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Surface Waters

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Research in surface water hydrology made important advances in the areas of river mechanics and streamflow routing, experimental study of overland flow, surface runoff models, partial area processes, effects of land use on surface runoff, and probability, statistics and analysis of uncertainty. In each area there was a fundamental need to apply mathematical and computer methods, and this is reflected in the following review of progress in each of these areas.

River Mechanics and Streamflow Routing

A broad-based effort went into developing numerical solutions of the Saint Venant partial differential equations for unsteady flow in open channels. Some papers suggested a numerical procedure; some looked at computational efficiency; some looked at convergence and/or stability properties; some looked at the importance of various terms; some looked at prediction accuracy; and some suggested procedures for branched or looped river networks. These papers offer testimony to widespread use in hydrology practice of models based either on the full Saint Venant equations or on one of many approximations to these equations, including both linear approximations with one or more terms neglected and nonlinear approximations with several terms neglected. Because some of these approximations have the same mathematical structure as certain well-known hydrologic routing techniques, it is now possible to give clearer physical meaning to the better established hydrologic methods such as the Muskingum method. Hopefully, this will stimulate more intelligent use of all of these techniques (e.g., through new physically based criteria for applying the lag and route model or new criteria for judging when the full nonlinear Saint Venant equations must be used rather than some approximation, etc.). Following is a review of some specific contributions.

Numerical procedures and computational efficiency. Nonlinear implicit finite difference methods were used by *Amein and Fang* [1970], *Fread* [1973*a*, *b*, 1974*a*, *b*], *Chaudhry and Contractor* [1973], *Contractor and Wiggert* [1972], and *Quinn and Wylie* [1972]. Quasi-linear implicit methods were used by *Gunaratnam and Perkins* [1970] and *Chen* [1973].

Explicit finite difference methods were used by *Strelkoff* [1970], *Terzidis and Strelkoff* [1970], and *Prandle and Crookshank* [1974].

Characteristic methods with curvilinear net were used by *Fread and Harbaugh* [1973] and *Abbott and Verwey* [1970].

Characteristic methods with rectangular net were used by *Wylie* [1970], *Yevjevich and Barnes* [1970], *Terzidis and Strelkoff* [1970], *Harris* [1970], *Ellis* [1970], and *Gientke* [1974].

Implicit finite difference formulations generally eliminate problems of numerical stability usually encountered by explicit formulations when large time steps are attempted. Large time steps are needed for computations of slowly varying transients to make implicit formulations more economical.

One way to reduce computation time is to retain only the most essential terms in the momentum equation. *Fread* [1974a] observed that the local acceleration term was negligible in comparison with the friction slope term and the convective acceleration term was 23% of the friction slope term during the 1963 flood on the lower Mississippi River. In this case, the momentum equation could be reduced to the friction slope term and the water surface slope term. This is known as the diffusion wave approximation. *Sevuk* [1973] found a 20% savings in computer time by using this approximation as compared to the full equations. *Fread* [1974a] concluded that the full implicit dynamic wave model was the appropriate model for computation of slowly varying transients in rivers of extremely mild channel bottom slopes.'

Prediction accuracy. *Terzidis and Strelkoff* [1970] found that computations of open channel surges by the method of characteristics were inconsistent and contained larger errors than those by finite difference methods on a rectangular mesh. *Amein and Fang* [1970] compared several methods and found the implicit finite difference method to be the only one able to handle significant changes in channel geometry from section to section with no difficulty. Amein estimated channel geometry from 1 : 62,500 scale maps and, without reliable estimates of lateral inflow and Manning's n, presented computed stage hydrographs generally within about 2-3 ft of the observed hydrograph on the Neuse River, North Carolina.

Fread [1974a] obtained root mean square errors between 0.20 and 0.50 ft in computed water levels for several locations along the Mississippi River using a limited amount of cross-section data.

Price [1974] compared four numerical methods of solving the Saint Venant equations and concluded that Amein's four-point implicit method is more accurate and efficient than the leap frog explicit method, Lax-Wendroff two-step explicit method, and an implicit characteristic method with fixed mesh. Price also found that the optimum value of $\Delta x/\Delta t$ is the kinematic wave speed except in tidal estuaries.

Convergence and stability properties. *Fread* [1974b] investigated the numerical properties of a linearized implicit four-point finite difference approximation that used a weighting factor θ to position the spatial difference quotient between adjacent time intervals. The difference equations were found to be unconditionally stable for certain values of θ and conditionally stable for others. Although the backward finite difference scheme ($\theta = 1$) is unconditionally stable for any Δt, it does not have as good convergence properties as the 'box scheme,' $\theta = 0.5$.

Prior to this detailed numerical analysis, others [*Amein and Fang*, 1970; *Fread*, 1973a] had made some numerical experiments to check convergence and stability. Fread found that the pseudo-instability sometimes associated with the box scheme may be eliminated with $\theta = 0.55$. *Chaudhry and Contractor* [1973] found considerable numerical dispersion of the solution if $\theta = 1$, experienced stability problems with $\theta = 0.5$, and empirically discovered that $\theta = 0.6$ worked well. *Quinn and Wylie* [1972] had a similar experience and found weakly stable solutions of $0.5 < \theta < 0.6$ and used $\theta = 0.75$.

Approximation and linearization. *Harris* [1970] found the progressive average lag routing method could be made to give essentially the same answers as those by the method of characteristics for real time flood routing in sewers. Field data presented by *Kellerhals* [1970] showed that flow in steep natural channels occurs according to the kinematic wave theory and channel response is not linear.

Keefer [1974], *Keefer and McQuivey* [1974], and *Sauer* [1973] have proposed linear routing methods with some discussion of their relation to the Saint Venant equations.

Gburek and Overton [1973] showed theoretically that kinematic wave conditions can exist in subcritical flow.

Branched or looped open channel networks. Efficient solution algorithms for implicit finite difference equations rely on the banded structure of coefficient matrices for flow in an isolated river with given inflow hydrographs. Coefficient matrices become unreasonably large and lose their banded structure for channel networks. *Fread* [1973c] proposed an iterative technique permitting an efficient application of the full nonlinear solution for dendritic networks. *Wood et al.* [1972] used an influence function method to extend a quasi-linear implicit scheme proposed by *Gunaratnam and Perkins* [1970] to any generalized network of channels.

Stage-discharge relations. *Fread* [1973b] developed a mathematical model based on the complete Saint Venant equations to simulate the dynamic relationship between stage and discharge when the energy slope is variable because of changing discharge. Given either a stage or discharge hydrograph, the other may be computed if channel slope, cross-sectional area, and roughness properties are known. Fread also gives a graphical procedure to estimate the magnitude of the loop in the dynamic loop rating curve produced by the changing discharge effect. This magnitude relates inversely to the channel bottom slope and directly to the rate of change of stage, the hydraulic depth, and Manning's n. The loop may be significant if the channel slope is less than 0.001 ft/ft and the transient flow is natural streamflow. More rapid transients may give significant loops on steeper slopes.

Simons et al. [1973] discussed stage-discharge ratings affected by change in bed forms in sand bed rivers due to unsteady flow. They developed an empirical procedure to predict the shift in the rating curve due to changes in bed forms and the mean elevation of the channel bed for a gaging station on the Rio Caris, Venezuela.

Experimental Study of Overland Flow

Graveto and Eagleson [1970] investigated the feasibility of scale modeling by finding quantitative answers to the following questions: '(1) To what extent are the similarity criteria derived by *Grace and Eagleson* [1965] adequate for physical modeling of surface runoff? (2) To what extent can these criteria be satisfied in small-scale laboratory models? (3) To what extent can these similarity criteria be violated while still obtaining valid results from the model, within a prescribed accuracy?'

Turf surfaces and smooth surfaces. *Morgali* [1970] analyzed much of Izzard's original overland flow data, including data for a turf surface. Laminar flow conditions appeared during the early part of the rising hydrograph and during the recession. *Phelps* [1970] conducted experiments on steady uniform flows over a simulated turf surface to investigate the general hydraulic roughness properties of natural turf. These experiments were designed to demonstrate the separate effects of Reynolds number and boundary geometry (corresponding to different depths of flow on the same surface) on the friction coefficient.

Overton [1972] analyzed a large number of overland flow hydrographs collected for airfield drainage investigations by the U.S. Army Corps of Engineers. An average dimensionless rising hydrograph was found to fit each of 214 experimental hydrographs within very small errors. This average hydrograph was approximated by a Manning kinematic solution with a 15% standard error and by a Chezy and a laminar solution, each with a 19% standard error.

Smooth surfaces only. *Yoon and Wenzel* [1971] used an experimental flume 3 × 24 ft with a plate glass bottom to develop a law of resistance for sheet flow from a correlation analysis between the boundary shear stress and rainfall, mean flow, and channel parameters. On a hydraulically smooth boundary, the rainfall intensity was the strongest single parameter affecting the flow. *Shen and Li* [1973] analyzed data collected by Li and by Yoon. By regression analysis the Darcy Weisbach friction coefficient for flow over a smooth surface was found to be a function of both Reynolds number and rainfall intensity for Reynolds numbers less than 900 but of Reynolds number only above 2000. *Schreiber and Bender* [1972] obtained by a trial-and-error process values of a friction parameter K that, when they are used in the kinematic wave equation, would minimize the rms difference between computed and measured hydrographs. The experimental catchment was an 8 × 16 ft concrete surface, and the Reynolds number did not exceed 110.

Meizik [1974] attempted to find the instantaneous unit hydrograph (IUH) for an experimental overland flow plane but concluded that the overland flow process was too nonlinear and an infinite number of IUH's exist depending on rainfall intensity. His results also supported the kinematic wave theory of overland flow.

Surface Runoff Models

Notable progress occurred in modeling both urban and natural catchments. Most catchment models have both surface and subsurface components, however simple or complex; but the main concern of this review is the surface runoff component, including overland flow and streamflow processes.

The value, if any, of a model is related to the smallness of some measure of the expected prediction errors. This value depends partly on how well the mathematical structure of the model imitates the physical structure of the catchment and partly on how well the input data to the model represent the natural events. Therefore it seems reasonable to judge models in terms of structure imitation, in terms of input representation, in terms of the importance of these qualities in limiting the expected prediction errors to acceptable levels, and in terms of practical issues arising in any particular application.

The most complete structure imitation currently achievable is with a hydraulic or hydrodynamic approach involving the partial differential equations for unsteady flow in open channels. This may be done on a very detailed basis [*Schaake*, 1971], or large catchment areas may be represented with a small number of overland flow and streamflow elements [*Leclerc and Schaake*, 1973].

Recent studies have shown that the kinematic wave formulation of the unsteady open channel flow equations can give very accurate simulations of overland flow and streamflow in natural and in urban catchments [*Schaake*, 1971; *Harley et al.*, 1970; *Leclerc and Schaake*, 1973; *Smith and Woolhiser*, 1971; J. C. Schaake, G. Leclerc, and B. M. Harley, unpublished data, 1973]. Additional study of experimental overland flow data reported herein adds more evidence to support the thesis that overland flow and streamflow occur according to the kinematic wave theory except (1) in very flat channels, (2) where flow is subject to downstream backwater conditions, (3) where storm sewers become surcharged, or (4) where unusually rapid hydraulic transients occur.

A few models have represented urban and natural surface runoff with the kinematic wave theory, including the solution of the governing partial differential equations. One of the most computationally efficient of these was developed at the Massachusetts Institute of Technology in a project sponsored by the Office of Water Resources Research [*Harley et al.*, 1970]. The Environmental Protection Agency (EPA) stormwater management model [*Metcalf and Eddy, Inc., et al.*, 1971; *Chen and Shubinski*, 1971; *Heaney et al.*, 1973] solves the kinematic wave equations for flow in sewers but uses a lumped parameter model for the hydrologic response of the catchment areas.

The kinematic wave applied to unsteady open channel flow where the flow rating curve does not have a noticeable hysteresis loop. *Fread* [1973] developed a simple method for estimating hysteresis loop thickness, and this method can be used to determine the downstream limits of applicability of the kinematic wave model. Downstream from this limit the hydrodynamic approach would require the solution of the diffusion form of the unsteady flow equations or the solution of the full unsteady flow equation if the hydraulic transients are rapid enough.

A widely used approach in hydrologic modeling surface runoff involves conceptual models. Applications were reported by *Nash and Sutcliffe* [1970], *Chow and Kulandaiswamy* [1971], and *Mandeville et al.* [1970]. Numerous other examples exist; some are listed among the references.

Black box techniques do not give physical explanation to system behavior but represent catchment dynamics with differential or integral equations through a curve-fitting or parameter estimation procedure. These techniques include linear and nonlinear systems methods.

Rao et al. [1972] applied linear systems methods in the analysis of the urban rainfall runoff process. They concluded that 'there is neither a unique unit hydrograph nor an instantaneous unique hydrograph applicable to any watershed.' Also they concluded that 'use of an average, representative value of time lag for a watershed leads to erroneous prediction performance.'

Nonlinear and time-varying systems methods were widely reported [*Amorocho and Brandstetter*, 1971; *Hino*, 1970*b*; *Mandeville and O'Donnell*, 1973; *Diskin and Boneh*, 1973, 1974]. Many other such studies are listed below among the references. The practical role of these models remains to be established, but potential applications exist in real time operation and in flood frequency studies.

Models for operational forecasting. Conceptual hydrologic models are now being used in the United States for operational forecasting of river discharges and stages [*Hydrologic Research Laboratory*, 1972; *Burnash and Ferral*, 1973; *Monro and Anderson*, 1974]. These models simulate both surface and subsurface processes and imitate catchment structure to a limited extent, somewhere between the hydrodynamic approach and the black box approach, balancing detailed representation of the mechanics of individual processes with the need to account for heterogeneities in the natural occurrence of these processes. Procedures for automatic estimation of parameters in these models were suggested by *Monro* [1971] and by others.

Catchment model testing. Hydrological models have proliferated since the first mass-produced computer appeared in 1956. Some have been developed and used for many years. Others were produced with mixed degrees of testing, evaluation, or awareness of the state-of-the-art. Therefore some attention is being given to model comparison and review. Some of this is being done at universities [*Sarma et al.*, 1973; *Papadakis and Preul*, 1973; *Heeps and Mein*, 1974]. A very important study of 18 urban hydrologic models was supported by the Environmental Protection Agency [*Brandstetter*, 1974]. This followed an earlier and less extensive study sponsored by the Office of Water Resources Research [*Linsley*, 1971].

In the EPA study [*Brandstetter*, 1974], seven of the most promising models for practical application were tested by using hypothetical and real urban catchment data. The evaluations considered model accuracy, cost of model use, computer requirements, data requirements, input data preparation requirements, and output options. The seven models selected for more detailed evaluation met the following minimum requirements: the capability to consider several rain gages, the capability to compute runoff from several catchments, and the capability to route flows in a converging branch sewer network. Models that rely heavily on mathematical formulations not readily derived from catchment and sewer characteristics were not among these seven, nor were models included with oversimplifications restricting their use unnecessarily, considering computer capabilities and the state-of-the-art of hydrologic modeling.

An international study 'Intercomparison of Conceptual Models for Purposes of Hydrological Forecasting' was conducted by the World Meteorological Organization (WMO). The objective was to inventory and make comparative tests of conceptual hydrological models actually in use for forecasting purposes by governmental organizations. Planning for this study began in 1967. Test basins were in the United States, Australia, Japan, USSR, Thailand, and Cameroun. A modified split sample technique was used involving a 6-yr calibration period, a 2-yr test period, and one error analysis of both periods. The project, as completed, involved 10 models from seven countries. The final report on the project is to be prepared by the WMO Secretariat and is expected to be completed in mid-1975.

Partial Area Processes

The effect on streamflow of surface and subsurface processes attracted notable attention during the last few years. Answers to questions about the mechanisms of runoff generation were sought from field experiments in first-order upstream source areas and from theoretical analysis of detailed mathematical models of surface and subsurface processes.

The following studies are of particular interest where rainfall rates do not exceed infiltration rates over large portions of a catchment or where much of the storm runoff hydrograph is generated from transient wetlands near stream channels. They offer valuable ideas for future mathematical models, both conceptual and distributed, and for future experimental studies of these processes.

Field experiments. *Rawitz et al.* [1970], in a 2-yr study of the water balance of a 16.2-ha watershed in Pennsylvania, showed that spring and summer storms produced practically no overland surface runoff during storms. They concluded that the most important runoff-regulating mechanisms were the properties of the soil and the amount of water stored in the surface layer.

Dunne and Black [1970*a*] reported that overland flow on large areas of well-drained hillside has not been observed in the 43-mi^2 watershed of the Sleepers River in northeastern Vermont. They also observed in experiments on a trenched hillslope that subsurface storm flow was not an important contributor to storm runoff in this watershed and found this surprising in view of other claims that subsurface storm flow or 'throughflow' is capable of producing runoff peaks in river hydrographs [e.g., *Kirby and Chorly*, 1967, p. 8]. Dunne and Black took a closer look at the data from a similar catchment on which some of these claims are based, and decided that 'water remaining below the soil surface on its way down hillside to a stream contributes only a small part of the water supplying the peak of a river hydrograph.'

Dunne and Black [1970*b*] also reported that the major portion of storm runoff in the Sleepers River experimental watershed was produced as overland flow on a small portion of the watershed near streams where the water table intersected the ground surface. These partial areas could expand or contract seasonally or during a storm.

Weyman [1970] reported that differences between inflow and outflow hydrographs over 270 m of channel in an experimental catchment were attributable to subsurface storm flow or throughflow in the 10- to 45-cm soil horizon, and observed streamflows contained no overland or groundwater flow components.

Mathematical models. *Freeze* [1972*a*] presented a mathematical model of a three-dimensional saturated subsurface flow system with rainfall input and output to a one-dimensional stream channel. *Freeze* [1972*b*] produced numerical solutions for a hypothetical rectangular hillside 1 acre in area, for different soil thickness above an impervious base, hydraulic conductivity, overall hillside slope, shape of slope, and rainfall intensity and duration. From these solutions, Freeze concluded that there are stringent limitations on the occurrence of subsurface storm flow as a quantitatively significant runoff component, and storm hydrographs are dominated by direct runoff through very short overland flow paths from precipitation on transient near-channel wetlands. Freeze presents some simulated storm hydrographs in which both surface and subsurface components are present.

Subsequent discussions of Freeze's work were offered by *Snyder* [1973] and *Knisel* [1973]. *Hewlett* [1974] commented on Freeze's work and on each of the previous comments as well.

Engman and Rogowski [1974] applied a model of unsaturated flow dynamics, overland flow, and channel flow to simulate a number of storm runoff events from a 58-ha experimental catchment in Pennsylvania. The model accounted for variable soil types throughout the catchment, for variable hillslopes, and for variable soil moisture conditions. U.S. Soil Conservation Service data, estimates of Manning's n for overland flow and channel flow, and initial soil moisture content are needed to apply the model.

Effects of Land Use on Surface Runoff

Two main areas of interest were apparent in the concern for the effects of land use on surface runoff. These areas were the effects of urban development on flood events and the effects of deforestation or vegetation on water yield and flood events.

Effects of urbanization. A comprehensive summary of the hydrologic effects of urbanization in the United States was prepared by *McPherson* [1972*a*, *b*]. *Leclerc and Schaake* [1973] proposed a physically based method for estimating changes in flood frequency caused by urbanization and by methods for controlling the effects of urbanization such as detention storage reservoirs.

Information from 81 sites, of which 59 were in the Washington, D. C., metropolitan area, was analyzed by *Anderson* [1970] to show that improvements in urban drainage systems may reduce lag times to one-eighth those of natural channels, and this combined with increased storm runoff from impervious surfaces increases flood peaks by a factor of from 2 to nearly 8.

Hammer [1972] studied 78 small watersheds near Philadelphia and found that urbanization causes stream channel enlargement to occur in response to changes in streamflow regimen. A correlation between physiographic, urban, and climate factors was used by *Espy and Winslow* [1974] to estimate urban flood frequency characteristics. The significant urban factors were found to be the impervious cover and a channel factor.

Effects of deforestation and vegetation. Converting two small chaparral watersheds to grass in central Arizona caused increases in annual water yield ranging from about 2 in. with annual rainfall of 16 in. to about 12 in. with annual rainfall of 34 in. according to *Hibbert* [1971].

Forest lands can be managed to produce wood, water, livestock, other products, an aesthetic environment, pollution control, or combinations of these. The ideal mix depends upon management objectives. *O'Connell and Brown* [1972] applied a production economics model to address these management issues and needs for hydrologic information.

Onstad and Jamieson [1970] suggest that conceptual models could be used to predict the hydrologic effects of change in crop cover, modification of topography, etc., but they conclude that the parameters of the model must have physical significance.

Rothacher [1970] found that increases in water yield following timber harvest vary in proportion to the area cleared, clear-cut logging can increase annual water yield by 18 in. in the high-precipitation areas of the Oregon Cascades, and the increase occurs during the October to March season.

Hewlett and Helvey [1970] studied storm hydrographs before and after a mature hardwood forest was clear-felled on a 108-acre catchment in the southern Appalachians and found an 11% overall increase in streamflow volume. Deforesting two mountain watersheds in West Virginia gave water yield increases in excess of 10 in. [*Patric and Reinhart*, 1971]. Forest clearing in New Hampshire increased storm flow by a maximum of 30 mm in the summer and just over 50 mm during spring snowmelt [*Hornbeck*, 1973].

Probability, Statistics, and Analysis of Uncertainty

Probabilistic methods are widely used in surface water hydrology. A new development is a growing interest in the use of Bayesian methods. Perhaps the original applications of probability theory was to the frequency of floods, but recent work reported below has provided a new theoretical basis for estimating flood frequency from rainfall. Statistical methods are used for the estimation of parameters in hydrologic models and for comparing and selecting among alternative models.

An important topic of recent interest is the occurrence of surface runoff as a stochastic process. Progress in this area has been so extensive that it is being reported in a special review by Matalas and is not covered in this review.

Bayesian methods. *Wood et al.* [1974] applied the methodology of Bayesian inference and decision making to extreme hydrologic events. Two types of statistical uncertainty, uncertainty in modeling the hydrologic process and uncertainty in the value of hydrologic parameters, were considered. A Bayesian distribution of flood discharge was developed that completely accounts for parameter uncertainty. Similarly, a composite Bayesian distribution was found to account for model uncertainty. The results show that when point estimates of model parameters are used in place of the true parameter value in a frequency distribution to estimate exceedance probabilities, they will underestimate the expected value of the exceedance probability of a given discharge.

Hardison and Jennings [1972] also recognize that 'the probability of exceeding a given flood size obtained from a mathematically fitted flood frequency curve is a biased estimate' and that this bias was largely due to the time sampling error inherent in a finite series of annual peaks.

Shane and Gaver [1970] addressed the problem of using prior information derived by regression and direct observations to estimate the Bayesian distribution of parameter values in an exceedance model of flood events.

Wood et al. [1974] found that a regional regression model provided information equivalent to 4–7 yr of data for the estimation of the probability of occurrence of floods in New England. *Vicens et al.* [1974] found that a regional regression model provided information equivalent to 3–27 yr of data for the estimation of parameters in a first-order autoregressive model of annual flows in New England.

Application of Bayesian methods analytically is plagued with great difficulty. One way to reduce the analytical problems is to use natural conjugate prior distributions. *Wood et al.* [1974], *Vicens et al.* [1974] and *Yakowitz et al.* [1974] took this approach in a variety of different applications.

Estimation of flood frequency. Theoretical issues in the estimation of flood frequency at ungaged locations were considered by a number of investigators. *Eagleson* [1972] presented the basis in probability theory for combining a model of rainfall as a stochastic process with a deterministic model of the rainfall-runoff process to make estimates of runoff frequency. He derived an analytical expression for the flood frequency curve for a particular combination of rainfall and catchment models. *Leclerc and Schaake* [1972] derived by simulation methods flood frequency curves for some of Eagleson's examples in order to check the importance of some of Eagleson's simplifying assumptions. Together, the work of Eagleson and Leclerc and Schaake offers a theoretical basis for the use of simulation in the estimation of flood frequency curves.

A procedure for generating rainfall events, selecting specific events for detailed analysis with a catchment model, correlating catchment model response with a storm index computed by the rainfall generator, and for estimating flood frequency from storm index frequency was developed by *Resource Analysis, Inc.* [1974*a*, *b*] and applied in practical engineering studies of potential flooding in Puerto Rico.

An empirical method for estimating flood frequency was applied to small Montana watersheds by *Robinson and Williams* [1972]. Their method uses the mean annual flood determined from short streamflow records and three factors relating rainfall frequency to annual flood frequency.

Current engineering techniques for drainage design, such as the rational formula, rely on rainfall intensity frequency curves that do not recognize important seasonal variations in storm characteristics and catchment soil moisture conditions. *Brater et al.* [1974] analyzed the potential impact of these variations in flood synthesis. Also a stochastic model for describing the occurrence of floods was advanced by *Todorovic and Zelenhasic* [1970]. The effect on flood frequency of seasonal variations was treated theoretically by *Todorovic and Rousselle* [1971]. Todorovic and Woolhiser applied this theory to explain historical seasonal distributions of extreme events. The frequency distribution of recurrence intervals between extreme events with seasonal variations was studied by *Woodyer et al.* [1972].

Parameter estimation for unsteady flow models. *Becker and Yeh* [1972] introduced an influence function method for estimating values of two empirical friction factors that occur in the unsteady open channel flow equations. This method was applied to multireach channels [*Becker and Yeh*, 1973]. Either a least squares criterion or a minimax criterion may be used [*Yeh and Becker*, 1973].

Effect of random errors on parameter estimation for conceptual hydrologic models. The effect of random errors in hydrologic records on parameter estimation for conceptual models was investigated. *Ibbitt* [1972] found lesser effects of random errors in potential evaporation (PE) records but noted that not all of the PE values were used because this was not always the limiting factor on evaporation. Errors in precipitation records were damped out by the storage components of the model and absorbed into the calculation of actual evaporation. The spread of parameter values around the true values was related to parameter sensitivity figures found by making small perturbations about the final parameter values. *Parmele* [1972] found that a constant bias in PE has a more important effect than random errors on the output of hydrologic models. *Haan* [1972] used Monte Carlo simulation to evaluate error probabilities of stochastic models as a function of the number of observations used to estimate the parameters of the model. This technique would show if a given probabilistic model has the reliability required with a given record length for parameter estimation.

Model comparison and selection criteria. An objective model selection criterion based on the concept of entropy as used in information theory was introduced by *Amorocho and Espildora* [1973]. Model assessment by this criterion depends not only on the model but also on the characteristics of the output series resulting from the natural process.

Correlation methods of analysis. Statistical methods of correlating variables of interest with other dependent variables continued to be applied. Many of these studies give estimates of streamflow characteristics at ungaged sites on the basis of physical characteristics of the catchment [*Hardison*, 1971; *Thomas and Benson*, 1970; *Haan*, 1972, 1974]. An elevation dependent model for annual runoff was presented by *Smith et al.* [1973].

Subjects for Further Study

Increased needs for water to be available at the right time and place and for the desired quality will continue to generate need for improved water management technology. Following are some specific needs related to the scope of this report.

1. Distributed catchment models are needed with computationally efficient models of subsurface processes that recognize the partial area contributions to direct runoff.
2. Data to test such distributed catchment models are needed.
3. There is need to merge stochastic and deterministic concepts into unified analytical frameworks involving stochastic inputs, deterministic relationships between inputs and outputs, and additional stochastic components in the outputs. Differences between hydrologic data subject

to various errors and actual hydrologic events being measured need to be recognized more clearly.

4. Improved methods of operational forecasting are needed that recognize the uncertainty in future streamflow events and quantify this in terms of the conditional distribution of a future event, given the current information, the present uncertainty in future precipitation, and the uncertainty in model parameters.

5. Improved real time data acquisition and information dissemination are needed for more intelligent management of both the water resource and the user response to extreme conditions.

6. Techniques are needed to predict effects of scour and fill and bed form changes on the hydraulics of unsteady flow.

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River Mechanics and Streamflow Routing

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