given in the list "Recently published selected references." The list is not meant to be exhaustive of all publications. In particular, the references in the categories of "Sedimentation," "Statistical Hydrology," and "Management and Operations" represent a very limited portion of documents and publication available in these specialized fields.

REFERENCES BEFORE 1970

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