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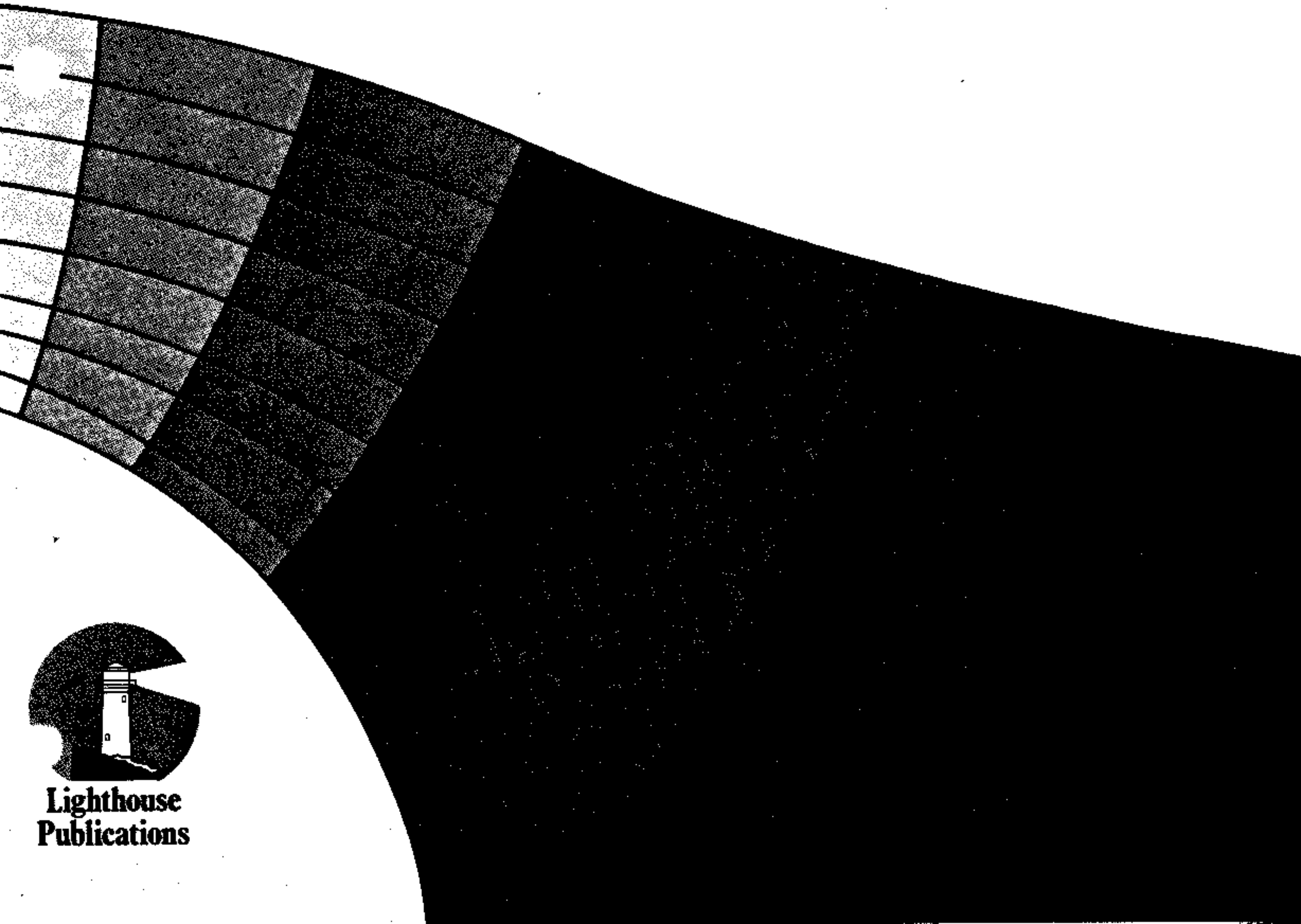

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Complex Watershed Models in Flood Control: Questions of Credibility

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Abstract

The flood control agencies of two large counties in California have recently completed a major study effort in the development of a flood control Hydrology Manual. The manual describes the methods and procedures to be used for all hydrology studies prepared for projects within the counties of Orange and San Bernardino. Included in the process is the evaluation of all available canned hydrology computer programs and the selection of a particular model. Based on the literature review, the huge set of available models was found to be an indication of the lack of success in modeling accuracy rather than an advancement in technology. As a result, a Hydrology Manual was prepared which prescribed a single model for use on all studies. It was decided that a simple model which provided reproducible results was the most important factor in the selection of a modeling approach. Included in the paper is a brief discussion of the selected model, the calibration effort, and the policy statement preparation contained implicity within the Hydrology Manual.

Introduction

Advanced in hydrologic modeling techniques typically involves the incorporation of higher complexity into the hydrology model by use of improved hydraulic submodels or a more refined approximation of the several subprocesses integrated in the hydrologic model. With over 100 models reported in the open literature, it is appropriate to review the progress achieved by the complexification of hydrologic models. That is, it is time to evaluate whether the general level of success afforded by the many types of complex models provide a marked improvement over that achieved by the more commonly used and simpler models such as the unit hydrograph method. Such a review indicates that, in general, an increase in modeling complexity does not result in an increase in modeling accuracy. It appears that the major limitation to the successful development, calibration, and application, of any hydrologic model is the uncertainty of the effective rainfall distribution over the catchment.

A review of the literature indicates that a substantial evolution in modeling complexity has occurred over the last two decades. The majority of changes have occurred in the incorporation of soil moisture accounting techniques and intricate link-node model discretization using approximations for hydraulics. However in spite of the advances made in the modeling complexity, the accuracy of models (in general) has not beeen significantly improved in the correlation of rain gage data to stream gage runoff data. Only a handful of papers and reports are available in the open literature which compare modeling performance, and each of these reports note that simpler models do as good as or better than complex models. Additionally, many of the papers indicate that the uncertainty in the effective rainfall distribution over the catchment may be a key factor in the lack of major gains in the development, calibration, and application, of hydrologic models. As a result of this lack in demonstrated success in the use of any particular advanced modeling technique or approach, there is continued reliance by the engineering community to use the more simpler modeling approaches such as the rational method for peak flow rate estimates, or the classic unit hydrograph method when a runoff hydrograph is needed.

Model Selection

In the selection of the hydrologic model, the need for both runoff peak flow rates and runoff volumes (for the testing of detention basins) require the selection of a model that produces a runoff hydrograph. The U.S. Army Corps of Engineers (COE) Hydrologic Engineering Center (HEC) Training Document (TD) No. 11, (1980) categorizes all hydrologic models into eight groupings of which three develop a runoff hydrograph; namely, single event (design storm), multiple discrete events, and continuous records (continuous simulation). These models can be further classified according to the submodels employed. For example, a unit hydrograph or a kinematic wave model may be used to represent the catchment hydraulics.

In the 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, October, 1984), 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 complex models by Federal agencies and the private sector, respectively. The frequent use of design storm methods appear 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 is most often selected for flood control and drainage policies (considerations in the choice of modeling approach are contained in the latter sections).

The next decision is whether to use the standard unit hydrograph method or the more recently advanced kinematic wave method to model catchment hydraulics. Again, it has not been clearly established that the kinematic wave approach (e.g., the overland flow plane concept) provides

an improvement in modeling accuracy over the unit hydrograph approach that has been calibrated to local rainfall-runoff data.
For the choice of design storm to be used, the work of Beard and Chang (1979) and HEC ("Hypothetical Floods", 1975) provide a logical motivation for developing a design storm using rainfalls of identical return frequency, adjusted for watershed area effects.

Finally, specific components of the modeling approach must be selected and specified. Inherent in the choice of submodels is the ability to calibrate the model at two levels: (1) calibration of model parameters to represent local or regional catchment rainfall-runoff characteristics, and (2) calibration of the model parameaters (or design storm) to represent local rainfall intensity-duration-frequency characteristics. Beard and Chang (1979) note that in a hydrologic model, the number of calibration parameters should be as small as possible in order to correlate model parameters with basin characteristics. They also write that a regional study should be prepared to establish the loss rate and unit hydrograph characteristics, "and to compute from balanced storms of selected frequencies (storms having the same rainfall frequency for all durations) the resulting floods."

In developing a flood control and drainage policy, the first, and possibly the most important question to answer is: what type of model should be used to form the basis for design calculations? To answer this question, the literature was reviewed extensively. Based on the research findings summarized in the following paragraphs, the design storm/unit hydrograph (UH) method appears to have continued support among practitioners. The question naturally arises as to why the simple UH method continues to be the dominant hydrologic tool when considerably more complex models (e.g., the continuous simulation class of models which has a mathematical approximation for each component of the hydrologic cycle, and typically utilizes physically based hydraulic flow routing approximations. The Stanford Watershed Model is an excellent example of this class of approach.) are available for public use. An explanation frequently cited in the literature appears to be that the uncertainty in the effective rainfall over the catchment overshadows the improved accuracy that may be possibly achieved by more complex models.

Complex vs. Simple Models: A Definition

A criterion for complex and simple models is given by Beard and Chang (1979) 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."

On Model Linearity and Data Availability

In their paper, Beard and Chang (1979) 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 be reasonably validated by available data, and there is little advantage in extending the degree of model sophistication beyond validation capability." It is suggested that "if 50 yr-100 yr of streawm flow were available for a specified condition of watershed development, a frequency curve of flows for that condition can be constructed from a properly selected set of flows."

On Parameters Variability and Model Performance

Schilling and Fuchs (1986) 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 model should employ a simplified surface flow model if there are many sub-basins; a simple runoff coefficient loss rate; and a diffusion (zero inertia) or storage channel routing technique. Hornberger, et al (1985) writes 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 (1986) note that errors in simulation 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, and (3) Model parameter estimates may be in error."

By reducing the rainfall data set resolution from a grid of 81 gages to a single catchment-centered gage in an 1,800 acre catchment, 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 a volume error of 60 percent and peak flow error of 80 percent."

In a similar vein, Beard and Chang (1979) 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 in this region of 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." They 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."

On Predicting Urbanization Impacts

Using another complex model, Mein and Brown (1978) write that on "the basis of several tests with the Boughton model it is concluded that for this model at least, relationships derived between any given parameter value and measureable watershed characteristics would be imprecise; i.e., they would have wide confidence limits.

One could not 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 inpredicting flows with these insensitive parameters, showing that individual parameter precision is not a prerequisite to satisying output performance."

Even When Fully Instrumented...

In the extensive study by Loague and Freeze (1985), three event-based rainfall-runoff models (a regression model, a unit hydrograph model, and a kinematic wave quasi-physically based model) were used on three data sets of 269 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 mile, and 35 acres in size, and were extensively monitored with rain gage, stream gage, neutron probe, and soil site testing.

For example, the 25 acre site contained 35 neutron probe access sites, 26 soil parameter sites (all equally spaced), an on-site rain gage, and a stream gage. The QPB model utilized 22 overland flow planes and four channel segments. In comparative tests between the three modeling approaches to measured rainfall-runoff data it was concluded that all models performed poorly and 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."

On Complex Model Applications and Comparisons

It is noteworthy to consider the HEC Research Note No. 6 (1979) where the Hydrocomp HSP continuous simulation model was applied to the West Branch DuPage River in Illinois. Personnel from Hydrocomp, HEC, and COE participated in this study which started with a nearly complete hydrologic/meteorologic data base. "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. 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."

On Nonlinearity: Use of a Nonlinear Kinematic Wave Method or a Linear Unit Hydrograph Method

Watt and Kidd (1975) write that in the comparison of so-called 'physically-based' or 'black-box' modeling 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 by 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."

In actual travel time measurements of flows in a 96-acre catchment using a radioactive tracing technique, Pilgrim (1976) noted that although the flood runoff process "is grossly nonlinear at low flows, linearity is approximated at high flows." Pilgrim also writes thats "simple nonlinear models fitted by data from events covering the whole range of flow lay give gross errors when used to estimate large events." It is noted that overbank flow was one of the factor for linearity in this study.

Beven (1979) 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.

A physical test of the KW concept was provided by Hjelmfelt and Burwell (1984), who studied a set of 40 similar erosion plots and the net response to storm events. Due to the large variability in measured runoff quantitites from the plots, however, it was concluded that a criterion for a valid rainfall-runoff model "is that it predicts the mean runoff for each event." However, it is noted that this test may be more of a test of effective rainfall variability over the catchment than a test of KW response.

In HEC Technical Paper No. 59 (1978), 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 on both UH and KW techniques were used in the test. 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.

It is of interest that Singl (1977) concluded that "if one is not very confident in estimates of watershed infiltration then in some circumstances linear mdoels may have an advantage over nonlinear models in runoff peak predictions 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 inusing a linear model when there are errors in loss rate and precipitation estimates.

On Design Storms

In complex watershed systems that include catchment subareas, and channel and basin routing components, Beard (1975) writes that "it is usually necessary to simulate the effects of each reservoir on downstream flows for all relevant magnitudes of peaks and volumes of inflows. Here it is particularly important that each hypothetical flood has a peak flow and volumes for all pertinent durations that are commensurate in severity, so that each computed regulated flow will have a probability or frequency that is comparable to that of the corresponding unregulated flow...In the planning of a flood control project involving storage or in the development of reservoir operation rules, it is not ordinarily known what the critical duration will be, because this depends on the amounts of reservoir space and release in relation to flood magnitude. When alternate types of projects are considered, critical durations will be different, and a design flood should reflect a degree of protection that is comparable for the various types of projects."

Beard (1975) notes that the balanced storm concept is an important argument for not using a historic storm pattern or sequence of storm patterns or sequence of storm patterns (e.g., continuous simulation or discrete event modeling) as "No one historical flood would ordinarily be representative of the same severity of peak flow and runoff volumes for all durations of interest." Indeed, should a continous simulation study be proposed such that the "project is designed to regulate all floods of record, it is likely that one flood will dictate the type of project and its general features, because the largest flood or peak flows is also usually the largest-volume flood." Hence a continuous simulation model of say 40 years of data can be thought of as a 40 year duration design storm with its own probability of re-occurrence, which typically reduces for modeling purposes to simply a single or double day storm pattern.

Conclusions

Of the over 100 models available, a design storm/unit hydrograph model (i.e., "model") is currently the most widely used modeling technique among practitioners. Some of the reasons are as follows: (1) the design storm approach--the multiple discrete event and continuous simulation categories of models have not been clearly established to provide better predictions of flood flow frequency estimates for evaluating the impact of urbanization and for design flood control systems than a calibrated design storm model; (2) the unit hydrograph--method it has not been shown that the kinematic wave modeling technique provides a significantly better representation of watershed hydrologic response than a model based on unit hydrographs (locally calibrated or regionally calibrated) that represent free-draining catchments; (3) model usage--the "model" has been used extensively nationwide and has proved generally acceptable and reliable; (4) parameter calibration--the "model" usually is based on a minimal number of parameters, generally giving higher accuracy in calibration of model parameters to rainfall-runoff data, and the design storm to local flood flow frequency tendencies; (5) calibration effort--the "model" does not require large data or time requirements for calibration; (6) application effort--the "model" does not require computational effort for application; (7) acceptability--the "model" (e.g., channel and basin routing) resulting in a highly flexible modeling capability; (8) model certainty evaluation--the certainty of modeling results can be readily evaluated as a distribution of possible outcomes over the probilistic distribution of parameter values.

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