# HYDROLOGICAL MODELLING AND RELEVANCE TO INDIA

## 1.0 INTRODUCTION

Water is a logical link between Earth and Man. It is highly variable and mobile resource. Water is not only a commodity which is directly used by man but also it is the main spring for his extensive economic development, commonly an essential element in man's aesthetic experience, and always a major formative factor of the physical and biological environment which provides the stage for his activities.

### 1.1 Water on Earth

The total water on earth approximately equals 1600 million cubic km (or 48 x $10^{45}$ molecules of water). Part of this water, however is not recognizable as such because it is chemically bound to the materials of the earth mantle. At present this water of crystallization amounts to 230 million cubic km and is declining each year by 170 cubic km. This quantity of 170 cubic km rises from the interior of the earth to its surface as so called juvenile water increasing surface and groundwater supplies.

According to these figures, the present amount of free water on earth equals 1370 million cubic km, corresponding to a layer 2700 m thick over the whole earth system (area of earth's surface = 510 million square km.

In this way it seems that the supply of water on earth is nearly inexhaustible, but a completely different fact is realised when water quality aspect is considered. Of the total amount of free water on earth (1370 million cubic km), 97.2% is salt water, which cannot be used for agriculture or for domestic and industrial consumption. Also the water present as snow and ice is 2.1% of free water and as water vapour in the atmosphere is 0.001% of free water. Both these are also unavailable for use of our society. Only the remaining 0.6% of free water is available as fresh water. This is equal to 8.2 million cubic km and when spread over the total land surface of our earth (area = 136 million square km) gives a depth of no more than 60 m. Hence it is necessary to exercise utmost economy with fresh water which is our raw material number one.

The stock of fresh water on earth, of 8.2 million cubic km, consists mainly of groundwater, with the surface water in rivers and lakes comprising only 1.2% of the total quantity. Half of the groundwater supply, however, is unavailable as it is situated below a depth of 800 m. Soil moisture and storage is also unavailable, but it comprises only 0.6% of the fresh water.

### 1.2 Hydrologic Cycle

Fresh water is not a mineral such as coal or oil, where on the one hand consumption means destruction and on the other hand new supplies are not formed, so that these resources are ultimately depleted on earth.

However, when using water, its quality may deteriorate (e.g. domestic and industrial water supplies) or it may be converted into another state (transpiration losses with irrigation), but it always remains water. The most important difference is that fresh water is constantly formed anew due to hydrologic cycle with the solar energy as the main driving force.

The water on earth, whether as water vapour in the atmosphere, as surface water in the streams, lakes, as salt water in seas and oceans, or as ground water in the interstices of the subsoil, is not at rest, but in a continuous circulatory movement and never ending transformation from one state to another with the Sun as the driving force. It undergoes various complicated processes of interception, infiltration, unsaturated flow, saturated flow, evaporation, transpiration, overland flow, channel flow, etc. All these processes depend on the location and time (Fig. 1)

### 1.3 Water as a Resource

The water is one of the important natural resource available to mankind. Due to its multiple benefits and the problems created by its excesses, shortages and quality deterioration, the water has a unique role as a resource and deserves special attention of development planners. All life depends on water and through the ages people have been dealing with water. With the growth of human civilization, man's requirement of water have increased considerably and it is being used for irrigation, power generation, navigation, industries, recreation, etc. apart from domestic supplies. With the increasing pressures of rising population, there is a growing need for finding, developing and maintaining suitable water supply and for proper management of this natural resource.

Water as a resource is available as surface water and ground water. Surface flow in streams is made up of flow due to direct response of the basin to precipitation input and the flow from snow melt and baseflow contributions representing delayed smoothed out response. The surface runoff data is thus subjected to seasonal and yearly variations and the information content of surface flow observation is very small. Moreover, surface flow is susceptible to changes in the basin brought about by nature or man's various activities. It is also subject to quality deterioration due to discharge of industrial effluents, sewage, etc. The surface water projects involve decisions regarding major investments generally with insufficient or non-existent flow information. In contrast to this, the ground water data information content is considerably greater than that of comparable surface flow data. Moreover, the initial investment in ground water development project is relatively less. However, for an integrated planning of water resources, both surface water and ground water have to be developed conjunctively. Both these represent two phases of occurrence of the total water potential of the basin and any intervention in one phase affects the other. The development of water resources has to be undertaken through integrated river basin development programmes.

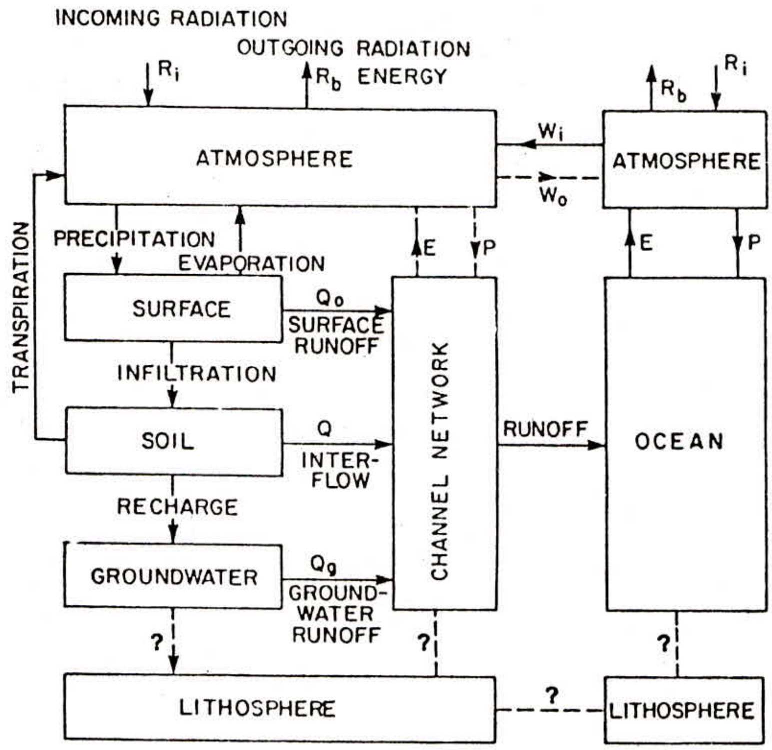


**Figure 1** : A System Representation of the Hydrologic Cycle (Singh, 1988).

Watershed or river basin implies a drainage area containing a few thousand or a few hundred thousand hectare from which water drains towards a single channel. It is a natural, social and economic unit for community development and conservation or water, soil, forests and related resources. The concept of the small watershed approach to land and water resource development at meso level and river basins at mega level is necessary for integrated planning of resources. This will also involve the application of principles of scientific hydrology for data collection and analysis for planning, design, construction, and operation of water resources development projects.

## 2.0 WATER RESOURCES OF INDIA

The atmospheric water balance for India indicates that roughly out of a total of 1677 million ha-m of water available as water vapour for an average year, only 400 million ha-m precipitates over the country. The surface water resources in the country are estimated at 178 million ha-m of which about 70 million ha-m can be utilized and the groundwater resources are estimated as about 35 million ha-m. The rainfall in India is quite erratic occurring mostly in monsoon months of June-Oct. and is subject to fluctuations in space and time. It has therefore, become obligatory to store the surface runoff during the monsoon periods and use it in fair weather season. It has been estimated that by utilizing the available resources an area of about 113 million hectares can be irrigated of which 40 million hectares is from groundwater exploitation. It is intended that this target is achieved by the turn of the century. This necessitates tremendous effort as well as physical and financial resources. Even after achieving this national target, about 45% of the total cropped area in the country would still have to depend upon the vagaries of monsoons. India is a very vast country with a large population of 684 million (1981 Census) which is estimated to reach 1000 million by 2000 A.D. The food production required for feeding this large population is estimated to be around 230 million tonnes which is nearly twice the present level of production. The total culturable area of the nation is around 189 million hectares and since nearly the entire area is being cultivated, the area under agricultural production can be marginally increased. As such the increase in agricultural production will have to come from improvement in the agricultural technology, extensive and intensive irrigation practices and efficient water use. The ultimate irrigation potential with integrated optimal utilization of surface and groundwater resources is of the order of 150 million hectares. The total hydro-power potential of the country is estimated to be 75000 megawatts at 60 percent load factor. The domestic water supply requirements may reach to about 30.8 x $10^9$ $m^3$ feet and the industrial water requirements may increase to 55.5 x $10^9$ $m^3$ by the year 2000 A.D. It has been estimated that in next two decades there will be almost doubling up of the different uses of water.

In recent years, considerable interest has been generated regarding optimum and efficient utilization of the country's water resources for the benefit of entire nation, over-riding narrow regional considerations. A large number of rivers in the country are interstate in character and as such a national view is as necessary in planning development and management of river basins. By adopting improved methodology of basin-wise development, by creation of additional storage reservoirs, conjunctive use of surface and groundwater and by interbasin transfer of surplus water to needy areas, it is possible to create an addition irrigation potential of 35 to 37 million hectares. As there is hardly any scope to increase the cultivated areas, as such conservation and efficient utilization for various purposes through storage reservoirs, conjunctive use and water transfer system have assumed importance.

### 2.1 National Water Policy

Realising the crucial importance of water for development and planning as the country is preparing itself to enter the 21st Century, a National Water Policy has been formulated, so that this precious resource is planned, developed and conserved as a national resource in an integrated and environmentally sound basis, keeping in view the needs of the States concerned. The water resource planning will have to be done for a hydrological unit, i.e. basin or sub-basin, and suitable data base and information system alongwith necessary infrastructure will have to be established for management of river basin as a unit. For effective and economical management of our water resources the frontiers of knowledge will have to be pushed forward in several directions by intensifying research efforts in various areas. These include hydrometeorlogy, assessment of water resources, snow and lake hydrology, ground water hydrology, and recharge, prevention of salinity ingress, water harvesting, evaporation and seepage losses, sedimentation of reservoirs, recycling and refuse, use of sea water resources and water management practices. A perspective plan for standardized training will also have to be an integral part of water resources development. The success of the national water policy will depend to much extent on the capabilities of the scientific manpower to take up new challenges (Min.of Water Resources, 1987).

## 3.0 HYDROLOGICAL PROCESSES

### 3.1 Hydrological Problems

Hydrology deals principally with movement, distribution and storage of moisture. Most hydrologic problems are related to either quantity or quality of water or both. Determination of water yield, streamflow hydrograph, frequency of magnitude, volume, duration and interarrival times of flood-peaks, dam breach etc. are some typical water quantity problems. These problems can be addressed in :

(a) Time domain - involving reconstruction of the past (prediction) and construction of the future (forecasting)on different scales viz. continuous time or desecrete time such as hour or less, daily, weekly, ten daily, monthly, seasonally, annual and longer.

(b) Space domain - involving spatial variability and its sampling, regionalization, effect of land use change etc. on different scales such as channel, field or plot, watershed, river basin consisting of number of watersheds, continental or global.

(c) Frequency domain - involving determining frequency of Extremes (high as well as low), volumes, means, hydrologic space-time characteristics, etc.

Some examples of hydrological problems as listed by Singh (1989) are reproduced in Tables 1,2, and 3.

**Table 1 : Some Example Problems At Different Time Scales**

| Scale | Example Problem |
|---|---|
| Short time or continuous time | a. Flood routing through a reservoir or channel reach<br>b. Determination of direct runoff due to a specified rainfall event.<br>c. Infiltration during a rainfall episode<br>d. Snow melting<br>e. Transport of contaminants by urban storm-water |
| Daily | a. Water balance<br>b. Flow forecasting<br>c. Precipitation forecasting<br>d. Reservoir operation<br>e. Evaporation and transpiration |
| Weekly | a. Water balance<br>b. Evaporation<br>c. Canal operation for farm irrigation<br>d. Weather forecasting<br>e. Flood damage assessment |
| Monthly | a. Water balance<br>b. Evaporation<br>c. Water supply<br>d. Reservoir sedimentation<br>e. Effect of land use changes |
| Seasonal | a. Water balance<br>b. Weather forecasting<br>c. Crop yield<br>d. Agricultural pollution<br>e. Irrigation water supply and scheduling<br>f. Effect of droughts |

| | |
|---|---|
| Yearly | a. Water balance<br>b. Evaporation<br>c. Maximum annual flood values<br>d. Sediment deposition and aggradation<br>e. Effect of land use changes<br>f. Drought modelling |
| Longer time | a. Effect of land use changes<br>b. Groundwater movement<br>c. Migration of chemicals in groundwater<br>d. Migration of chemicals in groundwater<br>e. Ecosystem modeling<br>f. River training works<br>g. Drought modeling |

**Table 2 : Some Example Problems At Different Space Scales**

| Scale | Example Problem |
|---|---|
| Short distance or continuous distance | a. Precipitation intensity<br>b. Surficial roughness<br>c. River meandering<br>d. Aggradation and degradation<br>e. Crop irrigation |
| Channel | a. Open channel flow<br>b. Flood routing through a channel<br>c. Erosion and sediment transport<br>d. Geomorphic features<br>e. Stage-discharge (rating) curve |
| Plot or field | a. Hydrology of a parking lot<br>b. Overland flow from a field<br>c. Farm irrigation efficiency<br>d. Interrill erosion<br>e. Land use change |
| Watershed | a. Unit hydrograph<br>b. Unit sediment graph<br>c. Effects of land use change<br>d. Water balance<br>e. Surficial features |
| River basin | a. Multiobjective development of water resources<br>b. Regional hydrologic analysis<br>c. Interbasin transfer of water<br>d. Droughts<br>e. Effect of land use changes, especially structural |

| | |
|---|---|
| Continental | a. Climatic prediction<br>b. Droughts<br>c. Water balance<br>d. Flood damage<br>e. Atmospheric pollution and its effects |
| Global | a. Water balance<br>b. Climatic pattern and changes<br>c. Earth-atmosphere-ocean interaction<br>d. Droughts<br>e. Effect of such human activities as unclear explosion |

**Table 3 : Some Example Problems in the Frequency Domain**

| Scale | Example Problem |
|---|---|
| Extremes | a. Extreme rainfall (hourly, every 6-h, daily, etc.)<br>b. Annual peak discharge<br>c. Extreme annual low discharge<br>d. Hurricane and tide flooding<br>e. Extreme annual temperature |
| Volumes | a. Yearly water yield<br>b. Annual sediment yield<br>c. Annual rainfall<br>d. Annual drop in water table<br>e. Annual flood damage |
| Means | a. Mean daily temperature<br>b. Mean daily river flow<br>c. Moving average of a time series<br>d. Mean daily rainfall intensity<br>e. Mean reservoir outflow |

In general, various approaches to the study of hydrologic problems can be grouped under two categories: (1) physical science approach - also referred to as a basic, pure, causal, dynamic or theoretical approach, and (2) systems approach - also known as an operational, applied, empirical, black box or parametric approach (Fig. 2).

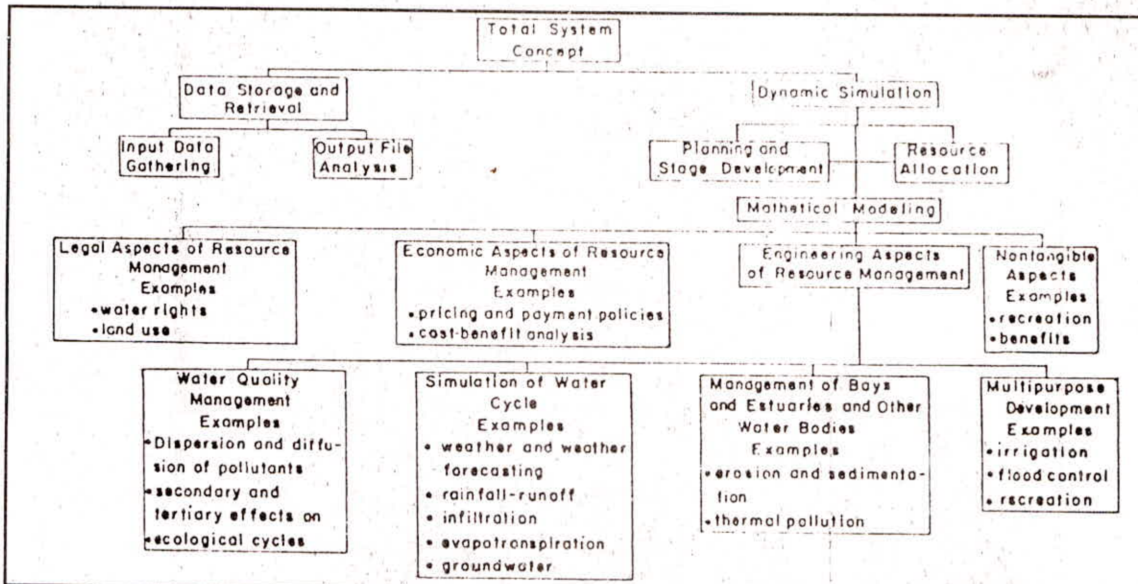


**Figure 2** : Nature of Hydrologic Problems from a Systems Points of View (Singh, 1988)

Water management is the application of all available knowledge to the practical development of water resources. One of the fundamental sciences of water management is hydrology. The engineers engaged in design, construction or operation of hydraulic works must solve practical problems. These are of varied nature and in most cases hydrology is needed for their solution. These include **(a) rural water management (b) river training (c) municipal water management (d) structural and hydraulic design of water control structures for different purposes.** Some typical questions that the hydrologist is called upon to answer are: **(i) Is the flow of a particular stream at a particular site is sufficient to meet the needs of (a) a city or industry seeking a water supply (b) an irrigation project (c) a proposed power development (d) navigation (e) recreation. (ii) Would a storage reservoir be required in connection with any of the proposed uses and if so, what should be its capacity ? (iii) In the design of a flood protection system, a bridge a culvert or a spillway for a dam, what is the maximum flood that may be expected to occur with any specified frequency. (iv) What would be the effect of draining upland area or a swampy region upon the flow of the stream from watershed ? (v) How would certain changes in land use or the removal of forests, affect the groundwater level or the stream flow from such an area?**

### 3.2 Deterministic and stochastic Processes

Hydrologic models are mathematical formulations to simulate natural hydrologic phenomena which are considered as 'processes or as systems'. Any phenomena which undergoes continuous changes particularly with respect to time may be called a process. As practically all hydrologic phenomena change with time, they are hydrologic processes. The hydrologic processes and their models can be divided into two broad classes :

#### 3.2.1 Deterministic Process

If the chance of occurence of the variables involved in a process is ignored and the model is considered to follow a definite law of certainty but not any law of probability, the process and its model are described 'Deterministic". For example, the conventional routing of flood flow through a reservoir is a deterministic process and the mathematical formulation of unit hydrograph theory is a deterministic model.

### 3.2.2 Stochastic or Probabilistic Process:

If the chance of occurence of the variables is taken into consideration and the concept of probability is introduced in formulating the model or process, then process and its model are described as 'stochastic or probabilistic'. For example, the probability of the flow is taken into account in the probability routing, the process and the governing model employed to simulate the process are considered as stochastic or probabilitistic.

### 3.2.3 Catchment as a system

Dooge defines a system as 'Any structure, device, a scheme or procedure, real or abstract, that interrelates in a given time reference, an input, cause or stimulus, of matter, energy or information, And an output, effect or response, of information, energy or matter.

The hydrological cycle of a drainage basin is a sequential, dynamic system in which water is a major throughput. Actual hydrologic system is a non-stationary stochastic process. However, since it is very complicated mathematically, the hydrologic system is generally treated as deterministic and modeled by deterministic models e.g. instantaneous unit hydrograph.

In practice, the hydrologist confines his attention to individual basins or catchment areas. Thus he leaves the problems of the atmosphere to the meteorologist, those of the lithosphere to the geologist and those of the seas to the oceanographer. This narrows down his concern to the particular subsystem of the total hydrological cycle.

Though classical hydrology described the hydrological cycle in terms of surface runoff, interflow,d and groundwater flow. In practice quantitative hydrology usually ignores this three fold division and considers the hydrograph being made up of a direct storm response and a base flow. Thus in the analysis of the relationship between storm rainfall and flood runoff, the system analyzed by the practical hydrologist corresponds closely to that indicated above.

The catchment system in this simplified approach consists of three subsystems.

1. The sub system involving direct storm response.
2. The sub system involving groundwater response.
3. The sub system involving the soil phase which has a feedback loop to the separation of precipitation into precipitation excess and infiltration.

There are many ways to classify systems and their models (Singh, 1988). Each classification is based upon a particular set of system characteristics. The same system can therefore fit into different categories. Thus systems could be (i) abstract or physical, (ii) natural or devised (iii) Open loop or closed loop, (iv) simple or complex (v) stable or unstable (vi) damped or undamped (vii) continuous time or discrete time (viii) causal or non causal (ix) memory or no memory (x) time invariant or time variant (xi) linear or non-linear (xii) lumped or distributed, and (xiii) deterministic or stochastic. Hydrologic systems are normally physical, sequential dynamic, natural, open loop, complex, stable, damped, causal, memory, stochastic, time variant, non-linear distributed. systems.

The hydrologic behaviour of watershed is a very complicated phenomenon which is controlled by an unknown large number of climatic and physiographic factors that very with both time and space. The catchment behaviour is distributed, nonlinear,s time varient and stochastic in nature.

The physics of separate hydrologic processes is known and the differential equations governing their deterministic behaviour can be written for physically homogeneous basins. In using these equations to study natural heterogeneous systems, the system is lumped into elements which are effectively homogeneous. This method can be improved by considering the coefficients of these equations to have a random component. However, in seeking general understanding of complex hydrologic systems there are conceptual and computational limitations in considering non-linear stochastic system. Hence deterministic linear system approach is adopted.

## 4.0 HYDROLOGICAL MODELS

In simple terms a hydrological model is a simplified description of (parts of) the hydrological cycle. However, the term hydrological model is often understood to be and is used more narrowly as a computer-based mathematical model. The development and application of such models have increased tremendously during the last two or three decades, so that engineering hydrology today usually involves consideration of some kind of hydrological model. With the current rapid developments within computer technology and hydrology the application of computer-based hydrological models can only continue to increase in the near future (Storm, 1989).

A mathematical model provides a quantitative mathematical description of the processes or phenomena, i.e. a collection of mathematical equations (often partial differential equations), logical statements, boundary conditions and initial conditions, expressing relationships between inputs, variables and parameters.

The usual aim is to model the interaction of an input (e.g. rainfall) with a system (e.g. a catchment) to produce an output (e.g. the outflow hydrograph). The hydrological cycle is represented mathematically to imitate the natural system. The mathematical functions employed can be designed to simulate the natural hydrological processes as closely as present knowledge, mathematical constraints, data availability and user requirements allow. Depending on the required accuracy of results, effort to be spent in data collection, effort to be spent in modelling and available funds, the model can approximate the natural system more or less closely (Storm, 1989).

### 4.1 Classification

Hydrological models can be classified in different ways as e.g. shown in Fig. 3. Two main groups of mathematical methods emerge from Fig. 3: those which involve optimization and those which do not.

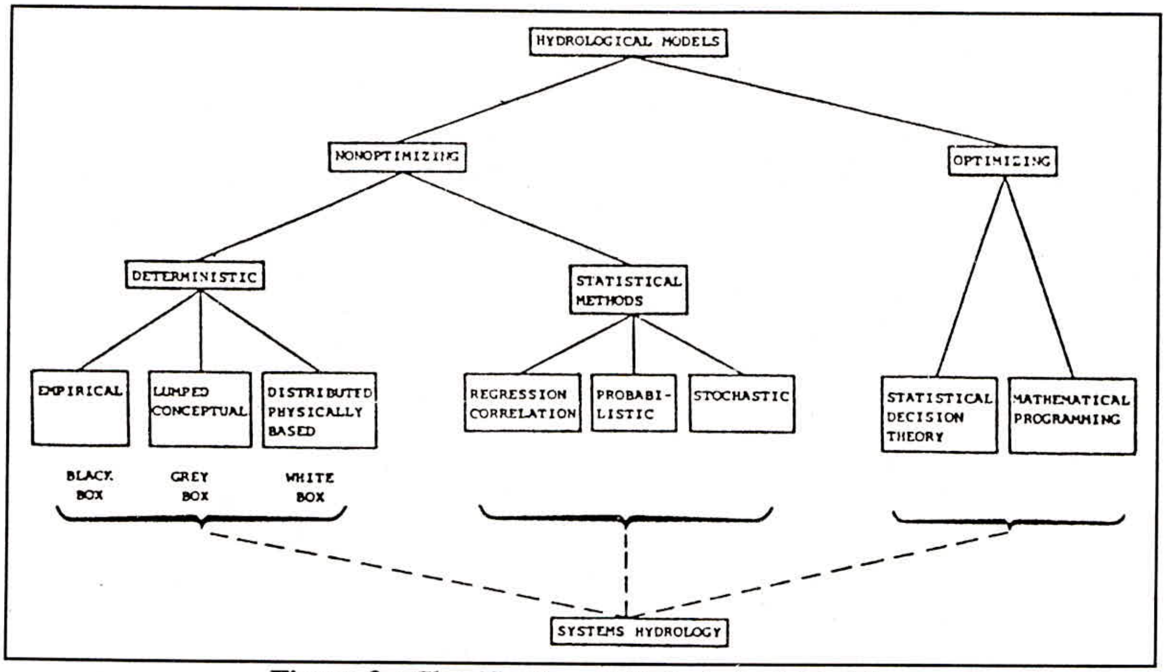


**Figure 3** : Classification of Hydrological Models

Here optimization is referred to strictly in the sense of decision making rather than in the optimization of model parameters. The non-optimizing methods are generally associated with the assessment of hydrological data and are used to quantify the physical process. Methods involving optimization are concerned with the problem of selecting the "best" solution among a number of alternatives in a planning process.

Non-optimizing methods are divided into two fundamentally different approaches, the deterministic and the statistical. However, although the deterministic and the statistical methods are fundamentally different, a strong interplay between the two approaches exists, mainly because the processes involved in the hydrological cycle are partly causal and partly random. Hence, some deterministic models contain random functions to relate processes, while some statistical models contain causal or deterministic functions as part of their structure. The interplay between the two approaches also includes the subsequent analysis of the information gained from the different models (Storm, 1989).

## 4.2 Black Box or Empirical Models

These contain no physically-based transfer function to relate input to output: in other words no consideration of the physical processes is involved. Such models usually depend upon establishing a relationship between input and output, calibrated from existing hydrometeorological records. Within the range of calibration data such models may be highly successful, often because the formal mathematical structure carries with it an implicit understanding of the underlying physical system. However, in extrapolating beyond the range of calibration, the physical link is lost and the prediction then relies on mathematical technique alone. Given the inherent linearity of many black-box models, which contrasts with the non-linearity of hydrological systems, such extrapolation is of dubious worth and is not recommended. Thus, for example, black box models cannot be used to predict the effects of a future change in land-use.

Probably the best known black box models in hydrology are the unit hydrograph principles.

Black box models were developed and extensively applied before advances in computer technology made it possible to use more physically correct (and thus more complex) models. Today, black box principles are more often used to form components of a larger model, e.g. the unit hydrograph is often used for streamflow routing in conceptual rainfall-runoff models.

### 4.3 Lumped Conceptual Models

These occupy an intermediate position between the fully physically-based approach and empirical black-box analysis. Such models are formulated on the basis of a relatively small number of components, each of which is a simplified representation of one process element in the system being modeled.

The mode of operation may then be characterized as a book-keeping system continuously accounting for the moisture contents in the storages. The non-linear form of such models reflects the thresholds present in hydrological systems, which cannot adequately by incorporated within a linear model. The source of this non-linearity is often the soil moisture condition, whether controlling groundwater recharge or surface/subsurface storm runoff.

### 4.4 Fully Distributed Physically Based Models

These are based on our understanding of the physics of the hydrological processes which control catchment response and use physically-based equations to describe these processes. From their physical basis such models can simulate the complete runoff regime, providing multiple outputs (e.g. river discharge, phreatic surface level and evaporation loss) while black box models can offer only one output. Also, almost by definition, physically-based models are spatially distributed since the equations from which they are formed generally involve one or more space coordinates. They can therefore simulate the spatial variation in hydrological conditions within a catchment as well as simple outflows and bulk storage volumes. On the other hand, such models make huge demands in terms of computational time and data requirements and are costly to develop and operate.

Unlike lumped conceptual models, physically-based distributed models do not consider the transfer of water in a catchment to take place between a few defined storages. Instead the transfers of mass momentum and energy are calculated directly from the governing partial differential equations, for example the Saint Venant equations for surface flow, the Richards' equation for unsaturated zone flow and the Boussinesq equation for groundwater flow. These cannot be solved analytically for cases of practical interest and solutions must instead be obtained using approximate numerical methods, an approach which has become feasible only with the introduction of powerful computers.

Physically-based distributed models treating single components of the hydrological cycle have been developed and applied extensively over the last two decades. Almost all groundwater models, for instance, conform to this type., However, physically-based distributed catchment models, integrating submodels of the major components of the hydrological cycle within one model, have progressed less rapidly. This is largely because of the heavy computer and data requirements of such models, although there are also numerical difficulties, such as mass balance errors, to be overcome in modelling the transfer of data between the separate submodels. Nevetheless, several physically-based distributed models have been successfully developed and tested during the past decade, although not applied operationally on a routine basis for practical projects. Prominent among these is the SHE modelling system (Storm, 1989).

The above types of hydrological models can also be broadly classified in two groups: (i) Event based streamflow simulation models, and (ii) continuous stream flow simulation models.

In the event based streamflow simulation models, direct runoff hydrograph or its peak characteristics are modelled. Streamflow simulation for individual storm events is required for solving a wide variety of water resources problems such as estimation of design flood for various hydraulic structures, urban and highway drainage, planning of flood control works, urban planning and development etc. A number of event based stream simulation models have been developed during last two decades. Some of the event based stream flow simulation model have been briefly described by Brown et al. (1974). The various aspects of event based stream flow simulation models including building an event based streamflow simulation model and some of the commonly used event based models have been discussed by Singh (1989) are reproduced in Table-4.

Continuous streamflow simulation models simulate streamflow for long periods of time. This model maintain continuous accounting of water in storage and in the watershed. In these models the emphasis is a simulation of the entire land phase of the hydrologic cycle. In these models the hydrologic processes such as evaporation, transpiration, depression storage, infiltration, linterception, sub-surface flow and base flow etc. are also taken into consideration. Some of these processes are not considered in the event based models, some are lumped and considered with approximate Larson et al. (1983) have discussed assembling these components into a continuous stream flow simulation model. Singh (1989) also briefly mentioned arrangements of the components of some of these models. The models summarized by the author are reproduced in Table-5.

Description of (parts of) the hydrological cycle. However, the term hydrological model is often understood to be and is used more narrowly as a computer based mathematical model. The development and application of such models have increased tremendously during the last two or three decades, so that engineering hydrology today usually involves consideration of some kind of hydrological model. With the current rapid developments within computer technology and hydrology the application of computer based hydrological models can only continue to increase in the near future.

4.5 Selection of Appropriate Model Type

A large number of hydrological models exists. However, many of the models function in fundamentally the same way. For instance, at least 20 different rainfall-runoff models of the lumped, conceptual type (like the NAM model) exist. Although these models at first sight may look very different they have fundamentally the same structure and basically function according to the same principles. Thus, differences in performance among the better half of the lumped, conceptual rainfall-runoff models are believed to be mostly dependent on the hydrologist who calibrates and operates the model, while the models themselves (apart from ease of operation, user friendliness, etc.) are basically of the same quality

Thus the question "which model is most appropriate for my particular hydrological problem?" cannot be answered strictly by giving the name of one model. Recommendations are instead given as to which of the above-mentioned model types are most appropriate for the different kinds of hydrological problems.

# Table 4 : Some Event Based Streamflow Simulation Models

| Model | | | Model Components | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| *Name* | *Author(s)* | *Year* | *Baseflow Separation* | *DR Volume* | *Infiltration and Loss* | *DR Hydrograph* | *Channel Routing* | *Reservoir Routing* | *Parameter Optimization* |
| HEC-1 | Hydrologic Engineering Center | 1981, 1982 | Yes | SCS curve number and two other methods | Variable loss rate method | Clark's and Snyder's unit hydrograph methods | Muskingum method and five other methods | Storage-indication method | Automatic calibration capability |
| TR-20 | Soil Conservation Service | 1973 | Constant rate method | SCS curve number method | SCS curve number method | Unit hydrograph method | Convex method | Storage-indication method | No |
| USGS | Dawdy et al. | 1972 | Constant rate method | Soil moisture accounting | Philip equation | Clark's unit hydrograph | Translation method | No | Rosenbrock's method |
| HYMO | Williams and Hann | 1973 | No | SCS curve number method | SCS curve number method | Nash model | Variable storage coefficient method | Storage-indication method | No |
| SWMM | Metcalf and Eddy, Inc. et al. | 1971 | No | Loss accounting | Horton's equation | Hydraulic method | Hydraulic routing method | No | No |
| WAHS | Singh | 1983 | Recession equation | SCS curve number method | Philip's equation | Geomorphological unit hydrograph method | Linear reservoir | No | Rosenbrock-Palmer method |
| RORB | Laurenson and Mein | 1983 | Two options | No | Constant and variable loss rate methods | Nonlinear storage routing | Nonlinear storage routing | Yes | No |
| WBNM | Boyd et al. | 1979a, 1979b | No | Yes | Φ-index | Linear as well as storage elements for routing | Storage routing | No | Yes |
| FHSM | Foroud and Broughton | 1981 | Yes | Yes | Modified Horton's equation | Time area curve + a linear reservoir | No | No | Nonlinear least square curve fitting |
| XJM | Zhao et al. | 1980 | Yes | Yes | Storage capacity curve | Unit hydrograph method | Muskingum method | No | No |
| GAWSER | Ghate and Whiteley | 1977 1982 | Yes | Yes | Holtan's equation | Time area curve + convolution | HYMO method | No | No |
| MIT | Maddaus and Eagleson | 1969 | No | No | Any suitable model | Linear channel and reservoir | Linear | No | Optimization |
| HM | Huggins and Monke | 1968 | No | Yes | Holtan's equation | Kinematic wave method | No | No | No |
| Kansas | Smith and Lumb | 1966 | Yes | Yes | Soil moisture accounting | Lag and route method | No | No | No |
| IHM | Morris | 1980 | Yes | Yes | Richards equation | St. Venant equation | St. Venant equation | No | No |

Table 5 : Some SCS Models

| Model | | Model Components | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Name | Author | Inter-ception | Infiltra-tion | Soil Moisture Storage | Evapotrans-piration | Surface Runoff | Snowmelt Runoff | Inter-flow | Groundwater Runoff | Channel Routing | Reservoir Routing | Parameter Optimiza-tion |
| SWM IV | Crawford & Linsley (1966) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| KWM | Liou (1970) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes |
| OPSET | James (1970, 1972) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| OSUM | Ricca (1972) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | No |
| NWSRFS | Hydrology Research Laboratory (1972) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes |
| SSARR | U.S. Army Engineer Division, North Pacific (1975) | No | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes |
| API | Sittner et al. (1969) | No | No | Yes | No | Yes | No | No | Yes | No | No | No |
| USDA | Holtan et al. (1975) | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No |
| TWM | Claborn and Moore (1970) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | Yes | Yes |
| TANK | Sugawara et al. (1984) | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes |
| HBV | Bergstrom (1976) | No | No | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes |
| SHE | Abbott et al. (1986a, 1986b) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | No |
| CEQUEAU | Charbonneau et al. (1977) | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No |
| MC | Deschenes et al. (1985a, 1985b) | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | No |
| SCM | Refsgard (1981) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | No |
| SRBM | Bultot and Dupriez (1986a, 1986b) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | No | Yes |
| JBCWM | Quick and Pipes (1977) | No | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| MRM | Porter and McMahon (1971, 1975) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | Yes | No | Yes |
| HYSIM | Manly (1978) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No |
| ARBM | Chapman (1968) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes |
| BM | Boughton (1966) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes |
| HHM | Ando et al. (1983) | No | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes |
| TVA | Tennessee Valley Authority (1972) | Yes | Yes | Yes | Yes | Yes | No | Yes | Yes | No | No | Yes |
| USUWSM | Andrews et al. (1978) | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | Yes | No | Yes |

For some hydrological problems the selection of model type is more or less obvious, e.g. probabilistic models for frequency analysis or stochastic time series models for generation of long (100-1000 years) synthetic streamflow series. Therefore, only the fields of applicability of the different deterministic simulation models are discussed (Storm, 1989) in the following paras:

Empirical(black box) models are mainly of interest as single event models or as subcomponents or more complicated models.

Lumped, conceptual models are especially well suited to simulation of the rainfall-runoff process when hydrological time series sufficiently long for a model calibration exist. Thus typical fields of application are:

- o Extension of short streamflow records based on long rainfall records.
- o Real-time rainfall-runoff simulation for example flood forecasting.

Other fields of possible application, to which the lumped conceptual models are not especially well suited, but where they can be used if no better model or method is available, are the following:

Prediction of runoff from ungauged catchments, i.e. catchments where calibration is not possible. In such cases the model parameters are typically estimated by calibrating against hydrologically similar, neighbouring catchments.

- o General water balance studies, availability of groundwater resources, irrigation needs, analyses of variations in water availability due to climatic variability, etc.

## 5.0 ROLE OF PHYSICALLY BASED DISTRIBUTED MODELS

Physically-based distributed models can in principle be applied to almost any kind of hydrological problem. Obviously, there are many problems for which the necessary solutions can be obtained using cheaper and less sophisticated empirical, lumped conceptual or statistical models. However, for the more complicated problems there may be little alternative, but to use a physically-based distributed model. Some examples of typical fields of application (Storm, 1989) are:

### 5.1 Catchment changes

These include both natural and man-made changes in land-use, such as the effects of forest fires, urbanization and forest clearance for agricultural purposes. The parameters of a physically-based, distributed model have a direct physical interpretation, which means that they can be evaluated for the new state of the catchment before the change actually occurs. This enables the effects of changes to be examined in advance of such changes. In addition, the characteristically localized nature of catchment changes can easily be accounted for within the spatially distributed model structure.

### 5.2 Ungauged Catchments

An application in a previously ungauged catchment requires the initiation of a programme of field work to provide data and parameters for calibration. Here, the physical significance of its model parameters enables e.g. the SHE to be applied on the basis of a much shorter, and therefore more cheaply obtained, hydrometeorological records than is necessary for more conventional models. Similarly the catchment parameters can be estimated from intensive short-term field investigations.

5.3 Spatial variability

Spatial variability in catchments inputs and outputs. Distributed models can be used to examine the effects on flood flow of different directions of storm propagation across a catchment and also the effects of localized river and groundwater abstractions and recharge. This facility is beyond the capability of lumped catchment models which can deal only with quantities averaged across the catchment.

5.4 Movement of Pollutants and Sediments

Movements of pollutants and sediments. In order to model the movement of pollutants and sediments, it is first necessary to model the water flows which provide the basic dispersion mechanism. Most water quality and sediment problems are distributed in nature, so distributed models are the most suitable for supplying the basic information on water flows.

## 6.0 REMARKS

In order to optimally develop and utilise India's water resources to meet the demands for various uses for our growing population, the application of hydrological modelling techniques would be very much necessary. This will be required not only for deciding about water yield or design parameters, but also for understanding and evaluating effects of developmental and other activities on hydrological regime of river basins.

Finally, the choice of model for a particular "real-world" application is likely to be heavily influenced by non-hydrological criteria such as the time, manpower and money available to support the project, availability of data, desired accuracy of results and computer resources. Selecting a model requires balancing the degree to which the model represents the hydrological system against the general difficulty in obtaining a result. If a highly complex mathematical representation of a system is used, the risk of not representing the system is minimized but the difficulty of obtaining a useful result is maximized. Many data will be required, programming effort and computer time are large, the general mathematical complexity may even render the problems formulation intractable and the resource constraints of time, money and manpower may be exceeded. Conversely, if a greatly simplified mathematical model is applied without a prosper examination of its physical significance, the difficulties in obtaining a result may be reduced but the risk of not representing the physical system is increased.

## REFERENCES

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