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Mathematical Modeling of Watershed Hydrology

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Abstract: Mathematical modeling of watershed hydrology is employed to address a wide spectrum of environmental and water resources problems. A historical perspective of hydrologic modeling is provided, and new developments and challenges in watershed models are discussed. These include data acquisition by remote sensing and space technology, digital terrain and elevation models, chemical tracers, geographic information and data management systems, topographic representation, upscaling of hydrologic conservation equations, spatial variability of hydraulic roughness, infiltration and precipitation, spatial and temporal scaling, model calibration, and linking with water quality models. Model construction, calibration, and data processing have received a great deal of attention, while model validation, error propagation, and analyses of uncertainty, risk, and reliability have not been treated as thoroughly. Finally, some remarks are made regarding the future outlook for watershed hydrology modeling.

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Introduction

Hydrology was defined by Penman (1961) as the science that attempts to answer the question, ‘‘What happens to the rain’’? This sounds like a simple enough question, but experience has shown that quantitative descriptions of the land phase of the hydrologic cycle may become very complicated and are subject to a great deal of uncertainty. The term ‘‘watershed hydrology’’ is defined as that branch of hydrology that deals with the integration of hydrologic processes at the watershed scale to determine the watershed response. The emphasis in this paper is on the models that accomplish this integration, not on the models of individual component processes.

A watershed may be as small as a flower bed or a parking lot or as large as hundreds of thousands of square kilometers as exemplified by the Mississippi River basin. Operative hydrologic processes and their spatial nonuniformity are defined by climate, topography, geology, soils, vegetation, and land use and are related to the basin size. The nonuniformity of hydrologic processes is also directly related to the watershed size.

Mathematical models of watershed hydrology are designed to answer Penman’s question at a level of detail depending on the problem at hand and are employed in a wide spectrum of areas ranging from watershed management to engineering design (Singh 1995a). They are used in the planning, design, and operation of projects, to conserve water and soil resources and to protect their quality. At the field scale, models are used for varied purposes, such as planning and designing soil conservation practices, irrigation water management, wetland restoration, stream restoration, and water-table management. On a large scale, models are used for flood protection projects, rehabilitation of aging dams, floodplain management, water-quality evaluation, and water-supply forecasting.

Watershed models are fundamental to water resources assessment, development, and management. They are, for example, used to analyze the quantity and quality of streamflow, reservoir system operations, groundwater development and protection, surface water and groundwater conjunctive use management, water distribution systems, water use, and a range of water resources management activities (Wurbs 1998).

Watershed models are employed to understand dynamic interactions between climate and land-surface hydrology. For example, vegetation, snow cover, permafrost active layer, etc. are quite sensitive to the lower boundary of the atmospheric system. The water and heat transfer between the land surface and atmosphere significantly influences hydrologic characteristics and yield, and in turn, lower boundary conditions for climate modeling (Kavvas et al. 1998). An assessment of the impact of climate change on national water resources and agricultural productivity is made possible by the use of watershed models.

Water allocation requires an integration of watershed models with models of physical habitat, biological populations, and economic response. Estimating the value of instream water use allows recreational, ecological, and biological concerns to compete with traditional consumptive uses, i.e., agriculture, hydropower, municipality, and industry (Hickey and Diaz 1999). Watershed models are utilized to quantify the impacts of watershed management strategies, linking human activities within the watershed to water quantity and quality of the receiving stream or lake (Mankin et al. 1999; Rudra et al. 1999) for environmental and water resources protection.

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In summary, watershed models have become an essential tool for water resources planning, development, and management. In the years ahead, the models will become even more common and will play an increasing role in our day-to-day lives. The objective of this work is to provide a historical perspective of watershed modeling, provide a short synopsis of currently used models, reflect on new developments and challenges, and conclude with a personal view of what the future has in store for mathematical modeling of watershed hydrology.

Historical Perspective

Hydrological modeling has a long and colorful history. Its beginning can be traced to the development of civil engineering in the nineteenth century for the design of roads, canals, city sewers, drainage systems, dams, culverts, bridges, and water-supply systems. Until the middle of the 1960s, hydrologic modeling primarily involved the development of concepts, theories and models of individual components of the hydrologic cycle, such as overland flow, channel flow, infiltration, depression storage, evaporation, interception, subsurface flow, and base flow. The Hortonian mechanism, subsurface flow mechanism, and partial and source area contributions were recognized as contributors to runoff.

Development of Component Models

The origin of mathematical modeling dates back to the rational method developed by Mulvany (1850) and an ''event'' model by Imbeau (1892) for relating storm runoff peak to rainfall intensity. About four decades later, Sherman (1932) introduced the unit hydrograph concept for relating the direct runoff response to rainfall excess. About the same time, Horton (1933) developed a theory of infiltration to estimate rainfall excess and improve hydrograph separation techniques. Horton (1939) investigated overland flow and produced a semiempirical formula. Keulegan (1944) made a theoretical investigation of overland flow and suggested that simplifying the equations to what is now termed the kinematic wave form would be appropriate. Izzard (1944) followed with an experimental analysis. Horton (1945) developed a concept of erosional land-form development and streamflow generation dominated by overland flow. Presented in this pioneering work were a set of empirical laws, now known as Horton's laws, which constituted the foundation of quantitative geomorphology. In these contributions, evaporation and other abstractions were treated using coefficients or indices.

Concurrent with Horton's work, Lowdermilk (1934), Hursh (1936), and Hursh and Brater (1944) observed that subsurface water movement constituted one component of storm flow hydrographs in humid regions. Subsequently, Hoover and Hursh (1943) and Hursh (1944) reported significant storm-flow generation caused by a ''dynamic form of subsurface flow.'' Roessel (1950) observed dynamic changes in streamside groundwater flow. Based on the works of Hewlett (1961a,b), Nielsen et al. (1959), Remson et al. (1960), among others, it is now accepted that downslope unsaturated flow can contribute to streamside saturated zones and thus generate streamflow. Through the years since the 1940s, this thinking culminated into what is now referred to as subsurface flow mechanism and has indeed expanded into a more integrated understanding of streamflow generation, of which Horton's theory is but a part.

One of the earliest attempts to develop a theory of infiltration was by Green and Ampt (1911) who, using simplified principles of physics, derived a formula that is still popular for computing the infiltration capacity rate. The empirical equations of Kostiakov (1932) and Horton (1933, 1935, 1939, 1940) are also used by some current watershed models. Early work describing evaporation from lakes was done by Richardson (1931) and Cummings (1935), while Thornthwaite (1948) and Penman (1948) made important contributions to models of evapotranspiration.

There were also attempts to quantify other abstractions, such as interception, depression storage, and detention storage. Horton (1919) derived a series of empirical formulas for estimating interception during a storm for various types of vegetal covers. The Soil Conservation Service (SCS) (1956), now called the Natural Resources Conservation Service of the U.S. Department of Agriculture, developed what is now referred to as the SCS-curve number method for computing the amount of storm runoff, taking abstractions into account. Although it was originally intended to model daily runoff as affected by land-use practices, it has been used to model infiltration as well as runoff hydrograph for continuous hydrologic simulation.

The underground phase of the hydrologic cycle was investigated by Fair and Hatch (1933), who derived a formula for computing the permeability of soil. Theis (1935) combined Darcy's law with the continuity equation to derive the relation between the lowering of the piezometric surface and the rate and duration of discharge of a well. This work laid the foundation of quantitative groundwater hydrology. Jacob (1943, 1944) correlated groundwater levels and precipitation on Long Island, N.Y. The study of groundwater and infiltration led to the development of techniques for separation of baseflow and interflow in a hydrograph (Barnes 1940).

Puls (1928), of the U.S. Army Corps of Engineers, Chattanooga District, developed a method for flow routing through reservoirs, assuming invariable storage-discharge relationships and neglecting the variable slope during flood propagation. This method, later modified by the U.S. Bureau of Reclamation (1949), is now referred to as the modified Puls method. Using the concept of wedge and prism storage, McCarthy and others developed the Muskingum method of flow routing in 1934–1935 (U.S Army Corps of Engineers 1936). This method is still used for flood routing in several watershed models.

After a lull of nearly a quarter century in the area of rainfall-runoff modeling, a flurry of modeling activity started around the middle of the 1950s. A major effort employed the theory of linear systems, which led to the theory of the instantaneous unit hydrograph by Nash (1957) and then the generalized unit hydrograph theory by Dooge (1959). Lighthill and Whitham (1955) developed kinematic wave theory for flow routing in long rivers. This theory is now accepted as a standard tool for modeling overland flow and a variety of other hydrologic processes.

Development of Watershed Models

The decade of the 1960s witnessed the digital revolution that made possible the integration of models of different components of the hydrologic cycle and simulation of virtually the entire watershed, as exemplified by the seminal contribution of the Stanford Watershed Model-SWM (now HSPF) by Crawford and Linsley (1966). This was probably the first attempt to model virtually the entire hydrologic cycle. Simultaneously, a number of somewhat less comprehensive models were developed. Examples of such models that became popular are the watershed models of Dawdy and O'Donnell (1965) and HEC-1 (Hydrologic Engineering Center 1968). Also, a number of semidistributed models capable of accounting for the spatial variability of hydrologic processes within the watershed were developed, as illustrated by tank models developed by Sugawara (1967) and Sugawara et al. (1974).

Indeed there has been a proliferation of watershed hydrology models since the development of SWM (or HSPF), with emphasis on physically based models. Examples of such watershed hydrology models are SWMM (Metcalf and Eddy et al. 1971), PRMS (Leavesley et al. 1983), NWS River Forecast System (Burnash et al. 1973), SSARR (Rockwood 1982), Systeme Hydrologique Europeen (SHE) (Abbott et al. 1986a,b), TOPMODEL (Beven and Kirkby 1979), IHDM (Morris 1980), and so on. All of these models have since been significantly improved. SWM, now called HSPF, is far more comprehensive than its original version. SHE has been extended to include sediment transport and is applicable at the scale of a river basin (Bathhurst et al. 1995). TOPMODEL has been extended to contain increased catchment information, more physically based processes, and improved parameter estimation.

The digital revolution also triggered two other revolutions, namely, numerical simulation and statistical simulation. The power of computers increased exponentially and, as a result, advances in watershed hydrology have occurred at an unprecedented pace during the past 35 years. During the decades of the 1970s and 1980s, a number of mathematical models were developed not only for simulation of watershed hydrology but also for their applications in other areas, such as environmental and ecosystems management. Development of new models or improvement of previously developed models continues today. Table 1 shows in chronological order a sample of popular hydrologic models from around the globe. These days virtually all federal agencies in the United States have their own models or some variants of models developed elsewhere.

In 1991, the Bureau of Reclamation (1991) prepared an inventory of 64 watershed hydrology models classified into four categories, and the inventory is currently being updated. Burton (1993) compiled the *Proceedings of the Federal Interagency Workshop on Hydrologic Modeling Demands for the 1990's*, which contains several important watershed hydrology models. Singh (1995b) edited a book that summarized 26 popular models from around the globe. The Subcommittee on Hydrology of the Interagency Advisory Committee on Water Data (USGS 1998) published the *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, which contains many popular watershed hydrology models developed by federal agencies in the United States. Wurbs (1998) listed a number of generalized water resources simulation models in seven categories and discussed their dissemination.

Currently used Watershed Models

There are several well known general watershed models in current use in the United States and elsewhere. These models vary significantly in the model construct of each individual component process, partly because these models serve somewhat different purposes. HEC-HMS is considered the standard model in the private sector in the United States for the design of drainage systems, quantifying the effect of land-use change on flooding, etc. The NWS model is the standard model for flood forecasting. HSPF and its extended water quality model are the standard models adopted by the Environmental Protection Agency (EPS). The MMS model of the USGS is the standard model for water resources planning and management works, especially those under the purview of the U.S. Bureau of Reclamation. The UBC and WATFLOOD models are popular in Canada for hydrologic simulation. The RORB and WBN models are commonly employed for flood forecasting, drainage design, and evaluating the effect of land-use change in Australia. TOPMODEL and SHE are the standard models for hydrologic analysis in many European countries. The HBV model is the standard model for flow forecasting in Scandinavian countries. The ARNO, LCS, and TOPIKAPI models are popular in Italy. The Tank models are well accepted in Japan. The Xinanjiang model is a commonly used model in China.

Comparison of Watershed Models

The World Meteorological Organization (WMO) sponsored three studies on intercomparison of watershed hydrology models. The first study (World Meteorological Organization 1975) dealt with conceptual models used in hydrologic forecasting. The second study (WMO 1986) dealt with an intercomparison of models used for simulation of flow rates, including snowmelt. The third study (WMO 1992) dealt with models for forecasting streamflow in real time. Except for the WMO reports, no comprehensive effort has been made to compare most major watershed hydrology models. However, efforts have been made to compare models of some component processes. Also, developers of some models have compared their models with one or a few other models.

Review and Synthesis

During the period 1970–1995, several very instructive state-of-the-art papers dealing with watershed modeling appeared. It is beyond the scope of this paper to deal with a large sample of such papers, but it is interesting to compare modeling concepts and challenges expressed by Hornberger and Boyer (1995) with those considered to be important 22 years earlier (Clarke 1973; Woolhiser 1973). Clarke (1973) discussed important issues regarding model identification and diagnosis and parameter estimation and showed that interdependence between model parameters required extensive exploration of error objective function surfaces, particularly when the model is used to determine the likely effects of land-use change. Woolhiser (1973) pointed out the importance of estimates of initial conditions for nutrient transport models and also reasoned that model verification and estimation of model parameters needed more attention.

Several investigators reviewed hydrologic models developed up to the beginning of the 1980s and discussed model reliability and future directions (Linsley 1982; Dawdy 1982; James et al. 1982; James and Burges 1982a,b; Delleur 1982; Jackson 1982). Todini (1988a,b) reviewed the historical development of mathematical methods used in rainfall-runoff modeling and classified the models based on a priori knowledge and problem requirements. He foresaw the increasing role of distributed models, satellite, and radar technology in watershed hydrology and noted that techniques for model calibration and verification remained less than robust.

Goodrich and Woolhiser (1991) reviewed progress in catchment hydrology in the United States and emphasized that a detailed process-based understanding of hydrologic response over a range of catchment scales, 0.01–500 km^2, still eluded the hydrologic community. El-Kady (1989) reviewed numerous watershed models and concluded that the surface water-groundwater linkage needed improvement, while ensuring an integrated treatment of the complexity and scale of individual component processes.

Table 1. Sample of Popular Hydrologic Models

Model name/acronym	Author(s) (year)	Remarks
Stanford watershed Model (SWM)/Hydrologic Simulation Package-Fortran IV (HSPF)	Crawford and Linsley (1966), Bicknell et al. (1993)	Continuous, dynamic event or steady-state simulator of hydrologic and hydraulic and water quality processes
Catchment Model (CM)	Dawdy and O'Donnell (1965)	Lumped, event-based runoff model
Tennessee Valley Authority (TVA) Model	Tenn. Valley Authority (1972)	Lumped, event-based runoff model
U.S. Department of Agriculture Hydrograph Laboratory (USDAHL) Model	Holtan and Lopez (1971), Holtan et al. (1974)	Event-based, process-oriented, lumped hydrograph model
U.S. Geological Survey (USGS) Model	Dawdy et al. (1970, 1978)	Process-oriented, continuous/event-based runoff model
Utah State University (USU) Model	Andrews et al. (1978)	Process-oriented, event/continuous streamflow model
Purdue Model	Huggins and Monke (1970)	Process-oriented, physically based, event runoff model
Antecedent Precipitation Index (API) Model	Sittner et al. (1969)	Lumped, river flow forecast model
Hydrologic Engineering Center—Hydrologic Modeling System (HEC-HMS)	Feldman (1981), HEC (1981, 2000)	Physically-based, semidistributed, event-based, runoff model
Streamflow Synthesis and Reservoir regulation (SSARR) Model	Rockwood (1982), U.S. Army Corps of Engineers (1987), Speers (1995)	Lumped, continuous streamflow simulation model
National Weather service-River Forecast System (NWS-RFS)	Burnash et al. (1973a,b), Burnash (1975)	Lumped, continuous river forecast system
University of British Columbia (UBC) Model	Quick and Pipes (1977), Quick (1195)	Process-oriented, lumped parameter, continuous simulation model
Tank Model	Sugawara et al. (1974), Sugawara (1995)	Process-oriented, semidistributed or lumped continuous simulation model
Runoff Routing Model (RORB)	Laurenson (1964), Laurenson and Mein (1993, 1995)	Lumped, event-based runoff simulation model
Agricultural Runoff Model (ARM)	Donigian et al. (1977)	Process-oriented, lumped runoff simulation model
Storm Water Management Model (SWMM)	Metcalf and Eddy et al. (1971), Huber and Dickinson (1988), Huber (1995)	Process-oriented, semidistributed, continuous stormflow model
Xinanjiang Model	Zhao et al. (1980), Zhao and Liu (1195)	Process-oriented, lumped, continuous simulation model
Hydrological Simulation (HBV) Model	Bergstrom (1976, 1992, 1995)	Process-oriented, lumped, continuous streamflow simulation model
Great Lakes Environmental Research Laboratory (GLERL) Model	Croley (1982, 1983)	Physically based, semidistributed continuous simulation model
Pennsylvania State University—Urban Runoff Model (PSU-URM)	Aron and Lakatos (1980)	Lumped, event-based urban runoff model
Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS)	USDA (1980)	Process-oriented, lumped parameter, agricultural runoff and water quality model
Areal Non-point Source Watershed Environment Response Simulation (ANSWERS)	Beasley et al. (1977), Bouraoui et al. (2002)	Event-based or continuous, lumped parameter runoff and sediment yield simulation model
Erosion Productivity Impact Calculator (EPIC) Model	Williams et al. (1984), Williams (1995a,b)	Process-oriented, lumped-parameter, continuous water quantity and quality simulation model
Simulator for Water Resources in Rural Basins (SWRRB)	Williams et al. (1985), Williams (1995a,b)	Process-oriented, semidistributed, runoff and sediment yield simulation model
Simulation of Production and Utilization of Rangelands (SPUR)	Wight and Skiles (1987), Carlson and Thurow (1992), Carlson et al. (1995)	Physically based, lumped parameter ecosystem simulation model
National Hydrology Research Institute (NHRI) Model	Vandenberg (1989)	Physically based, lumped parameter, continuous hydrologic simulation model
Technical Report-20 (TR-20) Model	Soil Conservation Service (1965)	Lumped parameter, event based runoff simulation model

Table 1. *Continued*

Model name/acronym	Author(s) (year)	Remarks
Systeme Hydrologique Europeen/Systeme Hydrologique Europeen Sediment (SHE/SHESED)	Abbott et al. (1986a,b), Bathurst et al. (1995)	Physically based, distributed, continuous streamflow and sediment simulation
Institute of Hydrology Distributed Model (IHDM)	Beven et al. (1987), Calver and Wood (1995)	Physically based, distributed, continuous rainfall-runoff modeling system
Physically Based Runoff Production Model (TOPMODEL)	Beven and Kirkby (1976, 1979), Beven (1995)	Physically based, distributed, continuous hydrologic simulation model
Agricultural Non-Point Source Model (AGNPS)	Young et al. (1989, 1995)	Distributed parameter, event-based, water quantity and quality simulation model
Kinematic Runoff and Erosion Model (KINEROS)	Woolhiser et al. (1990), Smith et al. (1995)	Physically based, semidistributed, event-based, runoff and water quality simulation model
Groundwater Loading Effects of Agricultural Management Systems (GLEAMS)	Knisel et al. (1993), Knisel and Williams (1995)	Process-oriented, lumped parameter, event-based water quantity and quality simulation model
Generalized River Modeling Package—Systeme Hydroloque Europeen (MIKE-SHE)	Refsgaard and Storm (1195)	Physically based, distributed, continuous hydrologic and hydraulic simulation model
Simple Lumped Reservoir Parametric (SLURP) Model	Kite (1995)	Process-oriented, distributed, continuous simulation model
Snowmelt Runoff Model (SRM)	Rango (1995)	Lumped, continuous snowmelt-runoff simulation model
THALES	Grayson et al. (1195)	Process-oriented, distributed-parameter, terrain analysis-based, event-based runoff simulation model
Constrained Linear Simulation (CLS)	Natale and Todini (1976a,b, 1977)	Lumped parameter, event-based or continuous runoff simulation model
ARNO (Arno River) Model	Todini (1988a,b, 1996)	Semidistributed, continuous rainfall-runoff simulation model
Waterloo Flood System (WATFLOOD)	Kouwen et al. (1993), Kouwen (2000)	Process-oriented, semidistributed continuous flow simulation model
Topgraphic Kinematic Approximation and Integration (TOPIKAPI) Model	Todini (1995)	Distributed, physically based, continuous rainfall-runoff simulation model
Hydrological (CEQUEAU) Model	Morin et al. (1995, 1998)	Distributed, process-oriented, continuous runoff simulation model
Large Scale Catchment Model (LASCAM)	Sivapalan et al. (1996a,b,c)	Conceptual, semidistributed, large scale, continuous, runoff and water quality simulation model
Mathematical Model of Rainfall-Runoff Transformation System (WISTOO)	Ozga-Zielinska and Brzezinski (1994)	Process-oriented, semidistributed, event-based or continuous simulation model
Rainfall-Runoff (R-R) Model	Kokkonen et al. (1999)	Semidistributed, process-oriented, continuous streamflow simulation model
Soil-Vegetation-Atmosphere Transfer (SVAT) Model	Ma et al. (1999), Ma and Cheng (1998)	Macroscale, lumped parameter, streamflow simulation system
Hydrologic Model System (HMS)	Yu (1996), Yu and Schwartz (1998), Yu et al. (1999)	Physically based, distributed-parameter, continuous hydrologic simulation system
Hydrological Modeling System (ARC/EGMO)	Becker and Pfutzner (1987), Lahmer et al. (1999)	Process-oriented, distributed, continuous simulation system
Macroscale Hydrolgical Model-Land Surface Scheme (MODCOU-ISBA)	Ledoux et al. (1989), Noilhan and Mahfouf (1996)	Macroscale, physically based, distributed, continuous simulation model
Regional-Scale Hydroclimatic Model (RSHM)	Kavas et al. (1998)	Process-oriented, regional scale, continuous hydrologic simulation model
Global Hydrology Model (GHM)	Anderson and Kavvas (2002)	Process-oriented, semidistributed, large scale hydrologic simulation model
Distributed Hydrology Soil Vegetation Model (DHSVM)	Wigmosta et al. (1994)	Distributed, physically based, continuous hydrologic simulation model
Systeme Hydrologique Europeen Transport (SHETRAN)	Ewen et al. (2000)	Physically based, distributed, water quantity and quality simulation model
Cascade two dimensional Model (CASC2D)	Julien and Saghafian (1991), Ogden (1998)	Physically based, distributed, event-based runoff simulation model
Dynamic Watershed Simulation Model (DWSM)	Borah and Bera (2000), Borah et al. (1999)	Process-oriented, event-based, runoff and water quality simulation model
Surface Runoff, Infiltration, River Discharge and Groundwater Flow (SIRG)	Yoo (2002)	Physically based, lumped parameter, event-based streamflow simulation model

Table 1. *Continued*

Model name/acronym	Author(s) (year)	Remarks
Modular Kinematic Model for Runoff Simulation (Modular System)	Stephenson (1989) Stephenson and Randell (1999)	Physically based, lumped parameter, event-based runoff simulation model
Watershed Bounded Network Model (WBNM)	Boyd et al. (1979, 1996), Rigby et al. (1991)	Geomorphology-based, lumped parameter, event-based flood simulation model
Geomorphology-Based Hydrology Simulation Model (GBHM)	Yang et al. (1998)	Physically based, distributed, continuous hydrologic simulation model
Predicting Arable Resource Capture in Hostile Environments-The Harvesting of Incident Rainfall in Semi-arid Tropics (PARCHED-THIRST)	Young and Gowing (1996) Wyseure et al. (2002)	Process-oriented, lumped parameter, event-based agro-hydrologic model
Daily Conceptual Rainfall-Runoff Model (HYDROLOG)-Monash Model	Potter and McMahon (1976), Chiew and McMahon (1994)	Lumped, conceptual rainfall-runoff model
Simplified Hydrology Model (SIMHYD)	Chiew et al. (2002)	Conceptual, daily, lumped parameter rainfall-runoff model
Two Parameter Monthly Water Balance Model (TPMWBM)	Guo and Wang (1994)	Process-oriented, lumped parameter, monthly runoff simulation model
The Water and Snow Balance Modeling System (WASMOD)	Xu (1999)	Conceptual, lumped, continuous hydrologic model
Integrated Hydrometeorological Forecasting System (IHFS)	Georgakakos et al. (1999)	Process-oriented, distributed, rainfall and flow forecasting system
Stochastic Event Flood Model (SEFM)	Scaefer and Barker (1999)	Process-oriented, physically based event-based, flood simulation model
Distributed Hydrological Model (HYDROTEL)	Fortin et al. (2001a,b)	Physically based, distributed, continuous hydrologic simulation model
Agricultural Transport Model (ACTMO)	Frere et al. (1975)	Lumped, conceptual, event-based runoff and water quality simulation model
Soil Water Assessment Tool (SWAT)	Arnold et al. (1998)	Distributed, conceptual, continuous simulation model

While reviewing advances in watershed modeling, Hornberger and Boyer (1995) emphasized the need to deal with spatial variability and scaling and the need to explicitly consider linkages among hydrology, geochemistry, environmental biology, meteorology, and climatology. The most important recent advances in watershed modeling were noted to have been the employment of geographical information systems (GIS), remotely sensed data, and environmental tracers. The need for the acquisition of more data and more experimentation were emphasized for future progress of hydrology.

Advances in scientific understanding and subsequent engineering applications come about through new theoretical insights, unique observations, or by the development of new measurement or computational techniques. It appears that there have been few theoretical breakthroughs. For example, Freeze and Harlan (1969) laid out the blueprint for a three-dimensional watershed model, including precipitation, surface runoff, porous media flow, open channel flow, interaction of groundwater and channel flow, and transport of water to the atmosphere by evaporation and transpiration. The model could not be implemented at the time because of computational and data limitations. However, it is a conceptual forerunner of the watershed model SHE (Abbott et al. 1986a,b). The Stanford Watershed Model (Crawford and Linsley 1962, 1966) was considered to be the standard for applied models in 1973. Many current models have essentially the same fundamental structure. The modeling of water quality was just beginning, and models of dissolved oxygen in a reach of stream, transport of conservative and nonconservative pollutants, radioactive aerosols, and nutrients in streams and watersheds were under development.

Many of the advances after 1973 were due to improvements in computational facilities or new measurement techniques. Others were due to insights obtained by comparing model results with experimental data. For example, little thought was given to the problem of subgrid scale variability in 1973. It was assumed that it was only necessary for a distributed model to accommodate the variability of saturated hydraulic conductivity due to different soil types and vegetative cover as well as watershed topography and channel geometry. Small-scale spatial variability of saturated conductivity, i.e., within a computational element, was not considered important until analysis of data from rainfall simulator plots showed an increase in infiltration rate with rainfall intensity (e.g., Hawkins and Cundy 1987). Many of the challenges discussed by Hornberger and Boyer (1995) result from new technology; the use of digital elevation models (DEMs) and GIS raises the question of subgrid variability and the effect of pixel size on model calibration. One new concept that appeared is the use of topographic indices such as those used in TOPMODEL (Beven and Kirkby 1979; Binley et al. 1989a,b). Another new approach is the use of chemical tracers in conjunction with numerical models. Another new concept is one of upscaling of hydrologic conservation equations and subgrid spatial variability.

Classification of Watershed Hydrology Models

A watershed hydrology model is an assemblage of mathematical descriptions of components of the hydrologic cycle. The model structure and architecture are determined by the objective for which the model is built. For example, a hydrologic model for flood control is quite different from the one for hydropower generation or reservoir operation. Likewise, a model for water resources planning is significantly different from the one used for water resources design or ecological management. Singh (1995a) classified hydrologic models based on (1) process description; (2)

timescale; (3) space scale; (4) techniques of solution; (5) land use; and (6) model use. ASCE (1996) reviewed and categorized flood analysis models into (1) event-based precipitation-runoff models; (2) continuous precipitation-runoff models; (3) steady flow routing models; (4) unsteady-flow flood routing models; (5) reservoir regulation models; and (6) flood frequency analysis models.

Although the mathematical equations embedded in watershed models are continuous in time and often space, analytical solutions cannot be obtained except in very simple circumstances. Numerical methods (finite difference, finite element, boundary element, boundary fitted coordinate) must be used for practical cases. The most general formulation would involve partial differential equations in three space dimensions and time. If the spatial derivatives are ignored, the model is said to be ''lumped''; otherwise, it is said to be ''distributed,'' and the solution (output) is a function of space and time. Strictly speaking, if a model is truly distributed, all aspects of the model must be distributed including parameters, initial and boundary conditions, and sources and sinks. Practical limitations of data and discrete descriptions of watershed geometry and parameters to conform to the numerical solution grid or mesh do not permit a fully distributed characterization. Most watershed hydrology models are deterministic, but some consist of one or more stochastic components.

Several scientific disciplines have developed mathematical descriptions of components of the hydrological cycle, using basic physical principles in conjunction with experimental data. The physical fidelity of these models depends on the objective of the researcher and the tools available to solve the resulting equations. The watershed modeler has wide latitude in choosing the level of rigor or detail required of an individual component model, and the choices are affected by the objectives, watershed topography, geology, soils, land use, and the available information.

Although watershed models may be complicated with many parameters, frequently, the information that they are required to provide is very simple, as for example, the mean annual groundwater recharge rate over part of the basin or the 100-year flood. Statistical tools, including regression and correlation analysis, time-series analysis, stochastic processes, and probabilistic analysis are necessary to analyze the output to provide this type of information. Because of uncertainties in model structure, parameter values and precipitation, and other climatic inputs, uncertainty analysis and reliability analysis can be employed to examine their impact.

Wurbs (1998) highlighted the availability and role of generalized computer modeling packages and outlined the institutional setting within which the models are disseminated throughout the water community. Generalized water resources models were classified into (1) watershed models; (2) river hydraulics models; (3) river and reservoir water quality models; (4) reservoir/river system operation models; (5) groundwater models; (6) water distribution system hydraulic models; and (7) demand forecasting models.

Hydrologic Data Needs

Frequently, the type of a model to be built is dictated by the availability of data. In general, distributed models require more data than do lumped models. In most cases, needed data either do not exist or are not available in full. That is one reason why regionalization and synthetic techniques are useful. Even if the needed data are available, problems remain with regard to completeness, inaccuracy, and inhomogeneity of data. Then, of course, storage, handling, retrieval, analysis, and manipulation of data have to be dealt with. If the volume of data required is large, data processing and management can be quite a sophisticated undertaking.

The data needed for watershed hydrology modeling are hydrometeorologic, geomorphologic, agricultural, pedologic, geologic, and hydrologic. Hydrometeorologic data include rainfall, snowfall, temperature, radiation, humidity, vapor pressure, sunshine hours, wind velocity, and pan evaporation. Agricultural data include vegetative cover, land use, treatment, and fertilizer application. Pedologic data include soil type, texture and structure, soil condition, soil particle size diameter, porosity, moisture content and capillary pressure, steady-state infiltration, saturated hydraulic conductivity, and antecedent moisture content. Geologic data include data on stratigraphy, lithology, and structural controls. More specifically, data on the type, depth, and areal extent of aquifers are needed. Depending on the nature of aquifers, these data requirements vary. For confined aquifers, hydraulic conductivity, transmissivity, storativity, compressibility, and porosity are needed. For unconfined aquifers, data on specific yield, specific storage, hydraulic conductivity, porosity, water table, and recharge are needed. Each dataset is examined with respect to homogeneity, completeness, and accuracy. Geomorphologic data include topographic maps showing elevation contours, river networks, drainage areas, slopes and slope lengths, and watershed area. Hydrologic data include flow depth, streamflow discharge, base flow, interflow, stream-aquifer interaction, potential, water table, and drawdowns.

New Developments and Challenges in Watershed Models

Data Acquisition

Remote Sensing and Space Technology

New data collection techniques, especially remote sensing, satellites, and radar, received a great deal of attention in the 1980s and continue to do so. Major advances have been made in recent years in remote sensing and radar and satellite technology, which are going a long way in alleviating the scarcity of data that is one of the major difficulties in watershed hydrologic modeling. This technology provides synoptic data regarding spatial distribution of meteorological inputs; soil and land-use parameters; initial conditions; inventories of water bodies; such as dams, lakes, swamps, flooded areas, rivers, etc.; mapping of snow and ice conditions; water-quality parameters, etc. (Engman and Gurney 1991). Digital imagery provides mapping of spatially varying landscape attributes. Goodrich et al. (1994) employed remotely sensed soil wetness for modeling runoff in semiarid environments.

Radar is being employed for rainfall measurements. In contrast with point measurements provided by the usual rain-gauging techniques, the advantage of radar measurements is that they provide spatial mapping of rainfall, which is badly needed for distributed models. The Next Generation Weather Radar, Weather Surveillance Radars-88 Doppler, among others, are being employed to near real-time high-resolution precipitation volume and intensity over space and time. The Soil (now Natural Resources) Conservation Service collects real-time data on snowpacks from a network of about 500 snowpack telemetry sites located in remote mountainous areas of the western United States. These point measurements are augmented by satellite remote sensing to provide spatial and temporal distribution of snowpack properties. The National Operational Hydrologic Remote Sensing Center of the National Weather Service provides data on real-time snow-water equivalents for river basins in more than 25 states through its airborne gamma radiation measurements, and maps areal extent of snow cover for more than 4,000 river basins nationwide through satellite data from the Advanced Very High Resolution Radiometer and the Geostationary Operational Environmental Satellite.

The Landsat Thematic Mapper, *T* Multispectral Scanner, or Systeme Probatoire d' la Terre produce satellite imagery that, in conjunction with aerial photos and terrain data, has proved successful for providing data for mapping and classification of land use and vegetative land cover. Similary, the airborne light detection and ranging technology is being employed to provide accurate real-time flood inundation maps.

Nicks and Scheibe (1992) employed the Simulations for Water Resources in Rural Basins (SWRRB) model with NEXRAD radar information for rainfall data in modeling runoff from the Little Washita River watershed in southern Oklahoma. Duchon et al. (1992) employed these remotely sensed data in updating the SWRRB model parameters for analysis of the water budget of the Little Washita River watershed. Kite and Kouwen (1992) obtained improved estimates of hydrograph components from the Simple Lumped Reservoir Parametric (SLURP) model when they used Landsat-derived land-cover classes. Rango (1992) employed remotely sensed areal extent of snow-cover data in the SRM (Snowmelt Runoff Model) for 50 basins worldwide and discussed the potential use of this model to evaluate the effects of climate change scenarios.

With the vastly improved capability to observe hydrologic data, remote sensing and space technology are being increasingly coupled with watershed models for real-time flood forecasting, weather forecasting, forecasting of seasonal and/or short-term snowmelt runoff, evolution of watershed management strategies for conservation planning, development of reporting services for drought assessment/forecasting, mapping of groundwater potential to support the conjunctive use of surface water and groundwater, inventorying of coastal and marine processes, environmental impact assessment of large-scale water resource projects, flood-damage assessment, and the development of remote information matrix for irrigation development, to name but a few (Goodrich et al. 1991).

Digital Terrain and Elevation Models

Because physical characteristics of a watershed, such as soils, land use and topography, vary spatially, distributed watershed models may require huge volumes of data. The primary source of topographic information prior to the 1980s consisted of contour maps. Advances in digital mapping have provided essential tools to closely represent the 3D nature of natural landscapes. One such tool is the digital terrain (DTM) or DEM models. DEMs automatically extract topographic variables, such as basin geometry, stream networks, slope, aspect, flow direction, etc. from raster elevation data. Three schemes for structuring elevation data for DEMs are: triangulated irregular networks (TIN), grid networks, and vector or contour-based networks (Moore and Grayson 1991).

The most widely used data structures are grid networks. The ANSWERS (Beasley et al. 1980), AGNPS (Young et al. 1989), and SHE (Abbott et al. 1986a,b) are examples of hydrologic models that use a square grid or cell network as their basic structure. Although most efficient, Mark (1978) remarked that grid structures for spatially dividing watersheds are not appropriate for many hydrologic and geomorphologic applications. Moore and Grayson (1991) reported that computed flow paths took on zigzag shapes. Moore et al. (1988a,b) used contour-based DEMs for hydrologic and ecologic applications. O'Loughlin (1986) employed them to identify zones of saturation, and Moore and Burch (1986) used them to delineate zones of erosion and deposition. The grid and vector networks are useful for planning purposes. Silfer et al. (1987) used a kinematic wave model for computing overland flow, based on TIN-DEM representation. A similar concept was employed by Grayman et al. (1975), Vieux (1988), and Goodrich and Woolhiser (1991).

Hydrologic models with a spatial structure are being increasingly based on DEM or DTM (Moore et al. 1988a,b). Many of the existing models, such as SHE, TOPMODEL, etc., have been adapted to the new type of data. Integration of hydrologic models with remotely sensed, GIS, and DEM-based data has started to occur. Examples of newly developed or adapted models are those by Fortin et al. (2001a,b), Wigmosta et al. (1994), Julien et al. (1995), Desconnets et al. (1996), and Olivera and Maidment (1999), among others.

Chemical Tracers

Data on the chemical composition of water can be used for modeling the flow of water along different paths. These data help define surface, subsurface, and groundwater flows and thus help define hydrograph separation. Stable isotopes have been used for defining conceptual models of water flow (Stewart and McDonnell 1991). Radiogenic isotopes, both natural and anthropogenic, have been used as tracers (Rose 1992). Chloroflurocarbons have been employed to trace flow paths in groundwater systems (Dunkle et al. 1993). Chemical data can be used for model calibration, as was done by Robson et al. (1992) in the case of TOPMODEL. Adar and Neuman (1988) used environmental isotopes and hydrochemical data to estimate the spatial distribution of groundwater recharge. Tracers can provide a wealth of information on flow of water, its origin, source, and flow paths, etc.

Data Processing and Management: Geographic Information System and Database-Management Systems

For processing large quantities of data, GIS, database-management systems (DBMS), and graphic and visual design tools are some of the techniques available (Singh and Fiorentino 1996). Integration of these techniques with watershed hydrology models accomplishes a number of significant functions: designing, calibrating, modifying, evaluating, and comparing watershed hydrology models. For example, the use of GIS permits subdividing a watershed into hydrologically homogeneous subareas in both horizontal and vertical domains. Depending on the type of application requiring categorization of hydrologic properties, many combinations of spatial overlays can be performed. With the GIS technique, it is possible to delineate soil loss rates, identify potential areas of nonpoint source agricultural pollution, and map groundwater contamination susceptibility. GIS enhances the ability to incorporate spatial details beyond the existing capability of watershed hydrology models. With much better resolution of terrain-streams and drainage areas, the ability to delineate more appropriate grid layers for a finite-element or finite-difference watershed model is enhanced. The USGS Precipitation-Runoff Modeling System (PRMS) employs automated methods to derive required model parameters in which the hydrological response units (HRUs) are delineated using terrain analysis (Leavesley and Stannard 1990). Using a data-parameter interface, a GIS system computes the necessary model parameters within each HRU. Battaglin et al. (1993) found this interface concept to be useful in model parameterization and calibration on a series of basins. Vieux (1991) discussed several aspects of the use of GIS in watershed modeling.

Spatial Description of Topography

The various methods of simplifying watershed geometry can be divided into grid methods and conceptual methods (Singh 1996). Either method subdivides the watershed into subareas that are linked together by routing elements. Hromadka et al. (1988) attempted to quantify the effect of watershed subdivision on prediction accuracy of hydrologic models. When the watershed was divided into subareas, each subarea having identical parameters, the variance of peak flow estimates decreased significantly with increasing number of subareas. A grid method attempts to maintain model flow patterns similar to those in the prototype watershed response. This concept was introduced by Bernard (1937). Huggins and Monke (1968) used the same grid method to represent watershed geometry. Surkan (1969) developed a computer algorithm for numeric coding of natural geometry on a rectangular grid for hydrograph synthesis. These days, different types of grid structures, such as finite-element grid, rectangular grid, and boundary-fitted coordinate grid, etc. are used, depending on the numerical scheme of a model.

Conceptual methods represent watershed geometry using a network of elemental sections, including plane, triangular section, converging section, diverging section, and channel. Each element represents a particular portion of the watershed. These elements may be arranged to provide a detailed representation of the gross topographic features of a watershed, regardless of its geometric complexity. Many simplified geometric configurations that depend on the arrangement of these elements have been employed in hydrology. Examples of such configurations are V-shaped geometry, composite geometry, cascade of planes and channels, complex configurations of planes and channels, and so on. Harley et al. (1970) and Rovey et al. (1977) employed configurations of planes and channels. There have been many techniques for generating such configurations. Berod et al. (1995, 1999) employed a geomorphologically based method to define planes and channels. Boyd (1978) employed a watershed-bounded method to generate a network representation for his WBN model. This representation is commonly used these days. Lane and Woolhiser (1977) suggested a statistical procedure to select an appropriate geometric simplification of a watershed.

Scaling and Variability

Scale is normally defined as the sampling interval size at which hydrologic observations are made or as the grid size used for numerical computations. Thus, the size of a scale will correspond to the length in the spatial domain and to the duration in the time domain. Parameters and hydrologic processes controlling the watershed response operate at many different space and timescales. Using five field examples, Seyfried and Wilcox (1995) analyzed how the nature of spatial variability affects the hydrological response over a range of scales: (1) infiltration and surface runoff affected by shrub canopy; (2) groundwater recharge affected by soil depth; (3) groundwater recharge and streamflow affected by small-scale topography; (4) frozen soil runoff affected by elevation; and (5) snowfall distribution affected by large-scale topography. Depending on the scale, the sources of variability can be stochastic or deterministic or both. It is not possible to describe watersheds in terms of a single deterministic length scale, independent of scale and watershed characteristics. For a consistent treatment of these hydrologic processes, observed and model scales should be commensurate. Morel-Seytoux (1988) reasoned that nature embodies both the elements of chance and the descriptive laws of physics. Therefore, excessive process description at one scale is lost through the processes of integration in time and space and through averaging. This justifies model simplification as long as the essential behavior is retained. He showed how simplifications can be made so that straightforward scaling integration is accomplished in a physically based stochastic framework.

Issues related to spatial and temporal scaling and variability started receiving much attention beginning in the 1980s. An assumption commonly employed in hydrologic modeling is one of homogeneity at the grid scale. Kavvas (1999) defined heterogeneity as the fluctuations in the values of hydrologic state variables, such as flow discharge, infiltration rate, and evapotranspiration rate, etc., in hydrologic parameters such as roughness, hydraulic conductivity, porosity, etc. and in boundary conditions and forcing functions such as rainfall, snowfall, wind, etc. Heterogeneity was further classified into stationary heterogeneity and nonstationary heterogeneity. If the mean, higher-order moments and probability density functions of the fluctuations in space/time remain constant with respect to all space/time origin locations, then the hydrologic process (or parameter) is stationary heterogeneous; otherwise, it is nonstationary heterogeneous. A stationary heterogeneous process (or parameter) is ergodic in the mean if the ensemble average of its fluctuations is equal to their spatial/time volumetric average or areal average. Kavvas (1999) showed that a hydrologic process (or parameter) that is nonstationary at one scale may become stationary at another scale. The fundamental reason for transformation from nonstationarity to stationarity with the increase in scale is the phenomenon of coarse-graining of hydrologic processes at increasing scales. The hydrologic equations, however, still remain parsimonious as the scales get larger.

Upscaling of Hydrologic Conservation Equations

The construction and complexity of a hydrologic model are greatly influenced by the domain in which it is built and the scale at which it is built. In the time domain, different scales are used, based on which models are classified as continuous, event-based, weekly, monthly, seasonal, or yearly models. Many hydrologic models employ equations based on conservation of mass, momentum, and energy. These equations are point-scale, and their averaging in space depends on the hydrologic process to be modeled. For example, for surface flow the St. Venant equations or their simplified forms are depth-averaged, but for subsurface flow, the governing equations are areally averaged. In either case, they require data at a scale much finer than is available. This means that the point-scale equations must be upscaled in order to conserve mass, momentum, and energy and to ensure compatibility between the scales of observed data and governing equations. Kavvas (1999) has shown that when a larger scale process is formed by averaging a small-scale process, the high frequency components of the smaller scale process are eliminated by averaging, and this leads to considerable simplification of the average hydrologic conservation equations. Indeed, there are evolving scales of heterogeneity with respect to space, and these scales influence the averaging of conservation equations as well as the removal of high-frequency components.

The upscaling of conservation equations plays an important role in dealing with subgrid variability and in parameter estimation. Because the parameters in the upscaled equations are also upscaled, the subgrid variability can be quantified by means of areal variance and covariance of the point-scale parameters. Chen et al. (1994a,b) treated spatially averaging of unsaturated flow equations under infiltration conditions over areally heterogeneous soils and presented a practical application. In these equations, areal median saturated hydraulic conductivity and areal variance of log-saturated hydraulic conductivity emerged as the main parameters when the saturated hydraulic conductivity was considered the main source of heterogeneity. Numerical experiments on unsaturated flow within a soil column with varying degrees of heterogeneity measured by the coefficient of the log-saturated hydraulic conductivity showed that the areally averaged Green-Ampt equation significantly outperformed the point-scale Richards equation incorporating areally-averaged, log-saturated hydraulic conductivity even in the 3D case.

For modeling overland flow over varying microtopographic surfaces, Tayfur and Kavvas (1994) showed that if these surfaces were replaced by smooth surfaces then the depth-averaged equations are indeed treated as large-scale averaged equations (Tayfur 1993). Such a treatment is mathematically not correct, and one should upscale the depth-averaged equations to conserve mass and momentum at a larger scale. Tayfur and Kavvas (1994) developed transectionally averaged flow equations for a hillslope transect. By assuming randomness in the flow variables due to randomness in parameters, Tayfur and Kavvas (1998) also obtained areally averaged flow equations for a hillslope surface. The resulting flow equations were only time-dependent and whose solution required a very simple numerical method. In the same vein, Horne and Kavvas (1997) averaged over the snowpack depth the energy and mass conservation equations that govern the snowmelt dynamics at a point location and obtained depth-averaged equations (DAE). By assuming the snowmelt process to be spatially ergodic, they then averaged the point-location DAE over the snowpack area. The areally averaged equations were obtained in terms of their corresponding ensemble averages.

The model parameters as normally determined these days are based on spatial variation of point-scale parameters obtained using GIS, and remote sensing, etc. In large-scale modeling of land-surface processes, the scales of upscaled hydrologic equations and upscaled parameters seem to be consistent with grid-area resolution. However, because of the subgrid scale variability within each grid area, there is a fundamental issue of the inconsistency of the point-scale parameter values with regard to the grid area they represent. Through regional scale land surface hydrologic modeling of California at 20 km grid resolution, Kavvas et al. (1998) have shown that this inconsistency can be removed by using the spatially averaged, upscaled conservation equations whose upscaled parameters are at the same scale as of the modeling grid areas.

Spatial Scaling

The spatial scale greatly influences the choice of a model. Hydrologic variables vary in space with respect to both direction and location. In case of terrestrial hydrology, one dimensional treatment is adequate in most cases. However, the variability is particularly high in the soil and aquifer environment in all three dimensions or at least in two dimensions. Thus, incompatibilities arise when the entire continuum is modeled and even more so when the model is coupled with a climatic model or an oceanic model, due to significantly different speeds of atmospheric processes, land-surface hydrologic processes, as well as oceanic processes caused by the significantly different time response characteristics of atmospheric, oceanic, and hydrologic processes (Kavvas et al. 1998).

Spatial heterogeneity in catchment response arises from three sources: variabilities, discontinuities, and processes. Spatial variabilities in climatic inputs such as rainfall and hydrometorological variables, in soil characteristics such as hydraulic conductivity and porosity, in topography, and land use, encompass a space-time continuum. The runoff from a watershed is governed by local combinations of these factors. Discontinuities encompass the boundaries separating soil types, geologic formations, or land covers. Physical properties control interception, surface retention, infiltration, overland flow, and evapotranspiration at different scales, and these processes control runoff. It has been observed empirically that the form of hydrologic response changes with the spatial scale of heterogeneities, usually considered to be simpler and more linear with increasing watershed size (Dooge 1981). This relation may be climate dependent because Goodrich et al. (1997) demonstrated that the response became more nonlinear in a semiarid watershed. When the spatial scale is extended from a point to larger areas, the runoff generation process becomes less sensitive to temporal variations of local precipitation or spatial variations of soil characteristics because of the averaging effect. However, the spatial extent is limited by differences in physical, vegetative, and topographic features. Sivapalan and Wood (1986) investigated the effect of spatial heterogeneity in soil and rainfall characteristics on the infiltration response of catchments. Eagleson and Qinliang (1987) found that both the first and second moments of peak streamflow decreased rapidly with increasing values of the catchment to storm scale ratio. Milly and Eagleson (1988) underscored the need to incorporate areal storm variability in large area hydrologic models. Osborn et al. (1993) found that runoff volumes calculated with input from a centrally located rain gauge on a 6.3 km^2 semiarid watershed was greater than runoff calculated using 10 recording rain gauges.

Investigating the impact of spatial rainfall and soil information on runoff prediction at the hillslope scale, Loague (1988) aggregated fine-scale realizations of rainfall fields and spatial hydraulic conductivity to coarser resolutions. He found that at the hillslope scale hydraulic conductivity was more critical than rainfall and that runoff peak, time to peak, and runoff volume required different information levels.

Physical Spatial Size

The minimum level of physical spatial scale to be used in watershed modeling, which would adequately represent the spatial heterogeneity of a watershed, has received considerable attention. Using the SHE model on the Wye watershed 10.55 km^2 in area, Bathurst (1986) suggested dividing the watershed into elements no larger than 1% of the total area to ensure that each element was more or less homogeneous. Introducing the concept of representative elementary area (REA), Wood et al. (1988) found that an REA of approximately 1 km^2 existed for hydrologic response of the Coweeta watershed and was more strongly influenced by basin topography than rainfall length scales.

Tao and Kouwen (1989) used 5×5 km and 10×10 km grid sizes on the 3,520 km^2 Grand River watershed containing four reservoirs in southwestern Ontario in Canada, and found that the two grid sizes had no significant effect on the model results. Pierson et al. (1994) employed a surface soil classification scheme to partition the spatial variability in hydrological and interrill erosion processes in a sagebrush plant community. Using a unit hydrograph model, Hromadka et al. (1988) found on 12 watersheds that the variance of model-simulated discharge decreased significantly with the level of discretization, but this decrease reflected a departure of the model results from the true watershed behavior. Using a length scale based on surface characteristics and excess rainfall duration, Julien and Moglen (1990) found that the influence of spatial variability of slope, roughness, width, and excess rainfall intensity on watershed runoff varied with the length scale.

Zhang and Montgomery (1994) examined the effect of digital elevation model (DEM) grid size on the portrayal of the land surface and hydrological simulations on two small watersheds in the western United States. They found that the DEM grid size significantly affected both the representation of the land surface and the results of hydrological simulation. A grid size smaller than the hillslope length was necessary to adequately simulate the processes controlled by land form. A 10 m grid size was proposed as a compromise between increasing spatial resolution and data handling requirements.

Using TOPMODEL on the 115.5 km^2 Sleepers River Research watershed in Vermont, Wolock (1995) found that a subwatershed should have an area of at least 5 km^2 before it is representative of larger watersheds along the same stream in terms of topographic characteristics and simulated flow paths. Wilgoose and Kuczera (1995) use subgrid approximations to provide an effective parameterization of the processes that occur on scales smaller than those that can be modeled. Using data from small plot experiments as well as large-scale watersheds, they found that infiltration parameters can be adequately calibrated from small-scale plots but not the kinematic parameters. Bruneau et al. (1995) analyzed the effect of space and time resolutions using TOPMODEL on the 12 km^2 Coetdan Experimental watershed in Britanny, France, with input derived from DEMs. An optimum region for modeling with a grid size of 50 m and a time step of about 1 h was found.

Vieux (1993) investigated the DEM aggregation and smoothing effects on surface runoff modeling and found that errors are propagated if the apparent slope is flattened or the flow path is shortened. Quinn et al. (1991) found that a grid-cell resolution larger than 5 m had a significant effect on soil moisture modeling. According to Tarboton et al. (1991), drainage network density and configurations are highly dependent on smoothing of elevations during the pit removal stage of network extraction. Low rainfall intensities produce proportionately larger errors than higher intensities for an extracted network.

Molnar and Julien (2000) evaluated the effects of square grid-cell size from 17 to 914 m on surface runoff modeling using a raster-based distributed CASC2D hydrologic model. For event-based simulation, their findings indicate that coarser grid-cell resolutions can be used for runoff simulations as long as parameters are appropriately calibrated, and the primary effect of increasing grid-cell size on simulation parameters is to require an increase in overland and channel roughness parameters. They found that they had to adjust overland and channel Manning's n values as grid size changed. Yao and Terakawa (1999) employed 1 km grids for a distributed model of the Fuji River basin (3,432 km^2) in Japan. Daily meteorological data were produced using GIS and step-wise regression. They found that it was possible to integrate daily and hourly scales to produce reasonable hydrologic response.

Winchell et al. (1998) investigated the effects of algorithm uncertainty and pixel aggregation on simulation of infiltration and saturation-excess runoff from a medium-sized (100 km^2) basin in northern Texas using radar-based rainfall estimates. Two types of uncertainty in precipitation estimates were considered: those arising from rainfall estimates and those due to spatial and temporal representation of the ''true'' rainfall field. The infiltration-excess runoff was more sensitive to both types of uncertainties than was the saturation-excess runoff. There was a significant reduction in infiltration-excess runoff volume when temporal and spatial resolution of the precipitation was reduced.

Mazion and Yen (1994) investigated the effect of computational spatial size on watershed runoff simulated by HEC-1, RORB, and a linear system. They found that the computational grid size had a significant effect on the model results if the physical scale was not finer, although the effects decreased with increasing rainfall duration. The effect of the computational size was about one order larger than the effect of the variability of surface conditions within the watershed, provided the overall watershed average runoff coefficient remained the same.

Recognizing the importance of spatial variability, the usual practice is to subdivide larger watersheds and then calibrate hydrologic models. However, a working concept of physical heterogeneity remains still elusive. For example, the methods of subdivision are governed more by data availability than by physical meaning. Song and James (1992) reviewed five scales used in hydrologic simulation: laboratory scale, hillslope scale, catchment scale, basin scale, and continental and global scale. They suggested a stochastic method in which a parametric-stochastic model can be formed from a parent parametric-deterministic model to find an optimal scale for its application.

The scaling issue assumes even a greater significance when developing regional or global hydrology models. There is a discrepancy in scale between regional climate models and hydrologic models. In fact there are incompatibilities among soil, surface water, and groundwater models attributed in part to oversimplifications of complex hydrologic processes in each of these models (Goodrich and Woolhiser 1991; Yu 1996). Thomas and Henderson-Sellers (1991) conclude that hydrologic and climatic models fail to represent day-to-day variability in streamflow and hypothesize that this variability could be accounted for by incorporating the spatial variability of different mechanisms of rainfall-runoff production (Wood et al. 1990).

Temporal Scaling

The timescale of model output (e.g., streamflow) greatly influences the type of the model or the details to be included in the model. For example, a monthly watershed hydrology model is quite different in its architecture and construct from, say, an hourly model. It remains an unresolved question as to the hydrologic laws operating at different timescales for different components of the hydrologic cycle. A solution to this question will greatly facilitate model construction and more clearly define data needs.

Many hydrologic simulation models employ more than one time interval in their computation. Diskin and Simon (1979) defined the time base as a combination of the interval used for input and internal computation and the time interval used for output and model calibration. They explored the relationship between the time bases of hydrologic models and their structure. Hughes (1993) suggested incorporation of variable time intervals in deterministic models. Woolhiser and Goodrich (1988) investigated the importance of time varying rainfall in a model of a small watershed and found that disaggregating total rainfall amounts into simple, constant, and triangular distributions caused significant distortion in the peak rate distributions for Hortonian runoff. Ormsbee (1989) found that uniform disaggregation grossly underestimated peak discharge frequencies from a continuous hydrologic model.

Spatial Variability of Hydraulic Roughness

Wu et al. (1982) examined the effects of spatial variability of roughness on runoff hydrographs from an experimental watershed facility and found that under certain conditions an equivalent uniform roughness could be used for a watershed with nonuniform roughness. Lehrsch et al. (1987, 1988) determined the spatial variation of eight physically significant roughness indices using a semivariogram analysis. Hairsine and Parlange (1986) demonstrated the formation of kinematic shocks on various surfaces with different degrees of roughness and analyzed the error incurred when a curved surface was represented by a kinematic cascade model. Vieux and Farajalla (1994) evaluated the error resulting from smoothing of the hydraulic roughness coefficients in modeling overland flow with a finite-element solution.

Spatial Variability of Infiltration

Spatial variability of infiltration has been amply documented (Sharma et al. 1980; Maller and Sharma 1984; Loague and Gander 1990; Sullivan et al. 1996; Turcke and Kueper 1996) and has been found to influence surface runoff characteristics, depending on rainfall and watershed characteristics. Milly and Eagleson (1988) showed that spatial variability in soil type and rainfall depth resulted in decreased cumulative infiltration and increased surface runoff. Smith and Hebbert (1979), Sivapalan and Wood (1986), and Woolhiser and Goodrich (1988), observed considerable differences in the infiltration rate when the average soil properties, as opposed to spatially varied properties, were used. Smith et al. (1990) incorporated small-scale spatial variability of soil saturated hydraulic conductivity into an infiltration model. This method has been enhanced by Smith and Goodrich (2000).

Using a 2D runoff model and a Monte Carlo methodology, Saghafian et al. (1995) examined the variability of Hortonian surface runoff discharge and volume produced by stationary storms on a watershed with spatially distributed soil saturated hydraulic conductivity. Greater peak flow was observed for spatially variable hydraulic conductivity than for uniform values. Woolhiser et al. (1996) showed that Hortonian runoff hydrographs were strongly affected by trends in hydraulic conductivity, especially for small runoff events. Using a 3D model of variably saturated flow on a hillslope, Binley et al. (1989a,b) found that the peak discharge and runoff volume generally increased with varying hydraulic conductivity, increasing with increasing variance and spatial dependence of the random saturated hydraulic conductivity field. For low permeability soils, they could not find an effective hydraulic conductivity parameter capable of reproducing surface and subsurface flow hydrographs.

Precipitation Variability

Singh (1997) reported on the effects of spatial and temporal variability in rainfall and watershed characteristics on the streamflow hydrograph. A short discussion of these effects is presented here.

Storm Movement

Yen and Chow (1968) and Marcus (1968) undertook laboratory studies to demonstrate the importance of rainstorm movement to the time distribution of surface runoff. Jensen (1984) determined the influence of storm movement and its direction on the shape, peak, time to peak, and other characteristics of the runoff hydrograph. Maksimov (1964) showed that rainstorm movement altered peak discharge. Niemczynowicz (1984a,b) determined the influence of storm direction, intensity, velocity, and duration on the runoff hydrograph and peak discharge on a conceptual watershed and an actual watershed in the city of Lund in Sweden. Roberts and Klingman (1970) found that the direction of storm movement might augment or reduce flood peaks and modify the hydrograph recession. Surkan (1974) observed that peak flow rates and average flow rates were most sensitive to changes in the direction and speed of the rainstorms.

Sargent (1981, 1982) determined the effects of storm direction and speed on runoff peak, flood volume, and hydrograph shape. Stephenson (1984) simulated runoff hydrographs from a storm traveling down a watershed. Foroud et al. (1984) employed a 50-year hypothetical moving rainstorm to quantify the effect of its speed and direction on the runoff hydrograph. Ngirane-Katashaya and Wheater (1985) analyzed the effect of storm velocity on the runoff hydrograph. Ogden et al. (1995) investigated the influence of storm movement on runoff. Singh (1998) evaluated the effect of the direction of storm movement on planar flow and showed that the direction of storm movement exercised a significant influence on the peak flow, time to the peak flow, and the shape of the overland flow hydrograph.

Spatial Variability of Rainfall

The shape, timing, and peak flow of a stream-flow hydrograph are greatly influenced by spatial and temporal variability in rainfall. While examining the effects of spatially distributed rainfall for a conceptual watershed 100 km^2 in area, Watts and Calver (1991) found that an efficient resolution of rainfall data was around 2.5 km^2 along the storm path. Dawdy and Bergmann (1969) and Wilson et al. (1979) concluded that errors in rainfall volume and intensity over a watershed were likely to limit the accuracy of runoff simulation. Phanartzis (1972) stressed the importance of altitudinal pattern in runoff simulation on a watershed in the San Dimas Experimental Forest. Beven and Hornberger (1982) found that in a relatively homogeneous watershed the most important effect of rainfall variability was in the timing of the runoff hydrograph. The effect on peak flows was smaller but still significant, and the effect on storm volume was relatively minor.

Julien and Moglen (1990) found that for both correlated and uncorrelated spatial variability in rainfall excess the discharge hydrograph was quite sensitive to excess rainfall intensity, and the degree of sensitivity decreased with increasing rainfall duration. Ogden and Julien (1993) concurred with the findings of Julien and Moglen (1990). Stephenson (1984) noted that the time of concentration was nearly the same for uneven rainfall as for uniform distribution. Naden (1992) found that the effect of spatial variation in rainfall on the network channel response could be marked. Using a distributed model on a midsize catchment 150 km^2 in area, Michaud and Sorooshian (1994) found that errors in simulated peaks due to inadequate raingauge density (one gauge per 20 km^2) represented 58% of the observed peak flow. Rainfall sampling errors accounted for approximately half the difference between observed and simulated peaks. Faurés et al. (1995) found that spatial variability of rainfall can have significant effects on simulated Hortonian runoff, even at a very small scale.

Temporal Variability of Rainfall

In general, time-varying rainfall produces greater peak discharge than does constant rainfall. Southerland (1983) found that design storms for flood estimation generally peaked in intensity in the first half of the storm. While evaluating the effect of maximum rainfall position, El-Jabi and Sarraf (1991) found that hydrograph timing was altered but not the hydrograph peak. Lambourne and Stephenson (1987) simulated runoff peaks and volumes for a series of synthetic 5-year storms having rectangular, triangular, and bimodal temporal distributions. The rectangular hyetograph underpredicted the peaks and volumes from an urbanized watershed. The triangular distribution overpredicted the peak discharge, and the bimodal distribution better predicted the runoff volumes and peaks than did the triangular distribution.

Ball (1994) employed 10 different rainfall excess patterns beginning with constant rainfall excess. The time of concentration for a watershed significantly changed with the pattern of rainfall excess. When compared with a constant rainfall excess pattern, hydrographs of design patterns of rainfall peaked early and were varied in shape. Stephenson (1984) noted that the peak runoff was approximately 10% greater for triangular distribution than for a uniform pattern of the same duration. Using weather radar for flood forecasting in the Sieve River basin in Italy, Pessoa et al. (1993) found no significant differences between hydrographs generated from 5, 15, and 30 min radar rainfall data. The hydrographs were generated from a distributed rainfall-runoff model (Cabral et al. 1990) that extracts topographic information from DEMs.

Model Calibration

Significant advances have been made in automated watershed model calibration during the past 2 decades, with focus on four main issues (Gupta et al. 1998): (1) development of specialized techniques for handling errors present in data; (2) search for a reliable parameter estimation algorithm; (3) determination of an appropriate quantity of and information-rich kind of data; and (4) efficient representation of the uncertainty of the calibrated model (structure and parameters) and translation of uncertainty into uncertainty in the model response. To account for data errors, maximum likelihood functions have been developed for measuring the closeness of the model and the data by Sorooshian and Dracup (1980), Sorooshian (1981), and Kuczera (1983a, b), among others.

Optimization methods have been developed for parameter estimation. A typical automatic parameter estimation methodology requires four elements: (1) objective function; (2) optimization algorithm; (3) termination criteria; and (4) calibration data. The choice of an objective function influences parameter estimates as well as the quality of model results. Rao and Han (1987) analyzed several objective functions in calibrating the urban watershed runoff model ILLUDAS and found the least-squares criterion to be the best. Servat and Dezetter (1991) employed five different objective functions for calibrating a rainfall-runoff model on a Sudanese savannah area in the Ivory Coast and found the Nash-Sutcliffe efficiency to be the best. Clarke (1973) noted that the assumptions underlying the use of a least-squares objective function for estimation of hydrologic model parameters were seldom valid and suggested basing the objective function on the stochastic properties of the errors in the model and the data. Investigating the effects of selecting different objective functions, Diskin and Simon (1977) proposed guidelines and made recommendations for selecting an objective function in model calibration.

Sorooshian and Gupta (1995) discussed several optimization methods, including direct search methods, gradient search methods, random search methods, multistart algorithms, and shuffled complex algorithms. The first two are local search methods and the remaining are global search methods. Population-evolution-based search strategies have been popular (Brazil and Krajewski 1987; Brazil 1988; Wang 1991; Duan et al. 1992, 1993; Sorooshian et al. 1993). The shuffled complex evolution global optimization algorithm has, however, been found to be consistent, effective, and efficient in locating the globally optimum hydrologic model parameters (Duan et al. 1992, 1993; Sorooshian et al. 1993; Luce and Cundy 1994; Gan and Biftu 1996; Tanakamaru 1995; Tanakamaru and Burges 1997; Kuczera 1997).

Termination criteria are needed in an iterative search algorithm to determine when the slope of the function response surface is zero and the function value is minimum. Sorooshian and Gupta (1995) discussed several criteria, including the function convergence, parameter convergence, and maximum iterations and their limitations. In fact, none of these criteria are reliable in ascertaining the attainment of the global optimum, although parameter convergence was found to be most suitable for model calibration studies. The proper choice of calibration data may mitigate difficulties encountered in model calibration. Critical issues pertaining to calibration data are the amount of data necessary and sufficient for calibration and the quality of data resulting in the best parameter estimates. However, our understanding to address such issues is less than complete.

One of the main problems of optimization methods is the difficulty of finding a unique ''best'' parameter set. Another difficulty is the inadequacy of these methods for multi-input-ouput hydrologic models (Gupta and Sorooshian 1994a, b). To address these concerns, the generalized likelihood uncertainty estimation (Freer et al. 1996), Monte Carlo membership set procedure (van Straten and Keesman 1991), and the prediction uncertainty method (Klepper et al. 1991) have been proposed. These approaches are related to the generalized sensitivity analysis method developed by Spear and Hornberger (1980). These methods have weaknesses, however. Therefore, a more powerful calibration paradigm that considers the inherent multiobjective nature of the problem and recognizes the role of model error is needed. To that end, Gupta et al. (1998) proposed a new paradigm based on the multiobjective approach.

Artificial Neural Networks and Genetic Algorithms

Another fascinating area that has emerged in the 1990s is the application of artificial neural networks (ANNs) to hydrologic modeling. Because ANNs have the ability to recursively learn from data and can result in significant savings in time required for model development, they are particularly suited for modeling nonlinear systems where traditional parameter estimation techniques are not convenient. Preliminary concepts and hydrologic applications of ANNs have been detailed by ASCE (2000a, b). The book edited by Govindaraju and Rao (2000) contains a variety of applications of ANNs to hydrologic modeling. Lorrai and Sechi (1995) applied ANNs to evaluating rainfall-runoff models and river-flow forecasting. Hsu et al. (1995) employed ANNs to identify the model structure and concluded that ANNs provide a viable and effective alternative for input-output simulation and forecasting models that do not require modeling the internal structure of the watershed. Therefore, they are not a substitute for conceptual watershed modeling. Mason et al. (1996) suggested the use of radial basis functions for developing a neural network model of rainfall runoff, especially when a large database is involved. Minns and Hall (1996) used ANNs as rainfall-runoff models. Tokar and Markus (2000) compared ANNs with traditional models in predicting watershed runoff on three basins and found ANNs to yield higher accuracy. Gupta et al. (2000) proposed a multilayer feed-forward neural network for application to streamflow forecasting.

Wang (1991) developed a genetic algorithm for calibrating conceptual rainfall-runoff models. Savic et al. (1999) developed a genetic programming approach to structured system identification for rainfall-runoff modeling.

Global Hydrology Models

The decade of the 1990s started with an emphasis on regional and global hydrology that called for integration of hydrologic (terrestrial, pedologic, and lithologic), atmospheric, and hydrospheric models to evaluate the impact of climate change. The integration became possible because of the data being gathered by large-scale field experiments, such as STORM, GEWEX, HAPEX-MOBILHY, MAC-HYDRO, and so on. As a result, there exists a multitude of hydrologic models for application at the continental and global scale. The global hydrology model developed by Anderson and Kavvas (2002), the continental scale model, UMUS by Arnold et al. (1999), the regional-scale model developed by Yoshitani et al. (2002), and ISBA-MODCOU developed by Ledoux et al. (2002), among others are examples. One of the difficulties with such models is the lack of compatibility in scales at which data are available and the scales at which hydrologic, pedologic, atmospheric, and hydrospheric processes operate.

Model Error Analysis

Most models perform little to no error analysis. Thus, it is not clear what the model errors are and how different errors propagate through different model components and parameters. This is one of the major limitations of most current watershed hydrology models. Thus, from the standpoint of a user, it is not clear how reliable a particular model is. It is, therefore, no surprise that the user runs into difficulty when selecting a particular model.

Expert Systems

There was also some attention paid to the development of expert systems in hydrology. Gashing et al. (1981) probably were the first to develop a knowledge-based expert system for water resource problems. Underlying this system was SWM/HSPF. Simanovic (1990) described an expert system for selection of a suitable method for flow measurement in open channels. Although the area of artificial intelligence is very appealing, it somehow has not attracted much attention in the hydrologic community.

Linking of Water Quality

The decades of the 1980s and 1990s also witnessed the linking of hydrologic models with those of geochemistry, environmental biology, meteorology, and climatology. This linking became possible primarily for two reasons. First, there was increased understanding of spatial variability of hydrologic processes and the role of scaling. This was essential because different processes operate at different scales, and linking them to develop an integrated model is always challenging. Second, the digital revolution made possible the employment of GIS, remote sensing techniques, and database management systems. Currently, a number of watershed hydrology models have water-quality components built into their architecture, as seen in Table 1, as for example, HSPF, SHETRAN, LASCAM, DVSM, DWSM, to name but a few.

Future Outlook

Mathematical models of watershed hydrology have now become accepted tools for water resources planning, development, design, operation, and management. It is anticipated that the future will witness even a greater and growing integration of these models with environmental and ecological management. With growing technologies triggered by the information revolution, remote sensing, satellite technology, geographic information systems, visual graphics, and data base management, the hydrologic models are getting increasingly more sophisticated and are being integrated with other process models.

The future of watershed hydrology models will be shaped by increasing societal demand for integrated environmental management; growing need for globalization by incorporation of biological, chemical, and physical aspects of the hydrological cycle; assessment of the impact of climate change; rapid advances in remote sensing and satellite technology, GIS, DBMS, and expert systems; enhanced role of models in planning and decision making; mounting pressure on transformation of models to user-friendly forms; and clearer statements of reliability and risk associated with model results.

The application of watershed hydrology models to environmental management will grow in the future. The models will be required to be practical tools—readily usable in planning and decision making. They will have to be interfaced with economic, social, political, administrative, and judicial models. Thus, watershed models will become a component in the larger management strategy. Furthermore, these models will become more global, not only in the sense of spatial scale but also in the sense of hydrologic details. Increasing fusion of biological and chemical courses in undergraduate curricula emphasizing hydrology is a healthy sign in that direction and will help achieve this goal.

Watershed hydrology models will have to embrace rapid advances occurring in remote sensing and satellite technology, geographical information systems, database management systems, error analysis, risk and reliability analysis, and expert systems. With the use of remote sensing, radar, and satellite technology, our ability to observe data over large and inaccessible areas and to map these areas spatially is vastly improved, making it possible to develop truly distributed models for both gauged and ungauged watersheds. Distributed models require large quantities of data that can be stored, retrieved, managed, and manipulated with the use of GIS and DBMS. This is possible because of literally unlimited computing capability available these days and will be even more so in the future. If watershed hydrology models are to become practical tools, then they have to be relatively easy to use, with a clear statement as to what they can and cannot do. They will need to assess the errors and determine how they propagate, define the reliability with which they accomplish their intended functions, and require the user to possess only a minimal amount of hydrologic training. Furthermore, the models will have to learn from the user as well as from empirical experience. Many of these functions can be performed by the use of expert systems in watershed hydrology modeling. Usually, the user is interested in what a model yields, its accuracy, and how easy it is to use, not the biology, chemistry, physics, and hydrology it is based on.

The models will have to be described in simple terms such that the interpretation of their results would not tax the ability of the user. They are designed to serve a practical end, and their constituency is one of users. After all, hydrologic models are to be used, not to be confined to academic shelves. Thus, model building will have to gravitate around the central theme of their eventual practical use in integrated environmental management. Although much progress has been made in mathematical modeling of watershed hydrology, there is still a long way to go before the models will be able to fully integrate rapidly evolving advances in information, computer, and space technology, and become ‘‘household’’ tools. Hydrologists are being challenged, but we have no doubt that they will meet the challenge.

Although much progress has been achieved in hydrology, there is a greater road ahead. A basic question is: What modeling technology is better? Because of the confusion, the technology developed decades ago is still in use in many parts of the world. This state of affairs is partly due to the lack of consensus as to the superiority of one type of technology to the other. Also, we have not been able to develop physically based models in a true sense and define their limitations. Thus, it is not always clear when and where to use which type of a model.

Conclusions

The following conclusions can be drawn from the foregoing discussion:

1. Many of the current watershed hydrology models are comprehensive, distributed, and physically based. They possess the capability to accurately simulate watershed hydrology and can be applied to address a wide range of environmental and water-resources problems.
2. The scope of mathematical models is growing, and the models are capable of simulating not only water quantity but also quality.
3. The technology of model calibration is much improved, although not all models have taken full advantage of it.
4. The models are becoming embedded in modeling systems whose mission is much larger, encompassing several disciplinary areas.
5. The technology of data collection, storage, retrieval, processing, and management has improved by leaps and bounds. In conjunction with literally limitless computing prowess, this technology has significantly contributed to the development of comprehensive distributed watershed models.

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