A REVIEW OF RAINFALL–RUNOFF MODELING

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Introduction

Mathematical modeling of the rainfall-runoff process has a long history. However, progress was slow prior to about the last half century. The decade of the 1930's saw an outburst of activity which laid the groundwork for most of the present developments. Hydrology advanced on all fronts during the 1930's. The concept of physical hydrology was introduced and led to an understanding of the physics of the hydrologic cycle. The tools developed during the 1930's to solve practical problems were tailored to costs in terms of time, money, and manpower, and they did not reflect the level of understanding at that time. Hydrology reached a point as a result of the advances of the 1930's where the ability to state the problem far exceeded the ability to solve it.

The Second World War brought a halt to the attention paid to the advancement of hydrology. However, the war led to the development of digital computers. That was a tool with which to solve the problems previously unsolvable. The constraint in hydrology changed from the inability to solve a problem to the inability to collect sufficient and sufficiently accurate data to prove that a solution is correct or more nearly correct or less incorrect than other solutions.

This paper will try to trace the developments outlined above, place them in perspective, and trace the history of how we arrived where we are today in hydrology. In addition, some suggestions will be made about where we are, why we are there, and where we might be going.

The essence of hydrology is modeling. As a physical science, hydrology is concerned with numbers—quantitative numbers are desired. A model is a mathematical statement of the response of a system which takes system inputs and transforms them into system outputs. Even though the jargon is modern, the rational method for estimating peak runoff used data available in the middle of the 19th century with a model based on physical principles—time response of the basin, rainfall intensity, and proportion of excess precipitation were used to determine the peak rate of runoff.

Linear Systems and Mathematical Hydrology.

The modern burst of development in deterministic modeling of rainfall–runoff processes dates from the 1930's, and the unit hydrograph concepts of Sherman (1932). Although not stated in those terms at that time, Sherman assumed that the runoff process was linear and time invariant, the basic assumptions of linear systems analysis.

The essence of a system is that it interrelates two things—the inputs to and the outputs from the system. The system is a model which determines a system function, a set of parameter values which
determine the response function, and a set of values for the state variables, which in hydrology describe how wet or how dry the system is. This model is an abstraction, a mathematical construct which, we hope, acts somewhat similar to the way the real world does. It is the modeler's conception of how the real world acts. The values of the parameters of the model define a particular system. They determine how the model reacts to inputs when they are applied to a particular basin. The state variables are measures on the system which change in response to inputs.

A linear system is one which can be described by a linear differential equation. The coefficients of the equation may be constant, as in Darcy's law for saturated flow in porous media, or they may be variable, as in Darcy's law for flow in unsaturated media, or they may describe a probability density function in a stochastic differential equation. If the coefficients are time invariant, then superposition holds, which is the basic tool of linear systems analysis. Superposition says that if an input is doubled, the output also is doubled. Thus, superposition is the property which places unit hydrograph theory in the realm of linear systems analysis, and it is the property on which most of linear hydrologic modeling has been based.

Confusion introduced by models. — A model is the choice of the modeler. It is a conceptual abstraction. Parameters are a part of the model, and they have no meaning outside the model. If the modeler builds a physically based model, then the parameters are abstractions which may approximate some physically meaningful quantity. In hydrology, approximations often are quite gross. That fact cannot be ignored by the model user. Much of the confusion in hydrology results from the attempt by the user to give a physical explanation to a rule of thumb without supplying a rigorous mathematical foundation.

An example in hydrology is the attempt to give physical meaning to the time response of a basin. The concept of linear storage is widely used and quite useful in hydrology. The assumption that outflow from a reservoir varies linearly with storage:

\[ S = KQ \] (1)

combined with an equation of continuity of mass:

\[ I - Q = ds/dt \] (2)

leads to the relation:

\[ I - Q = K dQ/dt \] (3)

to which the solution for no inflow is:

\[ Q_t = Q_0 e^{-(t-t_0)/K} \] (4)

where \( Q \) is the outflow discharge, \( S \) is storage, \( I \) is inflow discharge,
t is time, \( t \) is the starting time, and \( K \) is a coefficient. \( K \) has the dimensions of time, and it has a meaningful interpretation in terms of its use in the model. Time of concentration, lag time, and other such terms lead only to confusion unless presented and interpreted in such a mathematical framework.

Storage is not a discrete quantity in modeling a basin by use of an instantaneous unit hydrograph (IUH), so that the logic of equations 1 to 4 cannot be directly interpreted in a physically based manner. The linear storage concept in IUH modeling must account for all the storage attenuation of the hydrograph in a basin. Thus, the parameter \( K \) must account for dynamic storage as well as discrete storage distributed over a basin. \( K \) has been related empirically to size of basin, length of basin, and slope of the basin and/or the main channel, but it has no true physical definition.

On the other hand, much of the confusion in hydraulics results from the use of a rigorous mathematical formulation which is treated as if it were the real world. For example, the dynamic equation for one-dimensional, steady flow in open channels is

\[
\frac{1}{g} \frac{V}{t} + \frac{V}{g} \frac{V}{x} + \frac{H}{x} = S_0 - S_f
\]

(5)

Where \( V = \) velocity

\( H = \) depth of water

\( S_0 = \) slope of channel bottom

\( S_f = \) friction slope

With turbulent fluctuations

With turbulent fluctuations

'average' slope of a reach

a conceptual abstraction

The value for \( S_f \) is derived from a so-called 'friction formula', such as Chezy, which is 'theoretical', or Manning, which is 'empirical'. The theoreticians continually deride the empiricists for using the 'wrong' friction formula. However, the two can be shown to be almost equivalent if variation in relative roughness is considered. For example, if we were to assume that we have a gravel-bed stream with a 'characteristic grain size' of 2 centimeters and were to assume a depth of 0.5, 1, 2, 5, and 10 meters, the Prandtl equation would give different values for Chezy \( C \) as depth increased, because relative roughness would change. On the other hand, Manning's \( n \) would remain almost constant, because the values of Manning's \( n \) include changes of relative roughness. However one uses Equation 5, it entails black magic in the real world, even though it is a differential equation. Considerable 'engineering judgment' enters into the choice of \( S_f \), even with the aid of the excellent work of Barnes (1967) and others in the USGS, who have tried to rationalize the determination of resistance to flow for use in open channel flow problems.

The instantaneous unit hydrograph. — With the foregoing as a prelude, the IUH can be seen as a tool of linear systems analysis. The IUH is the impulse response function of a linear, time-invariant system. An impulse response function is the response of a system to a unit of input applied.
instantaneously in time—an abstract concept. Its mathematical statement is the convolution integral

\[ y(t) = \int_0^t h(t-\tau)x(\tau)d\tau \] (6)

where \( h(T) \) is the impulse response function and \( x(t) \) is the input. Equation 11 can be used to derive Sherman's T-hour unit graph. In hydrology, \( h(t) \) is conventionally denoted \( u(o,t) \) for the unit hydrograph of duration \( o \), and \( u(T,t) \), then is the T-hour unit hydrograph, so that.

\[ u(T,t) = \int_0^T u(o,t-\tau) S(T-\tau)d\tau \] (7)

where \( S(T-\tau) = 1 \) for \( 0 \leq T-\tau < T \)

\[ = 0 \text{ otherwise.} \]

Most of the theory of the instantaneous unit hydrograph (IUH) is based on the concept of a linear storage resulting from a hypothetical linear reservoir. As stated earlier:

\[ I-Q = dS/dt \quad \text{Continuity} \] (2)
\[ S = KQ \quad \text{Linear Reservoir} \] (1)

with the same notation as Equations 3 to 6, which leads to:

\[ I-Q = K \frac{dQ}{dt} \] (3)

for which the IUH is

\[ u_1(o,t) = \frac{1}{K} e^{-(t-t_o)/K} \quad \text{single linear reservoir} \] (8)

\[ u_n(o,t) = \frac{1}{K} \frac{t-t_o}{(n-1)!} e^{-(t-t_o)/K} \quad \text{n equal linear cascaded reservoirs.} \] (Nash cascade) (9)

For the Nash cascade (Nash, 1958) the response function is a gamma function. Although there are n "equal" reservoirs, n need not be discrete, and the IUH may be a generalized gamma function. Nash has shown that the parameters may be determined based on the gamma function, and that \( nK \) is the first moment about the origin and \( nK^2 \) is the second moment about the origin.
Thus, the problem of linear synthesis in IUH analysis involves the assumption of a reasonable model and the development of a method to estimate the parameter values for that model. This general approach leads in two major directions: the development of conceptual and of black-box models.

The Conceptual IUH - Conceptual models came first, with the greatest amount of activity in the 1950's. However, the work on conceptual models started earlier. The Muskingum method for flood routing (McCarthy, 1938) is in the form of a linear storage model. Nash (1959) showed that the Muskingum model routes flows through two linear reservoirs, the first with negative storage—which explains the anomalous results of a decrease in flow obtained at the beginning of a routing in many cases.

An interesting approach to channel routing by linear analysis was developed by Kalinin and Milukov (1958). They developed the concept of a characteristic length over which the routing was a single linear reservoir. The parameters of the length and the storage were related to channel measurements. Once the characteristic length is determined, longer reaches, routed sequentially, develop a gamma distribution similar to a Nash cascade for basin routing. Thus, the Soviets were working on similar problems and developing solutions similar to those described earlier during this period.

Most conceptual models of the IUH are based on the twin concepts of linear storage and linear channels. Linear storage was described earlier (Equation 3). A linear channel is one which passes an input hydrograph without attenuation. The linear channel is used to develop a time-area histogram (TAH), which is the outflow hydrograph from an instantaneous rainfall-excess applied uniformly over a basin if there were no storage acting to attenuate the hydrograph. The simplest form of a TAH is an isosceles triangle. An isosceles triangle routed through a linear reservoir with a storage coefficient on the order of the time base of the triangle yields a response function quite similar to the usual runoff hydrograph and to the gamma distribution of the Nash cascade. O'Kelly (1955) introduced the isosceles triangle TAH. This early formulation has some physical justification. Consider that overland flow generates a response function of uniform flow for time, $T_1$, into a main channel system with a time of travel of $T_2$. Thus, the response function of each of these, treated as linear channels, is a rectangular pulse. The outflow TAH is the convolution of two rectangles. If $T_1 = T_2$, the result is an isosceles triangle. Mitchell (1962) showed that most small streams in Illinois could be modeled with such a TAH. However, he found that some streams had a flat-topped IUH, and required the use of a trapezoid for a TAH. If $T_1 \neq T_2$, the convolution produces a trapezoid of base lengths $T_1 + T_2$ and $T_1 - T_2$. Thus, once again, physical justification may follow empirical observation.
Perhaps the "best" conceptual linear storage model for river basins in that developed by Clark (1945). Clark divided the basin into sub-basins by isochrones. The areas between isochrones determines a time area histogram (TAH). Excess precipitation on the basin is routed to the outflow point on the basis of the TAH and then is routed through a linear reservoir. That model is the basis for the surface water routing component of the Stanford Watershed Model (Crawford and Linsley, 1962), the U.S. Geological Survey model by Dawdy, Lichty, and Bergmann (1972) and is an alternative in the Corps of Engineers HEC-1 (1970).

Conceptual models blossomed forth in the 1950's. All had a common base in some form of linear reservoir routing and in the concept of a linear channel. The linear channel moves the precipitation excess through the basin without attenuation. The linear storage provides the means to attenuate the hydrograph so that it assumes the typical shape of a discharge hydrograph. The Clark TAH provides the means to model basins for which the IUH has a complex shape. The parameters of the conceptual IUH usually are related to physical measures of the basin. The theory was summarized in Dooge's excellent monograph (1959), but the theoretical justification had followed empirical development.

THE BLACK-BOX IUH

The 1960's saw an outburst of interest in black-box modeling of the IUH. The simplifications of linear reservoir models led to a search for alternative analysis. Simple harmonic analysis were tried by O'Donnell (1960). Truncation in the harmonic analysis caused problems or ringing and smoothing. Chiang and Wiggert (1968) placed harmonic analysis for the IUH in the framework of general black-box analysis as developed in electrical engineering.

Matrix inversion techniques for the derivation of the IUH were introduced simultaneously by Nash (1961) and by others, such as the TVA and Snyder. Each undoubtedly realized that digital computers operate most efficiently in matrix multiplication, and that an IUH is a linear matrix transformation. The realization that the IUH is a linear matrix transformation is discrete time has direct implications in conceptual IUH modeling, so that conceptual models gained by a spin-off from black-box modeling, particularly from the works of Nash and O'Donnel. Not all models utilize this principle completely, and their resulting computer program is made more complex and time consuming than is necessary.

Some black-box modelers gained knowledge from conceptual models in the development of methods for inversion. An example of this approach is shown by Dooge (1965), who used Laguerre functions for the inversion of input-output pairs to develop the IUH. The resulting IUH is similar to the Nash cascade conceptual IUH.
Finally, black-box modeling moved into the nonlinear domain, with the work of Amorocho and Orlob (1961). They developed a method to isolate and model the nonlinear elements in the response function. Later, Amorocho and Brandstetter (1971) developed a general, nonlinear, black-box inversion technique. Actually, black-box modeling implies a linear system. The nonlinear models might better be called non-structure imitating models, rather than black-box models.

Been shown that if a separate set of events not used in the fit is used to test the accuracy of the resulting models, conceptual models perform better than black-box models. The very constraints which make the fit for conceptual models worse are what also cause them to predict better. There have been some attempts to build constraints into black-box models in order to predict better at the expense of fitting worse. An example is Eagleson's (1966) optimum realizable IUH. He used a linear programming format with a non-zero constraint on the ordinates of the IUH.

A major drawback to the use of black-box models is that they cannot be used to model a changing system. Because black-box models are not concerned with the internal workings of the system they cannot be modified easily to reflect the results of such changes. Many of the uses of watershed models today are to assess the effect of past or potential future man-made changes on a watershed. Conceptual models are well suited for such uses, because the parameters in a conceptual model may be related to physical parameters of a basin.

That need for the modeling of the effects of man-made changes has led to developments in two major directions. Both developments are in conceptual modeling. The first development is in the use of a nonlinear routing model based on the kinematic wave equations. The second development is the building of distributed parameter models to replace the lumped parameter models of classical IUH theory.

COMPARISON OF BLACK-BOX AND CONCEPTUAL IUH

Black-box model development has tended to move in the direction of the use of the knowledge gained from the use of conceptual models. However, to the extent that black-boxes remain black, they are not concerned with the inner workings of the system which they model. Conceptual models are constrained so that their shape will "look right" in terms of real world hydrographs.

As a result of the lack of constraints in their structure, black-box models tend to fit a set of data better than do conceptual models. If a single event is used to derive a black-box IUH, the data can be fit perfectly. Conceptual models will, in general, not
fit even a single event perfectly. If a set of events is used with least squares fitting to derive an IUH, black-box models, in general will fit the data better. However, it has

Kinematic Wave Models

The kinematic wave (KW) is one step away from the linear storage assumption toward the use of a dynamic routing equation. It has long been known that as storms increased in intensity over a basin, the response time of the basin tended to decrease. Thus, the IUH was not identical for small and large storms. The kinematic wave equation tends to overcome the shortcoming of the IUH.

The KW equation still is based on the continuity assumption

\[ \frac{Q}{t} = \frac{\partial S}{\partial t} \]

or

\[ q_L = \frac{\partial q}{\partial x} \frac{\partial y}{\partial t} \] (10)

in partial differential terms, where \( q_L \) is the lateral inflow, \( \frac{\partial q}{\partial x} \) is the outflow per unit with, and \( \frac{\partial y}{\partial t} \) is the change in depth with time, which is equal to change in storage per unit width. Equation 10 is combined with the kinematic assumption.

\[ Q = \alpha A_m \] (11a)

or

\[ q = \alpha y_m \] (11b)

where \( \alpha \) and \( m \) are the KW parameters. Equations 10 and 11 are combined to yield

\[
m \alpha y^{m-1} \frac{\partial y}{\partial x} + \frac{\partial y}{\partial t} = q_L
\] (12)

which is used in place of the linear reservoir routing equation.

The appealing feature of Equation 12 is that the KW parameters have physical significance. For example, let us assume that Manning's equation applies over a reach of interest. Then
\[ Q = \frac{1.5}{n} AR^{2/3} S^{1/2} \]  

(13)

where \( n \) is Manning’s coefficient, \( R \) is hydraulic radius, \( S \) is slope, and our “theoretical approach” has already become empirical. If the width is much greater than the depth,

\[ R = A/(W + 2D) \approx A/W = D \]  

(14a)

\[ Q = \frac{1.5}{n} A^{2/3} W^{2/3} R^{2/3} S^{1/2} \]  

(14b)

\[ \alpha = \frac{1.5}{n} \frac{S^{1/2}}{W^{2/3}} \]  

(14c)

\[ m = 5/3 \]

and similar equations may be derived for other shapes of channels. Thus, \( \alpha \) is a function of physical measures of the reach, and both \( a \) and \( m \) are functions of the shape of the channel cross section and of the friction law assumed (Manning’s equation in this example).

The equation is quite similar to the results of earlier attempts at developing a nonlinear storage equation. If storage is assumed directly related to a power function of flow depth or to cross-sectional area, the two are identical. However, the use of the KW equation has taken a step away from the hydrologic assumptions of linear and nonlinear storage and toward hydraulic routing.

A major advantage of KW routing is that its parameters relate to the physical world. If that physical world is modified, the effect on the routing parameters can be estimated, and resulting changes in the basin response can be predicted. A major shortcoming of KW routing is that Equations 14 assume that a unique, single-valued, simple stage discharge rating applies wherever the equation is used. The kinematic wave number can be used to screen out those cases where the equation does not apply because dynamic effects cause stage and discharge to be related differently on the rising and the falling limb of the hydrograph. A more serious consequence of the kinematic assumption arises because Equations 13 and 14 apply best at constrictions or control reaches. The added storage
resulting from minor expansions and contractions of the channel system is not accounted for. This is particularly true of overbank flows at higher stages. Although overbank flow can be modeled by an iterative procedure involving multiple ratings, a single rating is assumed throughout a reach of stream channel. Such a case seldom occurs. Therefore, KW models tend to overcorrect for the nonlinearity in the routing function, and higher peaks tend to be overestimated, with the time of response of the basin decreasing with discharge more rapidly than occurs in the real world. One final major advantage of KW models is that they are perfectly suited for use in distributed parameter models. That fact may explain the widespread acceptance and use of kinematic wave models.

Distributed Parameter Models

The latest trend in basin response modeling is to use a distributed parameter description of the basin. A typical division of a basin for distributed-parameter modeling is shown in Figure 1. First, the main channel system is detailed. Reaches are then determined which have similar routing characteristics throughout their length. The overland flow and channel segments outlined in Figure 1A are then described in such a manner as to develop the schematic diagram shown in Figure 1B.

The assignment of input physical data to the basin defines the basin response function. Thus, there are several major advantages which the distributed parameter model has over a lumped parameter model such as an IUH. The first major advantage is that the response function can be developed directly from the input parameters if an appropriate model, such as KW, is used. A typical set of input data for a distributed parameter model is shown in Figure 2. A second major advantage is that nonuniform storms may be applied to the basin—typical isohyetalis of mean annual rainfall are shown in Figure 1A, which may be used to distribute rainfall over the basin.

The third, and compelling, major advantage of distributed parameter models is that the change in basin response resulting from man-made changes over part of the basin may be assessed. Any part of the schematic in Figure 1B may be modeled with "before and after" predictions by changing the set of parameters for that part of the basin.

One major disadvantage of distributed parameter models is that they generally require more data and much more computer time to run than do lumped-parameter models.
A. STREAM CHANNEL NETWORK OF BASIN

B. DIVISION OF BASIN INTO STREAM CHANNEL
AND OVERFLOW SEGMENTS

FIGURE 1. TYPICAL SCHEMATIC REPRESENTATION OF A BASIN FOR USE IN
DEVELOPING A DISTRIBUTED-PARAMETER RAINFALL-BRUNOF MODEL

As computers get larger and faster and cheaper that disadvantage decreases in importance. With the advent of minicomputers in - every office, it may reassert importance. An important point to consider is that proper programming can greatly reduce computing time. Note in Figure 1B that there are 34 overland flow sections flowing into 20 channel reaches, but overland flow reaches are numbered to 7 (in the corners of the overland flow segments) and channel reaches to 13. Thus 54 segments have been modeled as 20 segments. If segment characteristics are sufficiently similar, large savings in computer time can result. Even so, the canned bulk-par-
### ROUTING COMPONENT

**INPUT DATA:**

- Number of different segments in basin
- Upstream segments
- Lateral segments
- Type of segments
- Slope of segment
- Flow length of segment
- Roughness (corresponds to Manning's N)
- Channel dimensions, proportion of impervious area
- Thiessen coefficient
- Rainfall excess

**OUTPUT:**

- Streamflow hydrograph

*Figure 2. Typical Set of Input Data Used To Define a Segment for A Distributed-Parameter Rainfall-Runoff Model.*

Tank models — Off on another track a separate development has taken place in basin rainfall-runoff modeling. Sugawara (1961) introduced the concept of a tank model. A single tank yields a linear storage model such as equations 3 to 6. A series of tanks yields a Nash cascade. Therefore, tank models are very much in the spirit of linear systems analysis for IUH analysis. However, tank models have a major advantage and a major disadvantage in terms of mathematical development. Interestingly, the advantage and the disadvantage are the same — the model can be physically visualized. For the empiricist and the engineer that is an advantage. For the theoretician and the mathematician that is a disadvantage.

Each component of the hydrologic cycle for which there is a
linear approximation may be represented by a tank model. The set of tanks, each representing a linear storage, may be arranged in series or in parallel. The parameters for each tank may be estimated from physical parameters or by other means appropriate for the given component. The inputs and outputs for each tank are defined and Voila! We have a tank model.

The closed form solution of the response function for some configurations of tank models can be derived. Nash (1958) obviously solved the case for a series of n equal tanks. Sugawara (1961) solved many more complex cases. In addition he discussed piecewise linear solution of kernels by use of complex geometry and multiple outlet tanks. Sugawara discussed the interpretation and estimation of the tank parameters for different components. Finally, Sugawara presented a semi-distributed rainfall-runoff model development through the use of lumped parameter tank modeling of sub-basins.

A most interesting fact in the mathematical development of tank models is that most of the subsequent interest in this deterministic rainfall-runoff model outside Japan comes from stochastic hydrology. A simple series tank model with a single input of white noise and with a single output generates an autoregressive-moving average (ARMA) model. Moss and Dawdy (1973) showed that a conceptual rainfall-runoff model equivalent to a single tank developed an ARMA (1,1) model for stochastic simulation of monthly streamflow. Pegram (1977) showed the mathematical equivalent of a Clark IUH formulation and an ARMA model under certain assumptions. Selvalingam (1977), a student of Sugawara's, showed the exact equivalent of tank models and ARMA models. The fast fractional Gaussian noise model (Mandelbrot, 1971) is, of course, a parallel tank model, which should result in summation of ARMA (1,1) models rather than a summation of autoregressive models. Incidentally, simulation of average flows (daily, weekly, or monthly) adds one dimension to the moving average portion in relation to sampling at discrete intervals. Average flows are discretized but not discrete variables, and that fact should be kept in mind when building models for stochastic simulation.

Thus, tank models seem to be a tool for drawing together stochastic and deterministic models, physically-based, structure-imitating and conceptual models, and empirical and theoretical modelers. A general monograph is in order which draws together the work of Chiang and Wiggert (1968), Dooge (1959), Sugawara (1961), Moss and Dawdy (1973), Pegram (1977), and Selvalingam (1977). That monograph should become the classic paper which Dooge's paper is.

Today and Tomorrow - he trend today in rainfall-runoff modeling is toward physically-based distributed-parameter models. However, there is a trend at the same time toward introducing too many bells and whistles into the models because the modeler or his employer "knows" that a particular factor is important, and, therefore, that factor should be modeled.
The conceptual modelers have shown that very simple models perform as well as much more complicated models in deriving the model of the runoff component (IUH). They have shown empirically how some of the effects of man-made changes on the runoff hydrograph can be estimated (Carter, 1961). However, the model of the surface runoff is where the best case can be made for physical modeling. The KW model is a good example. There are problems with KW modeling which will be mentioned later, but the parameters are easy to derive and the effects of man-made changes can be estimated.

The infiltration function is much more difficult to model, and errors in rainfall input data tend to be passed directly into the estimation of parameter values for infiltration (Dawdy and Bergmann, 1969). Yet there is where modelers tend to proliferate in detail of modeling. The effects of man-made changes are assumed more than proven, and seldom are modeling results subjected to split-sample testing or other rigorous analysis. How does one estimate parameters for an infiltration model which contains six or seven or n soil layers? Perhaps the conceptual modelers should concentrate on the modeling of infiltration so that, eventually, a synthesis may result as in surface runoff modeling.

KW modeling still has problems, as mentioned. Introduction of the non-linearity into the model of the surface water component has over-corrected the model. Flood velocities are much too fast. The unique rating curve assumption holds fairly well because there exist in most channels a series of controlling reaches. However, the KW model assumes a prismatic channel, and it therefore does not allow for storage adequately. That problem cannot be solved by changing to dynamic routing. It is the assumption concerning the prismatic channel which is at fault. Modeling overbank flow is necessary for higher flows, but the assumptions of a prismatic channel still holds and the basic problem remains. How can the attenuation of flood peak as a result of irregularities in channel cross section be introduced into KW models?

More basically, is the Sugawara tank model a valid substitute for KW models for modeling the surface runoff component? Sugawara presents piece-wise linear models. The parameters for his models may have as much physical meaning as those for KW models for larger discharges where overbank flow exists. Is there a synthesis of KW and linear storage models which is more physically meaningful than either alone?

Deterministic and stochastic models are drawing closer together. Results concerning response functions for tank models are directly transferable from one to the other, as shown by Pegram (1977). Results along these lines have not been followed up aggressively. If a physically based stochastic model can be developed for which many closed form solutions are known, stochastic modeling of streamflow may take a step forward toward wider acceptance and use.
In conclusion, I will end on a pessimistic note and hope to be proven wrong. The tendency is for models to continue to proliferate and to become more complex. I predict that surface water routing will continue to be fine tuned and infiltration modeling will continue to receive relatively less attention. What attention modeling of infiltration does receive will be agency oriented and will tend to make infiltration models complex, distributed-parameter models without introducing rigorous error analysis to test whether complexity improves prediction. Furthermore, the commonality which tank models give to stochastic and deterministic modeling of streamflow will not be efficiently exploited to solve some to the as yet unanswered research problems in stochastic modeling.

I shall work hard the next few years to prove my predictions wrong. I hope you do, also.

REFERENCES


