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Surface Water Hydrology: On-Line Estimation

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Introduction

In recent years a large number of mathematical models of different types have been developed to represent various aspects of the rainfall-runoff (R-R) process. This proliferation of models has led some investigators to voice concerns about the difficulties that the practicing engineer faces in the selection of an appropriate model for his/her specific application. Given the amount of effort (in terms of money and time) that has been devoted to the development and improvement of R-R models, it is perhaps disconcerting that the most widely applied technique for short-interval (24 hours or less) on-line flow forecasting is still the unit hydrograph. Clearly there seems to be some reluctance on the part of practicing hydrologists to employ the newer models. A review of the current literature reveals many reasons for this; principal among them are two. First, there have been few comprehensive efforts to classify R-R models, according to the purposes for which they are useful. Linsley (1982) stated that in order to establish the utility of various types of models, it is important to be aware of the purpose for which a given model was originally developed and listed the following as being some of the principal ones; research, forecasting, and engineering applications (such as reservoir management, record extension and data revision). The focus of this review is the on-line estimation of streamflow discharges and, as such, will address the models that have been developed for the purpose of river flow forecasting.

The second reason for reluctance to use newer models relates to the trend in R-R modeling, which as stated by Klemes (1982) has been "to find that wonderful new calculus that will break through the barrier of the unknown separating raw hydrologic data from information on future valves of hydrologic variables". In pursuit of this goal many new modeling concepts (some of which has proven successful in other disciplines) have been employed to model the R-R relationship for possible on-line forecasting. This has resulted in the development of two types of models, namely, "conceptual" rainfall runoff models, and "systems-theoretic" models Unfortunately, many of these models have evolved so rapidly that inconsistencies and incompatibilities may have been incorporated in them through questionable assumptions whose validity have seldom been tested. Contributing further to this confusion surrounding model selection has been the often contradictory findings of many studies where in the perfromance of a selected conceptual model has been compared to that of a simpler systems-theoretic model. The results of these studies have, more often than not, favored the simpler model. The reasons for this are possibly quite varied and have not been clearly discussed in the literature. However, two important points stand out. First, the state-of-the-art of parameter estimation in conceptual models has not yet been adequately refined, whereas the solution techniques available for system-theoretic models are (comparatively) highly efficient. The second, but perhaps more important, reason is that the comparisons are rarely carried out under conditions which would highlight the inadequacies of model. As suggested by Linsley (1982), the most important property of a model (and the least often tested) should be its inherent accuracy; i.e., it should not be a question of prediction accuracy under known (recorded) conditions, but one of model credibility under unknown (not contained in available records) conditions (Klemes 1982).

As has been highlighted above there are many problems that need to be resolved before we can provide the practitioner with a set of guidelines for the selection of an appropriate model. In particular, there are many assumptions that have accompanied the modeling process that need to be thoroughly verified before these approaches can gain the complete confidence of the practicing hydrologist/engineers. It is encouraging to see that during the review period (1979—1982) there has been some (albeit slow) movement in this direction.

This review paper is divided into two sections; conceptual rainfall-runoff models, and systems theoretic models. In each section an attempt has been made to highlight those problem areas that were addressed during the past four years and those issues which are yet to be adebuately resolved. This review is not intended to provide a comparative evaluation of the merits of each approach and therefore no discussion of this topic is provid.

Conceptual Rainfall-Runoff Models

The so-called "conceptual" rainfall-runoff (CRR) models (e.g. HEC-1, Sacramento Model, Stanford Model, etc.) are intended to incorporate within their structure the general physical mechanisms which govern the hydrologic cycle. In this approach the internal description of the various subprocesses are modeled according to empirically determined functions which are linked in their conceptualized logical order. The precipitation "input" is routed through the various subprocesses, either to the watershed outfall as streamflow, to deep storage as groundwater flow or released to the atmosphere as evapotranspiration. The models are primarily used to study and forecast future riverflow magnitudes. In this review their real-time use for river forecasting is of particular interest. This includes forecasting of flood levels, inflows for reservoir operations and the likely range of future inflows both in terms of volume aud timing of water supply, irrigation, and power generation. It should be clear that for the above purposes the ability of the model to accurately compute discharges for time intervals of one day or less on a continuous basis is critical.

Duing the 60's and early 70's, there were numerous reports of new CRR models. Alley, Dawdy and Schaake (1980) recently stated that "many of these models have been developed as intellectual excercises rather than as useful tools for practicing engineers". They stressed the need for a balance between the devolopment stage involving the connection of algorithms representing the subprocesses involved, and the operational characteristics of the model affecting its utility for practical applications. Klemes (1982) states that "conceptual" models which purport to be causal models are sometimes only disguises, and goes on to say that they are "somewhat structured empirical constructs whose elements are regression coefficients with physically sounding names". It appears that such concerns have had some influence on the focus of current research. During the period under review there have been no reports of any new CRR models being developed in the U.S.. Instead, researchers are paying closer attention to the problems of the existing models and are making attempts to resolve them.

The reported work will be reviewed in relationship to the following there are as which may be considered as the main requirements of an operational CRR model:

1 - function development
2 - ralibration and verification procedures
3 - model application and forecasting

Function Development

There are two imporant issues that must be considered in the formulation of the structural equation of any CRR model. First, the subprocess equations selected should represent, as well as possible, the under physical phenomena. Second, the model should be "identifiable" based on the quantity and quality of the information avilable about the overall process.

Review of many existing models shows that they are highly parameterized and that most of their subprocess equations have been selected from the pool of techniques that has existed in the litersture for many years. However, the selected equations have often been modified to either fit the modeler's "coneceptualization" of the processes and/or to overcome the limitations associated with modeling. The majority of the existing CRR models are deterministic, nonlinear, lumped-parameter, time-invariant and discontinuous representations of a very complex stochastic, nonlinear, distributed-parameter, time-varying and continuous system. Many of these simplifying assumptions, depending on their degree of seriousness, can adversly affect the performance of the model as a forecasting tool.

Take for example, the lumped parameter representation of the watershed which requires that each parameter assume some sort of average value for the entire catchment. Freeze (1980), using Monte Carlo analysis, has shown that the parameters representing the spatial stochastic properties of the hydraulic conductivity distribution on a hillslope exert an important influence on the statistical properties of runoff events. He concluded that besides the mean, the standard deviation of the spatial distribution of the parameters has an important effect, but that the autocorrelation function is not very important. However there have been no reports by U.S. researchers of any CRR models being modified to include the heterogeneity of the watershed characteristics within their parameteric representation. This is one area in which future research is definitely needed.

The assumption that the parameters are time-invariant is also a critical one. Parameters obtained by calibration using wet season data may fail to adequately forecast dry season response (and vice versa), due to natural changes in the soil structure that are unmodeled. Sorooshian, Gupta and Fulton (1982b) obtained three different parameter sets for the soil moisture accounting mode of the U.S. National Weather Service River Forecast System (SMA-NWSRFS), using a dry, average and a wet year from an eighteen year data record of the Leaf River Basin Mississippi. Their results indicated that the large variation in the values of parameters was only partly due to data variability and that conceivably the paraments best representing the watershed response varied seasonally, or were trended with respect to time due to physical changes in the watershed (e.g. deforestation, urbanization etc.). They were, however, unable to isolate the influence of the time-invariancy assumption on the accuracy of the model's performance, They also discovered that some aspects of the model's structure (which will be discussed later) were contributing so profoundly to parameter variability that without their prior resolution, it would be impossible to study the impact of the time-invariancy assumption. In the meantime, as proposed by Alley, Dawdy and Schaake (1980), it may be desirable to operate models for simulation of seasonal records rather than for the entire year.

Another problem that has long been recognized concerns the lumping of data used by the model in order to correspond to the lumped-parameter natuue of the modls. Concurrent data from different rain guages are usually aggregated in some manner and converted to average equivalent uniform depth of rainfall over the watershed. The effects of lumping spatially distributed data are still not entirely clear and there have been no reports of any studies to investigate them. However, it is well known that for a large watershed, due to spatial variability of rainfall patterns, the identification of even a simple unit hydrograph model poses uniqueness problems, and the effects could possibly be much worse for CRR models.

An important factor that should not be overlooked relates to the relative accuracy (from a physical point-of-view) of the various model-subprocess equations. Most CRR models consist of an upper interception zone, a lower groundwater zone, and an interconnecting percolation process. Sorooshian and Gupta (1982) argued that a lumped linear reservoir representation of the lower zone is a relatiely more accurate representation of its corresponding physical subprocess than is a lumped, linear reservoir representation of the upper zone. Hydrologists have long recognized that baseflow into a stream can be fairly accurately represented by the outflow from one or more linear reservoirs. Also, as Gupta (1982) pointed out, the relative homogeneity and slower response of the lower zone makes it less sensitive to the spatial variability of inputs. On the other hand, the upper zone of the model, with a much faster response to inputs, is far more likely to be sensitive to spatial variability in rainfall patterns. The consideration of these issues, as will be discussed later, is crucial to the success of the calibration stage.

Related to the use of reservoirs to represent different vertically stratified zones of soil, are the difficulties resulting from the presence of "threshold parameters" in many CRR models. The extreme nonlinearities introduced by these parameters makes it rather impractical, if not impossible, to obtain an explicit functional representation of the model output in terms of the input and the parameters. There are two main effects of this that have received special attention in the literature. First, our ability to "automatically" estimate the parameter values is serioussly limited. Powerful nonlinear optimization techniques cannot be used, as the partial derivatives of the optimization function with respect to the parameters are not available. As a result, the use of the much less efficient "direct search" (derivative-free) algorithms is common. Sorooshian and Gupta (1982) stated that threshold parameters could prevent any search algorithm from terminating at the optimum parameter set. They used a simple two-parameter model to demonstrate the presence of an extended valley on the response surface (in the direction of the threshold parameter) and showed that if the initial value of the threshold parameter was poorly chosen the search algorithm would yield a nonoptimal parameter set. To overcome this problem it was suggested that low initial values be selected for the threshold rarameters so as to increase their chances of converging to optimal values.

The second problem associated with the presence of threshold parameters arises when one attempts to implement some of the recent advances in filtering theory (e.g. Kalman filtering) for on-line forecasting and adaptive parameter estimation. The nonexplicit from of the model's state-space eqations demands the development of specialized nonlinear filtering algorithms. Kitanidis and Bras (1980 b,c) and Goldstein and Larimore (1880) treated this difficulty by using statistical linearization and/or introducing smoothing functions in place of the thresholds. The model used in the above cases was a version of the SMA-NWSRFS models. The above mentioned modifications to the structural equations of the CRR models (with theshold parameters) were shown to facilitate the application of adaptive estimation algorithms based on the Kalman Filter. It is important, however, to ensure that any modification schemes, such as the ones employed do not compromise the physical integrity of the model. This is one area which needs considerable examination before any conclusions regarding the most appropriate method can be drawn.

The representation of the percolation process is considered by many to be one of the weakest components of CRR models. Sorooshian and Gupta (1982) examined the percolation function of the SMA-

NWSRFS model. This nonlinear equation, as shown by Gupta (1982), is conceptually similar to the Horton's equation, contains a total of eight parameters that need to be estimated. They reported difficulty in estimating unique and consistent values for the parameters of this epuation. The result of a controlled study using synthetic data revaled that even when calibrated under ideal conditions it was impossible to obtain unique estimates for two of the parameters. Closer examination revealed the esistence of a long interacting valley (line optimum) in the response surface of the two-parameter subspace. Gupta (1982) and Sorooshian (1982) showed that nonidentifiabilily problem was a result of the chosen structural representation of the percolation process and that the problem could be resolved by an appropriate reparameterization of the associated equation. They pointed out the import fact that it may often be possible to improve identifiability without compromising the physical integrity of the model.

Two interesting lessons may be learned from these studies. The first is that any process equation which seems appealing from a "conceptual" point-of-view of model identifiability (irrespective of the calibration method employed). Secondly, it is important to examine the behavior of the calibration procedures under ideal conditions (simulation studies) so as to detect nonidentifiability and nonobservability problems associated with the model that must be resolved if automatic (or even manual) calibration techniques are to be employed.

Another possible deficiency in the representation process in most CRR models, is the lack of any provision for the upward movement of water due to capillary action (an exception is the Dawdy, O'Donnell model). Considering the existence of these and other conceptual deficiencies, one is led to question whether the traditional infiltration theory employed in the development of these models is really dequate. Recent work by Australian researchers have indicated that a more realistic representation can be developed by employing the concept of retention hysteresis. Similar ideas have also been proposed by Nguyen and Wood (1981) in the context of the modeling of rainfall infiltration. This approach, which explicitly recognizes that the watershed behaves differently in its wetting and drying cycles, has the potential to significantly improve the performance of CRR models and deserves close attention.