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Rainfall-runoff models: A review

T.V. Hromadka II

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ABSTRACT

Rainfall-runoff research continues to focus upon the inclusion of additional modelling complexity such as hydraulics, or the subtler components of the hydrologic cycle. Recently, attention is being paid towards uncertainty and risk. This paper provides an update as to the state-of-health in the overall rainfall-runoff modelling effort. The paper indicates that as of publication date, no one rainfall-runoff model has been widely accepted as "best".

INTRODUCTION

The subject of rainfall-runoff modelling involves a wide spectrum of topics. Fundamental to each topic is the problem of accurately computing runoff at a point given rainfall data at another point. The fact that there is currently no one universally accepted approach to computing runoff, given rainfall data, indicates that a purely deterministic solution to the problem has not yet been found.

The technology employed in the modern rainfall-runoff models has evolved substantially over the last two decades, with computer models becoming increasingly more complex in their detail of describing the hydrologic and hydraulic processes which occur in the catchment. But despite the advances in including this additional detail, the level of error in runoff estimates (given rainfall) does not seem to be significantly changed with increasing model complexity; in fact it is not uncommon for the model's level of accuracy to deteriorate with increasing complexity. In order to demonstrate some of these issues, a literature review of the state-of-the-art in rainfall-runoff modelling is compiled which includes many of the concerns noted by rainfall-runoff modellers (a more comprehensive literature survey is contained in Hromadka et al.[1] The literature review provides many quotations which are truly "food for thought" as these references do not necessarily reflect the success of rainfall-runoff modelling; rather, they reflect points of serious concern. The review indicates that there is still no deterministic solution to the rainfall-runoff modelling problem, and that the error in runoff estimates produced from rainfall-runoff models is of such magnitude that they should not be simply ignored.

WATERSHED MODELING UNCERTAINTY

Watershed runoff is a function of rainfall intensity, the

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storm duration, the infiltration capacity of the soil, the cover of the soil, type of vegetation, area of the watershed and related shape factors, distribution of the storm with respect to space and time, watershed stream system topology, connectivity and branching, watershed geometry, stream system hydraulics, overland flow characteristics, and several other factors. Because of the dozens of variables which are included in a completely deterministic model of watershed runoff and due to the uncertainty which is associated to the spatial and temporal values of each of the various mathematical definitions, urban hydrologists need to include a measure of uncertainty in predicting surface runoff quantities.

With the widespread use of minicomputers and inexpensive microcomputers, the use of deterministic models are commonplace. These models attempt to simulate several of the most important hydrologic variables that strongly influence the watershed runoff quantities produced from severe design storm events. Generally speaking, the design storm (e.g., single event) and continuous simulation models include approximations for runoff hydrograph generation (coupled with models for estimating interception, evapotranspiration, interflow, and infiltration), channel routing, and detention basin routing. The computer program user then combines these processes into a link-node schematic of the watershed. Because each of the hydrologic processes involve several parameters, the resulting output of the model, the runoff hydrograph, may be a function of several dozen parameters. In a procedure called calibration, many or all of the parameters are estimated by attempts to duplicate significant historical runoff hydrographs. However, Wood[2] notes that the watershed model parameter interaction can result in considerable difficulty in optimizing the parameter set. In a similar deterministic modelling approach for soil systems and soil water movement, Guymon et al.[3] found that just the normal range of uncertainty associated with laboratory measurement of groundwater flow hydraulic parameters can produce considerable variation in the model output. A detailed analysis of the sensitivity corresponding to a watershed model is given by Mein and Brown[4]. Because of the vast spectrum of rainfall-runoff models available today, it is appropriate to review some of the comments noted in the literature as to the relative success of rainfall-runoff models in solving the runoff estimation problem in a purely deterministic setting. It is of interest to consider that possibly the point of diminishing returns has been reached in the improvement of rainfall-runoff models, and that further improvements are not necessary based upon the availability of the data.

Some Concerns in Deterministic Rainfall-Runoff Model Performance

The majority of the latest rainfall-runoff models develop runoff hydrographs. The "single event" models directly transform a design storm (hypothetical causative input) into a flood hydrograph. The "multiple discrete event" models transform an annual series of selected discrete rainfall events (usually one storm for each year) into an annual series of runoff hydrographs whose peak flowrates are used for subsequent statistical analysis. The "continuous record" or "continuous simulation" model results in a continuous record of synthetic runoff hydrographs for statistical synthesis. Each of the above three categories of deterministic models contain various versions and modifications which range widely in complexity, data requirements, and computational effort.

In general, the well-known unit hydrograph design storm approach has continued widespread support among practitioners and governmental agencies involved in flood control design. Such general purpose models include the U.S. Department of Agriculture, Soil Conservation Service or SCS model (1984) and the U.S. Army Corps of Engineers (HEC) hydrology computer program package (see TD-15[5]). In a recent survey of hydrologic model usage by Federal and State governmental agencies and private engineering firms (U.S. Department of Transportation, Federal Highway Administration Hydraulic Engineering Circular No. 19[6]), it was found that "practically no use is made of watershed models for discrete event and continuous hydrograph simulation." In comparison, however, design storm methods were used from 24 to 34 times more frequently than the discrete event or continuous simulation models by Federal agencies and the private sector, respectively. The frequent use of design storm methods appears to be due to several reasons: (1) design storm methods are considerably simpler to use than discrete event and continuous simulation models; (2) it has not been established in general that the more complex models provide an improvement in computational accuracy over design storm models; and (3) the level of complexity typically embodied in the continuous simulation class of models does not appear to be appropriate for the catchment rainfall-runoff data which is typically available. Consequently, the design storm approach continues to be the most often selected for flood control and drainage design studies.

A criterion for classifying a model as being simple or complex is given by Beard and Chang[7] as the "difficulty or reliability of model calibration.... Perhaps the simplest type of model that produces a flood hydrograph is the unit hydrograph model"...and..."can be derived to some extent from physical drainage features but fairly easily and fairly reliably calibrated through successive approximations by relating the time distribution of average basin rainfall excess to the time distribution of runoff." In comparison, the "most complicated type of model is one that represents each significant element of the hydrologic process by a mathematical algorithm. This is represented by the Stanford Watershed Model and requires extensive data and effort to calibrate."

The literature contains several reports of problems in calibrating complex models (such as used for flood flow estimation purposes in flood control design and planning), especially in parameter optimization. Additionally, it has not been clearly established whether complex models, such as in the continuous simulation or discrete event classes of models, provide an increase in accuracy over a simple single event unit hydrograph model. There are only a few papers and reports in the literature that provide a comparison in hydrologic model performance. From these references, it appears that a simple unit hydrograph model oftentimes provides estimates of runoff quantities which are comparable to considerably more complex rainfall-runoff models.

In their paper, Beard and Chang[7] write that in the case of the unit hydrograph model, "the function of runoff versus rainfall excess is considered to be linear, whereas it usually is not in nature. Also, the variations in shapes of unit hydrographs are not derivable directly from physical factors. However, models of this general nature are usually as representative of physical conditions as can reasonably be validated by available data, and there is little advantage in extending the degree of model sophistication beyond validation capability."

Schilling and Fuchs[8] write "that the spatial resolution of rain data input is of paramount importance to the accuracy of the simulated hydrograph" due to "the high spatial variability of storms" and "the amplification of rainfall sampling errors by the nonlinear transformation" of rainfall into runoff. Their recommendations are that a rainfall-runoff model should employ a simplified surface flow model if there are many subbasins; a simple runoff coefficient loss rate; and a diffusion (zero inertia) or storage channel routing technique.

In attempting to define the modelling processes by the available field data forms, Hornberger et al. find that "Hydrological quantities measured in the field tend to be either integral variables (e.g., stream discharge, which reflects an integrated catchment response) or point estimates of variables that are likely to exhibit marked spatial and/or temporal variation (e.g., soil hydraulic conductivity)." Hence, the precise definition of the physics in a modelling sense becomes a problem that is "poorly posed in the mathematical sense." Typically, the submodel parameters cannot be estimated precisely due to the large associated estimation error. "Such difficulties often indicate that the structural complexity of the model is greater than is warranted on the basis of the calibration data set." It was also noted by Hornberger et al.[9] that success in rainfall-runoff modelling "has proved elusive because of the complexity of the processes, the difficulty of performing controlled experiments, and the spatial and temporal variability of catchment characteristics and precipitation." They concluded that "Even the most physically based models...cannot reflect the true complexity and heterogeneity of the processes occurring in the field. Catchment hydrology is still very much an empirical science."

Schilling and Fuchs[8] note that errors in rainfall-runoff modelling occur for several reasons, including:

"1. The input data, consisting of rainfall and antecedent conditions, vary throughout the watershed and cannot be precisely measured.
2. The physical laws of fluid motion are simplified.
3. Model parameter estimates may be in error."

By reducing the rainfall data set resolution from a grid of 81 rain gauges to a single catchment-centered rain gauge in an 1,800 acre catchment (Fig. 1), variations in runoff volumes and peak flows "is well above 100 percent over the entire range of storms implying that the spatial resolution of rainfall has a dominant influence on the reliability of computed runoff." It is also noted that "errors in the rainfall input are amplified by the rainfall-runoff transformation" so that "a rainfall depth error of 30 percent results in

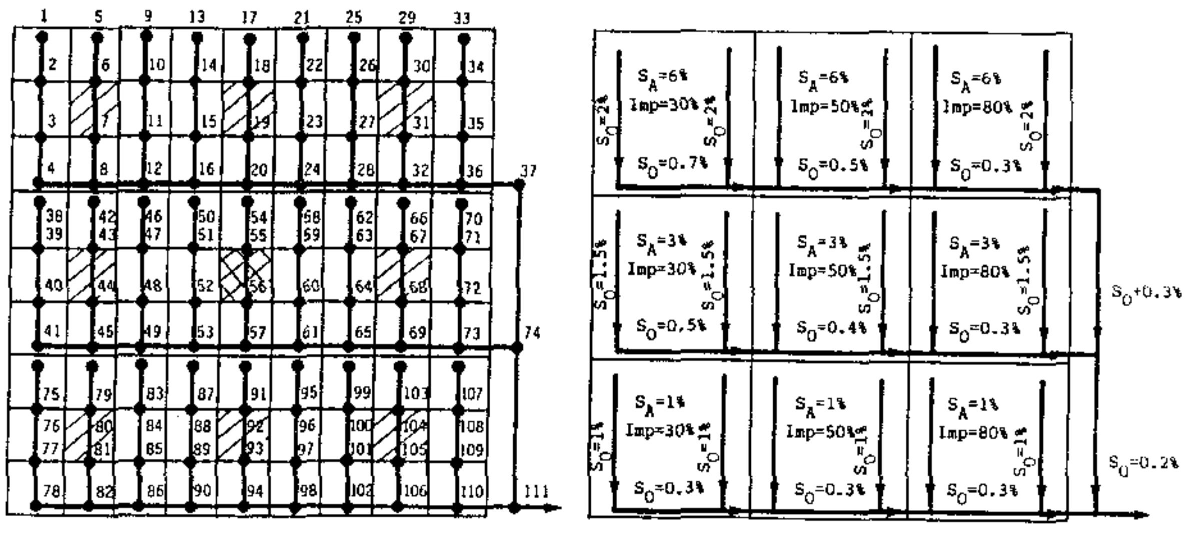

Fig. 1. The Schilling and Fuchs Study Catchment.

a volume error of 60 percent and a peak flow error of 80 percent." Schilling and Fuchs[8] also write that "it is inappropriate to use a sophisticated runoff model to achieve a desired level of modelling accuracy if the spatial resolution of rain input is low."

Similarly, Beard and Chang[7] write that in their study of 14 urban catchments, complex models such as continuous simulation typically have 20 to 40 parameters and functions that must be derived from recorded rainfall-runoff data. "Inasmuch as rainfall data are for scattered point locations and storm rainfall is highly variable in time and space, available data are generally inadequate...for reliably calibrating the various interrelated functions of these complex models." Additionally, "changes in the model that would result from urbanization could not be reliably determined." Beard and Chang[7] write that the application "of these complex models to evaluating changes in flood frequencies usually requires simulation of about 50 years of streamflow at each location under each alternative watershed condition."

Garen and Burges[10] noted the difficulties in rainfall measurement for use in the Stanford Watershed Model, because the K1 parameter (rainfall adjustment factor) and UZSN parameter (upper level storage) had the dominant impact on the model sensitivity. This is especially noteworthy because Dawdy and O'Donnell[11] concluded that insensitive model coefficients could not be calibrated accurately. Thus, they could not be used to measure physical effects of watershed changes.

In the extensive study by Loague and Freeze[12], three event-based rainfall-runoff models (a regression model, a

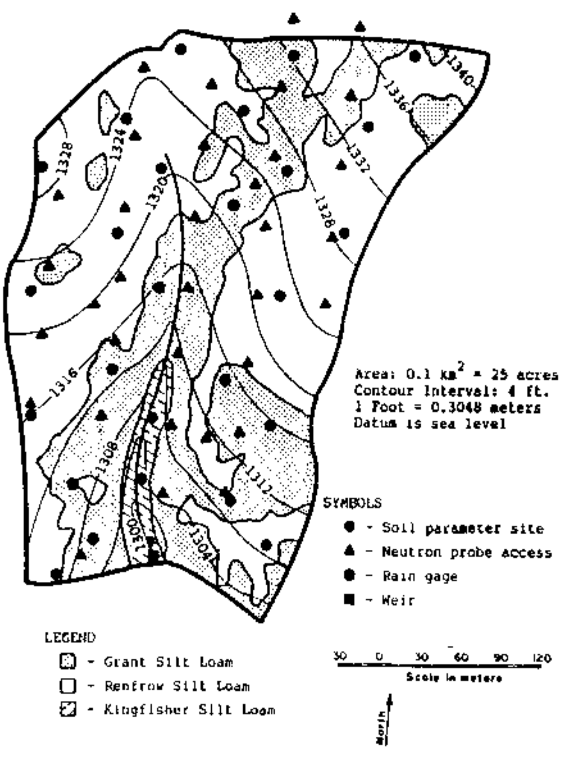

Fig. 2. The Loague and Freeze Catchment.

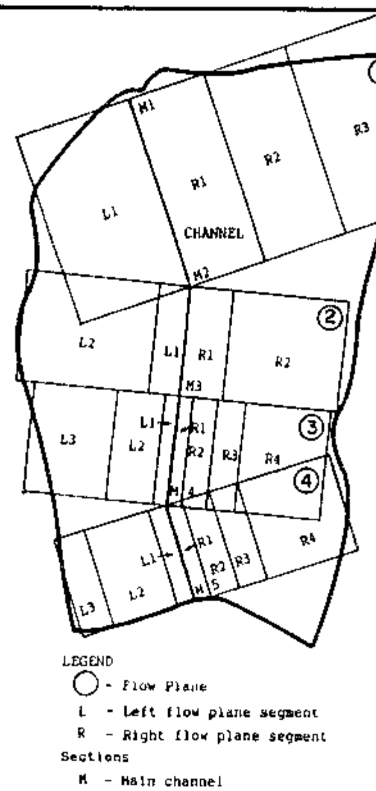

Fig. 3. The QPB Model.

unit hydrograph model, and a kinematic wave quasi-physically based model) were used on three data sets of 269 storm events from three small upland catchments. In that paper, the term "quasi-physically based" or QPB is used for the kinematic wave model. The three catchments were 25 acres, 2.8 square-miles, and 35 acres in size, and were extensively monitored with rain gauge, stream gauge, neutron probe, and soil parameter site testing.

For example, the 25 acre site instrumentation (Fig. 2) contained 35 neutron probe access sites, 26 soil parameter sites (all equally spaced), an on-site rain gauge, and a stream gauge. The QPB model (Fig. 3) utilized 22 overland flow planes and four channel segments. In comparative tests between the three modelling approaches to measured rainfall-runoff data it was concluded that all models performed poorly and that the QPB performance was only slightly improved by calibration of its most sensitive parameter, hydraulic conductivity. They write that the "conclusion one is forced to draw...is that the QPB model does not represent reality very well; in other words, there is considerable model error present. We suspect this is the case with most, if not all conceptual models currently in use." Additionally, "the fact that simpler, less data intensive models provided as good or better predictions than a QPB is food for thought."

Based on the literature, the main difficulty in the use, calibration, and development of rainfall-runoff models appears to be the lack of precise rainfall data and the high model sensitivity to (and magnification of) rainfall measurement errors. Nash and Sutcliffe[13] write that "As there is little point in applying exact laws to approximate boundary conditions, this, and the limited ranges of the variables encountered, suggest the use of simplified empirical relations."

It is noteworthy to consider the HEC Research Note No. 6[14] where the Hydrocomp HSP continuous simulation model was applied to the West Branch DuPage River in Illinis. Personnel from Hydrocomp, HEC and COE participated in this study which started with a nearly complete hydrologic/ meteorologic data base. The report stated that "It took one person six months to assemble and analyze additional data, and to learn how to use the model. Another six months were spent in calibration and long-record simulation." This time allocation applies to only a 28.5 square-mile basin. The quality of the final model is indicated by the average absolute monthly volume error of 32.1 and 28.1 percent for calibration and verification periods, respectively. Figure 4 shows a typical comparison of modeled and measured results. Peak flow rate average absolute errors were 26 and 36 percent for calibration and verification periods, respectively. It was concluded that "Discharge frequency under changing urban conditions is a problem that could be handled by simpler, quicker, less costly approaches requiring much less data; e.g., design storms or several historical events used as input to a single-event model, or a continuous model with a less complex soil-moisture accounting algorithm."

In another study, HEC Technical Paper No. 59 (Abbott[15]) compared six hydrologic models, plus two variants of one and a variant of another, in a preliminary evaluation of their relative capabilities, accuracy and ease of application on a 5.5 square-mile urban watershed near Oakland, California. Four continuous simulation models were tested: Storage Treatment Overflow Runoff Model (STORM), Hydrocomp Simulation Program (HSP), Streamflow Synthesis and Reservoir Regulation (SSARR), and Continuous Flood Hydrographs (HEC-IC). Single-storm event comparisons were made using STORM, HSP, SSARR, Storm Water Management Model (SWMM), Massachusetts Institute of Technology Catchment Model (MITCAT), and the HEC-1 unit hydrograph model (single area analysis). Each model was calibrated with the first 40 percent of a 42 month record, and the resulting calibration coefficients were used in simulating the remaining record. The study results showed that the more complex models did not produce better results in developing watershed runoff quantities than the simple models for this test watershed (see Fig. 5).

In the absence of more encouraging results in the use of complex hydrology models, the widespread use and continued acceptance of simpler rainfall-runoff models such as unit hydrograph methods for the estimation of watershed runoff quantities is understandable. For a new rainfall-runoff modelling approach to achieve widespread acceptance, it must clearly demonstrate a superiority in performance. For example, Hall[16] writes that some predetermined criterion of "goodness-of-fit" is typically used to assess a new model's capability in reproducing historic storm event runoff quantities. The new model is first calibrated to observed rainfall-runoff data and then "verified" using storm events excluded from the calibration storm event data set. This type of split-sample testing (for example, TP-59[15]; Loague and Freeze[12]) has been found to

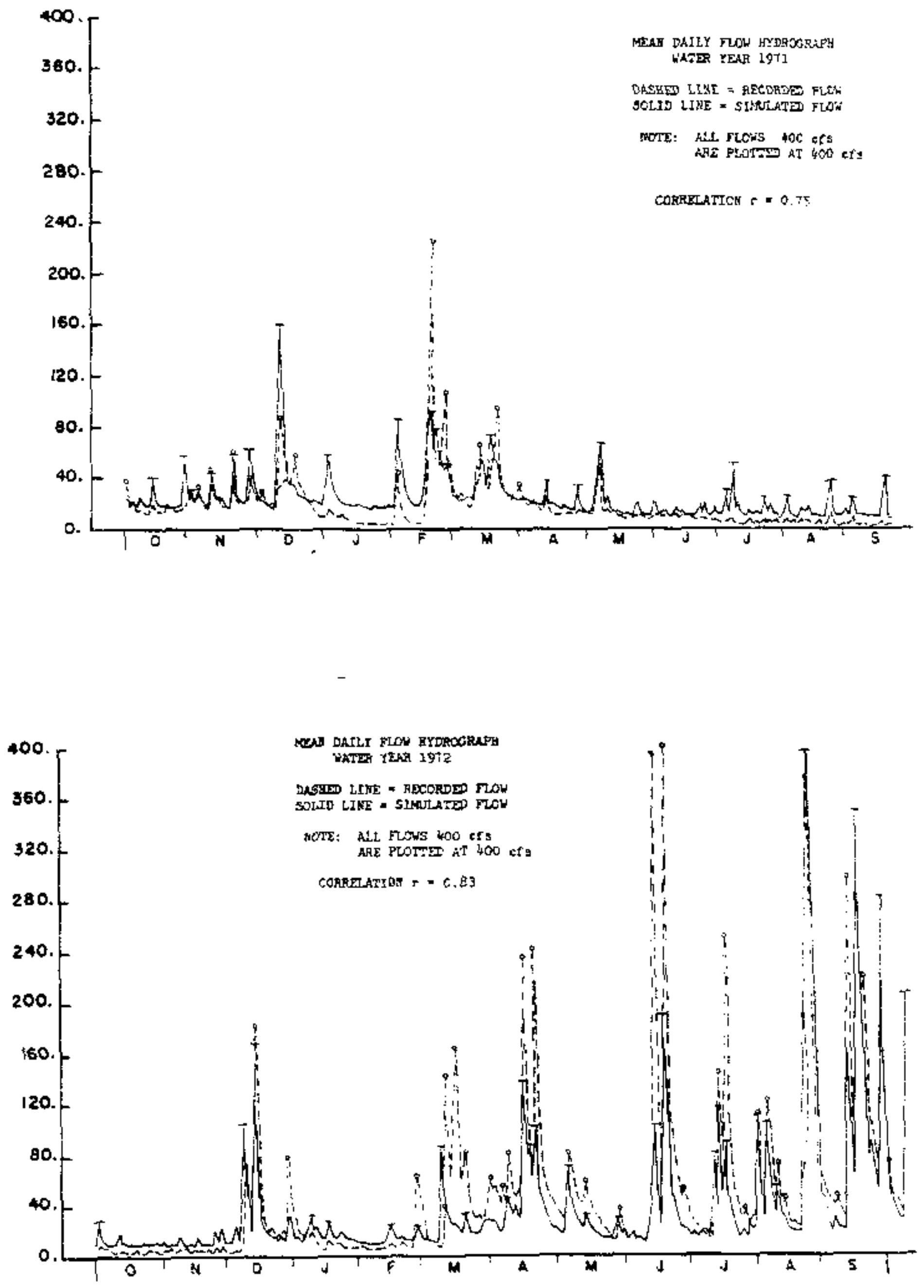

Fig. 4. HSP at Work.

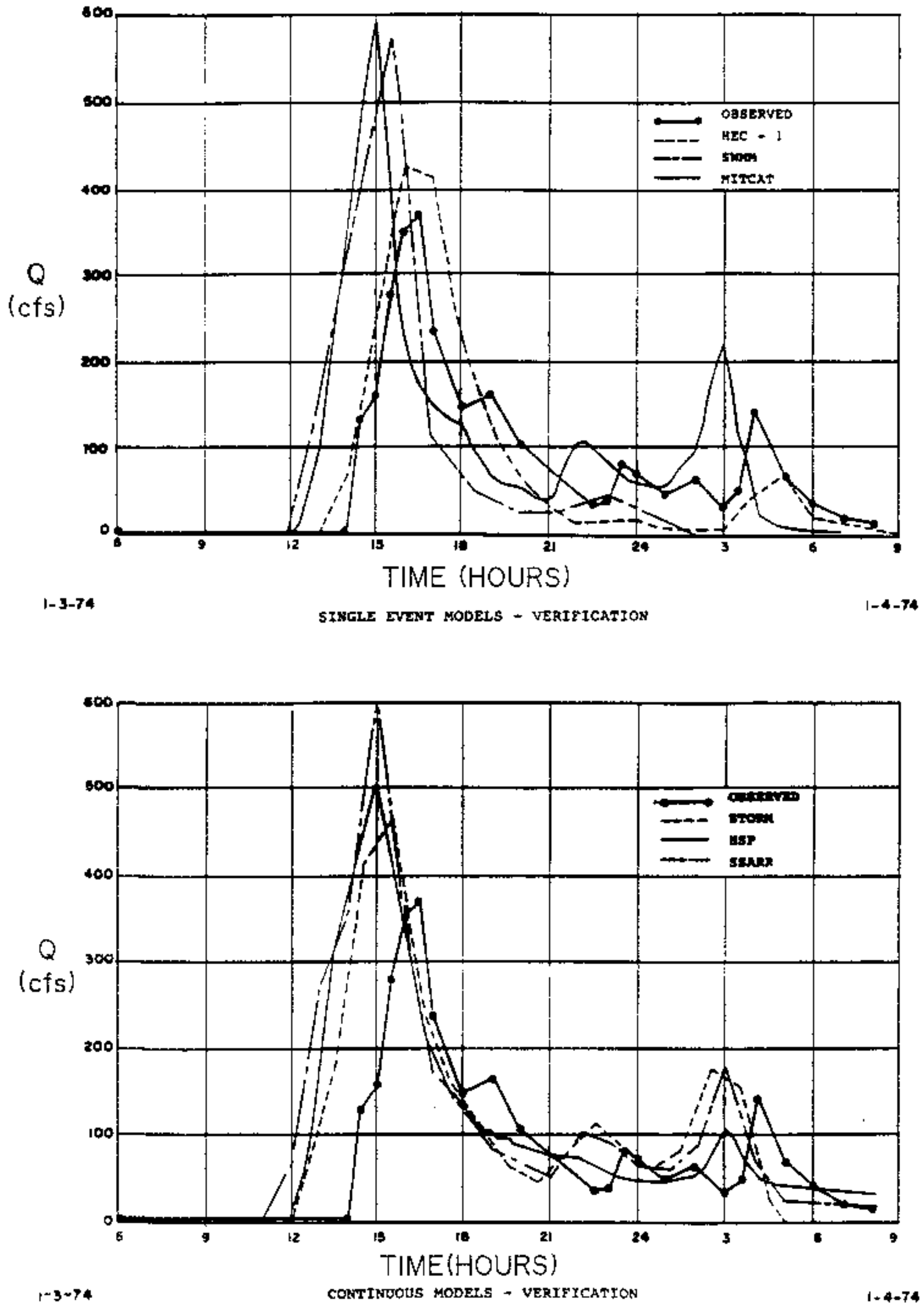

Fig. 5a. Comparison of Calibrated Models.

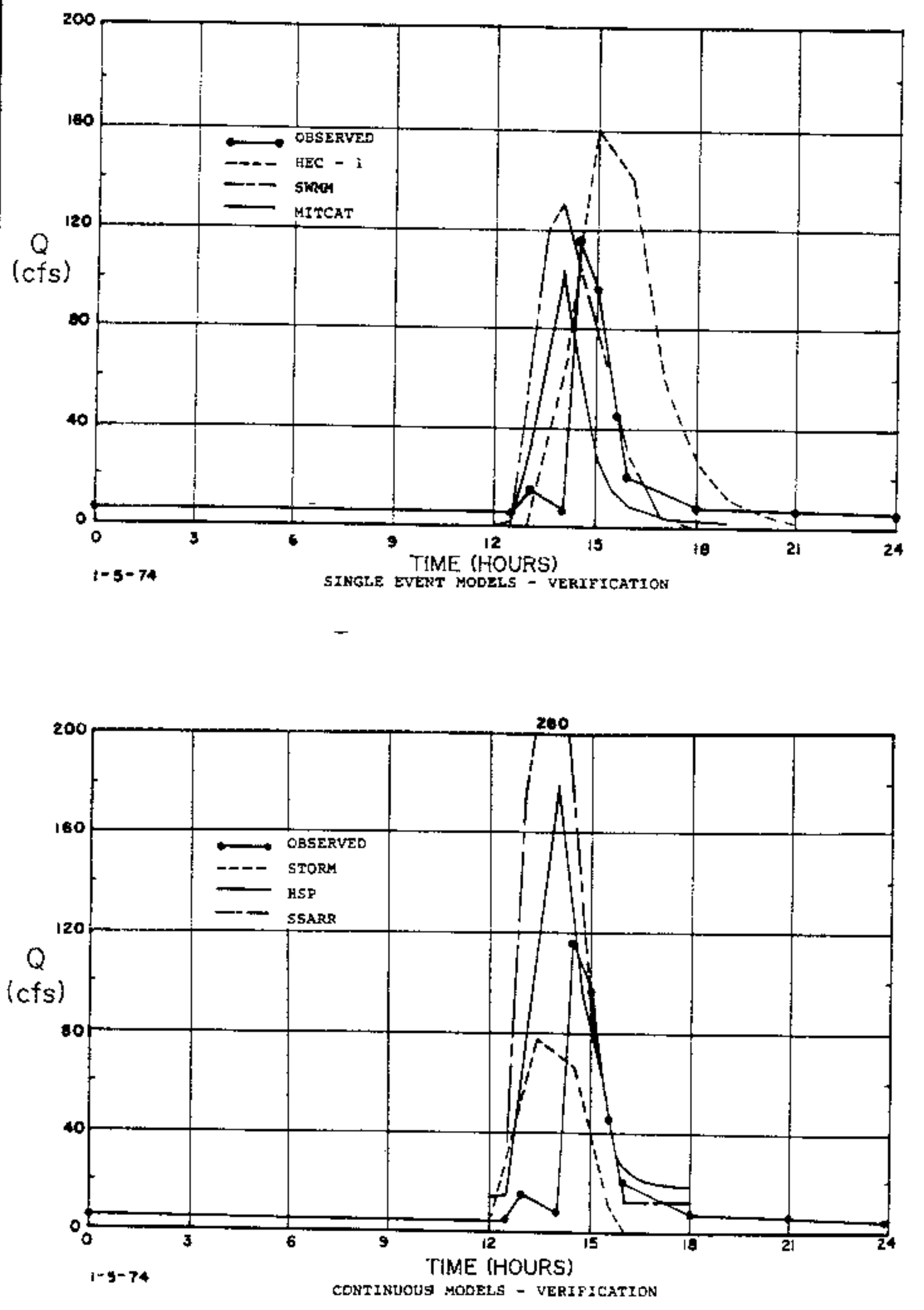

Fig. 5b. Comparison of Calibrated Models (Continued)

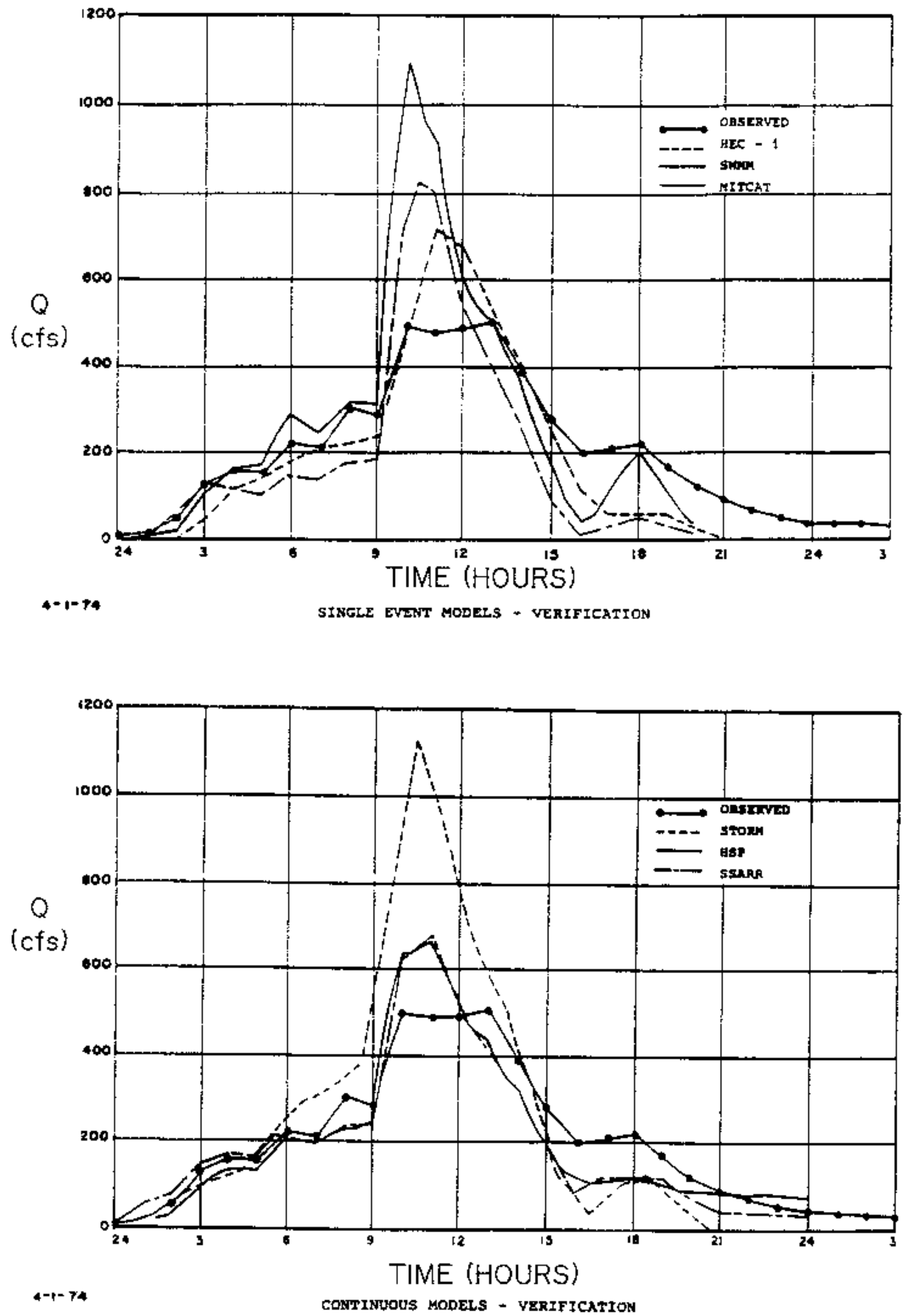

Fig. 5c. Comparison of Calibrated Models (Continued)

be a standard in comparing rainfall-runoff model performance.

A second set of criteria must be evaluated when using a new rainfall-runoff model for design storm flood estimation. Model parameters must be correlated to watershed characteristics, or regional values of the parameters must be established. More specifically, the model parameters used as the dependent variables must provide a relationship between the return frequency of runoff and the return frequency of the input rainfall. Acceptance of any new modelling technique typically depends upon the models ease of use and reproducibility of the results by different engineers and hydrologists. Hall[16] concludes that "until the additional steps required to develop a rainfall-runoff model into a flood estimation method are more widely appreciated, this apparent reluctance to accept innovation is liable to remain a feature of design practice."

The lack of success in concluding a purely deterministic rainfall-runoff modelling approach for developing watershed runoff quantities has motivated the proliferation of dozens of complex, conceptual or so-called physically-based models. However, based upon the available literature, the weight of evidence indicates that use of simpler models such as the well-known unit hydrograph approach will continue to be the most widely used modelling technique. It appears as though the simpler models are able to represent a considerable amount of the explainable phenomena that frequently occurs, and the improvement in modelling accuracy due to inclusion of additional complexity is oftentimes overwhelmed by the scale of uncertainty which cannot be reduced. In a study of stochastic hydrologic methods, Klemes and Bulu[17] write that often modellers "sidestep the real problem of modelling--the problem of how well a model is likely to reflect the future events--and divert the user to a more tractable, though less useful, problem of how to construct a model that will reproduce the past events. In so doing they expect, and perhaps rightly so, that by the time the prospective modeller has dug himself out of the heaps of technicalities, he either will have forgotten what the true purpose of modelling is or will have invested so much effort into the modelling game that he would prefer to avoid questions about its relevance." According to Gburek[18], "...a model system is merely a researcher's idea of how a physical system interacts and behaves, and in the case of watershed research, watershed models are usually extremely simplified mathematical descriptions of a complex situation...until each internal submodel of the overall model can be independently verified, the model remains strictly a hypothesis with respect to its internal locations and transformations...".

The current thrust in development of rainfall-runoff models is towards being physically based in that they model all the several components of the hydrologic cycle in rainfall-runoff processes. However the resulting products "...are simplified nonlinear, lumped parameter, time-invariant, discontinuous representations of a complex nonlinear, distributed parameter, time-variant, and continuous system" (Sorooshian and Gupta,[19]). The use of a lumped parameter approach means that a characteristic or representative value of a parameter is assumed to apply for the entire watershed, for each parameter used in the model. The invariant parameter assumption assumes that all parameters are constant with respect to seasonal moisture changes. Rain gauge data are also lumped by some selected procedure which ignores the time and spatial variations of rainfall over the watershed, and between storm events. Watt and Kidd[20] write that the differences between physically based and so-called "black box" models, (e.g., unit hydrograph models), become less obvious when applied to a field situation. The authors conclude that the considerations of whether the model is physically based or is a black box model "should carry very little weight in the selection process."

Another major issue involving use of rainfall-runoff models is that each of these models requires a calibration of the model parameters be performed in order to obtain an optimum parameter set. However, currently there is no proven technique to obtain this true optimum parameter set.

A brief summary of the success and failures in calibration of model parameters is contained in Sorooshian and Gupta[19] who write

> "In a recent paper, Alley et al. (1980) stated that 'many of these models have been developed as intellectural exercises rather than useful tools for practicing engineers'. They stressed the need for a balance between (1) processes and (2) the operational characteristics of the model affecting its utility for practical applications. Moore and Clark (1981) expressed a similar concern by stating that 'it is no exaggeration to say that the present state of rainfall-runoff modelling is extremely fragmented'. Among the reasons they provided in support of the above statement are (1) the difficulty in the selection (i.e., among the many models available) of the 'right model' by a potential user and (2) the difficulty encountered in the calibration of the selected model, using an 'automatic' approach. With respect to the latter difficulty they reference the work of Johnston and Pilgrim (1976) and Pickup (1977) with the Boughton model. The most important conclusion of the work of Johnston and Pilgrim was their inability, in over two years of full-time effort, to find a 'true optimum' parameter set for a nine-parameter version of the Boughton model on the Lidsdale 2 catchment in Australia. Perhaps more disturbing is the fact that even under ideal conditions (created by assuming a perfect set of parameters and using synthetic data), Pickup (1977) was unable (using an automatic approach) to obtain the 'true' values of the Boughton model's parameters. Worth mentioning is the fact that Ibbitt (1970), working with a version of the Stanford watershed model, experienced the same difficulty"

The study of Johnston and Pilgrim[21] highlighted the complexities associated to determining the optimum parameter set for a conceptual model, and although the Boughton model was used, it was concluded that "most of the findings are applicable to all rainfall-runoff models." Their study identified nine levels of difficulty in optimizing a parameter set, most of which are related to parameter interdependence and the use of a specific objective function to optimize the parameters.

They conclude that "until more confidence can be placed in the derivation of truly optimum values, some doubt must remain on the potential usefulness of rainfall-runoff models." When attempting to calibrate a simulation model to model-produced runoff data, Sorooshian and Gupta[19] reported that "even when calibrated under ideal conditions, it is often impossible to obtain unique estimates for the parameters."

In another examination of the 13-parameter Boughton model, Mein and Brown[4] examine the conceptual rainfall-runoff model's sensitivity to variations in each parameter of the 'optimized' parameter set. They conclude that "relationships derived between any given parameter value and measurable watershed characteristics would be imprecise, i.e., they would have wide confidence limits" and that "one could be confident therefore in changing a particular parameter value of this model and then claiming that this alteration represented the effect of some proposed land use change. On the other hand, the model performed quite well in predicting flows with these insensitive parameters, showing that individual parameter precisiion is not a prerequisite to study output performance."

Dawdy and Bergmann[22] identify two categories of error which impact rainfall-runoff models, namely, errors in the estimation of an optimum parameter set and errors resulting due to the unknown variability and intensity of rainfall and storm volume over the watershed. The second error category "places a limit of accuracy upon simulation results," even given the true long-term parameter set. The study concluded that for the test 9.7 square-mile California watershed, using data from a single rain gauge whose data had been adjusted to represent mean basin conditions, the prediction of flood peaks could not be made better than about 20 to 25 percent using a rainfall-runoff simulation model.

Ideally, a dense network of rain gauges within the watershed should be used to determine the spatial and temporal variation in storm rainfalls for each storm event. However, usually only one or two gauges are available, and often not within the watershed. "Even if measurements from a single gauge may be assumed to be representative of overall basin precipitation in an expected value sense, other statistical properties of point rainfall, mainly variability, will differ considerably from the corresponding properties of average basin rainfall. The result can be serious errors in runoff prediction and large biases in parameter estimates obtained by calibration of the model" (Troutman[23]).

Indeed, rainfall measurement errors at the rain gauges themselves provide a source of concern (see for example, Kelway[24]). "For single rainfall events, where the total catch exceeded 12mm (0.5 inch), the error ranged between 0 and 75 percent, depending on wind characteristics during the storm," (Neff[25]).

Another source of difficulty in the determination of the true optimum parameter set is the optimization procedure used during the calibration process, that is, the so-called objective function which is to be minimized. "The choice of the set of data and of the objective function to be used for any given model is a subjective decision which influences the values of the model parameters and the performance of the model," (Diskin and Simon[26]).

Pilgrim[27] writes that "Another approach uses a watershed model to simulate either a long flow record from continuously recorded rainfall, or a series of historical floods from the rainfall recorded in the major storms on the basin. While they are attractive theoretically, none of these approaches is used widely at present, and it is unlikely that any will make serious inroads on the use of a single design flood in the foreseeable future."

Pilgrim notes that "There has been a tendency for researchers to develop complex models of what they assume or imagine happens on real watersheds based on limited data. The enshrinement of procedures in sophisticated models may then lead to general acceptance that nature does actually behave in the assumed manner."

Runoff Hydrograph Generation Techniques (Linear vs. Nonlinear)

A common critique of the unit hydrograph method for producing runoff is that this approach results in a linear model whereas the watershed response is nonlinear. A popular technique for providing a nonlinear response is the kinematic wave modelling approach which involves the use of overland flowplanes for subarea runoff timing effects, and an approximation of the St. Venant equations for unsteady flow routing. The relative usage of KW by 1983 is indicated in Cermak and Feldman[28] who write that "actual applications by Corps field offices have been few to nonexistent. Even at HEC the KW approach has not been utilized in any special assistance projects." The relatively small usage of KW was then explained as being due to the slack in hydrologic studies and due to unfamiliarity with the technique.

Watt and Kidd[20] write that in the comparison of so-called 'physically-based' or 'black-box' modelling types (e.g., UH or n-linear reservoirs) the differences are not clear. For example, "except for certain 'ideal' laboratory catchments, the flow does not conform to the sheet-flow model but instead occurs in many small rivulets....The choice is then between a 'black box' model and a 'physically-based' model which is based on a physical situation quite different than the actual field situation, i.e., a 'black box' model." Dawdy and Saluja[29] write that "...the kinematic wave routing option is not recommended for channel routing, per se. It does not attenuate the flood wave when properly used. The purpose of channel routing, per se, is to model the attenuation of the flood wave. Therefore, almost by definition to a practicing engineer, kinematic wave models should give way to other models for that purpose, even hydrologic black-box models such as Muskingum routing."

However, use of KW implies a non-linear response whereas the UH implies a linear response. Nash and Sutcliffe[13] write that "the UH assumption of a linear time invariant relationship cannot be tested because neither the input (effective rainfall) nor output (storm runoff) are unequivocally defined." Although watershed response is often considered to be mathematically nonlinear, the nonlinearity of the total watershed response has not been shown to be exactly described as a KW. Indeed, a diffusion hydrodynamic model, DHM (Hromadka and Yen[30]), provides another nonlinear watershed response that includes an additional term in the governing St. Venant flow equations and that may differ significantly in response from a KW model (e.g., overland flow planes with KW channel routing). There are an infinity of nonlinear mathematical representations possible as a combination of surface runoff and channel routing analogs; therefore, merely claiming that the response of a watershed model can be classified as 'nonlinear' is not proof that the model represents the true nonlinear response of the catchment. Pilgrim[27] writes that the use of sheet-type overland flow models "allows a fairly rigorous mathematical treatment," however "the physical realism of sheet-type overland flow on either natural or urban watersheds is open to serious question." Pilgrim also noted, "surprisingly, little field evidence is available on the realism of the assumed sheet-type flow. Intuitively, the probability of its occurrence on even grassed natural slopes seems to be low...and on urban watersheds to be virtually nil." Additionally, "The nonlinear power-type relation is based on the hydraulics of extremely simplified models of the watershed systems, or on rather scanty empirical data."

Given that the KW analog is only used to obtain an approximation to catchment response, the KW approach does not appear to provide significantly better computational results (for floods of interest in flood control design and planning) than the commonly used UH method. Dickinson et al.[31] noted that "in the range of discharges normally considered as flood hydrographs, the time (of concentration) remained virtually constant. In other words, the range of flood interest, the nonlinear effect approached linearity." An explanation was advanced that "at low discharges, the mean velocity may vary considerably with discharge. However, for higher discharges contained within banks, the mean velocity in the channel remains approximately constant."

Pilgrim[27] writes that "Considerable attention has been paid to the choice between linear and nonlinear models, but to a surprising degree has been based on rather superficial consideration of vague evidence. Even less incisive consideration has been given to the form of nonlinearity. Virtually all forms of nonlinear models, whether using storage routing or the Saint Venant equations or simplifications such as kinematic wave, involve a power function type of relation with average velocity increasing as discharge increases."

In actual travel time measurements of flows in a 96-acre catchment using a radioactive tracing technique, Pilgrim[27] noted that although the flood runoff process "is grossly nonlinear at low flows, linearity is approximated at high flows." It is noted that "at medium to high flows the travel times and average velocities become almost constant, indicating that linearity is approximated in this range of flows. This explains why the unit hydrograph and other linear synthesis methods often give acceptable results in practical flood estimation, even though the entire flood runoff process is nonlinear." Pilgrim also writes that "simple nonlinear models fitted by data from events covering the whole range of flow may give gross errors when used to estimate large events." The study also noted that "only relatively high floods are generally considered in the derivation of unit hydrographs or other response parameters, and this is the region of approximate linearity."

Beven[32] proposed to place limits on the nonlinearity associated to KW by the specification of a constant flow velocity for catchment runoff for large floods. He proposes "a nonlinear channel system at low flows and a linear system at high flows into a single model." Hence for flood flows of interest in flood control planning and design, Beven's model would reduce to a linear representation of the catchment hydraulics. He writes that "the overall velocities of the flow of water through the (channel) network were markedly nonlinear at low to medium discharges but approached a slowly increasing or constant value at high discharges...The reasons for this type of behavior are undoubtedly complex, but, in the simplest terms, it would appear that at low flows the average velocities over a reasonable length of stream are controlled by slow tranquil flow...As flow increases, many of the controls...become drowned out."

Hjelmfelt and Burwell,[33] conducted a field study of 40 near-identical, contiguous, soil plots which all fit the kinematic wave flow plane concept. Surprisingly, a large variation in measured runoff was observed. "In the usual descriptions applied by current mathematical models of small watersheds, each plot was identical, so these results contribute to defining confidence limits that can be applied to model results, i.e., if a mathematical model were constructed that predicted the 40-plot mean for each event, and that model were compared with the observed values for any one plot, there would be differences between predicted and observed results."

In HEC Technical Paper No. 59[15], six models, plus two variants of one of these models and a variant of another, were calibrated and tested on a 5.5 square-mile urban catchment in Castro Valley near Oakland, California. Both single event and continuous simulation models based on both UH and KW techniques were used in the text. The study concluded that for this watershed "the more complex models did not produce better results than the simple models..." An examination of the test results between the KW and HEC-1 UH models did not show a clear difference between the methods (see Fig. 5).

It is of interest that Singh[34] concluded "It is shown that if rainfall excess errors are sufficiently large, a perfectly identified nonlinear model does not perform always as well as an optimally identified linear model in predicting runoff peak, according to an objective function based upon fitting of runoff peaks. Thus, if one is not very confident in estimates of watershed infiltration then in some circumstances linear models may have an advantage over nonlinear models in runoff peak prediction because they do not amplify the input errors." That is, the uncertainty in effective rainfall quantities may be magnified by a nonlinear model; consequently, there is an advantage in using a linear model when there are errors in loss rate and precipitation estimates. Pilgrim[27] notes that "If linear and nonlinear models are calibrated on medium-sized observed floods, and the calibrated models are then used to estimate a much larger design flood, the nonlinear model will give a higher flood peak and a shorter time to peak than the linear model...if a power-type nonlinear model is used, the increase in peak flow relative to the value from a linear model is commonly in the range of 10-50 percent..."

Because it is not clear whether the nonlinear KW method for modelling surface runoff provides an improvement in accuracy over the linear UH based hydrologic models, the UH model will probably continue to be used in hydrologic design and planning modelling studies. The UH approach is simpler to apply, and there is less chance that the UH approach will be incorrectly applied. Becker and Kundzewicz[35] writes that "One possible step toward nonlinear modelling is to use different linear models (i.e., different impulse responses) for different events. In this case the model is linear for one event and nonlinear from event to event if significantly different events are considered."

In the work of Dickenson et al.[31], they conclude "In other words, in the range of flood interest, the nonlinear effect approached linearity. This very example may be due partially at least to the distribution of mean velocity in a stream versus discharge. At low discharges, the mean velocity may vary considerably with discharge. However, for higher discharges contained within banks, the mean velocity in the channel remains approximately constant. Therefore, in the range of flood discharges...effects that are highly nonlinear in some parts of their ranges... approach linearity in the range usually considered for flood hydrographs."

Almost all rainfall-runoff models involves the subdivision (or discretization) of the catchment into subareas (each subarea assumed to be of a uniform runoff response with respect to land cover, loss rates, and other factors), and the definition of links which connect the several subareas as a representation of streamflow or pipeflow routing effects. Each link represents a specific reach of channel or pipe, and the flow routing effects are modeled by a variety of techniques. Almost all flow routing techniques (used in current rainfall-runoff models) neglect backwater effects due to downstream channel flow hydraulics, and assume that the runoff hydrograph at the downstream end of the channel link can be computed given only the upstream runoff hydrograph and some channel characteristics data. Currently, there is no universally accepted channel flow routing technique.

Hromadka and DeVries[36] demonstrated the wide range of computational results possible from the frequently proposed kinematic wave (KW) routing technique. They note that "This 'range of results' impacts the very credibility in using KW or channel routing hydrologic models." When the KW equations are solved correctly, there would not be an attenuation of the peak flow rate. "But many channel routing conditions do exhibit peak attenuation due to channel storage effects, and, therefore, use of the KW would contradict the fundamental channel routing characteristics. Possibly, KW should only be used when there is negligible peak attenuation in the channel. In that case, simple hydrograph translation would be a simpler method to use than KW."

With the variety of routing techniques used in rainfall-runoff models, it is useful to have a multilinear routing technique which can represent a nonlinear technique (such as KW) by use of a set of linear equations which are individually selected based upon the magnitude of the flow hydrograph being routed. Such a multilinear model would then be a linear model on a flow hydrograph class basis. Additionally, unit hydrograph or convolution techniques could then be defined which approximate the nonlinear routing technique on the flow routing class basis (see

Sauer[37]; Mitchell[38]; Doyle et al.[39]; Keefer[40]; Porter[41]; Becker and Kundzewicz[35]). The utility of the multilinear model of flow routing is that essentially all flow routing techniques used in rainfall-runoff models could be rewritten in terms of a multilinear model equivalent. Additionally, due to the decrease in nonlinearity observed in floods of interest with respect to flow magnitude, the multilinear model representation would require only a modest number of flow hydrograph classes in order to adequately perform as the original nonlinear model.

Important recent research in UH methods to model rainfall-runoff response, and to analyze basin response in a stochastic framework is contained in Rodrequez-Iturbe et al.[42,43,44], Troutman and Karlinger[45], and Gupta and Waymire[46]. Pilgrim[47] reviews runoff modelling difficulties, especially in transferring data between basins. With the modelling difficulties thus far reported, perhaps the point of diminishing return has truly been reached, and rainfall-runoff models should be coupled to a stochastic model in order to obtain confidence interval estimates in order to reflect the uncertainty in runoff predictions.

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