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LECTURE NOTE

RAINFALL RUNOFF MODELING USING REMOTE SENSING AND GIS

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REMOTE SENSING AND GIS APPLICATION IN RAINFALL-RUNOFF MODELLING

1.0 GENERAL

The problem of transformation of rainfall into runoff has been subject of scientific investigations throughout the evolution of the subject of hydrology. Hydrologists are mainly concerned with evaluation of catchment response for planning, development and operation of various water resources schemes. A number of investigators have tried to relate runoff with the different characteristics which affect it. Conventional models for rainfall-runoff analysis use maps and ground survey as tools to acquire the basic parameters of the watershed/catchment. However, for large and/or remote watersheds/catchments, the above analysis is both costly and time consuming. Integrating data acquisition by remote sensing techniques and data manipulation by GIS to establish the watershed geographic database, can provide both fast and accurate input on watershed hydrologic parameters. Collection of landuse, soil and other spatial data is expensive, time consuming and a difficult process. Remote Sensing and Geographical Information System (GIS) play a rapidly increasing role in collection and analysis of such spatial data. The role of remote sensing in runoff calculation is generally to provide a source of input data or as an aid for estimating equation coefficients and model parameters. Experience has shown that satellite data can be interpreted to derive thematic information on land use, soil, vegetation, drainage, etc which, combined with conventionally measured climatic parameters (precipitation, temperature etc) and topographic parameters height, contour, slope, provide the necessary inputs to the rainfall-runoff models. The information extracted from remote sensing and other sources can be stored as a georeferenced data base in geographical information system (GIS). The system provides efficient tools for data input into data base, retrieval of selected data items for further processing.

Due to the various reasons, adequate runoff data are not generally available for many of the small and medium size catchments. Indirect inferences through regionalisation are sought for such types of ungauged catchments. A large number of regional relationships have been developed by many investigators relating either the parameters of unit hydrograph (UH) or instantaneous unit hydrograph (IUH) models with physiographic and climatologic characteristics. Regionalisation of the parameters is, however, a very tedious task to accomplish since the hydrological behaviour of many nearby catchments have to be ascertained before being confident about the values of the parameters. These conventional approaches which are in vogue for estimation of design floods require rainfall-runoff records and the model parameters need to be updated from time to time. Many times, this task of regionalisation becomes very tedious, and in certain cases, even impossible. Geomorphological techniques have recently been advanced for hydrograph synthesis, adding a new dimension to hydrologic simulations. The Geomorphological Instantaneous Unit Hydrograph (GIUH) approach has many advantages over the regionalization techniques as it avoids the requirement of flow data and computations for the neighboring gauged catchments in the region as well as updating of the parameters. Another advantage of this approach is the potential of deriving UH using only the information obtainable from topographic maps or remote sensing, possibly linked with GIS and digital elevation model (DEM). Thus, linking of the geomorphologic parameters with the hydrologic characteristics of the basin can provide a simple way to understand the hydrologic behavior of different catchments, particularly the ungauged ones. This lecture presents applications of remote sensing and GIS in rainfall-runoff modeling.

2.0 GENERAL DATA REQUIREMENT

For rainfall-runoff modeling, it is advisable to assess the quantity and quality of available data. In general, the available data dictate the type of model to be used more than the problem itself. A general inventory of data frequently available or needed for rainfall-runoff modeling is given below:

2.1 Watershed Characteristics

Topographic information is the most commonly available information from which many useful geomorphic parameters can be extracted, that is, watershed area, subbasin areas, elevations, slopes, channel lengths, channel profiles, centroid, etc. Many other geomorphic parameters can then be computed. Another useful map is the landuse map, which provides data on areas of land-use practice, soil types, vegetation, forest areas, "lakes, urban development, etc.

2.2 Rainfall Characteristics

Determination of the average amount of rain that falls on a basin/subbasins during a given storm is a fundamental requirement for many rainfall-runoff models. A number of techniques for estimating mean areal rainfall have been developed. Rainfall hyetographs are needed for each subbasin. Some of the subbasins may not have a recording raingauge and may involve extrapolation of rainfall data from neighbouring subbasins. If a subbasin has more than one raingauge, then the mean areal rainfall hyetograph is to be determined. Sometimes, only standard/storage-type raingauges are available in some watersheds. The rainfall amounts then need to be properly distributed in time so that rainfall hyetographs can be prescribed.

2.3 Infiltration and other Loss Characteristics

In a majority of cases, no data are available on soil infiltration, interception, depression storage, and antecedent soil moisture. If data do exist in part or full, maximum advantage must be taken to estimate infiltration and other loss functions. If no information is available on antecedent soil moisture, then an antecedent precipitation index can be used to get an estimate of the antecedent soil moisture. Soil type and landuse vegetation complex can be used to estimate infiltration parameters.

2.4 Streamflow Characteristics

Streamflow may be available in terms of the stage at the watershed outlet and at some other gauges within the watershed. Appropriate rating curves can be used to convert stages into discharges. Part of the streamflow data may be used for model calibration and the remaining data for model verification.

3.0 GIS DATA AND DATA HANDLING APPROACHES

3.1 Topographic and Topologic Data

In hydrologic analysis a GIS can play an important role due to its capabilities to describe the topography of a region. In the modern computer age the techniques used in the description of topography are called digital elevation models (DEM's). Some spatial information is not directly described by elevation, and can be described as topologic data. Topologic data define how the various pieces of the region are connected. Topology can be described as the spatial distribution of terrain attributes. DEM and GIS representations of topologic data are part of the general grouping of digital terrain models (DTM's). An example of hydrologic topology is the collection of lines describing a stream network. Another is the collection of points delineating subregions of a watershed. Both forms of information are related to topography, but may be defined in a topological sense based on the topographic portion of the GIS data base.

While topographic data fit within the general classification of topologic data, there are significant hydrological attributes not related to land surface elevation. The more obvious of these are catchment areas, flow lengths, land slope, surface roughness, soil types, and land cover. These attributes help to describe the ability of a region to store and transmit water. Some topologic attributes are tied to the concept of a watershed unit. The most basic of these is the description of the watershed boundary. Given a drainage point, the topography alone can be used to define those areas that should drain to the point. Average slope and drainage path networks are related, topographically derived, topologic attributes. These attributes are useful in determining watershed attributes such as time of concentration, flow potential energies, and flow attenuation. The sorting and manipulation capabilities of a GIS are well suited to extracting such attributes.

3.2 Raster Data

Raster data is a grid of cells covering an area of interest. Each pixel, the smallest unit of information in the grid, displays a unique attribute. An example of raster data is a scanned image or photograph. A line drawn in a raster format must be defined by a group of pixels along the length of the line. As a result the size of a raster file is larger than that required by a vector file. The first applications of GIS in hydrologic modeling utilized grid cell or raster storage of information. The grid is made up of regularly spaced lines, and the enclosed area of each rectangle is described in terms of its center coordinates. It is important to note that there may be different grid scales for different attributes of the terrain, although following the scale of the available data is the obvious first choice. For attributes that are largely homogeneous, the use of the rigid resolution necessary for a DEM would require the storage of large amounts of redundant data. The reduction in data storage from the use of several grid scales comes at the cost of the complexity of translation between the scales to relate the data.

An inherent problem in hydrologic modeling with grid DEM data is the production of nonphysical depressions due to noise in the elevation data affecting interpolation schemes used to describe variation in elevation between raster points. The result is an unwanted termination of drainage paths in pits. The problem is particularly acute for relatively flat areas. The situation is complicated however by the existence of naturally pitted topography, sometimes called pothole regions. The methods are sufficiently flexible to allow accurate flow path delineation even with filling of real depressions.

3.3 Triangular Irregular Networks

An alternate approach to producing DEM's relies upon determination of significant peaks and valley points into a collection of irregularly spaced points connected by lines. The lines produce a patchwork of triangles known as a triangular irregular network (TIN). Most typically the triangles are treated as planar facets, but smoother interpolation is possible. The problems of depressions and interrupted drainage paths are partly avoided with a TIN as the path of water movement follows the slope of a plane or flows down the edge between two triangles. Due to the fact that triangle networks from points are non-unique, several algorithms have been developed to produce them from sets of points. The most widely used is known as

Delauney triangulation based on a principle of maximizing the minimum angle of all triangles produced by connector lines to nearest neighbor points. One of the main TIN systems available commercially is *ARC / INFO.*

3.4 Vector- or Contour-Based Line Networks

Contour line mapping is the third major form of representing topography. With the advent of computer based GIS, the contours can be represented digitally in vector form (as a set of point-to-point paths of a common elevation). An entire map stored in the digital form in a GIS is called a digital line graph (DLG). Most commercially available GIS's have the ability to transform between DLG'S, grid DEM'S, and TIN DEM'S. The main advantage of the approach is that an important hydrologic attribute (steepest descent path) is inherent in the resulting data structure.

4.0 USE OF REMOTELY SENSED DATA

The satellite capability to provide real time information makes it possible to have meaningful repetitive surveys, which can show the changes have taken place in a particular period in a catchment. Remote sensing technology for providing hydrological and morphological information such as physical characteristics, watershed boundaries and land use, catchment variables, soil moisture and snow cover have been recognised from a long time. In recent time the availability of remote sensing data, particularly satellite imagery in form of electromagnetic data from various spectral bands have a major effect on hydrological modeling. After manipulating, such information can be used as input for hydrological models. In recent years, satellite remote sensing and Geographical Information System (GIS) have emerged as powerful tools for collecting the requisite information on land use and land cover of large areas (Shih, 1988). Advantage of the information acquired by satellite remote sensing is of synoptic coverage, repetivity and spectral characteristics and especially in the easiness to compare the data before and after monsoons. Further, the information on land use/ land cover and hydrologic soil type can be integrated in a GIS environment for a quick and accurate estimation of runoff curve numbers (Stuebe et al, 1990).

5.0 CLASSIFICATION OF HYDROLOGICAL MODELS

A model represents the physical/chemical/biological characteristics of the catchment and simulates the natural hydrological processes. It is not an end in itself but is a tool in a larger process which is usually a decision problem. It aids in making decisions, particularly where data or information are scarce or there are large numbers of options to choose from. It is not a replacement for field observations. Its value lies in its ability, when correctly chosen and adjusted, to extract the maximum amount of information from the available data.

Hydrological models can be classified in different ways. Fleming (1975) and Woolhiser (1973) classified the hydrological maodel. Not all models fit easily into this classification but it is general with respect to fundamental principles. A related but less general classification is presented by Clarke (1973b) who suggests that many of the models presented in the literature can be divided into the deterministic and the stochastic. These two groups can each be further divided into the conceptual and the empirical and additional subdivisions occur between spatially lumped/spatially distributed and linear/nonlinear models.

Two main groups of mathematical methods emerge: those which involve optimization and those which do not.

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

Nonoptimizing 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 casual and partly random. Hence, some deterministic models contain random functions to relate processes, while some statistical models contain casual 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. For example, a deterministic model using a conceptual representation of the hydrological cycle may be used in producing a record of streamflow at a gauging station. This record may then be analysed by statistical methods to produce a flood frequency curve for that site. Conversely, a statistical method involving the generation of rainfall data by a stochastic model could provide input to a conceptual model producing information which is thenh again analyzed statistically.

5.1 Deterministic Models

Deterministic models can be classified according to whether the model gives a spatially lumped or distributed description of the catchment area, and whether the description of the hydrological processes is empirical, conceptual or fully physically-based. In practice, most conceptual models are also lumped and most fully physically-based models are also distributed, so three main groups of deterministic models can be identified as shown in Fig.1.

5.2 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 nonlinearity of hydrological systems, such extrapolation is of dubious worth and is not recommended (e.g. Anderson and Burt, 1985). 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 model and the models applying the unit hydrograph principles, Sherman (1932), Lyshede (1955), Nash (1959).

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.

5.3 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 modelled.

The SNSF model has been developed as a part of the Norwegian "Acid Precipitation : Effects on Forests and Fish" - project (Lundquist, 1978). In contrast to NAM and HBV, the SNSF model breaks the catchment down into four parallel subcatchments consisting of lakes, forests, bogs, and impervious areas respectively. The purpose of this breakdown is primarily to enable the runoff from ungauged catchments to be estimated using standard parameters together with data on the actual areal distribution between the four subcatchments and meteorological time series.

A detailed treatment of lumped models, including a description of the British Institute of Hydrology Lumped Model, is given by Blackie and Eeles (1985).

5.4 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. The advantages and disadvantages of physically-based models are considered in more detail below.

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.

For example soil conductivity obtained from a single core may not be representative of the effective conductivity at a larger grid scale, where allowance is required for macropore effects and spatial variability within the grid square.

Conceptual understanding of hydrological processes is not always sufficient or cannot always be expressed mathematically. For example, it may be necessary to assume soil conductivity to be constant spatially and temporally because there is insufficient information to allow for spatial variations or temporal changes associated with shrinkage or crusting. Macropore effects have similarly to be approximated for lack of a suitable theory.

6.0 RAINFALL-RUNOFF MODELLING USING REMOTE SENSING AND GIS

6.1 Hydrologic Engineering Center HEC-1 model

The HEC-1 model is designed to simulate the surface runoff response of a river basin to precipitation by representing the basin as an interconnected system of hydrologic and hydraulic components. Each component model an .aspect of the precipitation-runoff process within a portion of the basin commonly referred to as a sub-basin. A component may represent a surface runoff entity, a stream channel, or a reservoir. Representation of a component requires a set of parameters which specify the particular characteristics of the component and mathematical relations which describe the physical processes. The result of the modeling process is the computation of streamflow hydrographs at desired locations in the river basin. Various basin and land use characteristics derived from remote sensing and GIS can be used for developing a rainfall-runoff model using HEC-1 software (Figure 1).

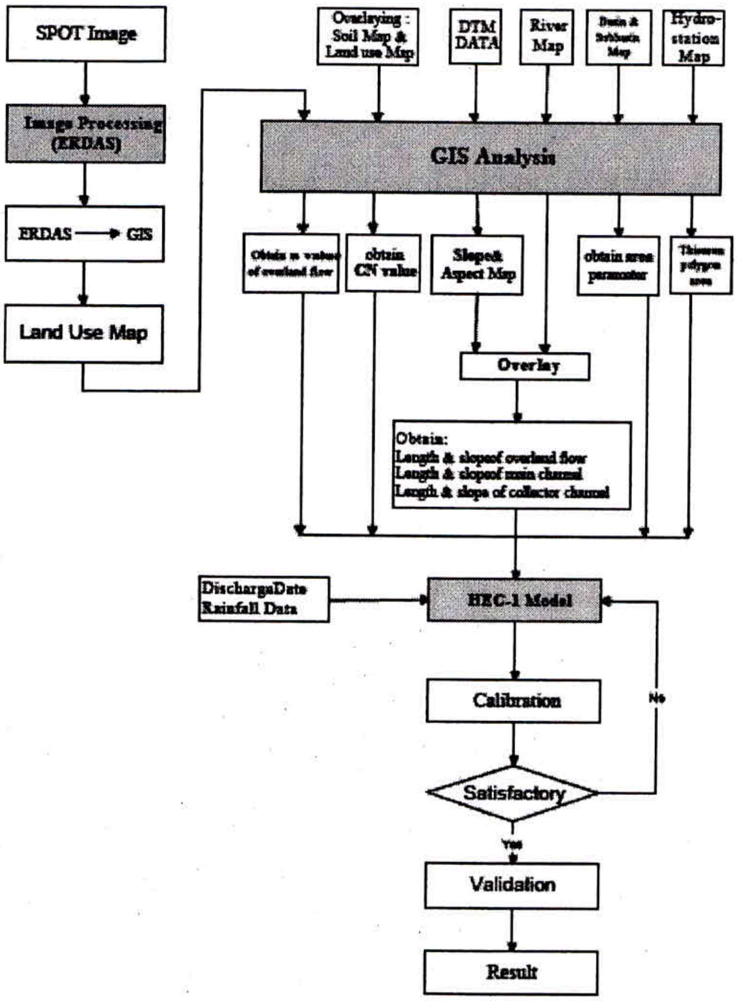

Fig. 1: Flow Chart showing RS & GIS data use in HEC-1 Model

6.2 Hydrologic Engineering Center - Hydrologic Modeling System (HEC-HMS)

For precipitation-runoff-routing simulation, HEC-HMS provides the following components:

Precipitation-specification options which can describe an observed (historical) precipitation event, a frequency-based hypothetical precipitation event, or an event that represents the upper limit of precipitation possible at a given location.

Loss models which can estimate the volume of runoff, given the precipitation and properties of the watershed.

Direct runoff models that can account for overland flow, storage and energy losses as water runs off a watershed and into the stream channels.

Hydrologic routing models that account for storage and energy flux as water moves through stream channels.

Models of naturally occurring confluences and bifurcations.

Models of water-control measures, including diversions and storage facilities.

These models are similar to those included in HEC-1. In addition to these, HECHMS includes:

A distributed runoff model for use with distributed precipitation data, such as the data available from weather radar.

A continuous soil-moisture-accounting model used to simulate the long-term response of a watershed to wetting and drying.

HEC-HMS also includes:

An automatic calibration package that can estimate certain model parameters and initial conditions, given observations of hydrometeorological conditions.

Links to a database management system that permits data storage, retrieval and connectivity with other analysis tools available from HEC and other sources.

6.3 GIUH Approach

Rodriguez-Iturbe and Valdes (1979) first introduced the concept of geomorphologic instantaneous unit hydrograph which led to the renewal of research in hydrogeomorphology. The expression derived by Rodriguez-Iturbe and Valdes (1979) yields full analytical, but complicated, expressions for the instantaneous unit hydrograph. Rodriguez-Iturbe and Valdes (1979) suggested that it is adequate to assume a triangular instantaneous unit hydrograph and only specify the expressions for the time to peak and peak value of the IUH. These expressions are obtained by regression of the peak as well as time to peak of IUH derived from the analytic solutions for a wide range of parameters with that of the geomorphologic characteristics and flow velocities. The expressions are given as:

$$q_p = 1.31\, R_L^{0.43}\, V / L_\Omega \qquad (1)$$

$$t_p = 0.44\,(L_\Omega / V)(R_B / R_A)^{0.55}\,(R_L)^{-0.38} \qquad (2)$$

where;

L_Ω = the length in kilometers of the stream of order Ω

V = the expected peak velocity, in m/sec.

q_p = the peak flow, in units of inverse hours

t_p = the time to peak, in hours

R_B, R_L, R_A = the bifurcation, length, and area ratios given by the Horton's laws of stream numbers, lengths, and areas, respectively.

Empirical results indicate that for natural basins the values for R_B normally ranges from 3 to 5, for R_L from 1.5 to 3.5 and for R_A from 3 to 6 (Smart, 1972).

On multiplying eq. (1) and (2) one get a non-dimensional term $q_p * t_p$ as:

$$q_p * t_p = 0.5764 \, (R_B / R_A)^{0.55} (R_L)^{0.05} \qquad (3)$$

This term is independent of the velocity and, thereby, on the storm characteristics and hence is a function of only the catchment characteristics.

6.3.1 Development of Relationship between Intensity of Rainfall-Excess and Velocity

For the dynamic parameter velocity (V), Rodriguez and Valdes (1979) in their studies assumed that the flow velocity at any given moment during the storm can be taken as constant throughout the basin. The characteristic velocity for the basin as a whole changes throughout the storm duration. For the derivation of GIUH, this can be taken as the velocity at the peak discharge for a given rainfall-runoff event in a basin. However, for ungauged catchments, the peak discharge is not known and, therefore this criterion for estimation of velocity cannot be applied. In such a situation, the velocity may be estimated using the velocity-rainfall excess relationship. The two approaches for developing this relationship, as described in the Technical Report of National Institute of Hydrology (NIH, 1994-95), are presented below.

Approach-I

This approach may be utilized when the geometric properties of the gauging section are known and the Manning's roughness coefficient can be assumed with an adequate degree of accuracy. The steps involved in this approach are as below.

Compute cross-sectional area (A), Wetted Perimeter (P) and hydraulic radius (R) from cross-sectional details for different depths.
Assume the frictional slope to be equal to the bed slope of the channel.

Choose an appropriate value of Manning's roughness coefficient (n) from the values given in literature (for example, Chow, 1964) for various surface conditions of the channel.
Compute the discharge (Q) using the Manning's formula corresponding to each depth.

Plot depth v/s discharge and depth v/s area curves.

Compute the equilibrium discharge (Q_e) corresponding to an excess rainfall intensity (i) (mm/hr) using the relation :

$$Q_e = 0.2778 \; i \; A_c \qquad (4)$$

where A_c is catchment area in sq. km.

Compute the depth corresponding to the equilibrium discharge (Q_e) using the depth v/s discharge curve.

Compute the cross-sectional area corresponding to the depth computed at step (vii) using the depth v/s area curve.
Compute the velocity V by dividing the discharge (Q_e) by the cross-sectional area computed at step (viii).
Repeat steps (vi) to (ix) to find velocity with respect to different intensities (e.g., 1, 2, 3 mm/hr. etc.) of rainfall-excess.
Develop the relationship between velocity and rainfall-excess intensity obtained at step (x) in the form: $V = a\ i^b$, using the method of least squares. Here, a and b are the regression coefficients.

Approach-II

This approach is based on the assumption that the value of the Manning's roughness coefficient is not available but the velocities corresponding to discharges passing through the gauging section at different depths of flow are known from observations. The steps involved in this approach are given below.

For different depths of flow, the discharge and the corresponding velocities are known by observation. Let these velocities and discharges be the equilibrium velocities V_e and the corresponding equilibrium discharges Q_e. For these Q_e values, find the corresponding intensities i of rainfall-excess from the expression:

$$i = Q_e / (0.2778\ A_c) \qquad (5)$$

From the pairs of such V_e and i develop the relationship between the equilibrium velocity and the rainfall-excess intensity in the form: $V_e = a\ i^b$, using the method of least squares. Here, a and b are regression coefficients.

It is noted here that this approach requires the information of discharges and corresponding velocities at the gauging site does not necessarily mean that it can be applied for the gauged catchments only. For the ungauged catchments too, this information may be easily obtained by gauging the stream intermittently for all ranges of depth of flow. This type of information may be gathered without incurring much cost and effort.

6.3.2 Derivation of Unit Hydrograph

6.3.2.1 GIUH Based Clark Model Approach

The Clark model concept (Clark, 1945) suggests that the IUH can be derived by routing the unit inflow in the form of time-area diagram, which is prepared from the isochronal map, through a single reservoir. For the derivation of IUH the Clark model uses two parameters, time of concentration (T_c) in hours, which is the base length of the time-area diagram, and storage coefficient (R), in hours, of a single linear reservoir in addition to the time-area diagram. The governing equation of IUH using this model is given as:

$$u_i = C\ I_i + (1 - C)\ u_{i-1} \qquad (6)$$

where;
u_i = ith ordinate of the IUH
C & (1-C) = the routing coefficients.
and $C = \Delta t / (R + 0.5\,\Delta t)$
Δt = computational interval in hours
I_i = ith ordinate of the time-area diagram

A unit hydrograph of the desired duration (D) may be derived using the following equation:

$$U_i = \frac{1}{n}(0.5\,u_{i-n} + u_{i-n} + u_{i-n+1} \ldots\ldots\ldots\ldots\ldots + u_{i-1} + 0.5\,u_i) \qquad (7)$$

where;
U_i = ith ordinate of unit hydrograph of duration D-hour and at computational interval Δt hours,
n = no. of computational intervals in duration D hrs = $D/\Delta t$, and
u_i = ith ordinate of the IUH.

The step by step explanation of the procedure to derive unit hydrograph for a specific duration using the GIUH based Clark model approach is given here under:

Rainfall-excess hyetograph is computed either by uniform loss rate procedure or by SCS curve number method or by any other suitable method. For a given storm, the peak velocity V using the highest rainfall-excess is determined from the relationship between velocity and intensity of rainfall-excess. Compute the time of concentration (T_c) using the equation :

$$T_c = 0.2778\,L / V \qquad (8)$$

where;
L = length of the main channel, and

V = the peak velocity in m/sec.

Considering this T_c as the largest time of travel, find the ordinates of cumulative isochronal areas corresponding to integral multiples of computational time interval with the help of the non-dimensional relation between cumulative isochronal area and the percent time of travel. This describes the ordinates of the time-area diagram at each computational time interval.

Compute the peak discharge (Q_{pg}) of IUH given by equation (1).

Assume two trial values of the storage coefficient of GIUH based Clark model as R_1 and R_2. Compute the ordinates of two instantaneous unit hydrographs by Clark model using time of concentration T_c as obtained in step (iii) and two storage coefficients R_1 and R_2 respectively, with the help of equation (1). Compute the IUH ordinates at a very small time interval say 0.1 or 0.05 hrs so that a better estimate of peak value may be obtained.

Find out the peak discharges Q_{pc1} and Q_{pc2} of the instantaneous unit hydrographs obtained for Clark model for the storage coefficients R_1 and R_2, respectively, at step (v).

Find out the value of objective function, using the relation:

$$FCN1 = (Q_{pg} - Q_{pc1})^2 \tag{9}$$

$$FCN2 = (Q_{pg} - Q_{pc2})^2 \tag{10}$$

Compute the first numerical derivative FPN of the objective function FCN with respect to parameter R as:

$$FPN = \frac{FCN1 - FCN2}{R_1 - R_2} \tag{11}$$

(ix) Compute the next trial value of R using the following governing equations of Newton-Raphson's method:

$$\Delta R = \frac{FCN1}{FPN} \tag{12}$$

and

$$R_{NEW} = R_1 + \Delta R \tag{13}$$

For the next trial, consider $R_1 = R_2$ and $R_2 = R_{NEW}$ and repeat steps (v) and (ix) till one of the following criteria of convergence is achieved.

(a) FCN2 = 0.000001
(b) No. of trials exceeds 200
(c) $ABS(\Delta R)/R_1 = 0.001$

The final value of storage coefficient (R_2) obtained as above is the required value of the parameter R corresponding to the value of time of concentration (T_c) for the Clark model.

Compute the instantaneous unit hydrograph (IUH) using the GIUH-based Clark Model with the help of the final value of the storage coefficient (R), time of concentration (T_c) as obtained in step (xi) and time-area diagram.

Compute the D-hour unit hydrograph (UH) using the relationship between IUH and UH of D-hour from equation (6).

6.3.3 GIUH Based Nash Model Approach

Nash (1957) proposed a conceptual model in which catchment impulse could be represented as the outflow obtained from routing the unit volume of the instantaneous rainfall-excess input through a series of *n* number of successive linear reservoirs having equal delay time. The equation for the instantaneous unit hydrograph for the Nash model is given as:

$$U(0,t)=\frac{1}{k}\cdot\frac{1}{\Gamma n}e^{-\frac{t}{k}}\cdot\left(\frac{t}{k}\right)^{n-1} \qquad (14)$$

where, U(0,t) is the ordinate of the instantaneous unit hydrograph, k is the storage coefficient and n is the number of reservoirs.

The complete shape of the GIUH can be obtained by linking q_p and t_p of the GIUH with the scale (k) and shape (n) parameter of the Nash model. Now, by equating the first derivative (with respect to t) of the equation (14) to zero, t becomes the time to peak discharge, t_p.

Taking logarithm to the both side of the equation (14):

$$\ln[U(0,t)]=\ln\left[\frac{1}{k}\cdot\frac{1}{\Gamma n}\right]+\ln\left[e^{-\frac{t}{k}}\right]+\ln\left[\left(\frac{t}{k}\right)^{n-1}\right]$$

$$=\ln\left[\frac{1}{k}\cdot\frac{1}{\Gamma n}\right]-\frac{t}{k}+(n-1)\ln\left(\frac{t}{k}\right)$$

Which when differentiated with respect to t on both sides:

$$\frac{\partial}{\partial t}\ln[U(0,t)]=0-\frac{1}{k}+(n-1)\frac{\partial}{\partial t}\ln\left(\frac{t}{k}\right)$$

Since, both k and n are constant,

$$\frac{\partial}{\partial t}\ln[U(0,t)]=-\frac{1}{k}+(n-1)\left[\frac{\partial}{\partial t}\ln t-\frac{\partial}{\partial t}\ln k\right]$$

or

$$\frac{\partial}{\partial t}\ln[U(0,t)]=-\frac{1}{k}+(n-1)\left[\frac{1}{t}-0\right]$$

or

$$\frac{1}{U(0,t)}\frac{\partial}{\partial t}\ln[U(0,t)]=-\frac{1}{k}+\frac{(n-1)}{t}$$

or

$$\frac{\partial}{\partial t}\ln[U(0,t)]=U(0,t)\left[-\frac{1}{k}+\frac{(n-1)}{t}\right]$$

Since U(0,t) can not be equal to zero, the factor

$$\left[-\frac{1}{k}+\frac{(n-1)}{t}\right]=0$$

or

$$\left[\frac{t + k\cdot(n-1)}{k\cdot t}\right] = 0$$

or

$$-t + k\cdot(n-1) = 0$$

Therefore, $t = t_p = k(n-1)$ (15)

Now, substituting t by t_p in equation (14)

$$U(0,t)_{peak} = q_p = \frac{1}{k}\cdot\frac{1}{\Gamma n}e^{-\frac{t_p}{k}}\cdot\left(\frac{t_p}{k}\right)^{n-1}$$

Substituting the values of t_p from equation (15) yields

$$q_p = \frac{1}{k\Gamma n}e^{\left(\frac{k(n-1)}{k}\right)}\left[\frac{k(n-1)}{k}\right]^{(n-1)}$$

or, $q_p = \dfrac{1}{k\Gamma n}e^{-(n-1)}(n-1)^{(n-1)}$ (16)

From equation (15) and (16)

$$q_p\cdot t_p = \frac{(n-1)}{\Gamma n}e^{-(n-1)}\cdot(n-1)^{n-1} \tag{17}$$

Equating equation (3) with equation (17), one gets

$$\frac{(n-1)}{\Gamma n}\cdot e^{-(n-1)}\cdot(n-1)^{n-1} = 0.5764\left[\frac{R_B}{R_A}\right]^{0.55}\times R_L^{\;0.05} \tag{18}$$

All terms in the right hand side in equation (18) are known. Only unknown is Nash Model parameter n, which can be obtained by solving the equation (18) using Newton Rapshon method of nonlinear optimisation.

The parameter n may be substituted in the following equation to determine the Nash Model parameter k for the given velocity V.

$$k = \frac{0.44L_W}{V}\cdot\left[\frac{R_B}{R_A}\right]^{0.55}\cdot R_L^{\;-0.38}\cdot\frac{1}{(n-1)} \tag{19}$$

The derived value of n and k, can be utilised for determination of the complete shape of IUH with the help of the equation (14).

6.3.4 Data Base Preparation in ILWIS

GIUH based approach and Clark model require some of the important geomorphological parameters from toposheets. Manual derivation of these parameters is tedious and time consuming and often involves certain degree of errors. The procedure is all the more difficult if the toposheets or maps of higher scale e.g. 1:50,000 or 1:25,000 are used for derivation of the geomorphological characteristics. To overcome this difficulty Geographical Information System (GIS) software like ILWIS, ARC/INFO, IDRISI etc. are now a days available for derivation of these characteristics in a less time consuming and simplified manner. Application of the GIS software makes the computation of geomorphological parameters easy, less time consuming, and accurate. On the other hand, the manual methods of the morphometric analysis such as length measurement using thread length, opisometer, rular, digital curvimeter or area measurement by planimeter or dot grid method are very much time consuming and tedious.

6.3.5 Geomorphological Data Base Preparation

Evaluation of geomorphologic characteristics involves preparation of a drainage map, ordering of the various streams, measurement of basin area, channel length and perimeter etc. and thereafter computing various geomorphological parameters such as bifurcation ratio, length ratio, area ratio, drainage density, drainage frequency, basin configuration and relief aspects etc. The geomorphological parameters viz. bifurcation ratio (R_b), length ratio (R_L), area ratio (R_A), length of the highest order stream (L_ς), length of the main stream (L) are required to be evaluated for a catchment for application of the GIUH based model. The methodology adopted for estimation of these geomorphological parameters is described below:

6.3.5.1 Stream ordering

Strahler's stream ordering system may be used for stream ordering (u). The principles of Strahler's method of stream ordering are mentioned below.

(i) Channels that originate at a source are defined to be first order streams.
(ii) When two streams of order u join, a stream of order u+1 is created.
(iii) When two streams of different orders join, the channel segment immediately down stream has the higher of the order of the two continuing streams.
(iv) The order of a basin is the order of the highest stream.

This ordering system can be applied through ILWIS over the entire drainage network . In ILWIS, length of each stream is stored in a table. Then, after adding length of each stream for an order, one can get the total stream lengths of each order. The total stream length divided by the number of stream segment (N_u) of that order gives the mean stream length L_u for that order.

6.3.5.2 Stream number (N_u)

In ILWIS, the number of streams of each order can be stored in a table and for each order the total number of streams can be computed. Horton's law of stream numbers states that number of stream segments of each order is in inverse geometric sequence with order number i.e. $N_u = R_b^{u-k}$ where, k is the order of trunk segment, u is the stream order, N_u is the number of stream of order u and R_b is a constant called the bifurcation ratio.

6.3.5.3 *Stream length (L_u)*

Length of each stream is stored in a table. Then after adding length of each stream for a given order, the total stream length of each order (L_u) may be computed. The total stream length divided by the number of stream segments (N_u) of that order gives the mean stream length L_u for that order. Length of the main stream from its origin to the gauging site is indicated as (L) while the length of the highest order stream is indicated as L_Ω.

6.3.5.4 *Bifurcation ratio (R_b)*

Horton's law of stream numbers states that number of stream segments of each order is in inverse geometric sequence with order number i.e.

$$N_u = R_b^{u-k} \qquad \ldots(19)$$

where, *k* is the order of trunk segment, u is the stream order, N_u is the number of stream of order u and R_b is a constant called the bifurcation ratio.
Bifurcation ratio (R_b) is defined as the ratio of stream segments of the given order N_u to the number of stream segments of the next higher order N_{u+1} i.e:

$$R_b = N_u \,/\, N_{u+1} \qquad \ldots(20)$$

6.3.5.5 *Length ratio (R_l)*

Length ratio is one of the important geomorphologic characteristics. Horton (1945) defined length ratio (R_l) as the ratio of mean stream length ($\bar{L}_u$) of segment of order u to mean stream segment length ($\bar{L}_{u-1}$) of the next lower order u-1, i.e.:

$$R_l = \bar{L}_u \,/\, \bar{L}_{u-1} \qquad (21)$$

6.3.5.6 *Area ratio (R_a)*

The area of streams of each order can be estimated using the area and length relationship (Strahler, 1964). Horton stated that mean drainage basin areas of progressively higher order streams should increase in a geometric sequence, as do stream lengths. The law of stream areas can be expressed as:

$$A_u = A_1 R_a^{u-1} \qquad (22)$$

Here, A_u is the mean area of basin of order u, A_1 is the mean area of first order basin, and R_a is the area ratio. Areas for different order basins were estimated using the relationship between area of any order and area of highest order as given below:

$$A_u = A_1 R_b^{u-1} (R_{lb}^{u}-1)/(R_{lb}-1) \qquad (23)$$

Where, R_{lb} is the Horten's term for the length ratio to bifurcation ratio. In this relationship the only unknown is A_1 and it can be computed from physical characteristics. The mean areas are computed using the value of A_1.

Area ratio (R_a) is defined as the ratio of area streams (A_u) of order u to the area of streams (A_{u-1}) of the order u-1, i.e.:

$$R_a = A_u \,/\, A_{u-1} \qquad (24)$$

Area ratio is one of the important geomorphologic characteristics.

6.3.5.7 Preparation of time-area diagram

In the GIS and Clark based GIUH model, the time area diagram of a catchment serves as a basic input. The central idea in time-area diagram preparation is a time contour or an isochrone. The time-area diagram illustrates the distribution of travel time of runoff in different parts of a catchment. The application of GIS makes preparation of the time area diagram of a catchment less time consuming and quite easier. Steps for derivation of the time area diagram are described below:

Measure the distance from the most upstream point in the basin upto the gauging site along the main stream. It is assumed that the time of travel between any two points is proportional to the distance and inversely proportional to the square root of the slope between these points expressed mathematically,

$$t = KL / \sqrt{S} \qquad (25)$$

where, t is the time of travel, L is the length of the stream, S is the slope of the stream between two points, and K is the proportionality constant. An initial estimate of time of concentration may be made be derived using Kirpich's formula as:

$$T_c = 0.06628\ L^{0.77}\ H^{-0.385} \qquad (26)$$

where, T_c is the concentration time in hours, L is the length of stream in kilometers, and H is the average slope of the stream. Substituting the values of L and H in equation (26), the value of T_c can be computed. The value of T_c computed in step 3 may be substituted in equation (25) and then, it may be rearranged as:

$$K = t_c \sqrt{S_A} / L \qquad (27)$$

where, S_A is mean slope of the main stream
By substituting values of T_c, L and S_A in the equation (27), the value of K may be computed.
The computed value of constant of proportionality K is used in equation (25) for computing time of travel between the two points of the catchment.
Beginning from the gauging site of the catchment progressively, compute the time of travel at various locations in the catchment.
Mark all the values of the time of travels for each stream on the map of the catchment. Then, transfer these points in the digital format.
Using an interpolation technique, draw a map of time distribution through these points.
From the time distribution map values, prepare a map at a desired interval, e.g. 1-hour.

6.3.5.8 Computation of Direct Surface Runoff using the Derived Unit Hydrograph

The direct surface runoff (DSRO) for a storm event whose rainfall-excess values are known at D-hour interval are computed using convolution of the D-hour unit hydrograph. The convoluted hydrograph ordinates can be given as:

$$Q(t) = \Delta t \sum_{i}^{n} [U(D, t-(i-1)\Delta t] * I_i \qquad (28)$$

where,

U(D, t) = ordinate of D hour unit hydrograph at time t,
I_i = excess-rainfall intensity at ith interval (i.e., at time = $\Delta t * i$),
n = number of excess-rainfall blocks, and
Δt = computational time interval.

6.4 SCS Curve Number Method

The SCS model computes direct surface runoff through an empirical relation that requires the rainfall and a watershed coefficient namely runoff curve number (CN) as input. The curve number is a function of some of the major runoff producing properties of a basin namely, the hydrologic soil type, land use and treatment, ground surface condition and antecedent moisture condition. Of these, the determination of land use and land cover is one of the most important tasks for estimation of runoff curve number. The prime variable in the basin wide runoff curve number estimation is land use changes with the time.

6.4.1 SCS Runoff Curve Number System

The runoff curve number method is a procedure for hydrologic abstraction developed by the USDA Soil Conservation Service. In this method, runoff depth (i.e. effective rainfall) is a function of total rainfall depth and an abstraction parameter referred to as runoff curve number or simply curve number which is usually represented by CN. The curve number varies in the range 1 to 100, being a function of the following runoff producing catchment properties: (1) hydrologic soil type, (2) land use and treatment, (3) ground surface condition, and (4) antecedent moisture condition.

The method is based on an assumption of proportionality of the following form:

$$\frac{P - I_a - Q}{S} = \frac{Q}{P - I_a} \qquad (29)$$

where; P = total storm rainfall, Q = actual direct runoff, S = potential maximum retention, and I_a = initial abstraction. P, Q and S are expressed in the same units e.g. cm or inches. This assumption underscores the conceptual basis of the runoff curve number method.

Solving for Q from Eq. (1) leads to the following.

$$Q = \frac{(P - I_a)^2}{P - I_a + S} \qquad (30)$$

which is physically subject to the restriction that $P \geq I_a$ (i.e. the potential runoff minus the initial abstraction cannot be negative). To simplify Eq. (30), initial abstraction is related to potential maximum retention. Vandersypen et al. (1972) developed the following relationship between initial abstraction and potential maximum retention for Indian conditions.

For Black Soil Region (Antecedent Moisture Condition I) and For All Other Regions:

$$I_a = 0.3S \qquad (31)$$

Therefore Eq. (30) reduces to

$$Q = \frac{(P - 0.3S)^2}{P + 0.7S}, \qquad P \geq 0.3S \qquad (32)$$

For Black Soil Region (Antecedent Moisture Condition II & III):

$$I_a = 0.1S \tag{33}$$

Therefore Eq. (30) reduces to

$$Q = \frac{(P - 0.1S)^2}{P + 0.9S}, \qquad P \geq 0.1S \tag{34}$$

Eq. (34) is used with the assumption that the cracks which are typical of black soil when dry are filled. Since potential maximum retention varies widely, it is expressed in terms of a runoff curve number, an integer varying in the range 1 to 100, in the following form.

$$S = \frac{2540}{CN} - 25.4 \tag{35}$$

in which CN is the runoff curve number (dimensionless) and S is in cm. Hence, the values of P and Q in Eqns. (32) and (34) are also to be expressed in cms. The runoff curve number is a function of hydrologic soil group, land use and treatment, hydrologic surface condition and antecedent moisture condition.

7.0 REMARKS

The use of remote sensing technique for determination of land use/cover not only saves time but is less expensive as compared to conventional methods like ground surveys. Further, the satellite based remote sensing has advantages like large area coverage, synoptic view and capability to provide information over all accessible and inaccessible regions. Land use and hydrologic soil information of the basin serve as the basic input to the curve number technique. Geomorphological characteristics, which are quite commonly used in geomorphological based instantaneous unit hydrograph, can be evaluated using a GIS package. Manual estimation of the geomorphological parameters is a tedious and cumbersome process and often discourages the field engineers from developing the regional methodologies for solving various hydrological problems of the ungauged basins or in limited data situations. At times, it also leads to erroneous estimates. On the other hand, modern techniques like the GIS serve as an efficient approach for storage, processing and retrieval of large amount of database. Spatial modelling and tabular databases of GIS constitute a powerful tool and enable a kind of analysis which was not possible until recently. Also, the database created and stored in GIS system may be updated as and when required.

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