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RAINFALL-RUNOFF RELATIONSHIP

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RAINFALL-RUNOFF MODELS—AN OVERVIEW

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ABSTRACT

The current status of rainfall-runoff modeling reflects the historical development of the science of hydrology, the perceived needs for solutions to hydrologic problems, and the disciplines from which the modelers come. Thus the development of models has been largely pioneered by practitioners who needed solutions to real problems. Only very recently have some modeling efforts been directed to theoretical solutions.

This paper traces the historical development of hydrology and the types of models currently in use. It discusses the purposes of modeling and the properties of models required to serve these uses. Relevant properties include accuracy, applicability, generality, and ease of use. Finally the paper presents some speculation on the future trend in hydrologic models and their applications.

INTRODUCTION

A model is defined as a mathematical or physical system obeying certain specified conditions, whose behavior is used to understand a physical, biological, or social system to which it is analogous in some way (McGraw-Hill, 1974). Hence, a discussion of models can encompass a broad field including physical models as well as almost any mathematical or graphical relationship. Since physical models have not been notably successful in rainfall-runoff analysis I shall restrict my discusssion to mathematical models dealing with the process of transformation of rainfall into runoff primarily for use in engineering studies or flow forecasting.

A comprehensive literature search would no doubt disclose the existence of several hundred (thousand ?) "models" and the number of unpublished models probably exceeds the published ones. I shall not attempt an exhaustive review of models of the past or present, but merely to highlight the more notable historic developments.

THE BEGINNING

One begins most discussions of the history of hydrology with Perreault since he is believed to have published a report (Perreault,1674) of the first known quantitative experiment in hydrology. He discovered by comparison of measured precipitation and estimated streamflow that, for one year at least, the annual flow,Q, of the Seine River near Paris could be described by

$$Q = P/6 \qquad (1)$$

where P is annual precipitation. A modern hydrologist might be inclined to view this model as primitive, but it was a significant finding in its time. It was commonly believed at that time that rainfall was not sufficient to supply the flow of streams. It is also worth noting that over three hundred years later the concept of runoff as a percentage of precipitation is still widely used.

THE BIG GAP

The work of Perreault was followed by a long period in which very lttle was accomplished (or published) on the subject of hydrologic models. Mariotte (1686) published experimental data confirming the findings of Perreault. A few years later Halley (1694) demonstrated that evaporation from the oceans was adequate to supply continental precipitation. A century later Dobson and Dalton experimented with the measurement of evaporation, leading eventually to the development of Dalton's Law (Dalton, 1802)

$$E = C(e_w - e_a) \qquad (2)$$

As a matter of interest, it may be noted that at about the same time Benjamin Franklin was experimenting with the suppression of evaporation by use of oil films.

The big gap was a period of important research in hydraulics. Names such as Pitot, Bernouilli, Chezy, Du Buat, and Venturi include only a few of the hydraulicians of the period. By the beginning of the nineteenth century, methods for calculating the flow of streams existed and techniques for measuring stream velocity with floats or simple meters were available. During the first half of the nineteenth century flow records for several European streams were developed and published, each spanning several decades. No doubt many more such records were developed but not published. These records must have provided the base for the development of "models" of the hydrologic process during the latter part of the nineteenth century.

Before we leave this period of the great gap,another point needs to be made. The absence of publications does not prove the absence of methods. Water-powered mills were used in Europe from the time of the Romans and a major period of canal building began during the fifteenth century under Karl the Great. Both types of projects required some practical basis of hydrology, but if this basis was written down, it has been lost. Suffice it to point out many of the mills and canals still exist and are operable.

THE EMPIRICAL ERA

In 1844 Roberts (Dooge, 1957) was using runoff coefficients in drainage design in Ireland and a few years later Mulvaney (1851) described what is now known as the "rational formula" in a paper to the Institution of Civil Engineers of Ireland. This gives Mulvaney the distinction of presenting the first known general hydrologic model and also the model which has the longest record of continuous use by the profession. The latter point would probably have greatly surprised Mr. Mulvaney. The equation in question is

$$q = Cia \qquad (3)$$

Another name which deserves note is that of Nathaniel Beardmore. Beardmore developed no models but he published in 1850 a book called HYDRAULIC TABLES and in 1862 his MANUAL OF HYDROLOGY. Beardmore summarized much of the data and experience of the time and may well have served as a reference for some of the models of later years. About the same time Symons was responsible for the publication in 1860 of ENGLISH RAINFALL, a publication which has continued to this date (Biswas, 1970). Finally in 1864 Henry introduced the first "telegraphic" current meter (Frazier,1964) making flow measurement in streams easier and probably more reliable. I mention these names to emphasize the importance of data to model building. Without adequate data we probably would not understand the hydrologic process sufficiently to construct a model, and we certainly would not be able to test models.

The last part of the 19th Century and the early years of the 20th saw the publication of a profusion of formulae, for the most part modifications of the Mulvaney formula (Eq.3) or even simpler expressions making flow rate or volume a function of drainage area alone. Chow (1962) has published an extensive summary of these formulae.

THE RECENT PAST

Two important books on hydrology were published about the time of World War I--ELEMENTS OF HYDROLOGY (Meyer,1915) and HYDROLOGY (Mead,1919). In 1914 Fuller was among the first to introduce the concept of frequency into hydrology and Horton (1919) presented an extensive discussion of the process of interception. Important concepts were being discussed and hydrology was being viewed as a science for application rather than solely an area of research. As the 20th Century advanced more of the basic concepts fundamental to understanding and applying hydrology, and hence, fundamental to modeling, were discussed in the literature. Hazen (1930) published FLOOD FLOWS, strengthening the concern for the probabilistic aspects of hydrology. Sherman (1932) presented the concept of the unit hydrograph, and Horton (1933) described his theory of infiltration, one of the most important concepts in hydrology. These were followed by McCarthy (1938) outlining the first approach to kinematic routing then known as Muskingum routing. Hertzler (1939) described the process of interflow as he observed it at the Coweeta Experimental Forest. Linsley and Ackermann (1942) described trials of an elementary moisture accounting procedure using measured evaporation and a simple infiltration process to calculate daily runoff values. Two years later Thornthwaite (1944) presented his concept of potential evapotranspiration. At this point the basic groundwork for hydrologic models was in place awaiting some practical means of carrying out the extensive computations required.

MODELS

The first effort of which this writer is aware to develop a comprehensive hydrologic model is the work of Zoch (1934,1936). Zoch was a mathematician with the U. S. Weather Bureau and was seeking an improved tool for use by the Bureau in carrying out its function for "....gaging and reporting the rivers,......". Zoch's work predates some of the development of basic hydrologic concepts. He tried to develop a closed form solution to the rainfall-runoff process. He assumed saturated soil with runoff at any time proportional to the volume of rainfall which had not yet runoff.

$$Q = Ai(1 - e^{-\frac{t}{c}}) \qquad (4)$$

where Q is volume of runoff in inch square miles/ hour, A is drainage area in sq. mi., i is rate of rainfall in inches per hour assumed to be constant, t is time and c is essentially a coefficent of runoff. Zoch then proceeded to derive the hydrograph of overland flow and the hydrograph from catchments of different shapes using the velocity of flow as a parameter. It is not known whether the resulting equations were ever put to practical use.

In 1890 Hollerith (Hazel, 1945) of the U. S. Bureau of Census designed a system using punched paper cards and machines that could sort these cards into classes and count the cards in each class. These machines enabled the Bureau to tally the 1890 census in one year instead of seven years required for the 1880 census. The punched-card system had in fact been first utilized by Jacquard in the control of looms in the late 18th century. Pollak (1927) first applied the punched-card machine to the processing of climatological data in Czechoslovakia (Conrad and Pollak,1950). World War II saw extensive use of such equipment in developing statistical information for use of the armed forces. During World War II the first IBM Automatic Sequence Calculator was developed, the forerunner of the powerful digital computers of the present day.

By the early 1950s digital computers became generally available and hydrologists began to explore the applications to hydrologic problems. The computers of that era were slow but still far faster than manual computation and they could handle large amounts of data without error (except for errors introduced by the user through incorrectly punched cards or erroneous instructions). Initially most efforts were directed at using those techniques which were already in use but were generally too slow when applied manually or with the desk calculators of the day. Least squares regression of runoff volume or flow rate with various hydrometeorolgical and physical parameters of the catchment was popular and many such regressions were attempted. The results were not spectacular except possibly as to the number of regressions performed. Derivation and application of unit hydrographs, streamflow routing, and reservoir operation studies were performed with reasonable success. This experience with computers initiated a new series of studies aimed at the development of hydrologic models.

Rockwood (1958) reported the use of a digital computer to route flows through the Columbia River Basin. Rainfall excess and snowmelt runoff were computed separately and input to the model which was a routing model adjusting for basin, channel and lake storage. This model was subsequently modified to become the SSARR model with provision for a user supplied rainfall-runoff relationship to determine the rainfall excess (Schermerhorn and Kuehl, 1968). Like all models it has undergone still further modification.

In 1960 Linsley and Crawford reported their work with the Stanford Watershed Model I (SWM). This was a very simple model using daily rainfall, a simple infiltration function, and a combination of unit hydrograph and recession function to reproduce the mean daily flow hydrograph. This model underwent extensive changes (Crawford and Linsley, 1962 and 1966) emerging as SWM IV which used hourly rainfall inputs, an infiltration function, and a routing scheme to develop the hourly flow hydrograph. Surface runoff, runoff from impervious areas, interflow and groundwater flow were computed separately and combined to obtain total runoff. Infiltration was computed as a function of the current soil moisture condition which was in turn computed by a moisture accounting system in which moisture storage was the continuing sum of accretions from rainfall or snow melt and losses by evapotranspiration. This model was subsequently modified further to become the Hydrocomp Simulation Program (HSP) and finally the Hydrologic Simulation Program Fortran--HSPF (Johanson, Imhoff, and Davis, 1980).

In 1961 Sugawara published a description of a "tank-type" model. He utilized a number of linear storages in various arrangements in series and parallel to simulate the flow of Japanese streams. Some storages had their outlet above zero to simulate permanent abstractions from the input rainfall. The best system was determined by trial and many iterations were required if the number of storages was large. This system has been modified for more effective application.

The Storm Water Management Model (SWMM) was developed for the Environmental Protection Agency in 1971 (Metcalf & Eddy, et al, 1971) This was an event model, i.e., it was designed to simulate individual storm events and, hence, did not require the moisture accounting procedures of a continuous simulation model. Initially SWMM utilized the Horton infiltration equation to calculate rainfall excess and a routing system to construct the hydrograph. The routing was designed to permit detailed analysis of the hydrographs of overland flow and the subsequent flow in the storm drainage system. Like all other models it has undergone modification with time and now offers a number of options for calculating runoff from rainfall.

Freeze (1971) described a model of three-dimensional, transient, saturated-unsaturated groundwater flow. He treated the problem as a boundary-value problem formulated as a system of differential equations and solved by appropriate numerical techniques. Subsequently he extended the model to include the the contribution of groundwater to surface streamflow (Freeze, 1972) and later he extended the model to include surface runoff and subsurface stormflow (interflow), thus including all of the hydrologic cycle except evapotranspiration (Freeze, 1978). The nature of the solution restricts the model to a very simple physical situation and constant rainfall intensity. This model represents a basic theoretical approach to rainfall-runoff modeling which is useful for investigating the process, although not yet suitable for the requirements of engineering application.

A totally different approach to rainfall-runoff modelling is the Constrained Linear System (Natale and Todini, 1974). The CLS operates on the basis of dividing a lumped precipitation input into multiple time streams on the basis of accumulated antecedent precipitation. Hence the non-linear system is simulated by a set of concurrent linear systems. Quadratic programming is used as the fitting technique and input parameters are those specifying the instantaneous unit hydrograph (IUH). This is esentially a "black-box" approach and is the total antithesis of the Freeze model.

Many other models now exist but time does not permit a detailed discussion of each of them. They include such models as the National Weather Service River Forecast System (National Weather Service, 1972), the U.S. Agriculture Research Service Model (1975) , an API-type model (Sittner et al, 1969),HEC-1 (Corps of Engineers, 1973), ILLUDAS (Terstriep and Stall, 1974), STORM (Corps of Engineers, 1976), the Sacramento Model, (Burnash et al, 1973) and a number of variations on the SWM. My appologies to all the models which have not been mentioned.

MODEL CLASSIFICATION

The models described above cover a range of model types which can be classified in a number of ways. Usually several adjectives are necessary to completely describe a particular model. Among these adjectives one may include the following:

Deterministic--Based on assumption that the process can be defined in phsyical terms without a random component.

Stochastic--Based on the assumption that the flow at any time is a function of the antecedent flows and a random component.

Conceptual--model is designed according to a conceptual understanding of the hydrologic cycle with empirically determined functions to describe the various sub-processess.

Theoretical--model is written as a series of mathematical functions describing a theoretical concept of the hydrologic cycle.

Black-box--Model uses an appropriate mathematical function or functions which is fitted to the data without regard to the processes it represents.

Continuous--Model is designed to simulate long periods of time without being reset to the observed data. Such models require some form of moisture storage accounting.

Event-- Designed to simulate a single runoff event given the initial conditions.

Complete--Includes algorithms for computing the volume of runoff from rainfall and distributing this volume into the form of a hydrograph.

Routing--Model contains no algorithms for rainfall-runoff but simply distributes a given volume of runoff in time by routing or unit-hydrograph computations.

Simplified--Uses algorithms which have been deliberately simplified or large time increments to minimize computer running time.

By appropriate selection from this list of adjectives one could describe almost any of the models which have thus far been presented to the hydrologic profession (Table 1).

Table 1 Characteristics of Selected Rainfall-Runoff Models.

Model Characteristic	ZOCH	SSARR	SWM-HSP	SUGAWARA	FREEZE	SWMM	CLS
Deterministic	○	○	○	○	○	○	
Stochastic							○
Conceptual		○	○	○		○	
Theoretical	○				○		
Black-box							○
Continuous		○	○	○			○
Event	○				○	○	
Complete			○		○		
Routing				○		○	
Simplified	○	○					

WHY MODELS?

In order to discuss the utility of various types of models we must have some statement of purpose for modelling in the first place. Different purposes may well require different types of models. Some of the principal purposes for which modeling has or can be employed are discussed below.

Research--Models offer an opportunity to extend the range of hydrologic research. Sensitivity to various factors can be evaluated fairly quickly with a model which is a reasonably faithful description of the hydrologic processess or a model may serve as a control in field experiments.

Forecasting--An important hydrologic function is the forecasting of streamflow. Reliable models offer the special advantage of speed and avoidance of computational errors.

Engineering applications--A variety of engineering tasks can be accelerated and the accuracy of the results greatly improved by appropriate use of models. Some of the more important such tasks include:

Record extension --Most engineering answers must be in the form of probability statements. We know that the larger the data sample, the more reliable are the estimates of probability. Continuous models can be used to lengthen an available flow record or compute a synthetic record for an ungaged site.

Operational simulation Some tasks require a determination of the effects of one or several alternate solutions to a particular problem. A model may be used to simulate a synthetic record assuming a certain alternative in place.

Data fill-in --Data is often missing from an otherwise useful hydrologic record. In many cases simulation from rainfall may be the most reliable way of estimating this missing data.

Data revision --Longer records of streamflow are often unrepresentative of the current hydrologic situation in a catchment because of changes in the catchment conditions. A model may be able to simulate natural flow conditions or even conditions expected to exist at some future time.

In addition to the above hydrologic models can serve as a basis for algorithms for simulation of water quality or sediment transport, and they may eventually be incorporated in climatic models.

PROPERTIES OF HYDROLOGIC MODELS

Earlier we discussed some properties of models which permit us to describe and classify them. There are some other properties which models can and should possess. These include such characteristics as accuracy, applicability, generality, and ease-of-use.

Accuracy: Despite the position taken by some individuals and agencies to the effect that one should use the simplest possible model, I am firmly convinced that the most important property of a model is its inherent accuracy and that, in general, the best basis for model selection is accuracy.

Three components of error exist in any model application. These are the inherent model errors, calibration or parameter errors, and data errors. The inherent errors in the model caused by the fact that it does not perfectly represent the system are difficult to evaluate. However, experience with the SWM and HSP models suggests that given good quality data and careful calibration, a model of this type can reproduce the historic streamflow with errors that are probably no larger than the errors in estimating the streamflow from stream gage and current meter. In the sense implied in the preceding statement "good" data are rainfall data which correctly represent the rainfall over each segment of the catchment. These conditions are typical of the northern California area where the SWM was developed. General storms moving from a narrow sector of the compass and with areal distribution of precipitation largely controlled by orography seems to assure that station rainfall can be representative of the rainfall in a fairly large region. Representivity of station records deteriorates rapidly as one moves into regions without orographic controls and/or subject to convective precipitation. One might expect that a very small catchment with one or more centrally located rainfall stations would also constitute "good" data.

The discussion above suggests that in testing models one should especially seek test catchments where the data can be classified as good. An inherently reliable model should perform well under such circumstances. This discussion may be said to refer to absolute accuracy, i. e., the ability to closely reproduce the historic hydrograph throughout the range of flows. Under such conditions the process of calibration becomes fairly simple and the errors in the catchment parameters derived from the calibration are small.

From the practical viewpoint of a user who is trying to extend a short record, a model which correctly defines the probability distribution of flood peaks, daily flows, monthly flows, etc. may be quite satisfactory. After all, for most planning purposes there is little need to correctly reproduce the hydrograph of a particular historic event. This permits another test of model accuracy in use. In this case the rainfall data need only correctly represent the probability characteristics of local rainfall. Indeed, the raingage need not even be in the catchment. We assume that the random errors in representivity of the rainfall data compensate over time to produce the correct streamflow probability. This infers that there is no bias in the rainfall data or the model, and that the parameters are correctly determined. The parameter problem now becomes paramount since a good day-to-day fit is not expected. Under these conditions the calibration period must be long enough to permit testing of simulated vs observed probability distributions.

Calibration of a model by comparison of observed and synthetic probability distributions is not an easy task. It requires careful consideration of the overall comparison, not the point for point comparison of events. Under these conditions one must expect the parameters to be less accurate than in the case of good data. The calibration period must be longer and time trends in data must be removed. As the quality of the data deteriorates still farther with errors of observation or interpretation, or the effect of human activity or unusual natural events, the data must be checked with special care. A point may be reached in which it seems impossible to achieve a calibration. At this point one frequently is told that it is better to use some simpler method since the data are not good enough for the model. It may be true that the data are not adequate but if one reflects on my comments regarding accuracy it will be noted that what I have said applies equally well to all hydrologic models. If the data are too poor for the use of a good simulation model they are also inadequate for any other model. Nothing in the simpler models substitutes for the accuracy of the data.

These discussions bring up the issue of the model which "does not need to be calibrated". This statement implies that judgement is superior to a test against real data. There are times when there are no data and hence calibration on the catchment under study is impossible. This does not preclude the use of other catchments with parameter adjustment based on the evident differences between catchments. Given a model whose parameters have some physical meaning such an indirect calibration should be far superior to a simple model whose parameters are intended to represent a dozen different effects. All hydrologic models should be tested against observed data, preferably from the watershed under study.

Applicability: A model which is to be used for some task should obviously be applicable to the task. In other words it should be capable of providing the answers required. Many tasks require a determination of flood frequency, flow duration, or similar probabilities. Generally a continuous model is to be preferred for this purpose. Event models do not define initial conditions and hence cannot really aid in defining flood frequency. The assumption that the frequency of the input rainfall determines the frequency of the computed flood flow is pretty well disproved. Hence, the use of event models with a design storm is likely to lead to answers which are substantially in error.

Similarly, if a catchment experiences much snow, the model should incorporate snowmelt algorithms. If seepage from the channels accounts for a large portion of the runoff, algorithms simulating this seepage should be included. Small amounts of seepage may be effectively represented as a direct contribution to groundwater during the infiltration process. The routing algorithms of the model should be capable of representing the important hydraulic features of the system under study. A model which is expected to reproduce flood peaks on small catchments must operate on time intervals appropriate to the catchment (usually on the order of an hour or less). The use of daily rainfall will rarely be satisfactory.

Generality: Hydrology has inherited a tradition of many models for the same purpose. Decades ago when it was necessary to utilize simplified empirical models, a model was rarely applicable to a catchment other than the one for which it was derived. In rare cases, the better models could be applied to catchments within a limited region having similar characteristics. Consequently, it was common practice that each hydrologist developed his own relationships for a particular catchment. It seems axiomatic that the fundamental processes of hydrology are the same in all catchments. The amount of interception or the rates of infiltration do vary with the vegetation and soil characteristics of catchments. In some cases a process may not be present, e.g., snowmelt runoff in tropical catchments. In many catchments true surface runoff may be extremely rare or non-existent. Runoff from impervious area may dominate urban drainage and if the task is to design a system of storm sewers, interflow and groundwater flow may be irrelevant. These differences do not mean that a single model cannot be applied in all cases. The model must represent the various processes with sufficient fidelity so that irrelevant processes can be "shut off" or will simply not function. Differences in interception, infiltration rates, groundwater recession rates, etc. must be represented by model parameters which can be preset to represent these characteristics.

The previous discussion is intended to suggest that it is no longer really necessary for each hydrologist to develop his or her own model for each catchment. Such an approach does not necessarily lead to erroneous results, but it does involve much more work than if a "stock" model were used in each case. More importantly, a new model for every application eliminates the opportunity for learning that comes with repeated applications of the same model. As long as some error may result from a less than precise representation of one or more of the hydrologic processes, a careful analysis of the results of model applications to many different catchments may be our only means of detecting these errors and, hence, devising modifications to correct the problem. Additionally, application of a model to many catchments results in many sets of parameters which can conceivably serve as a basis for objective determination of parameters from physical characteristics of the catchments. Alternatively many sets of parameters can form the basis for mapping parameter variation over a region. Either objective parameter estimation procedures or regional parameter maps could be of great assistance in dealing with ungaged watersheds for which direct calibration is impossible. If a multitude of models is employed, the data for comparative analysis of parameters will not be available.

Some will say that the views expressed above represent a suppression of research and that progress will only come if many models are developed and tested. This is, of course, an alternative approach to the development of improved models, but only if the new models are extensively tested. Because almost any model with sufficient free parameters can yield good results when applied to a short sample from a single catchment, effective testing requires that models be tried on many catchments of widely differing characteristics, and that each trial cover a period of many years. Such testing is expensive and time consuming and is unlikely to be undertaken except as part of a series of applications which are paid for by the clients of the the several applications.

Ease of use: Ease of use seems to be viewed by some as the most important characteristic of a model. How else does one explain the fact that the most popular hydrologic model is the "rational equation" more than one hundred years after it was first presented in the literature. This thought equates ease-of-use with simplification even at the sacrifice of accuracy. It is not completely clear why hydrologists are willing to accept inaccuracy to avoid a little work. There was a time past when the slide rule, pencil and paper solution imposed on us prevented the use of the best concepts then known.That time is gone. Users of SWM and HSP have said that they require no more labor effort than a thorough application of older procedures. Misguided economy serves no useful purpose. The goal is the right answer.

Fortunately ease-of-use can be achieved in other ways than by simplification. Interactive programs through which the user is prompted to provide the instruction or data next required. An information management system such that once the necessary input data is in the computer is is in a form most readily usable by the program with least effort by the user. Computerized methods for testing the internal consistency of the input data and for filling in missing data can make application much simpler. The growing availability of mini-computers which can employ large models and yet cost only a fraction of the price of the giant computers of the past seems to me to be a large step in the direction of ease-of-use. Even a micro-computer which in itself is incapable of solving a major simulatiopn model can often serve as a remote terminal to a larger computer, eliminating the need to travel from office to computer center. Data banks storing data in a form suitable for ready access and use can greatly reduce the labor involved in simulation. We should search for means of reducing the effort of using a model without reducing the accuracy of the answers.

THE FUTURE OF HYDROLOGIC MODELING

I am convinced that hydrologic modeling is here to stay and that we will eventually use it for tasks we have not considered thus far. I hope that the next decade will see the abandonment of crude empirical relationships in favor of modern modeling techniques. With the inflating costs of the works we build and the decisions we make on the basis of hydrologic analysis, we should not be satisfied by anything less than the best available method. Forecasting the future is always hazardous but it seems to me that a general discussion of hydrologic models would be deficient if something were not said about the future. A forecast which seems to be quite safe is that there will be continual improvement in hydrologic models. I do not think that this will come about by some sudden breakthrough in hydrology. Rather I would expect a slow and rather deliberate process accompanied and aided by occasional breakthroughs in the field of computers. Surely one can expect continuous advance in the computer hardware available for use in modeling. This will make programming and use easier, and cheaper. The day may not be far off when a mini-or micro-computer can be built for the specific purpose of hydrologic modeling. This will come about only if there is sufficient agreement among hydrologists as to the proper model (or models) to be used and a sufficient number of users to make the project economically sound.

New models will come more slowly. Existing models are very good but surely not perfect. One thing that will be very important in achieving improved models will be sets of test data. These sets should consist of carefully checked data with as few errors as it is humanly possible to achieve. They should cover a time span of 20 years at least and preferably 30 or 40. Thus, the absence of time trend in the data will be important. The rainfall data must be adequate to represent the catchment and the streamflow data should be as accurate as possible--U. S. Geological Survey rating of "excellent". The data normally used for modelling should be supported with other information such as soil moisture profiles and groundwater levels so that intermediate computations within the model can be verified. There should probably be data of the kind just described for at least 50 and preferably 100 sites distributed around the world. With such information it will be possible to test model performance and compare different models to determine whether one algorithm is superior to another. Clearly it will be necessary to develop records for many if not all of the test catchments and we can look forward to 20 years or more before an adequate test base is available. We should begin development of this test base now. Some testing can and will go on, using a less than adequate test base. It will be important to assure that inadequacies in the test data do not lead to false conclusions.

We will find it necessary to develop more effective means of applying our models. The calibration process would be greatly aided by objective estimators or regional maps as discussed earlier. This would probably be an end product of the establishment of the test base described above. A planned program aimed at easier and more reliable calibration would be a good project for the profession.

Application of continuous simulation to small catchments can be expensive if each application stands alone in data collection, calibration, and simulation. This could be simplified on a regional basis by developing files of computed runoff at each rainfall station so that when a nearby catchment is to be studied, only the channel routing need be done. This approach would eliminate repeated, independent efforts at collection and checking precipitation data and computing runoff.

We will see some major changes in the way hydrologists approach such tasks as calculating flood or drought probability. The major shortcoming of such analyses today is that the record lengths available at gaged locations are too short for reliable probability analysis and, of course, where streamflow is not measured there is no record for analysis. It has seemed to me for some time that one could combine the capabilities of stochastic and deterministic models, using the stochastic model to generate long records of hourly rainfall to be used as input to a deterministic model (Franz, 1969; Ott, 1971; Nasseri, 1976). Acceptance of this idea has not been overly enthusiastic and it may not be possible. However, I believe it deserves a thorough test. After all, there are not many other obvious solutions to the difficult problem of record length. Because most water resource plans are dependent on reliable hydrologic probability estimates, erroneous estimates can destroy the reliability of the whole planning effort.

We should be considering the data requirements of models and plan station installations with locations that are representative and suitable for model use. Recording equipment should be used at all stations and this equipment should be such that a range of data intervals can be used depending on the particular problem. A fixed interval of one hour is certainly not acceptable for all catchments. Recording equipment should be computer compatible so that the data can be utilized in a model with a minimum of processing and with a minimum of time delay between event and the availability of the data. The above should not be interpreted to imply that screening and checking of data for accuracy should be diminished. Such checks are always necessary and should be as thorough as possible.

Many other points could be brought up in an overview of hydrologic models and there are many possible future developments on which one might speculate. I have tried to stress the importance of models which are responsive to the needs of users or are useful tools for research or instructions. Accuracy should be a primary goal in model development and all models should be thoroughly tested to verify their performance. For this purpose we need some top quality data to be used as a test base. All of this will require a lot of work and take a long time to accomplish. There will be few opportunities for journal papers. Nevertheless, it is a task which needs to be undertaken by the profession. Will we face it?

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