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on

Synthetic Unit Hydrographs for Ungauged Basins

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CERTIFICATE

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ABSTRACT

The progress in the development of SUH techniques made in the past was assessed and the SUH models were broadly classified into four groups as: (i) Traditional or Empirical, (ii) Conceptual, (iii) Probabilistic, and (iv) Geomorphological. It is found that the traditional SUH models have several inconsistencies associated with them; however, these models are still widely used for SUH derivation. However, as a successful replacement, the probabilistic SUH models and the models based on geomorphological perception of a drainage basin can be applied for flood estimation from ungauged catchments. Therefore, the geomorphological class of the SUH models can be thought of as the most scientific and modern approach for estimation of flood hydrograph from ungauged basins. The facilities of GIS softwares and remote sensing can be harnessed for this purpose. As an example, the Digital Elevation Model, Drainage Network Map, and geo-morphological parameters of the watershed were also extracted for development of SUHs from ungauged catchments.

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Spatel

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1: INTRODUCTION

The Unit hydrograph (UH) remains as a basic tool in the hands of hydrologist since Sherman (1932) introduced it to represent the hydrologic response of ungauged watershed through which effective rainfall is transformed to direct runoff. The UH is a surface runoff hydrograph resulting from one unit of rainfall excess uniformly distributed spatially and temporally over the watershed for the entire specified rainfall excess duration (Chow 1964). The concept of UH has undergone many changes over time and is termed as instantaneous unit hydrograph (IUH), geomorphologic instantaneous unit hydrograph (GIUH), synthetic unit hydrograph (SUH) based on the duration and stream and watershed properties respectively. In a purely ungauged watershed, the paucity of observed rainfall runoff data sparkled the idea of synthetic unit hydrograph (SUH) concept which are derived from watershed characteristics rather than rainfall- runoff data. The examples of some of traditional methods of SUHs as proposed by Snyder (1938), SCS (2002), Taylor and Schwarz (1952), Gray (1964), Espey and Winslow (1974) are available to hydrologists and these are region specific, simple, easy for development and requires less data. These methods utilize a set of empirical equations relating to physical characteristics of watershed to a few salient points of the hydrograph such as peak flow rate (qp), time to peak (tp), time base (tb) and UH width at 0.5 and 0.75 qp. However, in SUH development a great degree of subjectivity is involved in fitting the remaining points on the SUH such that the area under the SUH reaches unity corresponding to unit rainfall excess.

Sherman (1932) was the first to see the possibilities of extending the UH theory he had developed. He listed out the physical basin characteristics he thought would be reflected in a unit hydrograph and could be used to estimate the stream flow for an ungauged basin from given rainfall data. These characteristics were drainage area, size and shape, distribution of water courses, slope of main stream, slope of valley sides, and pondage due to surface or channel obstructions. The Sherman's idea has been the basis of many synthetic unit hydrograph procedures (Hoffmeister and Weisman, 1977). Most procedures seek to establish relationships between parameters used to describe the unit hydrograph and parameters used to describe the basin. The procedures differ either in the relationships established or in the methodology employed. The Sherman's UH concept used for estimating the storm runoff hydrograph at the gauging site in a catchment corresponding to a rainfall hyetograph is one of the widely accepted and admired tool in hydrologic analysis and synthesis. This is one of the first tools available to hydrologic and water resources community to determine the complete hydrograph shape rather than the quantum of peak discharge only (Todini, 1988). As discussed above, the UH concept needs the observed rainfall-runoff data at the gauging site for hydrograph generation, the paucity of these data sparkled the idea of synthetic unit hydrograph (SUH) concept. The term "synthetic" in synthetic unit hydrograph denotes the unit hydrograph (UH) derived from watershed characteristics rather than rainfall-runoff data. The need for a synthetic method to develop UHs has inspired many studies as the drainage basins in many parts of the world are ungauged or poorly gauged, and in some cases existing measurement networks are not working properly. Moreover, the problem is further aggravated by the impacts of human-induced changes to the land surface and climate, occurring at the local, regional and global scales and thus making the predictions of ungauged or poorly gauged basins highly uncertain.

Accurate and reliable predictions are becoming extremely important to civic society, with local and regional communities increasingly being asked to make independent judgments about actions required to prevent and manage natural disasters, and manage the natural environment around them and their water resources in a sustainable manner (Sivapalan et al., 2003). Notably, these decisions can only be made with the widest possible information being made available based on accurate and reliable predictions. Thus the time has come (*Successful completion of PUB decade: 2003-2012*) to identify the new techniques/models of UH developed along with the existing one to have the state-of-the-art of this multifaceted technique. Thus, the basic purpose of this report is to quantify and assess the progress in the development of SUH techniques made in the past and to provide a quick reference guide for researchers and practicing engineers to further explore new methods those can be used for hydrological prediction in ungauged basins (PUB). The efforts have also been put in this report to explore the geo-morphological characteristics of a study watershed using Geographic Information System (GIS) and Remote Sensing for ease in application of SUH technique in field applications.

2: SYNTHETIC UNIT HYDROGRAPH METHODS (SUH)

The beginning of SUH concept can be traced back to the distribution graph proposed by Bernard (1935) to synthesize UH from watershed characteristics, rather than the rainfall-runoff data. In general the synthetic unit hydrographs can be broadly classified in four groups as: (i) Traditional synthetic unit hydrograph methods; (ii) Conceptual synthetic unit hydrograph methods; and (iii) Probability Distribution Function (pdf) Based SUH Methods; and (iv) Geo-morphological IUH Based SUH Methods. This section of the report critically discusses the SUH methods falling in each group as follows.

2.1: Traditional Synthetic Unit Hydrograph Methods (TSUH)

The popular SUH methods in this group include Snyder (1938), Taylor and Schwarz (1952), and Soil Conservation Service (SCS 1957). In application of these methods some degree of subjectivity is involved in fitting the salient points on SUH. In addition to this, simultaneous adjustments are also required for area under SUH to be unity corresponding to unit rainfall-excess. The empirical equations describing these methods also have certain constants, which vary over a wide range. However, despite their inherent inconsistencies these methods are still widely used in engineering problems. A brief description of some of these methods is also given here.

Snyder Method

Snyder (1938) was perhaps the first to establish a set of empirical relations among the watershed characteristics such as area (A) (km^2); length of main stream (L) (km); and the distance from the watershed outlet to a point on the main stream nearest to the center of the area of the watershed (L_c) (km) to the three basic parameters of the UH, e.g., t_p = lag or time to peak (h), Q_p = peak discharge rate (m^3/s), and t_b = base time (d) to describe the shape of the UH. These relationships can be expressed as:

$$t_p = C_t(LL_c)^{0.3} \tag{1}$$

$$Q_p = 2.78\left(\frac{AC_p}{t_p}\right) \tag{2}$$

$$t_b = 3 + 3\left(\frac{t_p}{24}\right) \tag{3}$$

where, C_t and C_p are non-dimensional constants. Snyder (1938) found C_t to vary from 1.8 to 2.2 and C_p from 0.56 to 0.69. Das (2009) reported C_t and C_p as 0.65 and 0.94, respectively, for Ramganga catchment of Himalayan range, India. Eqs. (1) to (3) hold good for rainfall-excess duration (or unit duration) $t_R = t_p/5.5$. However, if the duration of rainfall-excess say t_{R1} differs from the above defined duration (t_R), a modified lag time t_{mlag} is determined as:

$$t_{mlag} = t_p + \frac{(t_{R1} - t_R)}{4} \tag{4}$$

Since one can sketch any number of UHs through the three known characteristic points of the UH, i.e., Q_p, t_p, and t_b, with its specific criteria, i.e., area under the SUH to be unity. To overcome this ambiguity associated with the Snyder's method, the U.S. Army Corps of Engineers (USACE, 1940) proposed empirical relations between widths of UH at 50% (W_{50}) and 75% (W_{75}) of Q_p as a function of ($Q_p/A = q_p$), expressed as: $W_{50} = 830/q_p^{1.1}$ and $W_{75} = 470/q_p^{1.1}$. W_{50} and W_{75} are in the units of hour. However, in practical applications, this procedure is very tedious, and involves great degree of subjectivity and error due to manually fitting of the points and simultaneous adjustments for the SUH area.

Soil Conservation Service (SCS) SUH Method

The Soil Conservation Service (SCS) SUH method (SCS, 1957) was developed by U.S. Department of Agriculture (USDA) for synthesizing the UH using a specific average dimensionless unit hydrograph derived from the analysis of large number of natural UHs for the watersheds of varying sizes and geographic locations (Singh, 1988). To define the time base (t_b) in terms of time to peak (t_p) and time to recession (t_{rc}), the SCS method represents the dimensionless UH as a triangular UH, which further facilitates the computation of the runoff volume (V) and peak discharge (q_p) as:

$$V = 0.5(q_p t_b) = 0.5 q_p (t_p + t_{rc});\ t_{rc} = 1.67\ t_p \tag{5\&6}$$

$$q_p = 0.749\left(\frac{V}{t_p}\right) \tag{7}$$

where q_p is in (h^{-1}); V is in mm; t_p and t_{rc} are in h. To determine the complete shape of the SUH from the non-dimensional (q/q_p vs t/t_p) hydrograph, the time to peak is computed as:

$$t_p = t_L + t_r/2 \tag{8}$$

where t_L = lag time (h) from centroid of rainfall-excess to peak discharge (q_p) and t_r = the excess-rainfall duration (unit duration) (h). The lag time (t_L) can be estimated from the watershed characteristics using curve number (CN) procedure as:

$$t_L = \frac{L^{0.8}(2540 - 22.86CN)^{0.7}}{14104CN^{0.7}Y^{0.5}} \qquad (9)$$

where L = length of main stream or hydraulic length of watershed (m), CN = curve number (50 ≤ 95), and Y = average catchment slope in (m/m). Alternatively Eq. (7) can be expressed as:

$$Q_p = 2.08\left(\frac{A}{t_p}\right) \qquad (10)$$

where Q_p = peak discharge in $m^3/s/cm$ of rainfall-excess.. Thus with known q_p, t_p, and specified dimensionless UH, the SUH can be easily derived.

2.2: Conceptual Synthetic Unit Hydrograph (CSUH) Methods

The popular conceptual models of Clark (1945) and Nash (1957) along with some recently developed conceptual models used for SUH derivation has been discussed in this section as follows.

Clark IUH Based SUH Model

To the enhancements in the concepts and understanding of physical factors which influence runoff and flood producing capacity of streams, Clark (1945) developed IUH model for flood prediction form gauged/ungauged basins. Clark's method for developing a SUH involves the application of an instantaneously applied unit (1 in. or 1mm) of rainfall excess over a watershed and thereafter, the precipitation is mathematically conveyed to the watershed outlet through two components namely a translation hydrograph and a linear reservoir routing.

For derivation of IUH, the Clark model uses two parameters: (i) time of concentration (T_C) in hours and (ii) storage coefficient (K) in hours of a single linear reservoir in addition to the time-area diagram as shown in Figure 1. The governing equation of the Clark IUH model can be expressed as:

$$U_i = C_1A_i + C_2U_{i-1} \qquad (11)$$

where, U_i = i^{th} ordinate of IUH and A_i = i^{th} ordinate of time-area diagram. C_1 and C_2 are the Clark's routing coefficients and can be computed as:

$$C_1 = \Delta t/(K + 0.5\Delta t);\ C_2 = 1\text{-}C_1 \qquad (12\&13)$$

where, Δt = computational interval in hours.

Finally a UH of desired duration (D) can be derived as:

$$U_i = \frac{1}{N}\left(0.5_{i-N} + U_{i-N+1} + \ldots\ldots + U_{i-1} + 0.5U_i\right) \tag{14}$$

where, U_i= i^{th} ordinate of unit hydrograph of D-hour duration and computational interval Δt hours; N = number of computational intervals in D-hours = $D/\Delta t$.

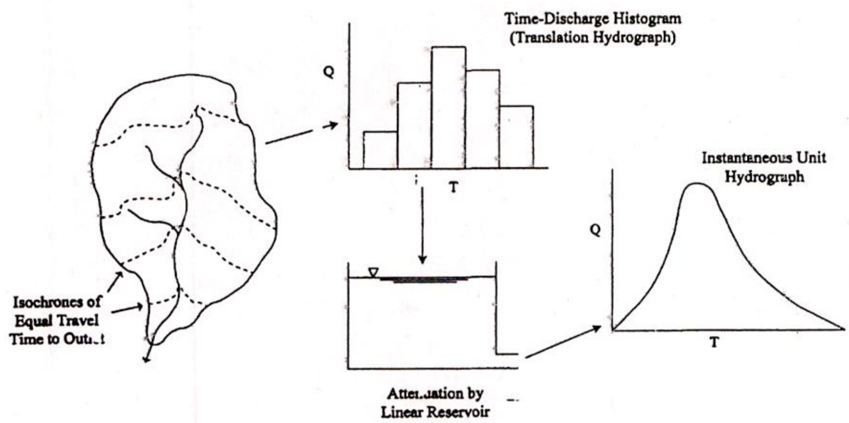

FIG. 1. Clark's Method Conceptual Model

Figure 1: Clarks Conceptual Model (source: Kull and Feldman, 1998)

Nash IUH Based SUH Model

Nash (1957) developed a conceptual model based on a cascade of n equal linear reservoirs with equal storage coefficient K for derivation of IUH for a natural watershed as shown in Figure 2. The outflow of each reservoir serving as the inflow into the next reservoir in the series as the flow moved toward the outlet of the watershed. The outflow of the first reservoir of the series, at the outlet of the watershed, is considered to be the IUH for the watershed. The model can be expressed as:

$$q(t) = \frac{1}{K\Gamma(n)}\left(\frac{t}{K}\right)^{n-1} e^{-\frac{t}{K}} \tag{15}$$

where, q (t) is the depth of runoff per unit time per unit effective rainfall. It is noteworthy that parameter n is dimensionless and K has the unit of time. The area under the curve defined by Eq. (15) is unity. Thus, the rainfall-excess and direct surface runoff depths are equal to unity.

The parameters n and K are often termed respectively, as the shape and scale parameters of the Nash model, which can be computed using method of moments or empirical equations available in literature (e.g., Singh , 2000 and Bhunya et al., 2003). To obtain the SUH, the parameters of Eq. (19) are related to catchment characteristics. The IUH (Eq. 19) is used to derive the resultant flood hydrograph for a given input rainfall.

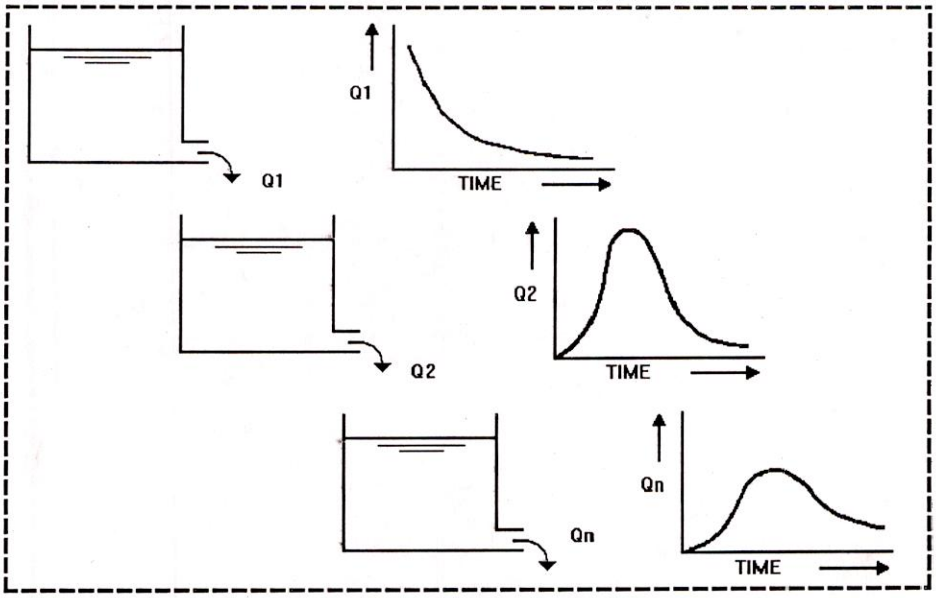

Figure 2: Nash Conceptual Model

Hybrid Model (HM)

The Hybrid Model (HM) was developed by Bhunya et al. (2005) for developing SUHs by splitting Nash single linear reservoir into two serially connected reservoirs of unequal storage coefficients (one hybrid unit) to have a physically realistic response. The HM model for two hybrids units in series can be expressed as:

$$Q_2(t)=\frac{1}{(K_1-K_2)^2}\left[\left(te^{-\frac{t}{K_1}}+te^{-\frac{t}{K_2}}\right)-\frac{2K_1K_2}{(K_1-K_2)}\left(e^{-\frac{t}{K_1}}-e^{-\frac{t}{K_2}}\right)\right] \qquad (16)$$

in which $Q_2(t)$ = the output from the second hybrid unit (mm/h/mm); and K_1 and K_2 = the storage coefficient of first and second reservoirs (h), respectively, of each hybrid unit.

Extended Hybrid Model (EHM)

The Extended Hybrid Model (EHM) was developed by Singh et al. (2007) by inserting a linear channel between the two linear reservoirs having different storage coefficients to derive SUHs . The mathematical expression of the model can be expressed as:

$$Q_2(t) = \frac{1}{(K_1 - K_2)^2}\left| e^{-\frac{(t-2T)}{K_1}}\left[t - 2\left(T + \frac{K_1K_2}{(K_1 - K_2)}\right)\right] + e^{-\frac{(t-2T)}{K_2}}\left[t - 2\left(T - \frac{K_1K_2}{(K_1 - K_2)}\right)\right]\right| \quad \text{for } t \geq 2T \tag{17}$$

$$= 0 \qquad \text{otherwise}$$

where $Q_2(t)$ is the output from the second hybrid unit (m/h/m) or from the system; K_1 and K_2 in the units of hours to be the storage coefficients of the first and second linear reservoirs, respectively, and T (h) as the translation time of linear channel, the outflow due to an unit input is deduced as follows.

2.3: Probability Distribution Function Based SUH Methods

The density functions (pdfs) of probability distribution functions have been successfully applied in hydrologic applications for development of SUHs. Due to similarity in the shape of the statistical distributions and a conventional unit hydrograph, several attempts have been made in the past to use their probability density functions (pdfs) for derivation of the SUH. Two approaches are followed for deriving a UH from recorded flood hydrograph and simultaneous rainfall records.

The first one is a *non-parametric approach* based on a discretization technique, i.e., determination of a model at a finite number of discrete points. This includes the least square method (Snyder, 1955), matrix inversion (Eagleson et al., 1966), non-linear programming (Mays and Taur, 1982) and transfer function approach (Yang and Han, 2006). The second one is a *parametric approach* that fits some prescriptive functional curves with limited number of parameters, and these parameters are estimated by means of optimization using an objective function or through any suitable approach. For instance, Nash (1957) derived an IUH (Eq. 15) based on the concept of n-linear reservoirs of equal storage coefficient and showed that the shape of IUH can be represented by a two-parameter Gamma distribution (2PGD).

The parametric approach fits the unit hydrograph through selected salient points like (t_p, q_p), (t_p, t_i) or (q_p, t_i); where t_p is the time to peak (T), q_p is peak runoff rate (T^{-1}), and t_i is the point of inflection after the peak (*T*). The parametric approach has also been used in SUH derivations, with the most common analytical forms being the triangular and the gamma-PDF (Koutsoyiannis and Xanthopoulos, 1989). Their simplicity and ease in development can characterize these SUHs as they require less data and yield a smooth and single valued shape corresponding to one unit runoff volume, which is essential for unit hydrograph derivation. The SUH methods of Gray (1961), Croley (1980), Aron and White (1982), Singh and Chowdhury (1985), McCuen (1989), Haktanir and Sezen (1990), Singh (2000), Bhunya et al. (2003, 2008 & 2009) are some of the popular examples.

Koutsoyiannis and Xanthopoulos (1989) presented eight suitable analytical forms for UH originated from known probability density functions or their transformations. The proposed distributions can be explored for SUH derivation. Haktanir and Sezen (1990) explored the applicability of two-parameter gamma (2PGD) and three-parameter beta distributions (3PBD) for SUHs derivation. Bhunya et al. (2007) explored the potential of four popular pdfs, e.g., two-parameter Gamma (2PGD), three-parameter Beta (3PBD), two-parameter Weibull (2PWD), and one-parameter Chi-square distribution (1CSD) to derive SUH. Nadarajah (2007) explored the usefulness of eleven of the most flexible probability distributions for SUH derivation. He also derived expressions for the unknown parameters in terms of the time to peak (t_p), the peak discharge (q_p) and the time base (t_B).

Croley SUH Method

Croley (1980) developed SUH method by fitting 2PGD for different set of boundary conditions, i.e., (t_p, q_p), (t_p, t_i) or (q_p, t_i). These boundary conditions were used to estimate the parameters n and K of the distribution. The general expression of the SUH can be expressed as:

$$q(t) = \frac{V}{K\Gamma(n)}\left(\frac{t}{K}\right)^{n-1} e^{-\frac{t}{K}}; \quad \int_0^{\infty} q(t)dt = V \qquad (18\&19)$$

where t_i is the point of inflection (T), q_p is the peak discharge per unit area per unit effective rainfall (T^{-1}), t_p is the time to peak (T), and n and K are the shape and scale parameters, respectively. Following this model, Singh (2000) and Bhunya et al. (2003) developed simplified forms of the 2PGD model for SUH derivation.

2PGD Transmutation SUH Method

The traditional methods of SUH, i.e., Snyder, Soil Conservation Service (SCS), and Gray method were transmuted into gamma distribution by Singh (2000) for SUH derivation. The approach gives a smooth shape of SUH and the area under which is guaranteed to be unity. Assuming that Eq. (15) represents UH of unit duration, the condition at the peak ($t = t_p$) $dq(t)/dt =$ yields:

$$K = t_p / (n-1) \tag{20}$$

Using Eqs. (15) & (20), a simple analytical expression relating number of linear reservoirs 'n' and dimensionless term β was developed as:

$$\beta = \frac{(n-1)^{(n-1)} e^{-(n-1)}}{\Gamma(n-1)} \tag{21}$$

where, β = a product of peak flow rate (q_p) and time to peak flow rate (t_p). The parameter β is also known as shape factor and has generally been observed to vary between 0.35 and 1.25. Substituting the approximate expression for the Gamma function in Eq. (21), the following simple analytical equation for inverting Eq. (21) was obtained as:

$$n = 7/6 + 2\pi\beta^2 \tag{22}$$

Eq. (22) can be used to calculate β, if n is known from other sources.

Simplified 2PGD SUH Method

A simplified version of 2PGD was developed by Bhunya et al. (2003) to derive SUHs more conveniently and accurately than the popular Snyder, SCS, Gray models. Simple relationships were developed between *n*, β, to obtain the simplified versions of the gamma distribution for SUH derivation as:

$$n = 5.53\beta^{1.57} + 1.04; \quad \text{for} \quad 0.01 < \beta < 0.35; \quad \text{COD} \approx 1 \tag{23}$$

$$n = 6.29\beta^{1.998} + 1.157; \text{for} \quad \beta \geq 0.35; \quad \text{COD} \approx 1 \tag{24}$$

Eqs. (23)-(24) & (20) can be used for estimation of parameters n and K of ungauged watersheds and thus the complete shape of SUH.

2.4: Geomorphologic Instantaneous Unit Hydrograph (GIUH) Based SUH Methods

The geomorphological models, coupling the principles of hydrologic systems with quantitative geomorphology, were proposed to represent the instantaneous unit hydrograph (IUH) of a given basin, popularly known as Geomorphologic Instantaneous Unit Hydrograph (GIUH) models. The pioneering works of Rodriguez-Iturbe and Valdés (1979), Valdés et al. (1979), Rodriguez-Iturbe et al. (1979), and Gupta et al. (1980) which explicitly integrate the geomorphology details and the climatological characteristics of a basin in the framework of travel time distribution could be thought of as the boon for stream flow synthesis in ungauged basins or partial information on storm event data (Singh et al., 1985).

Regarding the geomorphological UH identification, Rodriguez-Iturbe and Valdés (1979) formulated the geomorphologic IUH (GIUH) trying to reach the universality with the conviction that the search for a theoretical coupling of quantitative geomorphology and hydrology is an area which will provide some of the most exciting and basic developments of hydrology in the future.

The roots can be traced back to Horton (1945) who originated the quantitative study of channel networks and developed a system for ordering streams networks and derived laws relating the stream numbers (N), stream lengths (L), and catchment area (A) associated with streams of different order. The quantitative expressions of Horton's laws can be expressed as:

Law of stream number: $N_w/N_{w+1} = R_B$ (25)

Law of stream length: $\overline{L}_w/\overline{L}_{w-1} = R_L$ (26)

Law of stream areas: $\overline{A}_w/\overline{A}_{w-1} = R_A$ (27)

where N_w is the number of streams of the order w, $\overline{L}_w$ is the mean length of stream of order w, and $\overline{A}_w$ is the mean area of basin of order w. R_B, R_L, and R_A represent the bifurcation ratio, length ratio, and area ratio whose values in nature are normally between 3 and 5 for R_B, between 1.5 and 3.5 for R_L, and between 3 and 6 for R_A.

Geomorphologic Instantaneous Unit Hydrograph (GIUH) Method

Rodriguez-Iturbe and Valdés (1979) expressed the initial state probability of one droplet of rainfall in terms of geomorphological parameters as well as the transition state probability matrix. The final probability density function (pdf) of droplets leaving the highest order stream into the trapping state is nothing but the GIUH. An exponential holding time mechanism, equivalent to that of a linear reservoir was assumed in its conceptualization. They suggested that it is adequate to assume a triangular IUH and only specify the expressions for the time to peak (t_p) and peak value (q_p) of the IUH. These expressions were obtained by regression of t_p as well as q_p of IUH derived from the analytic solutions for a wide range of parameters with that of the geomorphologic characteristics and flow velocities. The expressions for peak flow (q_p), time to peak (t_p) and time to base (t_B) of the IUH can be expressed as:

$$q_p = \left(\frac{1.31}{L}\right) R_L^{0.43} v \tag{28}$$

$$t_p = 0.44\left(\frac{L}{v}\right) R_B^{0.55} R_A^{-0.55} R_L^{-0.38} \tag{29}$$

$$t_B = 2/q_p \tag{30}$$

where, L is the length of main channel or length of highest order stream in km, v is the average peak flow velocity or characteristic velocity in m/s; q_p and t_p are in units of h^{-1} and h, respectively.

Further, Rodriguez-Iturbe and Valdés (1979) defined a non-dimensional term β (= shape factor) as the product of q_p (Eq. 28) and t_p (Eq. 29) as:

$$\beta = 0.584\left(\frac{R_B}{R_A}\right)^{0.55} R_L^{0.05} \tag{31}$$

If one of the IUH parameters q_p or t_p is known, say from observed records or some regional IUH analysis, the terms vL^{-1} and $v^{-1}L$ in RHS of Eqs. (28) & (29), respectively, can be computed from the geomorphological data of the catchment. And, on substituting the values of vL^{-1} and $v^{-1}L$, the other IUH parameter (q_p or t_p) can be obtained. Thus, with q_p and t_p known, a suitable two-parameter pdf can be used to describe the complete shape of the UH. Thus, GIUH provided a scientific basis for the hydrograph fitting and yielded a smooth and single valued shape corresponding to unit runoff volume.

GIUH Coupled 2PGD Model

The possibility of preserving the form of the SUH through a two-parameter gamma pdf was analyzed by Rosso (1984), where Nash model parameters were related to Horton's order ratios using Eq. (31). Rosso used an iterative computing scheme and proposed the following equations for n and K as:

$$n = 3.29(R_B/R_A)^{0.78} R_L^{0.07} \tag{32}$$

$$K_* = 0.70[R_A/(R_B R_L)]^{0.48} \tag{33}$$

where $K_* = KvL^{-1}$ is a dimensionless scale parameter. Thus, for an observed v, the parameters of the 2GPD and the shape of the UH can be computed from the geomorphological parameters of the catchment.

2.5: Width Function Based GIUH Model (WFIUH)

One of the most important hydrological characterizations of geomorphology can be represented by the geomorphological width function $W(x)$, defined as the probability measure obtained by dividing the number of links at given distance x from the outlet by the total number of links in the network, where x being the distance to the outlet of the i^{th} link measured along the network and normalized by the maximum path distance along the streams from source to outlet (Rinaldo and Rodriguez-Iturbe, 1996). $W(x)$ provides a good first step in quantifying the influence of the network geometry on the runoff response of a basin (Kirkby, 1976; Mesa and Mifflin, 1986; and Naden, 1992). The form of the width function also reflects the shape of the GIUH (Botter and Rinaldo, 2003).

Although the network width function approach is a recent development in the field of predictions in ungauged basins, it has its practical limitations of extracting the network widths, particularly for large catchments with complex network structures. However, the $W(x)$ approach could pay a significant role in modelling the geomorphologic hydrologic response at the small basin scale. Recently, the hydrologists are finding it more convenient to couple the distribution function based SUH approach with the classical GIUH approach for development of SUHs models by using the geographic information systems (GIS) and remote sensing (RS) techniques.

3: Development of Drainage Network Map and Digital Elevation Model of Watersheds

In general practice, the geomorphological characteristics of the watersheds are computed by manual process using Survey of India (SOI) Toposheets, which is a very tedious and time consuming task and at the same time there are always some degree of errors. With the recent advancements in GIS and remote sensing tools and techniques, the extraction of geomorphological parameters can be done very easily.

For geomorphologic analysis, the digital elevation model (DEM) of the catchments can be prepared using NASA Shuttle Radar Topographic Mission (SRTM) DEM data having fineness of 3-arc second (90 m) spatial resolution, which can be freely downloaded from the website of University of Maryland (http://glcf.umd.edu/data/srtm) or from the Consortium for Spatial Information (CGIAR-CSI) (http://srtm.csi.cgiar.org/). The DNM, DEM and the geomorphologic parameters of the watersheds can be extracted from the downloaded SRTM data using ArcGIS Version

9.3 and Arc Hydro Tools Version 1.3. The general extraction procedure is briefly given here as a flow chart in Figure 3.

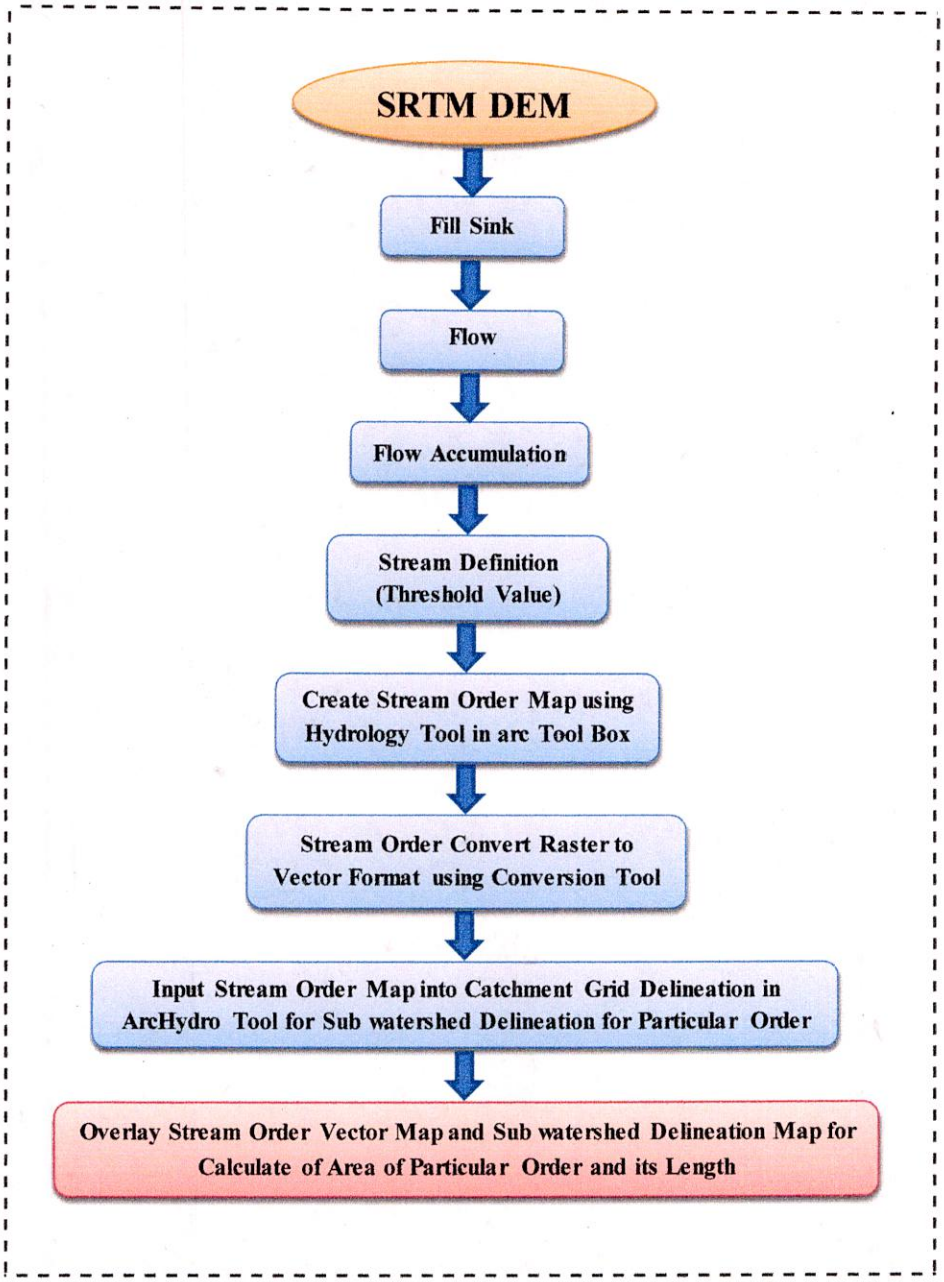

Figure 3: Flow chart showing extraction of digital elevation model, drainage network map, and extraction of geomorphological parameters

DEM, DNM and Geo-morphological Parameters of Hadaf Watershed

As a case study the Hadaf watershed (a sub-catchment of Panam river) located in the middle Gujarat region of India and lies between 22°55'16" to 23°08'00" N Latitude and 73°50' E to 74°05'3" E Longitude was selected for development of DEM, DNM and extraction of the geo-morphological parameters. . The Hadaf watershed has catchment area of 531.00 km^2 with perimeter of 145.0 km. The highest order stream (order of watershed) is found to be 4^{th} order. The catchment is approximately rectangular in shape with a minimum elevation of 137 m at the outlet and a maximum of 490 m above mean sea level (MSL) at the upstream end of the catchment. The length of the main stream is found to be 57.0 km. The Horton's ratios, i.e., bifurcation ratio (R_B), length ratio (R_L), and area ratio (R_A) are found to be 4.25, 2.59, and 3.10, respectively.

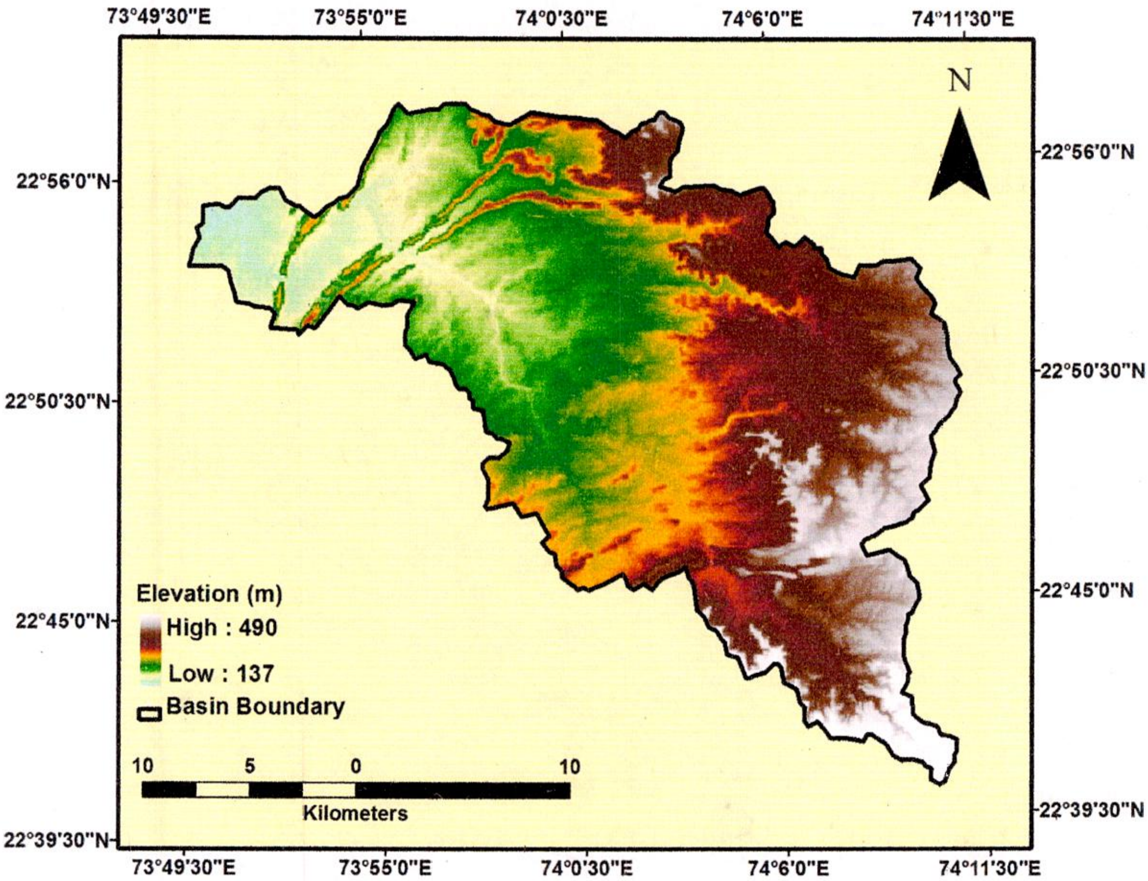

Figure 4: Digital Elevation Model of Hadaf watershed

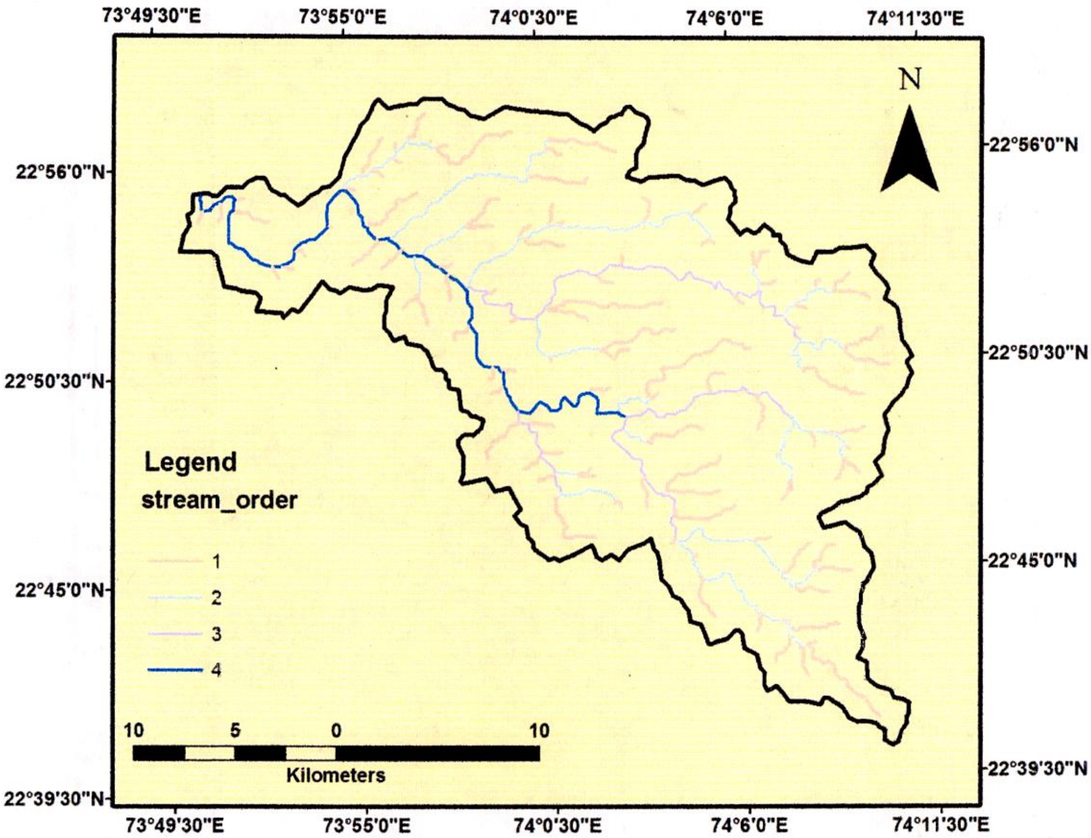

Figure 5: Drainage Network Map and Stream ordering of the Hadaf watersheds

4: CONCLUSIONS

This report quantifies and assesses the progress in the development of SUH techniques made in the past and provides a quick reference guide for researchers and practicing engineers to further explore new methods those can be used for hydrological prediction in ungauged basins (PUB). The SUH models were classified into four groups as: (i) Traditional or Empirical, (ii) Conceptual, (iii) Probabilistic, and (iv) Geomorphological. It is found that the traditional SUH models have several inconsistencies associated with them; however, these models are widely used for SUH derivation. At the same time, the probabilistic SUH models and the models based on geomorphological perception of a drainage basin can be successfully applied for flood estimation from ungauged catchments. Therefore, the geomorphological class of the SUH models can be thought of as the most fascinating approach for ungauged basins. The facilities of GIS and remote sensing can be harnessed for this purpose.

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