GENERAL REPORT ON MODEL STRUCTURE AND CLASSIFICATION

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1. INTRODUCTION

The objective of this Symposium is to discuss the implementation and use of mathematical models in hydrology and water resources development. The past 15 years have seen a proliferation of mathematical models in this area and the growth of an immense literature in which such models are recommended, partially described, but hardly ever evaluated. The practitioner faced with the need to solve a human problem without delay is like an unfortunate traveler lost in a jungle. Before his eyes is a riot of growth reflecting a variety of scale, color, and type and his ears are assailed by a cacophany which in many cases can be interpreted as "my model solves all problems". If only a fraction of the research that has gone into the development of new models had been devoted to the objective evaluation of models and the objective matching of type of model to type of problem, the whole subject area would be in a healthier condition. If the aims of the organizers of this Symposium are achieved, at least a small path will have been cleared through the present jungle. The purpose of this general report is to provide a background to the presentation and discussion of the Symposium papers.

One possible methodology for obtaining as objective a choice as possible between mathematical models is shown in Figure 1 (Dooge 1977) and this can serve as a general framework for the present discussion. Thus section 2 of this report is devoted to defining the problem, section 3 to discussing the different classes and types of models available, and section 4 to fitting the model chosen to the problem. The two remaining sections deal with one possible classification of the Symposium papers.

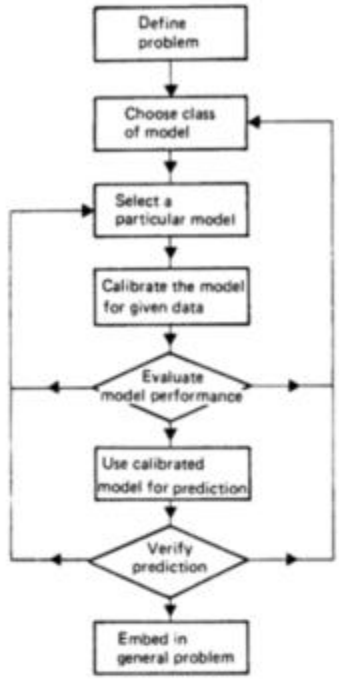

FIGURE 1 A possible methodology for selecting a mathematical model.

2. DEFINING THE PROBLEM

It is conventional wisdom that unambiguous and adequate definition of the problem is essential to its successful solution. However, like much conventional wisdom, this wise advice is frequently ignored in practice. One prerequisite toward an adequate definition of any modeling problem is to be clear about the nature of the prototype system that the model is intended to represent. In hydrology and water resources we are concerned at different times with systems and models whose scope varies from conditions at a point, through conditions on a small experimental plot or a hillside component of a subcatchment, to a major river catchment of regional or continental scale. In some cases we may only be concerned with the physical elements of the hydrological cycle, whereas in others we are concerned with water quality and ecological factors, and in some we are concerned with the water-related problems of an entire socioeconomic system. In many cases, we are concerned with a hierarchy of models, either nested one within the other or more loosely linked together. Consequently, it is essential to be clear in regard to the boundaries of the system which we are attempting to model at any one particular time and also to be clear about the variables whose fluxes cross that boundary and whose storages and fluxes within that boundary are of immediate interest.

Another prerequisite for the proper definition of a modeling problem is the objective of the model. The struggle of man to master his environment through knowledge has been described as involving four phases: observation, understanding, prediction, and control. Mathematical models are used in water resources engineering today in relation to all four of these phases. Because the process is iterative rather than sequential, models based on known data frequently give rise to new data requirements and the most efficient way of providing these new data may itself be the subject of mathematical modeling (Matalas and Langbein 1971). Mathematical models play a key role in the formulation of our understanding of natural processes. Thus Shanin (1972) states:

> The basic *function* of theoretical models, which explains their extraordinary significance in contemporary scholarship, is their use as the major bridge between the language of theory and that of empirically corrected data, between the general and unique, between the subject and the object.

The third phase of prediction (without reference to time of occurrence) or forecasting (within a specific time reference) characterizes the main objective of most of the models of catchment behavior presented at this and similar symposia. Mathematical models of water resource systems are, on the other hand, concerned largely with the fourth phase of design and control.

All models are selective and simplify reality in different ways. Each model reflects some but not all the properties of the prototype. Hence the choice of an effective and economic model frequently involves, either implicitly or explicitly, a designation of those properties of the prototype that are considered relevant to the problem.

A further prerequisite for the adequate definition of a modeling problem is clear understanding of the nature of the input data available in the prototype and of the output data required from the model. In the case of hierarchies of models, part of the input to the model under consideration may be the output from another model and the output from the present model may be part of the input to a third model. In such cases the relationship between the models must be carefully considered, and in many cases it is advantageous to study the behavior of a simplified global model before choosing a structure or a solution technique for the individual models.

3. TYPES OF MODELS AVAILABLE

It is not the purpose of this general report to catalog the various types of catchment models which appear so abundantly in the hydrological literature. The variety of models can be best appreciated by reference to review papers and proceedings of similar symposia. In this connection one might mention the proceedings of three symposia organized by the International Commission on Water Resource Systems at Warsaw (IAHS 1971), Bratislava (IAHS 1975), and Baden (IAHS 1978); the 1974 Workshop on Mathematical Models for Surface Water Hydrology held also at the IBM Scientific Center in Pisa (Ciriani *et al.* 1977); the symposia on open channel flow held at Fort Collins (Mahmood *et al.* 1975) and Newcastle-upon-Tyne (BHRA 1976); review papers on stochastic models by Clarke (1973), Svanidze (1975), and Lawrence and Kottegoda (1977); review papers on subsurface flow by Freeze (1972, 1978); the collected work on the systems approach to water management edited by Biswas (1976); the work by Fleming (1975) describing the structure of 19 conceptual models of total catchment response which have been fairly widely used; and the report of the intercomparison study of 10 models of total catchment response from several different countries (WMO 1975).

The choice of a mathematical model is governed largely by the factors discussed in the last section: the structure of the prototype system, the objective of the modeling, and the nature of the input and output data. Mathematical models in hydrology and water resources can be grouped for classification in a number of ways. For the purpose of this report, a primary division has been made into (1) models of catchment behavior that simulate the hydrologic storages and fluxes relevant to various parts of the hydrological cycle and in various elements of a catchment area, and (2) models simulating the hydraulic and economic performance of complex water resource systems. This primary division seems justified by the clear demarcation between (1) models of catchment behavior that are concerned solely with relationships between hydrologic variables, and (2) prescriptive models of water resource systems that are concerned with decision making. Such a division is based essentially on the nature of the objective of the modeling process involved in each case. It is hard to visualize cases in which it would not be a simple matter to decide which category of problem is involved.

Once we attempt any further classification of catchment models or of water resource models, serious difficulties arise. One usual division of catchment models is into deterministic, stochastic, and probabilistic catchment models in which the categories may be considered to correspond respectively to the sum of (a) deterministic input data, (b) random input data, and (c) no input data as such. This classification has the disadvantage that it isolates from one another deterministic and stochastic methods that frequently are based on identical mathematical assumptions which cannot be recognized in the resulting models because two sets of jargon are used to describe them. An alternative classification is to divide catchment models into (a) blackbox models, (b) regression models, (c) simple conceptual models, and (d) models based on the equations of continuum mechanics. Such a procedure is tantamount to classifying models on the basis of the connection between input and output as being assumed to be (a) simple causality of unknown form, (b) statistical correspondence, (c) simplified physical theory, or (d) more complex physical theory developed in order to promote the understanding of the phenomena involved. Catchment models can also be classified according to whether they are (a) linear or nonlinear, (b) time-invariant (i.e., stationary) or time-variant (i.e., nonstationary), (c) lumped (i.e., space-invariant) or distributed (i.e., space-variant), (d) short-memory or long-memory. The question of classification is returned to in section 5 below.

The whole discussion of mathematical models in hydrology would be greatly simplified if a common nomenclature were adopted or at least if the correspondence between different sets of nomenclature were recognized. For example, the only essential difference between the first order ARIMA (1,0,1) model used by O'Connell (1971) to model the Hurst phenomenon in stochastic time and the Muskingum method introduced by McCarthy (1939) in flood routing is that the input in the former case is Gaussian white noise while the input in the latter case is the known (or assumed) flow at the upstream end of the reach. More generally, choosing an ARMA model is equivalent to assuming that the system function (i.e., the Laplace transformation of the impulse response) is a rational function; and that the number of moving average terms is identical to the degree of the polynomial in the numerator of the system function and that the number of autoregressive tons is identical to the degree of the denominator. The outputs from the two model systems when taken continuously are governed by the same differential equation, and when sampled are governed by the same differential equation.

To assume in blackbox analysis that the system behavior can be adequately represented by the first term of a convolution type Volterra series (i.e., the use of the impulse response for identification) is equivalent to making the assumption that the system is governed by a linear ordinary differential equation with constant coefficients. Recognition of such correspondences enables us to recognize equivalent models and to transfer techniques and sometimes results from one class of model to another.

Model simulation of the more complex water resource systems can also be classified in a number of different ways. One obvious basis for classification is the structure of the system itself, i.e., whether we are dealing with a single reservoir, a chain of reservoirs, or a complex water resource system involving diversions and pumpings as well as storages, and so on. Such models can also obviously be classified on the basis of whether the schemes are single-purpose or multipurpose. The nature of the input data, whether single-site or multisite and whether deterministic or stochastic, provides another element in classifications. In the case where the operation of the system is described by a transition matrix, this matrix may be deterministic, stochastic, or uncertain, and the nature of the model and the techniques used in it will vary accordingly. It is clear that in the case of multipurpose objectives the mathematical model will include a procedure for the reduction (either explicitly or implicitly) of the multiple purposes to a single objective function and also a methodology for the optimization of this objective function. The methodology used (direct search, unconstrained optimization, constrained optimization, linear programming, quadratic programming, dynamic programming, simulation, etc.) offers another basis for classification.

All of the variations mentioned above are essential parts of the description of the particular model and can play a larger or smaller role in the classification of systems models depending on the purpose of the classification.

In the analysis of complex water resource systems, it is frequently useful to formulate an overall model in terms of a hierarchy of related models. Sometimes a lower-order model would be completely embedded in or nested in a higher-order model but at other times the separate lower-order models would be linked in various ways. In this approach the boundary of the lower-order model is established and certain assumptions made about its exterior environment, which is equivalent to the remainder of the model as well as the external environment of the latter. By making plausible assumptions about the boundary conditions of the lower-order model it is frequently possible to reduce the range of choice considerably and to proceed to another part of the total model. In many applications this procedure involves an iteration among the lower-order models. Shamir (1970) has outlined the type of nested models used in the national water planning of Israel.

4. FITTING THE MODEL TO THE PROBLEM

This section is concerned with choosing and fitting an appropriate model for a given real problem. The huge range of choice will be narrowed somewhat by the definition of the problem. If we are concerned with the prediction of catchment response rather than the control of a reservoir system, our range of choice includes behavioral models and excludes prescriptive models. If there are no rainfall data, the use of the unit hydrograph method or of a conceptual model of catchment response is clearly ruled out. Even after all this elimination, there is still a wide range of choice in the case where only records of streamflow are available. The choice may well be directed by the nature of the problem.

If we are interested only in extreme events of rare occurrence, we might wish to neglect the time dependence between events and hence to use a probabilistic model. If, however, we wish to take minor floods into account, a stochastic model which allows for such persistence is indicated.

Even after choosing the class of model, there is still a good deal of freedom in choosing a particular model from that class and in choosing the structure of the particular model. Basing this choice on prototype data is referred to as model identification. This should be done by selecting a given model (or range of models), fitting the model (or models) to the data in some prescribed way, and evaluating the extent to which the prototype data are simulated by the model. Preliminary examination of the data can give some guidance in narrowing the choice of model. In the case of probabilistic models, the plotting on a diagram showing the relationship between the coefficient of skew and the coefficient of variation (or on a Pearson shape-factor diagram) for one or more sites in a region should give a preliminary indication of whether the regional data are likely to be best fitted by a log-normal distribution, a Pearson type III distribution, or a Gumbel distribution. Similarly, in the case of an ARMA model, examination of the autocorrelation and partial correlation functions of a time-series (Box and Jenkins 1970) should reveal when a purely moving average (i.e., short-memory) or autoregressive (i.e., long-memory) model is appropriate or when it is necessary to use a mixed ARMA model. In the case of catchment elements and components such as surface runoff or the response of groundwater to recharge, the use of a shape-factor diagram based on the dimensionless moments (Nash 1960, Dooge 1973) should be of use as an indicator. In the case of conceptual models of total catchment response no such approach is presently available. This could be remedied if a procedure was available to detect from an input-output set whether a threshold existed in the system and the approximate size of the threshold. If this could be done, the threshold could be removed from the system and the two parts of the input-output record used separately to give some idea of the nature of the two subsystems of the total catchment system.

None of the above procedures proves as objective and reliable in practice as theory would indicate. Part of the difficulty is undoubtedly due to the presence of errors of measurement in the data and to the sampling problems arising from the length of the data record. However, even with long records of very reliable data the approach assumes that the models tested are adequate to represent the prototype. This may not be so. There is scope for research on relating the simple models used in applied hydrology to assumptions about the hydrologic processes. Thus, in the case of probabilistic models, we have the suggestion by Kalinin (1962) that the power transformation of the gamma distribution in the Kritskii-Menkel (1950) model for streamflow represents the nonlinear relationship between runoff and rainfall and that the gamma distribution of monthly or annual flows can be considered as arising from an alternation of wet and dry periods. Becker (1966) and Diskin (1970) have discussed the relationship between regression models and conceptual models. Many authors have discussed the question of "reasonable" parameter values in regression models and conceptual models. However, a great deal of work remains to be done in this area and to be incorporated into the procedure for model selection.

Even when the model type has been chosen there remains the important question of the degree of complexity of the model. Two alternatives are possible: (a) to start with a simple model and move to a more complex one if the model fails to simulate the prototype behavior or (b) to start with a complex model and omit certain components if they appear to make little difference to the performance of the model. The present reviewer has a strong preference for (a), both from the point of view of the principle of parsimony and because the limited information content in the data should not be spread over the many parameters.

The optimization of model parameters on the basis of given data sets is a study area in itself. Given enough parameters, it is possible to fit any set of data, but the parameter values may well be without any real meaning. On the other hand, *a priori* values of parameters, based on laboratory or field measurements, may be unsuitable for use in models because a parameter may represent in the model several features of prototype behavior besides the one that was the basis of the measurement. The need to obtain realistic values of the parameters is particularly important when the model parameters from different systems are to be used as the basis of correlation with catchment characteristics or change of land use. Moment matching, maximum likelihood estimation, Bayesian estimation, unconstrained and constrained least-squares estimation, and direct search techniques are among the methods that have been used to estimate the parameters of models in hydrology and water resource systems. These optimization methods use a variety of objective functions based on some measure of the output from the model. The values of the parameters are frequently sensitive to the objective criterion chosen and to the particular output used in the objective function. Despite much research in recent years, no clear knowledge has developed in this area.

If models or variants of a given model are to be compared, it is necessary to have an objective evaluation of the model or a given version of it. In some cases, techniques are available from standard statistical procedures. Thus in the case of a probabilistic model of a time-series of events assumed to be independent, the Kolmogorov-Smirnov test can be used in the usual way as the basis of whether a model should be accepted or not. Similarly in regression models in hydrology and water resources, the standard analysis of variance can be applied. In the case of stochastic models of dependent time-series the adequacy of the deterministic part of the model can be measured by the extent to which the cross-correlation between the input and the output is reduced by subtracting from the measured output the predicted output from the deterministic part of the model. The residual output obtained in this way can then be tested for autocorrelation and a stochastic model fitted whose efficiency can be judged by the degree to which this autocorrelation in the residuals is removed. The properties of the final residual output, which should approximate Gaussian noise, can then be determined. The general model, with its triple components of (a) deterministic operation on the known input, (b) stochastic modeling of the persistence in the residual, and (c) element of white noise, can be used as a prediction model. In the case of models of total catchment response, the question of model evaluation is even more difficult. This subject has been reviewed in a number of papers, notably by Nash and Sutcliffe (1970) and by Pilgrim (1975). A good deal of work still remains to be done on the objective comparison of such models.

5. METHOD OF CLASSIFICATION

The purpose of this section is to establish a basis for the description of the papers submitted for this Symposium in the light of the general principles discussed in the previous sections. A complete classification of the mathematical models used in hydrology and water resources would be a formidable task. If the classification were to be based on a multifacet approach, then the vector necessary to describe any particular model completely would be very large indeed. If a hierarchical system of classification were used, then all the difficulties of deciding the basis of the different levels of hierarchy would be very great. Just as there is no hydrologic model or water resource model that will solve all problems, so too there is no method for the classification of such models that will be satisfactory for all purposes. Accordingly, the discussion will be confined to the description of a classification which is put forward as being suitable for the purpose of describing within a defined context the papers of this Symposium.

The proposed classification is not a classification of mathematical models but rather a classification of the papers of this Symposium. The classification is based on a list of 10 items which could be considered important in the description of papers on mathematical models in hydrology or water resources. A list of descriptions is then established for each item and, for convenience, a symbol is assigned to each descriptor. The papers are then classified according to these descriptors and the result presented in tabular form.

The following is suggested as a suitable list of headings under which mathematical models in hydrology and water resources could be described:

(1) Extent of the model
(2) Objective of modeling
(3) Hydrologic processes and water uses involved
(4) Nature of prototype data
(5) Class of model
(6) Type of model
(7) Algorithms used in solution
(8) Computational requirements
(9) Method of model evaluation
(10) Results of application of model

It will be noted that a hierarchical element is introduced into the classification system in items (5) and (6) but that only two levels of hierarchy are involved. This was thought adequate for the present purpose but might well be varied if the method of classification is adapted for purposes other than that of this report. Only headings (1) to (6) are considered in connection with the tabulation of the Symposium papers since the later headings are the concern of the other general reporters.

The extent of the model, item (1), is concerned with the way in which the boundary of the prototype system which is to be modeled has been drawn. It is proposed that the models in the Symposium papers be classed under this heading according to the following list of descriptors and symbols:

- Conditions at a point (*P*)
- The state of catchment element (*E*)
- Water balance of a complete catchment (*C*)
- Performance of a water resource system (*WRS*)
- Behavior of a socioeconomic system (*SEC*)

Some of the above categories are very broad and could readily be subdivided, but the list is thought appropriate for the purpose of comparing the papers under review. The objective of modeling, item (2), has already been discussed in section 2, and the following listing is suggested:

- Observation of prototype system (*O*)
- Understanding of prototype behavior (*U*)
- Forecasting of prototype output (*F*)
- Prediction of prototype output (*P*)
- Control of prototype system (*C*)
- Design of prototype system (*D*)

In the above list the distinction is made between the forecasting (either deterministic or stochastic) of the value of the output at some definite future time and the prediction (either deterministic or stochastic) of the value of the output at some frequency in some future period. The distinction is also made between the control of a system which involves the optimization of its performance for a given system structure and the design of a system which may involve altering the structure of the system or of the timing of its development in order to optimize the given objective. The latter distinction corresponds to the distinction in economics between short-term and long-term planning.

The need to distinguish between understanding reality and making useful predictions is important. Kuhn (1957) in his book *The Copernican Revolution* writes:

> Judged on purely practical grounds, Copernicus' new planetary system was a failure; it was neither more accurate nor significantly simpler than its Ptolemaic predecessors...to astronomers the initial choice between Copernicus' system and Ptolemy's system could only be a matter of taste.

The question of taste and fondness for the familiar affect the choice of hydrologic models as well as astronomic systems.

The third basis for model classification listed above is that which distinguishes between the various hydrologic processes in a catchment area and between the various uses of water in a water resource system. While a complete classification would seek to apply both sets of descriptors to both types of model, it is sufficient for tabulation purposes to make the above division. Catchment models can be classified in accordance with their concern with the following variables:

- Precipitation (*P*)
- Evapotranspiration (*ET*)
- Catchment runoff (*RO*)
- Channel flow (*CF*)
- Overland flow (*OF*)
- Groundwater flow (*GW*)
- Physical water quality (*WQP*)
- Chemical water quality (*WQC*)
- Biological water quality (*WQB*)

Many catchment models will involve more than one of the above hydrologic variables (*HV*).

In the case of water resource models, the corresponding classification is in respect to the type of water use for which the system is designed. The following list of water uses would appear appropriate in the present context:

- Water supply—domestic, industrial, agricultural—(*WS*)
- Pollution control, including waste water disposal (*PC*)
- Hydropower development (*HP*)
- Irrigation (*IR*)
- Drainage of agricultural and urban areas (*D*)
- Flood control (*FC*)
- Inland navigation (*N*)
- Recreational use (*R*)

As in the case of catchment models, many mathematical models of water resource systems will be considered with more than one of the above water uses and will be classified as multipurpose (MP).

The three factors discussed above (the extent of the model, the hydrologic processes and water uses involved, and the objective of the modeling) will, when considered in conjunction, narrow considerably the range of choice of a model. However, this choice will also depend on the nature of the data available in regard to the prototype which is also an essential part of the definition of the modeling problem. The following is one listing of the various types of information that may or may not be available in respect of the prototype and that may or may not be used in developing the model structure and determining appropriate values for the parameters:

- The natural topography of the catchment (*T*)
- Geotechnical information on soils and bedrock (*G*)
- Records for meteorologic variables (*MV*)
- Records for hydrologic variables (*HV*)
- Records for water quality variables (*WQV*)
- Regional information for adjacent catchments (*RI*)
- Data and projections of water use (*WU*)
- Capacity of hydraulic installations (*HI*)
- Data relevant to project costs and benefits (*CB*)
- Information on global economic and social impacts (*ESI*)

As mentioned above, all of this information may not be required in certain problems, and even when it is required, it may not be available in reliable quantitative form. The first six headings listed above are of key importance in the case of models of catchment behavior, and the last four are more important in the case of large-scale complex water resource systems. It must be appreciated that each of the above headings covers a wide area. Thus, the listing of hydrologic variables (*HV*) covers all of the variables mentioned under section 3 above. Also a heading such as biological water quality can in turn cover a very large number of variables and parameters in the case of models with a substantial ecological component. Similarly, under the heading of global economic information are included such factors as national environmental objectives and all information in relation to the effects of a project of the size contemplated on the economy of the country.

It has already been stressed that the division of the model into classes and subclasses under (5) and (6) is of necessity arbitrary. Accordingly, the divisions discussed below are even more specifically affected by the context of the Symposium papers than the factors described above. For convenience, behavioral models of catchment behavior and prescriptive models of water resource systems have been dealt with separately. Since catchment models are concerned with the manner in which hydrologic inputs are converted to hydrologic outputs, the primary classification of this case has been based on the extent to which physical theory has been used in the basic model structure. On this basis we can distinguish between:

- Models based on blackbox analysis (*BB*)
- Regression models (*RM*)
- Lumped conceptual models (*LCM*)
- Distributed conceptual models (*DCM*)
- Models based on physical equations (*PE*)

The boundaries between some of these categories (e.g., blackbox and regression, lumped and distributed conceptual models) are not sharp, and in some cases, the final classification contains a degree of subjectivity.

The further subdivision is made for the purpose of the present general review on the basis of whether the model structure is linear (L) or nonlinear (NL) and time-invariant (TI) or time-variant (TV) and also on the basis of whether the input (and consequently the output) is deterministic (D), stochastic (S), or a combination of both (D-S).

The choice of the primary basis for the classification of mathematical models of water resource systems is difficult. One possibility is to base the classification on the nature of the objective function, that is,

- The hydraulic performance of the system (*H*)
- Ecological factors and parameters (*E*)
- The benefits and costs of the individual project (*BC*)
- The global economic and social impacts (*ESI*)

In the case of the latter two types of objective function, the problem formulation will differ greatly for a subsistence economy, a market economy, and a fully planned economy.

Another possibility is to classify on the basis of the type of decision involved into:

- Decision making under conditions of assumed certainty (*C*)
- Decision making under risk (*R*)
- Decision making under uncertainty (*U*)

These criteria have the disadvantage that they are not highly discriminatory in practice since most models at present are based on decision making under conditions of risk.

A second level of classification can appropriately be based on the type of methodology used to compare alternative strategies and might consist of:

- Analytical methods (*A*)
- Mathematical programming (*LP*,*NLP*)
- Dynamic programming (*DP*)
- Simulation methods (*SIM*)
- Game theory (*GT*)

Each of the above categories can be further divided in a number of ways.

6. CLASSIFICATION OF SYMPOSIUM PAPERS

The models in the 34 papers presented at this Symposium have been divided into models of catchment behavior (summarized in Table 1) and decision models for water resource systems (summarized in Table 2). The paper by Eichert is included in both tables.

The 24 papers in Table 1 are divided as follows:

- 4 papers on catchment elements (*E*)
- 18 papers on total catchment behavior (*C*)
- 2 papers on both types of model (*E*,*C*)

The individual assignments are given in column 2 of Table 1. The papers dealing with catchment elements relate to:

- 1 paper on evapotranspiration (*ET*)
- 1 paper on groundwater (*GW*)
- 3 papers on channel flow (*CF*)

as indicated in column 3. The papers dealing with total catchment response are classified as follows:

- 16 papers on the total catchment runoff (*RO*)
- 1 paper on several hydrologic variables (*HV*)
- 1 paper on physical water quality (*WQP*)
- 2 papers on various models

Again, the individual listings are given in column 3 of Table 1.

The importance of understanding clearly the objective of the model has been stressed above. The papers in Table 1 may be divided into:

- 2 papers on observation (*O*)
- 1 paper on understanding and forecasting (*U*,*F*)
- 17 papers on forecasting (*F*)
- 1 paper on forecasting and control (*F*,*C*)
- 1 paper on prediction (*P*)
- 1 paper on design and control (*D*,*C*)

One paper is not classified because it gives different objectives for different models.

TABLE 1 Descriptive models of catchment behavior.

Authors	Extent of model	Hydrologic process	Object of modeling	Nature of data	Class of model	Type of model
Abbott *et al.*	*C*	*HV*	*F*	*T,G,MV,HV*	*DCM*	*NL*
Anselmo *et al.*	*C*	*RO*	*F*	*HV*	*LCM*	*S*
Askew	*C*	*RO*	*F*	*MV,HV,WU*	various	
Baniukiewicz	*C*	*RO*	*F*	*MV,HV*	*LCM*	*NL*
Bergström	*C*	*RO*	*F*	*MV,HV*	*DCM*	*NL*
Bobiński *et al.*	*C*	*RO*	*F*	*MV,HV*	*LCM*	*NL*
	E	*CF*	*F*	*HV*	*BB*	*NL*
Buchtele	*C*	*RO*	*F*	*HV*	*R,LCM*	
Eichert	*E,C*	various	various	*HV*	various	
Hall *et al.*	*C*	*RO*	*F*	*HV*	various	
Handel *et al.*	*E*	*CF*	*F*	*HV*	*R,PE*	*NL*
Ishizaki	*C*	*RO*	*F*	*HV*	*DCM*	*NL*
Jaworski	*E*	*ET*	*U,F*	*MV*	*PE*	*NL*
Lambert	*C*	*RO*	*F,C*	*MV,HV*	*DCM*	
Liddament *et al.*	*E*	*GW*	*D,C*	*HV,WU*	*PE*	
Manley	*C*	*RO*	*F*	*MV,HV*	*DCM*	*NL*
Matondo *et al.*	*C*	*WQP*	*F*	*HV*	*R*	*L*
Nemec *et al.*	*C*	*RO*	*F*	*MV,HV*	*DCM*	
Ostrowski	*C*	*RO*	*F*	*HV*	*LCM*	*L*
Romonov	*E*	*CF*	*F*	*HV*	*PE*	
Rumiantsev	*C*	*RO*	*O*	*MV,HV*		
Sugawara	*C*	*RO*	*F*	*HV*	*LCM*	*NL*
Svanidze *et al.*	*C*	*RO*	*P*	*HV*	*LCM*	*S*
Volpi *et al.*	*C*	various	*O*		*R*	
Wingard	*C*	*RO*	*F*	*MV,HV*	various	

On the basis of the nature of the model input, the papers can be divided into:

- 1 paper involving meteorologic variables (*MV*)
- 11 papers involving hydrologic variables (*HV*)
- 8 papers involving meteorologic and hydrologic variables (*MV*,*HV*)
- 1 paper involving topography (*T*), geometric information (*G*), meteorologic (*MV*) and hydrologic variables (*HV*)
- 1 paper involving meteorologic variables (*MV*), hydrologic variables (*HV*), and water uses (*WU*)
- 1 paper involving hydrologic variables and water uses (*HV*,*WU*)

Of course, the above division is only approximate.

In regard to class of model as listed in column 6 of Table 1, we have:

- 1 paper on blackbox analysis (*BB*)
- 4 papers on regression analysis (*R*)
- 7 papers on lumped conceptual models (*LCM*)
- 6 papers on distributed conceptual models (*DCM*)
- 4 papers on physical equations (*PE*)
- 1 paper on regression and physical equations (*R*,*PE*)
- 4 papers on various types of models

Again, the division is approximate. For example, it is difficult to determine whether a conceptual model is lumped or distributed from a brief description.

The 11 papers wholly or largely concerned with water resource systems are summarized in Table 2. The scope of the papers is as follows:

- 8 papers on water resource systems (*WRS*)
- 3 papers on socioeconomic systems (*SEC*)

The 11 papers include the following types of system:

- 1 paper on single-reservoir systems (*SR*)
- 6 papers on multireservoir systems (*MR*)
- 3 papers on distribution systems (*DS*)

as indicated in column 3 of Table 2. The water uses involved in the models described by the papers break down as follows:

- 2 papers on water supply (*WS*)
- 1 paper on irrigation (*IR*)
- 7 papers on multipurpose systems (*MP*)
- 1 paper on various water uses

The objective of the modeling (column 5 of Table 2) divides as follows:

TABLE 2 Decision models of water resource systems.

Authors	Extent of model	Type of system	Water uses involved	Object of modeling	Type of objective function	Type of methodology
Ambrosino *et al.*	*WRS*	*SR*	*MP*	*C*	*H*	*NLP*
de Graan *et al.*	*WRS*	*DS*	*MP*	*C,D*	*H,E*	*SIM*
Eichert	*WRS*	various	various	various	various	various
Fabi *et al.*	*WRS*	*MR*	*MP*	*C,D*	*BC*	*SIM,LP*
Kaczmarek *et al.*	*WRS*	*MR*	*MP*	*C*	*BC*	*NLP*
Nelson *et al.*	*SEC*	*DS*	*IR*	*D*	*BC*	*SIM*
Pearson *et al.*	*WRS*	*MR*	*MP*	*C,D*	*H*	*SIM*
Reid	*SEC*	*DS*	*WS*	*D*	*BC,ESI*	*SIM*
Sexton	*WRS*	*MR*	*WS*	*C,D*	*H*	*SIM*
Sigvaldason	*WRS*	*MR*	*MP*	*C,D*	*H*	*NLP*
Wright	*SEC*	*MR*	*MP*	*C*	*P,BC,ESI*	*GT*

- 3 papers on control (*C*)
- 2 papers on design (*D*)
- 5 papers on control and design (*C*,*D*)
- 1 paper on various objectives

and classification on the basis of the type of objective function gives:

- 4 papers on hydraulic objectives (*H*)
- 3 papers on benefit and cost objectives (*BC*)
- 3 papers on two or three objectives
- 1 paper on various objectives

as shown in column 6 of Table 2.

The final classification on the basis of the methodology of solution gives:

- 6 papers on simulation (*SIM*)
- 1 paper on linear programming (*LP*)
- 3 papers on nonlinear programming (*NLP*)
- 1 paper on game theory (*GT*)
- 1 paper on various methods of optimization

which is again an approximate division.

Though the above classification may be in error in some instances, it should give a rough idea of the types of models dealt with in the papers submitted to this Symposium. If these models are a representative sample of the world population of models, certain features can be discerned. The most common model of catchment behavior would appear to be a conceptual model that converts an input of certain hydrologic variables to an output of total catchment runoff and is used for forecasting purposes. The most common decision model of a water resource system would appear to be a model of a multi-reservoir system with multiple water uses which is solved by a simulation in order to optimize the control or design of the system. Perhaps we should take these two types of model and study them closely in order to establish a standard against which other models can be evaluated. Whatever we do, if we continue to produce more models that are inadequately evaluated, neither the interests of science nor of technology will be well served and scarce resources of money and man-power will be squandered.

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