Chapter I

CHAPTER I

HYDROLOGIC SYSTEM

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HYDROLOGIC SYSTEMS

INTRODUCTION

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

Deterministic Process

If the chance of occurrence 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.

Stochastic or Probabilistic Process

If the chance of occurrence of the variables is taken into consideration and the concept of probability is introduced in formulating the model of 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 probabilistic.

Strictly speaking, there is a difference between the stochastic process which is generally considered both time and chance dependent and the probabilistic process which is considered as time independent and only chance dependent.

(a) For the time independent probabilistic process, the sequence of occurrence of the variates involved in the process is ignored and the chance of their occurrence is assumed to follow a definite probability distribution in which the variables are considered pure random. For example, the flow duration curve procedure is probabilistic.

(b) For the time dependent stochastic process, the sequence of occurrence of variates is observed and the variables may be either pure random or non pure random, but the probability distribution of the variables may or may not vary with time.

If pure random, the members of the time series are independent among themselves and thus constitute a random sequence. If non pure random, the members of the time series are dependent among them selves, and are composed of a deterministic component and a pure random component and thus constitute a non random sequence. For example probability routing is a stochastic process.

In reality, all hydrology processes are more or less stochastic. They have been assumed deterministic or probabilistic only to simplify their analysis. Mathematically speaking stochastic process is a family of random variables x(t) which is a function of time (or other parameters) and whose variates 'x' is running along in time't' within a range 'T'. Quantitatively, the stochastic uniform intervals of t = 1,2 ....., and the values of sample form a sequence of x1, x2,...., starting from a certain time and extending for a period of T. This sequence of sampled values is known as time series which may be discrete or continuous. For example, a hydrograph is a continuous time series. Daily, monthly, and annual discharges represent a discrete time series, e.g. T=12 months, x_1 to x_{12} be monthly flows from January to December. Then if series is 30 years we have 30 values for each monthly flow which have a particular probability distribution for each month and these 30 values are sampled values of that month's flow.

DEFINITION OF SYSTEM

Dooge defines a system as 'Any structure, device, 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 of response of information, energy or matter'.

Chow defines a system as aggregation or assemblage of objects united by some form of regular interaction or independence. The system is said to be dynamic if there is a process taking place in it. If the process is considered probabilistic or stochastic, the system is said to be stochastic. Otherwise, it is a deterministic system. Furthermore, the system is called sequential if it consists of an input, output and some working fluid (matter, energy or information) known as throughout passing through the system.

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 modelled by deterministic models e.g. instantaneous unit hydrograph.

Concept of System Operation : (Deterministic System)

The role of the system of generating output from input, or interrelating input and output, is a essential feature of systems approach. The output, from any system depends on the nature of the input, the physical laws involved , and the nature of the system itself both the nature of the components and the structure of the system according to which they are connected.

In physical hydrology, as in other branches of applied physics of all three are taken into account in predicting the output.

(a) In the systems analysis approach,the overall operation of the system is examined without taking into account all the complex details of the system or all the complex physical laws involved. Concentration is on the system operations which depend on the physical laws and the nature of the system, however, the nature of this dependence may not be known and may be ignored in this analysis approach to the problem. This is represented by the horizontal components in the Fig. 1.1. Thus in unit hydrograph studies , once the unit hydrograph has been derived from records of input and output, it can be used as a prediction tool without reference to the nature of the catchment or the physical laws involved.

(b) However in Systems synthesis approach,if we wish to derive a synthetic unit hydrograph or to examine the validity of the unit hydrograph procedure, it is necessary to examine the connection between the unit hydrograph the characteristics of the watershed and the physical laws governing its behaviour. This relationship is governed by vertical components in Fig. 1.

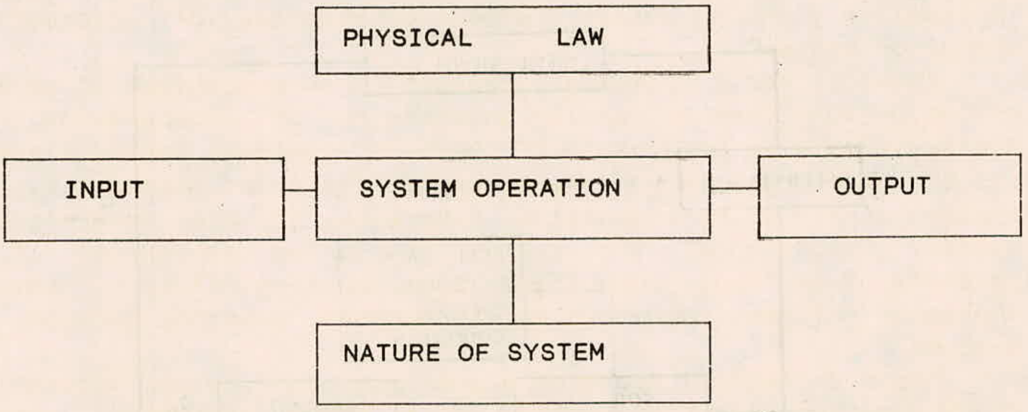


Fig. 1 System Approach

HYDROLOGIC CYCLE

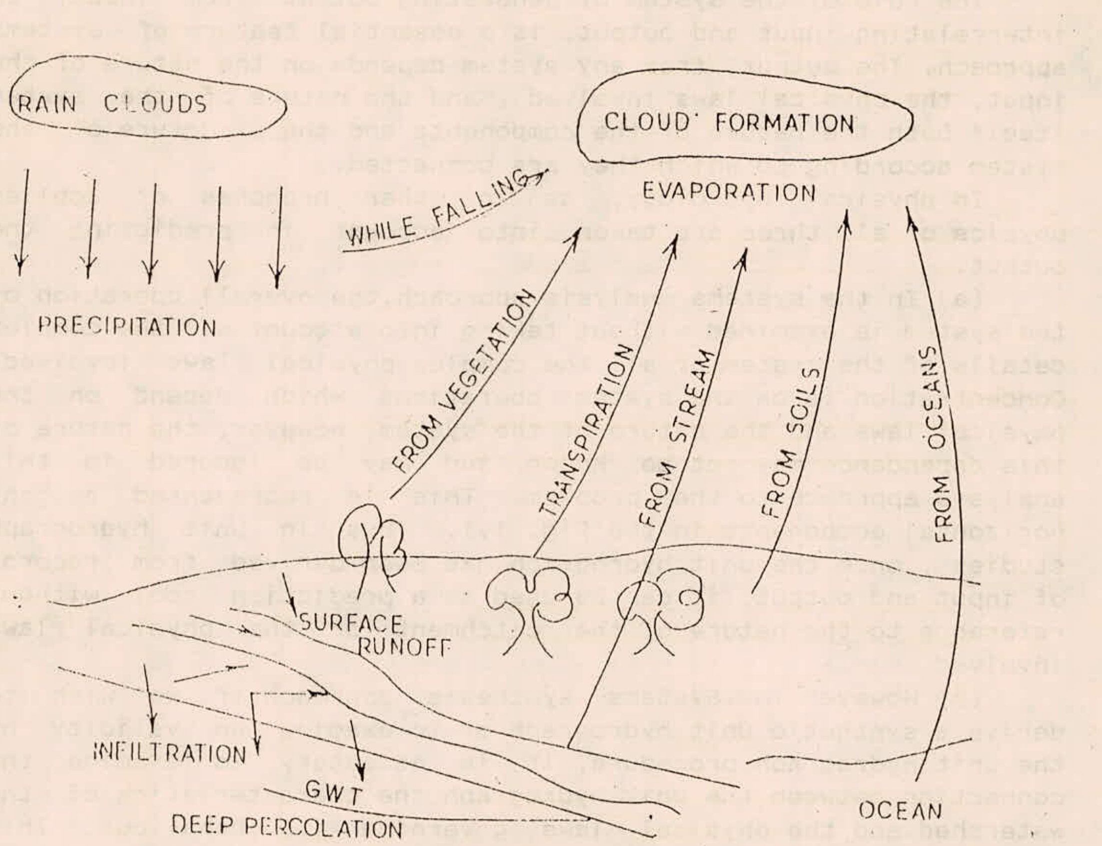


Fig. 2

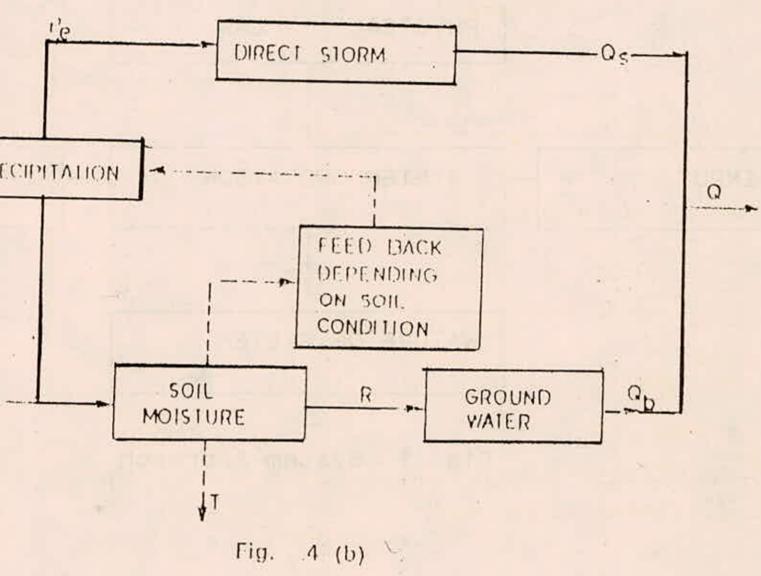
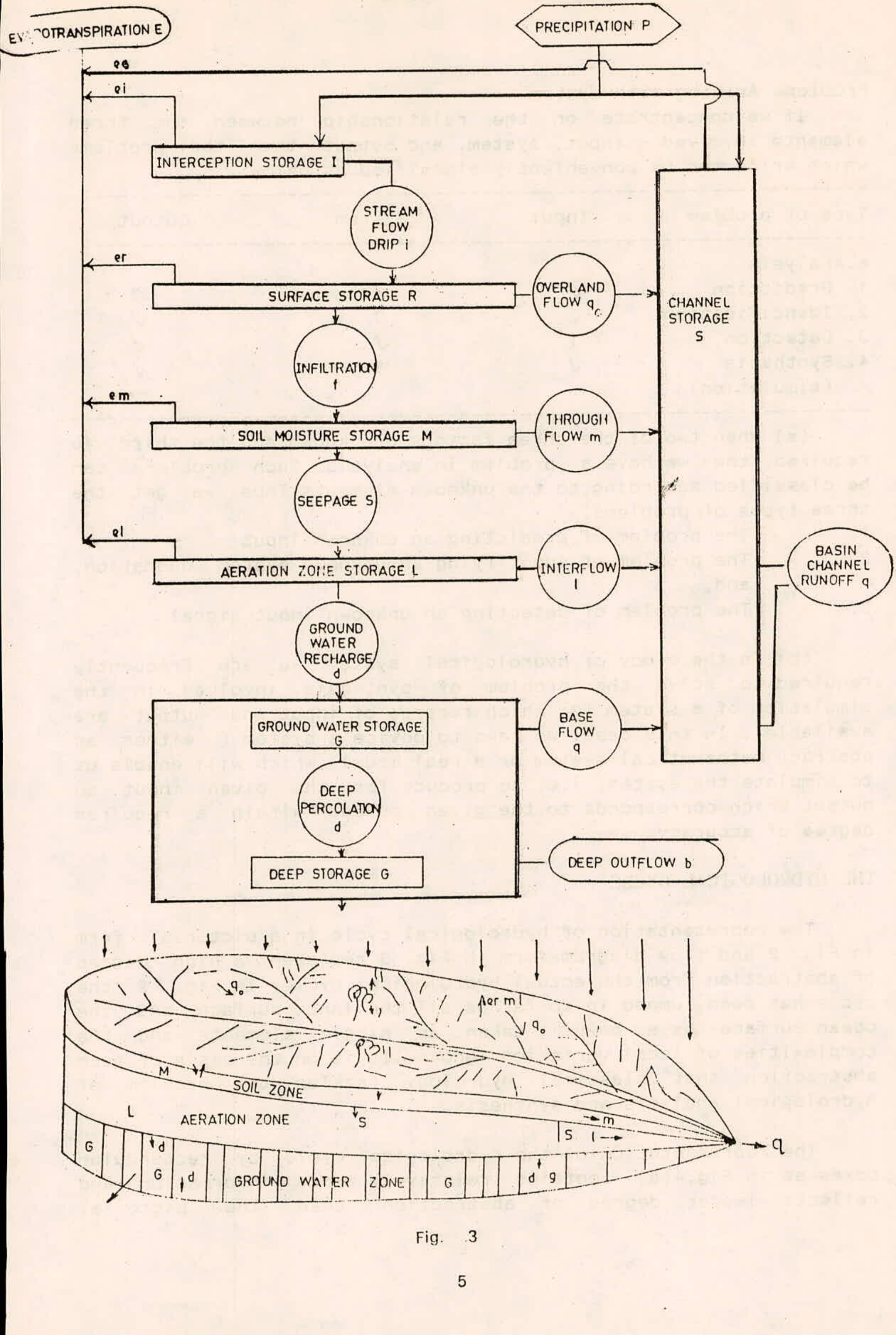


Fig. 4 (b)


EVAPOTRANSPIRATION E
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INTERCEPTION STORAGE I
STREAM FLOW DRIP i
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SURFACE STORAGE R
OVERLAND FLOW q_o
CHANNEL STORAGE S
INFILTRATION f
em
SOIL MOISTURE STORAGE M
THROUGH FLOW m
SEEPAGE S
el
AERATION ZONE STORAGE L
INTERFLOW l
BASIN CHANNEL RUNOFF q
GROUND WATER RECHARGE d
GROUND WATER STORAGE G
BASE FLOW q
DEEP PERCOLATION d
DEEP STORAGE G
DEEP OUTFLOW b
SOIL ZONE
AERATION ZONE
GROUND WATER ZONE
M
L
G
S
m
d
g
q

Fig. 3

Problems Arising with System

If we concentrate on the relationship between the three elements involved - input, system, and output then the problems which arise can be conveniently classified as below:

Type of problem	Input	System	Output
a. Analysis			
1. Prediction	✓	✓	?
2. Identification	✓	?	✓
3. Detection	?	✓	✓
4. Synthesis (simulation)	✓	?	✓

(a) When two of the three factors are known and the third is required, then we have a problem in analysis. Such problems can be classified according to the unknown elements. Thus we get the three types of problems.

1. The problem of predicting an unknown input
2. The problem of identifying an unknown system operation, and,
3. The problem of detecting an unknown input signal

(b) In the study of hydrological system we are frequently required to solve the problem of synthesis involved in the simulation of a system for which records of input and output are available . In this case, we have to device a system (either an abstract mathematical system or a real model) which will enable us to simulate the system, i.e. to produce for the given input an output which corresponds to the given output within a required degree of accuracy.

THE HYDROLOGICAL CYCLE

The representation of hydrological cycle in a pictorial form in Fig. 2 and flow diagram form in Fig. 3 represent a high degree of abstraction from the actual hydrological cycle, in Fig. 2 the cycle has been lumped in so far as all the land surface and the ocean surface have been taken as single elements and the complexities of local variation ignored. It is on the basis of such abstraction that classical hydrology tackles the problem of hydrological analysis and synthesis.

The representation of the hydrological cycle by rectangular boxes as in Fig.4(a) contains relatively more information and reflects lesser degree of abstraction than the pictorial representation. The hydrological cycle is a system which operates as a result of the surplus in coming radiation over back radiation. Thus , if we look at the hydrological cycle as a system involving energy changes, the cycle is an open system. If on the other hand, we consider the hydrological cycle in terms of the movement of moisture only, then the hydrological cycle is a closed system. It is this closed system involving transfer and transformation of water that is the main concern of the hydrologist.

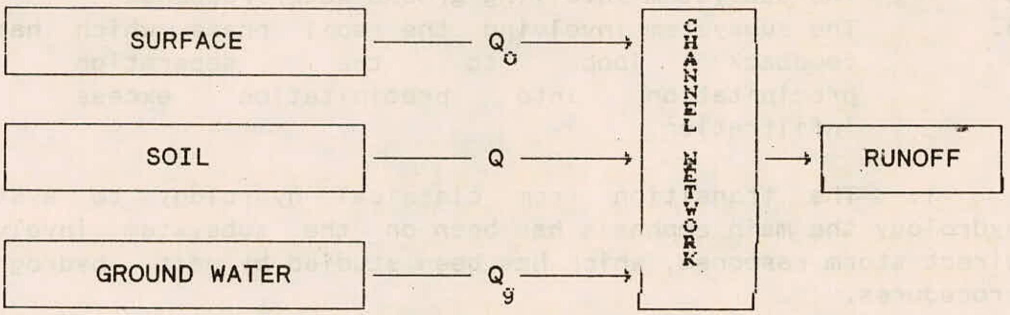

Fig 4 (a)

The activities of water extend through these three parts of the earth system form an average depth of about half mile in lithosphere to a height of about 10 miles (16 km) in the atmosphere. Another representation of hydrologic cycle in quantitative form is given by Chow (1964).

THE CATCHMENT AS A SYSTEM

In practice, the hydrologist confines his attention to individual basin 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.

In isolating the subsystem from the larger system represented by the hydrological cycle, it is nessary to cut across certain lines of transport of moisture for one part of the cycle to the other. The broken lines thus produce and shown in fig. 4(b) represent either inputs or outputs from the subsystem representing the catchment area. The catchment system, therefore, is not a closed system and can only be treated as such if a record is available of all the inputs and outputs.

Through classical hydrology described the hydrological cycle in terms of surface runoff, inter flow, and ground water flow. In practice quantitative hydrology usually ignores this three fold division and considers the hydrograph being made up of a direct 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 subsystem involving direct storm response
2. The subsystem involving ground water response
3. The subsystem involving the soil phase which has a feedback loop to the separation of precipitation into precipitation excess and infiltration.

1. The transition from classical hydrology to systems hydrology the main emphasis has been on the subsystem involving direct storm response, which has been studied by unit hydrograph procedures.

2. Even though drainage engineers use linearized equation to solve special cases in ground water hydraulics, the use of linear systems theory has only recently been applied to this part of the hydrologic cycle. The work of Prof. K.V.Deleur in recent years is worth mention.

3. The third subsystem involving the unsaturated phase has not been studied as a system to any great-extent and remains the most difficult part of the hydrologic cycle to deal with.

LUMPED, LINEAR TIME-INVARIANT DETERMINISTIC SYSTEM

a. Linearity and Non-linearity

The concept of linearity may be defined as below-

If $X_1(t) \rightarrow Y_1(t)$ and $X_2(t) \rightarrow Y_2(t)$

then $X_1(t) + X_2(t) \rightarrow Y_1(t) + Y_2(t)$

b. Time variance and time invariance

The concept of time invariance can be defined as :

if $Z(t) \rightarrow Y(t)$

then $X(t + \tau) \not\subset\rightarrow Y(t + \tau)$

(c) Lumped and distributed

For simulation by a lumped system model, the catchment or watershed is treated as a 'black box'. A gross representation of the black box is determined from the input and output data pertaining to the box, but no concern is given to the process carrying out in the box. In such models position or space is not important and all components of the system being simulated are regarded as being located at single point in space.

CATCHMENT BEHAVIOUR

The hydrologic behaviour of watershed is a very complicated phenomenon which is controlled by an unknown large number of climatic and physiographic factors that vary with both time and space. The catchment behaviour is distributed, nonlinear, time variant 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 nonlinear stochastic system. Hence deterministic linear system approach is adopted.

Assuming lumped system parameters to be invariant with time and the system completely at rest at t = 0, the stationary, time invariant, lumped parameter, linear hydrologic system is as below:

$$g\ (f) = \int_{o}^{t} h\ (t-\tau\ )\ f\ (\tau)\ d\tau \qquad (1.1)$$

The above equation is the familiar convolution equation which form the basis of unit hydrograph theory.

Conceptual Linearization

The linear simulation is based on the principle of superposition or proportionality. Mathematically the linear simulation is represented by the convolution integral

$$Q\ (t) = \int_{o}^{t\leq t} u(t-\tau\ )\ i\ (\tau)\ dr \qquad (1.2)$$

Where Q (t) is the direct runoff of the watershed, $u(t-\tau)$ is the Kernel function or I.U.H. (instantaneous unit hydrograph), $i(\tau)$ is the input function or the effective rainfall intensity, t is the time since the beginning of runoff, τ is the time for rainfall intensity since its beginning, t_o is the duration of effective rainfall and $t' = t_o$ when $t > t_o$.

A second approach to finding the kernel of a linear hydrologic system is through a synthesis of a system behaviour in terms of one or more lumped elements which reproduce in linear from, the primary hydraulic operations such as storage and translation of concern to the phenomena being modeled.

Linear Reservoir

The storage function of hydrologic systems is represented conceptually by a reservoir which outlet control. In general form, the storage S is related to the outflow stage Y according to

$$S = A_1 \; Y^m \qquad (1.3)$$

and outflow Q to the stage Y by

$$Q = A_2 \; Y^p \qquad (1.4)$$

combining these two, and putting (m/p) =1, we get the basic dynamic relation for the linear reservoir.

$$S = KQ^{m/p} - KQ \qquad (1.5)$$

Assuming $K = (A_1 / A_2)$ = Constant and using the continuity equation,

$$dS/\,dt = I - Q \qquad (1.6)$$

where I is the reservoir inflow, the differential equation,

$$Q + K\,(dQ/dt) = I \qquad (1.7)$$

For zero initial conditions, this gives the unit impulse response u (t) as

$$u(t) = (1/K)\; e^{-t/K} \qquad (1.8)$$

This expression represents IUH for a single linear reservoir. The constant of proportionality or the sto r age constant K of the linear reservoir is the time lag of the outflow.For nonlinear simulation the convolution integral does not apply for such models

$$S = KQ^n$$

i.e. storage is an exponential function of the outflow.

Mathematically speaking, a drainage basin system is linear, if the differential equation of the input and output relation is linear and it is non-linear if the differential equation is nonlinear. For practical purposes, the IUH can be formed a basis for defining linearity of rainfall-runoff relationship. The rainfall-runoff relationship of a basin is said to be linear if its IUH has a unique unchangeable shape. However the variability of IUH for drainage basin with storm and season indicates non-linearity with respect to storm and seasonal variable.

The linear model employed as the Kernel function may be treated non-linearly if the parameters of the model are considered as functions of time or the magnitude of the input function. For example, the storage coefficient of the linear reservoir may be a function of time and /or of the magnitude of effective rainfall. In such cases, the reservoir is theoretically linear only at the specific time and /or magnitude of effective rainfall. This is thus a non-linearised model

One example of non linear model is that proposed by Ramanand Prasad. He took storage discharge relationship of nonlinear form as below-

$$S = K_1 Q^N + K_2 (dQ/dt) \qquad (1.10)$$

and $dS/dt = I-Q$

combining these two relationship, we get

$$K_2 (d^2Q/dt^2) + K_1 NQ^{N-1} (dQ/dt) + Q = 1$$

which is a nonlinear second order differential equation.

LINEAR AND NON-LINEAR SYSTEMS

A system is said to be linear if its behaviour can be described by a linear differential equation. If x (t) represents (as a function of time t) an input to a system and y (t) the corresponding output from the system then the system is linear if y (t) is related to x (t) by an equation of the form, such as

$$A_n (d^n y/dt^n) + A_{n-1} (d^{n-1} y/dt^{n-1}) + \ldots$$

$$.A_1 (dy/dt) + A_n y = x \qquad (1.12)$$

If y or any differential of y appeared other than to the first power, the system, described by such an equation would be non linear.

The coefficients A_i (i= 0, 1, ...n) may be constants or may themselves be functions of time t. A time invariant linear system is one described by an equation of the form as given above in which all the coefficient A_i are constant. If any or all coefficients are functions of time the system is a time-variant linear system. Their outstanding property is that of superposition. Such superposition is not permissible for non-linear systems. Even a single non-linear component in a system of many components will make that system non linear. If we have

$$S = KQ^{N} \text{ (nonlinear reservoir)} \quad (1.13)$$

and

$$dS/dt = I - Q \quad (1.14)$$

then equation describing the nonlinear system is

$$KNQ^{N-1} (dQ/dt) + Q = I$$

where $N \neq 1$. (1.15)

LUMPED, DISTRIBUTED SYSTEMS

A lumped system model intended for the simulation of an entire watershed should be used to represent individually many areas. This will take into consideration the distributed nature of catchment. However, in that case each sub area will be represented by a lumped system model. By routing the flow space wise through all the sub areas, the total simulation of entire watershed becomes a distributed system of lumped system models. Besides such models there are basically distributed system models which are described by the hydrodynamic equations of energy and momentum for overland and open channel flows.

LINEAR SYSTEM ANALYSIS

The analysis methods of deriving an IUH or an unit hydrograph do not require models. They operate directly on the effective rainfall and direct runoff data to give the IUH or UH. Such methods can be applied to linear time invariant systems, Modern

methods of linear system identification or analysis , which have been proposed in hydrology are basically grouped under the following two categories:

1. Transform methods
2. Correlation methods

Transform Methods

These methods include the following techniques proposed by various researchers:

a. Laplace transforms (Paynter, 1952)
b. Method of moments (Nash, 1959)
c. Harmonic coefficients (O'Donnel, 1960)
d. Fourier transforms (Lavi, 1964)

e. Laguerre Coefficients (Diskin, 1965)

The essential features of transform methods are:

i. The transformation of the known input and known output in same manner,

ii. The use of a linkage equation which is used to determine the transform of the impulse function from the transforms of input and output

iii. The inversion of the transform of the impulse function to obtain the impulse function itself.

Correlation Methods

The second category of identification methods is that of correlation methods which are based on a least squares approach to the problem. Snyder (1955, 1966) and Body (1959) presented methods based upon the least squares criterion to determine optimum values of the discrete ordinates of the unit hydrograph. Both the researchers expressed the necessary computations in matrix form and developed digital computer programme for the solutions. The matrix formation of the convolution equation is as follows:

$$(Q)_{P,1} = [I]_{P,N} (U)_{N,1} \qquad (1.16)$$

The (I) matrix is not a square and it can not be inverted. But if the equations are solved by a least squares method, the matrix equation becomes

$$(I)^T (Q) = (I)^T (I) (U) \qquad (1.17)$$

where $(I)^T$ is the transpose of the matrix (I), since the product of the transpose and the original matrix gives a square matrix , this product can be inverted and the set of equations solved for the values of the impulse response i.e. unit hydrograph ordinates

SYSTEM SYNTHESIS

Synthesis techniques employ conceptual model of catchment behaviour. The structure of the conceptual model, its various components and their interlinking and functioning of the model are all based more or less subjectively on quantitative and semi qualitative knowledge of the phenomena involved in the runoff process of a catchment. The principle of continuity is the main basis of operation of such models. At all times a complete balance is maintained between the input, the output and inner storage changes. Using this basis a model is fitted to a specific catchment in some systematic way using recorded input and output data for that catchment. The input data generally consist of rainfall and potential evaporation and output data is that of runoff at the catchment outlet. The fitting of the model is done by using optimisation technique. This involves making of adjustments to the parameters governing the performance of the model until the output computed by the model when supplied with the recorded input agrees with the recorded output within some specific tolerance. Such quantitative models are inevitably complex. But at the same time they must be feasible to operate. The use of high speed digital computers and system approach to hydrology has helped inconsiderable advancement in synthesis techniques. The cascade model proposed by Nash (1959) and Dooge model are well known examples of linear system synthesis. Stanford watershed model developed by the Crawford and Linsley at Stanford University is the best example of nonlinear synthesis. Some other non linear models, are those proposed by Laurenson, Prasad, Kulandaiswamy etc.

GENERAL REMARKS

The problem of floods and their computation is one of the main and most complex problems facing the hydrologists. The optimal development of water resources depends on flood flow control, the design and construction of culverts, bridges, spillway etc. and for taking proper measures for flood control mitigation. All these problems require accurate and reliable data of floods, and also appropriate procedures for data analysis in order to arrive at desired design variable. However, the requirement of safety of structure under flood conditions should not lead to over design and consequent increase in costs. The main objective of study of floods from hydrologic point of view, is to study the runoff process and to estimate the flood flow, and also to develop methods for estimation of floods for design purposes when available data is limited inadequate or absent.

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