


Assessment of the empirical methods for the development of the synthetic unit hydrograph: a case study of a semi-arid river basin

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ABSTRACT

This study aims to assess various empirical synthetic unit hydrograph (SUH) methods and find the best method. Ideally, each river should have a definite rain gauge station (RGS) to get sufficient rainfall data that is available for carrying out meaningful analysis. The provisions of [Indian Standard \(IS\) 4987:1994](#) determined the optimum number of RGS. In the absence of RGS, the SUH is recommended. SUHs have been developed using various methods such as Snyder's, Taylor and Schwarz, Soil Conservation Service, Mitchell's and Central Water Commission (CWC). In the present study, the Rel River Basin (RRB) is considered as the study area which has two existing RGS. IS 4987:1994 suggested that four RGS are required for more reliable rainfall data. Various efficiency criteria such as Correlation Coefficient, Pearson Coefficient, Nash Sutcliffe Efficiency, Index of Agreement, Normalized Root Mean Square Error, Mean Absolute Error, Root Mean Square Error and Kling-Gupta Efficiency have been used to compare SUH methods. The ranking of SUH methods was reported based on the compound factor (CF) through efficiency criteria. The 1.125 CF was observed as the minimum for the CWC method and recommended for determining peak discharge and timing for the study area.

Key words: compound factor, multiple criteria decisions making, optimum number of rain gauge stations, synthetic unit hydrograph, ungauged basin

HIGHLIGHTS

- An optimum number of RGS has been examined at the initial level of the study.
- Various empirical methods of SUH have been evaluated.
- Numerous efficiency criteria have been used to compare different SUH methods.
- The compound factor (as an MCDM technique) has been used to find the best SUH method, which is a new concept in SUH.

INTRODUCTION

Rainfall is one of the most essential and complex hydrological modelling parameters ([Mishra & Singh 2010](#)). After Bangladesh, India is another important country frequently affected by floods ([Gupta *et al.* 2003](#)). 12.5% of India's geographical area is prone to flooding ([Patel & Dholakia 2010](#)). Due to this large area of submergence in India, flood analysis has become an essential feature ([Kumara & Mehta 2020](#); [Mehta *et al.* 2020](#)). Rainfall measurement for any basin is the primary requirement for flood analysis ([Marchi *et al.* 2010](#)). RGS must be distributed equally in the basin to achieve reliable results ([Berne *et al.* 2004](#)). The installed RGS in the basin should be adequate to measure the rainfall. If the RGS is higher, the economy will be affected, and if the RGS is lower, the results will be unreliable ([Buytaert *et al.* 2006](#)).

In the ungauged and semi-gauged basins, flood estimates and predictions are among the significant issues resulting from heavy rainfall over the basin. There are many approaches in existence to the assessment of floods ([Shaikh *et al.* 2018](#)). Few approaches are based on statistics, while others based on the characteristics of the basin are designed to meet this objective. The Unit Hydrograph (UH) concept has been implemented in the runoff estimation for the last four decades. [Sherman \(1932\)](#) was the originator of the UH theory. UH is defined as a surface runoff hydrograph in a given basin due to effective rainfall for the unit duration.

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Previous studies related to UH evaluation were devoted to Sherman's famous principle in 1932, which ended in a tremendous style of empiric and semi-empiric techniques used by hydrologists for many years. This technique is popular among hydrologists and is defined in several popular hydrology texts (Mujumdar *et al.* 2014). Many hydrologists have used various UH approaches such as deterministic, probabilistic, statistical and mathematical, and many others (Tunas *et al.* 2019). The UH is a conventional means of representing the basin's linear system response to rainfall over the basin (Maidment *et al.* 1996). The UH concept assumes that the basin acts linearly and time-invariantly with the introduction of effective rainfall to provide an instant output of storm runoff (Bruen & Dooge 1992). The UH form shows the runoff traits of the watershed (Wesley *et al.* 1987). In an ungauged or semi-gauged basin, the lack of observed rainfall and runoff data gave rise to the SUH's perception of the basin's characteristics rather than the rainfall-runoff data. Some of the SUH methods have been suggested for hydrologists and scientists by Snyder (1938), Mitchell (1948), Taylor & Schwarz (1952) and SCS (2002). However, these techniques are specific to the region and being simple, and require limited information for their use.

Snyder (1938) used an empirical approach to evaluate the salient hydrograph features such as lag time, peak time, base time, peak discharge, UH widths at 50, and 75% peak flow. Taylor & Schwarz (1952) derived SUH for 20 basins ranging from 50 to 4,000 km² of basin area, all in North and Middle Atlantic States. The most significant features considered are the area, the length of the longest path, the main stem's length from the centre of the basin, and average slope. The United State Soil Conservation Service (SCS) (1957) approach determined SUH through an average dimensionless hydrograph and avoided physical fitting. SCS dimensionless UH is assumed to be an invariant of the shape, size and location of the catchment area, which may not be justified (Singh 2000). Mitchell (1948) had examined fifty-eight watersheds in Illinois. He had developed the summation curves and grouped them based on the watershed area. The error in peak discharge has been reported at 39.0 per cent and 37.5 per cent during the peak time. CWC has provided SUH for distinctive sub-zones to be used for flood assessment of 25, 50 and 100 years return period for small to medium-sized drainage basins (Central Water Commission 1993). This method provides seven points of one-hour SUH. Seven points are peak time, peak discharge, 50 per cent width of peak discharge (two points), 75 per cent width of peak discharge (two points) and the base time. The traditional methods like Snyder, Mitchell, Taylor & Schwarz and SCS method are the beneficial methods for SUH generation all over the globe. The CWC method is newly developed for India for SUH generation. So, in this study, these five methods have been compared and identified which method is the best method suitable for the study area. Some recent studies are listed here in which different SUH methods have been used. Prajapati & Subbaiah (2005) identified Snyder as the best suitable method for the Rawat Sagar Basin, India. Velez & Botero (2011) concluded that Taylor & Schwarz method also gave similar results to Snyder's method for San Luis Creek Basin, Manizales. Salami *et al.* (2009) had summarised that the SCS method was best for eight rivers in South-West, Nigeria. Patel & Thorvat (2016) found that Mitchell's method gives an acceptable percentage error for the Upper Kumbhi Basin and the Dhamani Basin, Maharashtra, India. Salami *et al.* (2017) again recommended the SCS method to estimate the ordinate required to develop peak runoff hydrograph for Ogun-Osun river catchment, south-west, Nigeria. Reddy *et al.* (2019) had identified that the CWC is also a suitable method for the ungauged catchments of the West coast of Karnataka, India. Pradipta & Nurhady (2019) concluded the SCS method was determined as the representative SUH in Juana Watershed, Indonesia. Idfi *et al.* (2020) identified SCS has a high level of accuracy for Ngotok River watershed, Indonesia. Hence, every method is not suitable for every river basin. So, it is essential to find which method is best for the selected study area.

The scarcity of the observed stage (depth) and flow hydrograph and the lack of decent quality surveyed data are the main reasons for the restriction of river hydraulics studies in India (Mehta & Yadav 2020; Mehta *et al.* 2021). The Rel river flows west and has a total basin area of about 1,455 km², was flooded in July 2017 due to an unprecedented inflow of water. The Dhanera town received rainfall of 800 mm within 48 hours, i.e., 24/7/2017 and 25/7/2017, while the average annual rainfall in the basin was 600 mm. Historical data shows that similar rainfall occurred on the 24th and 25th of July 2017, which amounted to 112 years before. This high rainfall was triggered by the Bay of Bengal's simultaneous activation and the Arabian Sea's low-pressure system (a rare phenomenon).

There are only two RGS and one Stage Discharge Station (SDS) in the Rel River Basin (RRB). So, this region falls under scarce region as far as data is concerned. The depth of the river is almost negligible. As a result, the carrying capacity decreases from the confluence of the river downstream. The nearby villages and the riverbed are almost on the same elevation. Water in this region tends to spread in the lateral direction, resulting in

severe flooding (Shaikh *et al.* 2021a). In the July 2017 flood, the total payable relief for agriculture, horticulture, cattle and land damage was INR 16.53 billion from the post-flood survey results. Nearly 14,300 cattle died, while more than 200 human lives were lost during the monsoon season of 2017 (Shaikh *et al.* 2020). Five National Highways, 156 State Highways and 550 Panchayats roads were heavily affected by the 2017 flood. Therefore, it is necessary to study flood behaviour and thereby develop flood inundation maps in order to select appropriate mitigation measures. This study focuses on flood analysis in the case of data scarcity. The selection of the best SUH technique has been made using multiple criteria approaches is employed in this study in order to make appropriate recommendations.

This study evaluates SUH's various empirical methods for the RRB and finds the best method. An optimum number of RGS has been examined in order to obtain sufficient and meaningful data at the initial level of this study. Various SUH methods have been developed. Numerous efficiency criteria have been used to compare different SUH methods. Finally, the MCDM technique has been used to find the best SUH method for the RRB. The Compound factor (as an MCDM technique) has been used to find the best SUH method, which is a new concept in SUH. Hence, an evaluation among the SUH methods has been made under the current effort to identify the study area's practicability. The discharge obtained may be used for the design of hydraulic structures within the river basin.

STUDY AREA AND DATA COLLECTION

The RRB is selected for this study (Figure 1). It is the Luni River branch, which is one of the major rivers in the Rajasthan state of India. RRB has the latitude $24^{\circ}23'$ – $24^{\circ}45'$ N, longitude $71^{\circ}59'$ – $72^{\circ}30'$ E and watershed area was approximately 1,455 km². In The Spatial Analyst tool has been used in the present work. Spatial Analyst is an extension for ArcGIS that includes tools for raster-based (cell-based) spatial modelling and analysis. ArcGIS Spatial Analyst software may be found at: www.esri.com. The watershed ridge line and all the drainage lines were mapped using digitisation at the scale of 1:50,000. The 40P/14, 40P/15, 45D/2, 45D/3, 45D/5 and 45D/6 Survey of India (SOI) toposheets were used for mapping. Strahler (1957) method was used for stream

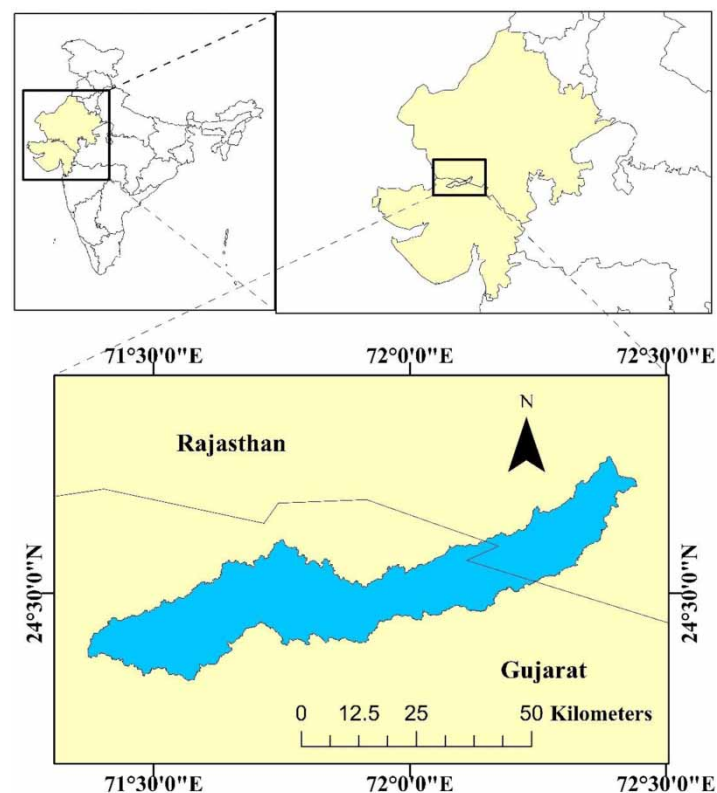


Figure 1 | Index map of study area.

ordering. According to the stream order, it was found that the RRB had the sixth order (Shaikh *et al.* 2021b). In the GIS environment, each stream was digitised, and the total length of each stream was evaluated.

In the current study, dataset types such as SOI toposheet, DEM, precipitation and discharge were used. SOI toposheets were downloaded from the Soinakshe (Survey of India) portal based on the basin's location. A Shuttle Radar Topography Mission (SRTM) DEM with a resolution of $30 \times 30 \text{ m}^2$ was downloaded from the website earthexplorer.usgs.gov. The records of hourly rainfall at the Bapla RGS were collected from the State Water Data Centre (SWDC), Gandhinagar, Gujarat, India. The hourly discharge from the SDS at Dhanera Highway Bridge was collected from the River Gauging (RG) section, Palanpur, Banaskantha, Gujarat, India.

METHODOLOGY

The current study aims to determine the optimum number of RGS, and generation of UH for an isolated storm event (22/07/2017–31/07/2017). They have been selected to generate UH for the isolated flood event in the RRB. The rainfall is recorded at Bapla RGS, and the depth-discharge is recorded at the Dhanera Highway Bridge SDS. Due to the availability of rainfall and discharge data on an hourly basis, it could be possible to select the UH duration as one hour, which is generally appropriate for all the basins. Hyetograph and the Hydrograph are then plotted.

The development of the UH and storm hydrograph has been performed for this study. Hydrograph that results from one-unit rainfall over the entire basin with uniform intensity is called UH. Geographical characteristics of the basin have been used in the generation of UH. First of all, it identified the gauged neighbouring basin, which has approximately the same geographical characteristics. Then, generate the UH for the gauged basin and use it for the ungauged basin. In the generation of storm hydrographs, rainfall data has been used to obtain direct runoff. This study addressed the empirical approaches like Snyder, TS, SCS, Mitchell and CWC methods for UH generation for the RRB. The authors have been used these empirical approaches to determine peak discharge, peak time, base period, and widths at 50 and 75% of SUH's peak discharge. Figure 2 shows the methodology used in this analysis.

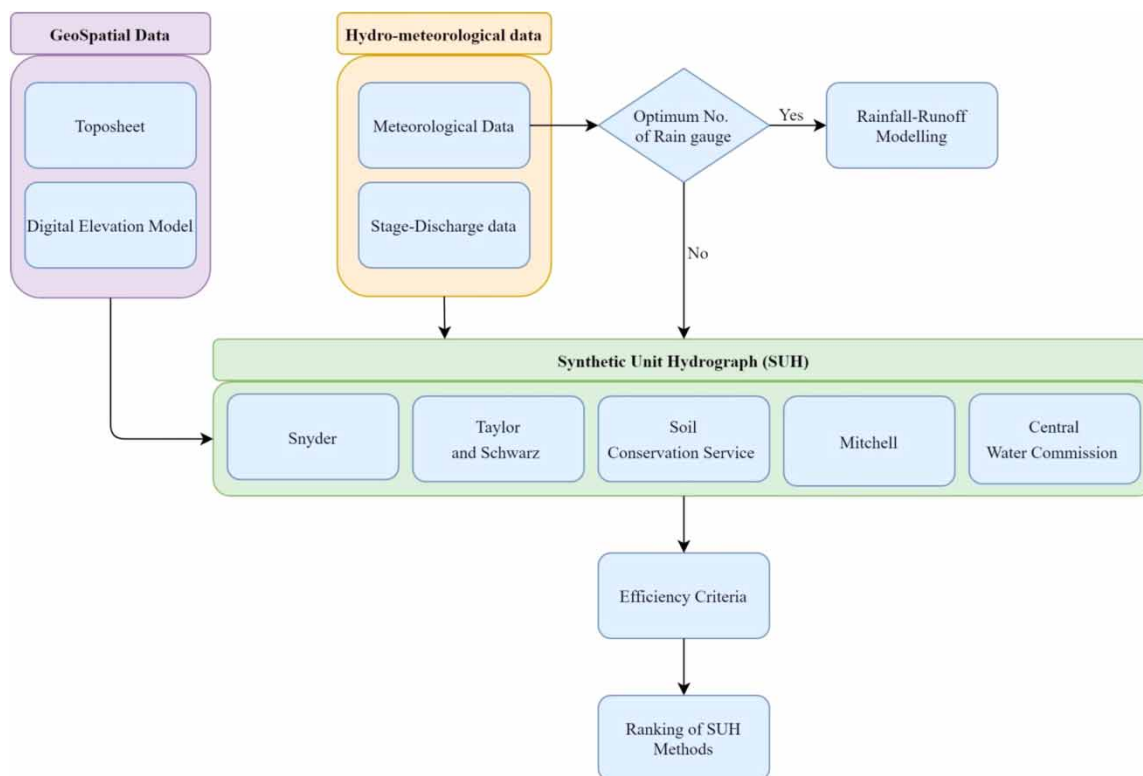


Figure 2 | Flowchart of methodology.

Optimum number of RGS

Indian Standard 4987:1994 recommended the distribution, density and repetitiveness of the RGS network for hydrometeorological studies. The various formulas involved in estimating the optimum number of RGS are

considered; hence, the mean annual rainfall (\bar{P}) and mean of squares of rainfall ($\overline{P^2}$) of all RGS is determined with Equation (1) and (2); the sample standard deviation (σ) and the coefficient of variation (C_v) is calculated with Equations (3) and (4), and finally, the optimum number of RGS (N) is computed with Equation (5).

$$\bar{P} = \frac{\sum_{i=1}^n P_i}{n} \tag{1}$$

where, P = rainfall (mm), n = existing RGS

$$\overline{P^2} = \frac{\sum_{i=1}^n P_i^2}{n} \tag{2}$$

$$\sigma = \sqrt{\frac{n}{n-1}(\overline{P^2} - \bar{P}^2)} \tag{3}$$

$$C_v = \frac{100\sigma}{\bar{P}} \tag{4}$$

$$N = \left(\frac{C_v}{E}\right)^2 \tag{5}$$

where, E = allowable percentage error (generally, it is taken as 10%). The mean rainfall shall be estimated correctly within allowable percentage errors of 10 ($E = 10\%$). With the decrease in the percentage error, the adequate number of rain gauges or the rain gauge network would also increase. This would increase the operating cost. Therefore, in establishing the optimum number of rain gauges, the problem of operating cost shall also be considered. However, in the case of special requirements, suitable methods may be used.

SUH methods

This section is divided into two parts, namely, the UH development and the storm hydrograph development. The geographical features of the basin were used in UH generation. First of all, identify the neighbouring gauge basin, which has about the same geographical features. Then, derive the UH from the gauged basin and use it for the ungauged basin. The rainfall data is used to get direct runoff while developing storm hydrographs. The Sub-Watershed 1 (SW1) corresponds only to RGS, SW2 has neither RGS nor SDS and SW3 has only SDS. The UH of SW1 was developed, and the SUH of Sub-Watershed 2 (SW2) and Sub-Watershed 3 (SW3) were developed too (Figure 3).

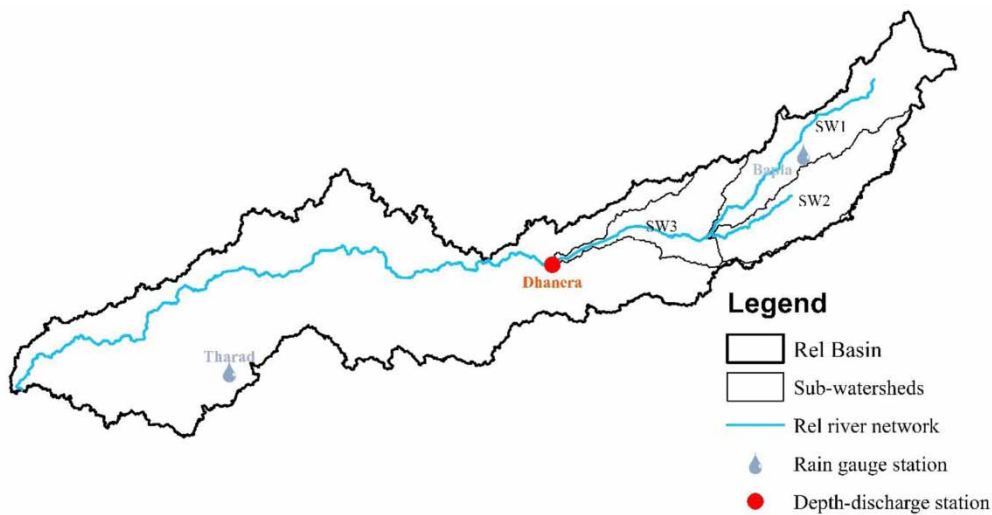


Figure 3 | Location of SW, RGS and SDS in RRB.

Snyder’s method

In the first place, Snyder (1938) established a set of empirical relationships for the ungauged basin, which deals directly with the watershed characteristics. The study of Snyder was done in the Appalachian Mountains. There

are various formulas involved in Snyder's method to develop UH; hence, the Lag time (h) (t_L), the Base time (h) (t_b), the Peak time (h) (t_p) and Peak discharge rate (ft^3/s) (Q_p) are Equations (6)–(9).

$$t_L = C_t(LL_c)^{0.5} \quad (6)$$

where, C_t = Non-dimensional constant which varies from 1.8 to 2.2, L = Main stream length (miles)(mi), L_c = Distance from watershed outlet to the centre of watershed along the mainstream (mi).

$$t_b = 24 \left(\frac{t_L}{8} + 3 \right) \quad (7)$$

$$t_p = \frac{D}{2} + t_L \quad (8)$$

where, D = Unit duration (h)

$$Q_p = \frac{640AC_p}{t_L} \quad (9)$$

where, A = Area of the watershed (mi^2) and C_p = Non-dimensional constant which varies from 0.56 to 0.69.

The U.S. Army Corps of Engineers (USACE 1940) suggested an empirical relation between the width of UH at 50% (W_{50}) and the width of UH at 75% of Q_p (W_{75}), expressible in Equations (10) and (11).

$$W_{50} = \frac{770}{(Q_p/A)^{1.08}} \quad (10)$$

$$W_{75} = \frac{440}{(Q_p/A)^{1.08}} \quad (11)$$

As a result, a smooth curve can be drawn through seven points (t_p , t_b , Q_p , two points of W_{50} and two points of W_{75}) instead of three points (t_p , t_b and Q_p). The widths are generally distributed in such a way that one-third is placed before the t_p and two-thirds placed after. Snyder's method is very monotonous, involving a higher level of subjectivity and error due to human fitting points and synchronised modifications for the area under SUH.

Taylor and Schwarz (TS) method

This method was presented by Taylor & Schwarz (1952). The data from twenty drainage basins were used for the derivation of SUH. The drainage basins ranged from 20 to 1,600 mi^2 and were situated in the North and Middle Atlantic States. Here, we used the same basin characteristics that were used in Snyder's method, with the average slope factor (S_e) of the main flow path being an additional factor introduced and derived by Equation (12). S_e is also referred as vertical distance/horizontal distance. Then the simplification parameters (m_1 and m_2) of this model are calculated by Equations (13) and (14). Finally, Peak time (h) (t_p), Peak discharge rate (ft^3/s) (Q_p) and Base time (h) (t_b) are calculated by Equations (15)–(17).

$$S_e = \left[\frac{N}{\sum_{i=1}^N \left(\frac{1}{S_i} \right)^{0.5}} \right]^2 \quad (12)$$

where, N = Total numbers of reaches along the main flow path, S_i = slope of i^{th} reach of the main flow path.

$$m_1 = \frac{0.212}{(LL_c)^{0.36}} \quad (13)$$

$$m_2 = 0.121 S_e^{0.142} - 0.05 - m_1 \quad (14)$$

where, L = Mainstream length (mi), L_c = Distance from watershed outlet to the centre of watershed along the mainstream (mi).

$$t_p = \left(\frac{0.6}{S^{0.5}}\right) e^{(m_1 D)} \quad (15)$$

where, D = Unit duration (h).

$$Q_p = \left[\frac{382}{(LL_c)^{0.36}}\right] e^{(m_2 D)} A \quad (16)$$

where, A = Area of the watershed (mi²).

$$t_b = \frac{60t_p}{11} \quad (17)$$

In the TS method, W_{50} and W_{75} The equation suggested by [USACE \(1940\)](#) was estimated for the smooth drawing of SUH, such as the Snyder method. The base time appeared to be approximately five times the actual peak time in this method ([Ponce 1989](#)). The fundamental incompatibility associated with the TS model is similar to Snyder's method ([Singh et al. 2014](#)).

Soil conservation service (SCS) method

This method suggested by the U.S. Department of Agriculture (USDA), which Victor Mockus developed. This method synthesises averaged dimensionless UH ([McCuen & Bondelid 1983](#)). It was obtained from assessing many natural UH for the various watershed, which varies in location and size in order to synthesise the UH ([Singh & Frevert 2003](#)). Initially, the watershed characteristics like the length of the longest drainage path, Curve number, the average land slope and the watershed area were found in this method. Then, Lag time (h) (t_L), Time to peak (h) (t_p), Base time (h) (t_b) and Peak discharge (ft³/s) (Q_p) were calculated sequentially by Equations (18)–(21).

$$t_L = \frac{L^{0.8} \left(\frac{1,000}{CN} - 9\right)^{0.7}}{1,900(S)^{0.5}} \quad (18)$$

where, L = Length of the longest flow path (feet), S = Average watershed land slope (%), CN = Curve number ($30 < CN < 100$).

$$t_p = t_L + \frac{D}{2} \quad (19)$$

where, D = Excess-rainfall unit duration (h).

$$t_b = 2.67t_p \quad (20)$$

$$Q_p = \frac{484A}{t_p} \quad (21)$$

where, A = Watershed area (mi²).

The length of the longest flow path can be measured with aerial photographs, quadrangle sheets, or GIS techniques. Victor Mockus established an empirical relationship between the watershed area and the flow length using the Agricultural Research Service (ARS) data, and it is calculated by Equation (22).

$$L = 100,90A^{0.6} \quad (22)$$

Curve number values range from 100 to 30. For water bodies, CN is nearer to 100 and approximately 30 for permeable soils with high infiltration rates ([SCS 1986](#)). Thus, a SUH can be easily derived with the help of known Q_p , t_p and t_b . A triangular shape is generally used to calculate the UH using SCS method.

Mitchell's method

Mitchell (1948) established a model for developing SUH based on summation curve and basin lag by analysing UH for 58 basins in Illinois from 10 to 3,090 mi². Several approaches were offered for developing SUH under each of the three situations, wherein: (1) lag was known (2) lag was computed from time to peak (3) lag is computed from the drainage area. The 3rd condition applies when a UH for a watershed area must be derived using only the information to be created on a topographic map. Mitchell also developed the three-summation curve based on the basin's size: $A < 175$ mi², 175 mi² $< A < 750$ mi² and $A > 750$ mi². Mitchell suggested Equations (23)–(27) for the determination of Lag time (h) (t_L), Peak discharge (ft³/s) (Q_p), Time to peak (h) (t_p) and Base time (h) (t_b).

$$t_L = 2.80 t_p^{0.81} \quad (23)$$

$$t_L = 1.05A^{0.6} \quad (24)$$

where, A = Watershed area (mi²).

$$Q_p = \frac{An_d}{0.03719} \quad (25)$$

where, n_d = number of intervals per day

$$t_p = t_L + \frac{D}{2} \quad (26)$$

where, D = Excess-rainfall unit duration (h)

$$t_b = 2.67t_p \quad (27)$$

Central water commission (CWC) method

Central Water Commission (1993) has also developed an empirical method for India's basin. Then, Lag time (h) (t_L), Maximum (peak) discharge per unit area (m³/s) (q_p), Width at 50% of maximum (peak) discharge ordinate (h) (W_{50}), Width at 75% of peak discharge ordinate (h) (W_{75}), Width of the rising side at 50% of peak discharge ordinate (h) (W_{R50}), Width of the rising side at 75% of peak discharge ordinate (h) (W_{R75}), Base time (h) (t_b), Time to peak (h) (t_p), and Peak discharge (m³/s) (Q_p) are determined by Equations (28)–(36).

$$t_L = 0.257A^{0.409}S^{0.432} \quad (28)$$

where, A = Watershed area (km²), S = Equivalent stream slope (m/km).

$$q_p = \frac{2.165}{t_L^{0.893}} \quad (29)$$

$$W_{50} = \frac{2.654}{q_p^{0.921}} \quad (30)$$

$$W_{75} = \frac{1.672}{q_p^{0.816}} \quad (31)$$

$$W_{R50} = \frac{1.245}{q_p^{0.571}} \quad (32)$$

$$W_{R75} = \frac{0.816}{q_p^{0.559}} \quad (33)$$

$$t_b = 6.299t_L^{0.612} \quad (34)$$

$$t_p = t_L + \frac{D}{2} \quad (35)$$

where, D = Excess-rainfall unit duration (h).

$$Q_p = q_p A \tag{36}$$

Efficiency criteria

The Presentation and evaluation of efficiency criteria are carried out in this part of the study. These are a few efficiency criteria: Pearson Coefficient (r), Correlation Coefficient (r^2), Nash Sutcliffe Efficiency (E), Index of Agreement (d), Kling-Gupta Efficiency (KGE), Root Mean Square Error ($RMSE$), Normalized Root Mean Square Error ($NRMSE$) and Mean Absolute Error (MAE), which are used in the present study (Table 1).

Table 1 | Efficiency criteria

Efficiency criteria	Formula
Pearson coefficient (r)	$r = \frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \tag{37}$
	Where, O_i = observed value, P_i = predicted value \bar{O} = average of observed values and \bar{P} = average of predicted values.
Correlation Coefficient (r^2)	$r^2 = \left(\frac{\sum_{i=1}^n (O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum_{i=1}^n (O_i - \bar{O})^2} \sqrt{\sum_{i=1}^n (P_i - \bar{P})^2}} \right)^2 \tag{38}$
Nash Sutcliffe Efficiency (E)	$E = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (O_i - \bar{O})^2} \tag{39}$
Index of Agreement (d)	$d = 1 - \frac{\sum_{i=1}^n (O_i - P_i)^2}{\sum_{i=1}^n (P_i - \bar{O} + O_i - \bar{O})^2} \tag{40}$
Kling-Gupta efficiency (KGE)	$KGE = 1 - \sqrt{(r - 1)^2 + \left(\frac{\sigma_P}{\sigma_O} - 1\right)^2 + \left(\frac{\mu_P}{\mu_O} - 1\right)^2} \tag{41}$
	Where; r = Pearson coefficient, σ_P = standard deviation of predicted values, σ_O = standard deviation of observed values, μ_P = mean of predicted values and μ_O = mean of observed values.
Mean Absolute Error (MAE)	$MAE = \frac{1}{n} \sum_{i=1}^n O_i - P_i \tag{42}$
Root Mean Square Error ($RMSE$)	$RMSE = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_i)^2} \tag{43}$
Normalised Root Mean Square Error ($NRMSE$)	$MBE = \frac{1}{n} \sum_{i=1}^n O_i - P_i \tag{44}$

Compound factor (CF) model

The CF model was used to rank the methods with the help of Multiple Criteria Decision Making (MCDM). The CF model is based on the knowledge-driven approach principle (Todorovski & Džeroski 2006). It changes qualitative understanding into a quantitative estimation of the phenomenon (Hembram & Saha 2018). In this method, ranking is based on the efficiency criteria of different methods. The total rank numbers provided in this model are based on several methods. Ranks have been provided from one to five as the study uses five methods. Rank one was provided so that the efficiency criteria value represents the highest precision to be observed and rank five represents the minimum precision. The CF values are the average of all method ranks. It reflects the collective effect on the precision of a method of all efficiency criteria. It can be expressed in Equation (45). However, the CF model has some inherent disadvantages; for example, it assigns a lumped value for efficiency criteria

of the SUH method and it can only be used in a comparison study as has been done in this study. Further, it also imparts the same weightage to all the efficiency criteria involved, which in some cases can exaggerate the final output. However, in the absence of robust numerically or physically based models, which often relies on the detailed estimation and parameterization of the processes involved, the *CF* model is one of the best models to compare land surface processes between similar entities. Due to this reason, various researchers have extensively used the *CF* model for sustainable planning and management in regions of data scarcity. *CF* model has been used by Hembram & Saha (2018) for soil erosion, Patel *et al.* (2012) for water harvesting structure positioning, and Kadam *et al.* (2017) for plant growth potential. However, the *CF* model has been used for the first time in the field of SUH. This is the main highlight of the current study.

$$CF = \frac{1}{n} \sum_{i=1}^n R \quad (45)$$

where; R = rank of the efficiency criteria.

RESULTS AND DISCUSSION

In the present study, the optimum number of RGS and UH derived for an isolated storm event (22/07/2017–31/07/2017) was carried out for RRB. As rainfall and discharge data were available hourly, selecting the UH duration as one hour was possible. Hourly rainfall and hourly discharge data were analysed by the single-event method to derive the UH. Results showed considerable variation in peak discharge and the peak time for the storm event.

Optimum number of RGS

According to Indian Standard 4987:1994, a single RGS is required within 750 km², 100–250 km², and 1,500–10,000 km² for plain, hilly and arid regions. The basin area of the RRB is 1,455 km², and the total available RGS are two only (Table 2 and Figure 3). So, the average area per RGS is 727.5 km². RRB lies between the flat as well as the hilly region. The average elevation is 400 m from the mean sea level. Thus, the existing two RGS are not enough for estimating the average rainfall of the basin within an allowable error of 10%. According to Equations (1)–(5), $\bar{P} = 445.8$, $\bar{P}^2 = 202,107.1$, $\sigma = 82.55$, $C_v = 18.52$ and $N = 3.5$, the optimum number of RGS should be at least four. Hence, two extra RGS are required within the basin.

Table 2 | Average annual rainfall of RGS

No.	Station name	Taluka	Average annual rainfall (mm)
1	Bapla	Dhanera	504
2	Naroli	Tharad	387

The isohyetal map has been plotted at an equal interval. The developed isohyetal map was also compared with the annual rainfall map of the India Meteorological Department Pune (2012). The isohyetal map was very similar to IMD. So, this isohyetal map can be used for further study. Isohyetal lines for 387 mm, 411 mm, 445, 479 and 504 mm are shown in Figure 4. The proportionate area is determined by the area of that zone divided by the basin's total area. The proportionate area then determines the required RGS for the zone into the optimum number of RGS for the entire basin. Bapla and Tharad RGS are already situated in Zones X4 and X1, respectively. Tables 3 and 4 show that new RGS are provided in X2 and X3. In both zones, one RGS will be provided for each.

Thi Hong *et al.* (2016) had established an optimum RGS network on the Vu Gia-Thu Bon river basin to develop an up-to-date flood warning system in real-time in Vietnam. According to the investigation, the study area had nine RGS, which showed that the existing network's error was approximately 7.47%. If the error decreases from 7.47% to 5%, the additional RGS should be twenty. Similarly, Patel (2018) had also analysed the optimum number of RGS in the Sabarmati River Basin, India. According to the analysis, the study's optimal number of RGS was thirty-seven, while the existing number of RGS was thirty-one. So, six additional RGS are required.

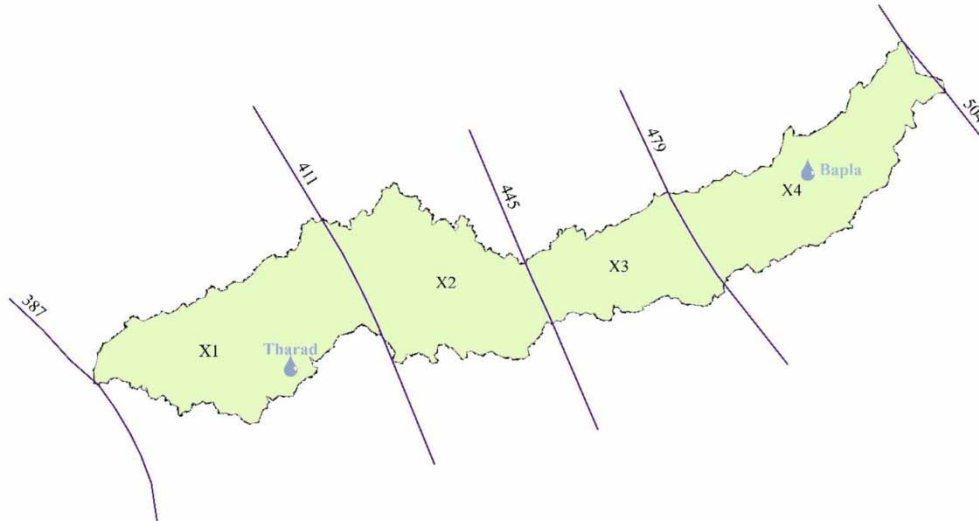


Figure 4 | Distribution of RGS in RRB.

Table 3 | RGS in different isohyetal zone

Zone	Area (km ²)	Proportionate area	RGS required
X1	454	0.31	1.25
X2	372	0.26	1.02
X3	240	0.17	0.66
X4	388	0.27	1.07
Total	1,455	1.00	4.00

Table 4 | Existing/additional/total RGS in each isohyetal zone

Zone	Existing RGS	Additional RGS	Total RGS
X1	1	0	1
X2	0	1	1
X3	0	1	1
X4	1	0	1
Total	2	2	4

SUH methods

These methods were used to calculate the lag time, peak discharge, base time and the widths of peak flow with the help of basin characteristics, which were acquired from the topographic map of the river basin (Ramirez 2000). The parameters were obtained in a GIS environment. The UH of SW1 and the SUH of SW2 and SW3 was developed (Figure 3). SW1 has RGS only. SW2 has neither RGS nor SDS, and SW3 has SDS only (Table 5). Table 6 and Figure 5 show the UH property for each SW and method.

The ordinates of UH were used to generate the direct runoff hydrographs (DRH) due to total precipitation over the basin. DRH is derived by multiplying the UH ordinates by incremental precipitation excess, adding and lagging in an arrangement to generate a storm hydrograph. This is also called hydrograph convolution (Salami *et al.* 2009). The incremental precipitation was determined by consecutively deducting the precipitation excess from the earlier time events. The combined storm hydrograph of SW1, SW2 and SW3 are shown in Figure 6. The rainfall of Bapla RGS is used for SW1. Bapla village is located under SW1, which has RGS. However, for SW2 and

Table 5 | Basin parameters generated from toposheet

Parameters	SW1	SW2	SW3
RGS availability	Yes	No	No
SDS availability	No	No	Yes
L (km)	37.70	19.47	18.11
L_c (km)	27.66	13.98	13.55
Average slope of the main channel (S)	0.0035	0.00344	0.00226
A (km ²)	174.45	138.61	94.09

Table 6 | UH component of all SUH methods

Method	Component	SW1	SW2	SW3
Snyder	t_p (hr)	13.88	10.27	10.05
	t_b (hr)	104.65	93.82	93.15
	Q_p (m ³ /s)	77.39	92.01	64.43
	W_{50} (hr)	14.11	9.13	8.83
	W_{75} (hr)	8.06	5.22	5.05
TS	t_p (hr)	11.75	12.98	16.14
	t_b (hr)	64.07	70.80	88.05
	Q_p (m ³ /s)	74.46	87.52	59.98
	W_{50} (hr)	14.71	9.64	9.54
	W_{75} (hr)	8.41	5.51	5.45
SCS	t_p (hr)	17.18	11.48	12.80
	t_b (hr)	45.86	30.64	34.18
	Q_p (m ³ /s)	53.74	63.91	38.89
	W_{50} (hr)	20.92	13.54	15.23
	W_{75} (hr)	11.96	7.73	8.70
Mitchell	t_p (hr)	16.13	14.44	12.07
	t_b (hr)	43.06	38.55	32.21
	Q_p (m ³ /s)	102.57	81.50	55.32
	W_{50} (hr)	10.41	10.41	10.41
	W_{75} (hr)	5.95	5.95	5.95
CWC	t_p (hr)	4.15	3.79	2.85
	t_b (hr)	13.90	13.07	10.62
	Q_p (m ³ /s)	118.95	103.48	95.10
	W_{50} (hr)	3.78	3.47	2.63
	W_{75} (hr)	2.29	2.12	1.66

SW3, the same rainfall data was used because SW2 and SW3 did not have RGS. Nearly all the SW have similar characteristics. These three hydrographs were generated for the upstream part of the entire basin. At some distance from downstream, the flows of two tributaries of SW1 and SW2 meet at a junction, namely Mevada village. Mevada was the most affected area of the 2017 flood because of this confluence. Now, the total flow from Mevada to Dhanera is the summation of these three hydrographs.

Snyder's method

The t_p (h), t_b (h) and Q_p (m³/s) were calculated for all the sub-watersheds using Snyder's formula (Equations (6)–(9)). In this method, t_p was calculated from t_L . The t_L was introduced by Horner (1936). The t_L was assumed constant for a particular watershed. The main affecting factors for t_L are the area and the shape of the basin. The C_t takes care of the slopes and storage variations and has not changed significantly in the basin. After a lot of trial-and-error processes, the values of C_t and C_p were fixed for all the sub-watersheds as 1.8 and 0.69, respectively. Generally, C_t and C_p have an inverse relation; that is, if C_t was maximum then C_p would become minimum or vice versa. A similar relationship was observed in this study too. The primary purpose of fixing the values

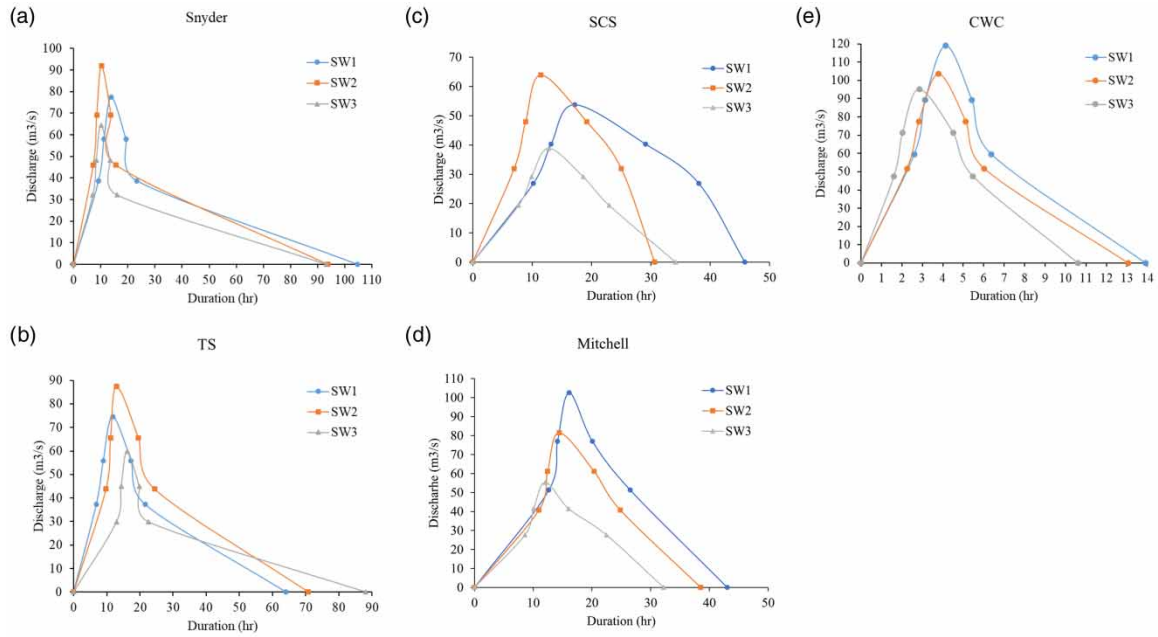


Figure 5 | UH of (a) Snyder’s method (b) TS method (c) SCS method (d) Mitchell’s method (e) CWC method for SW1, SW2 and SW3 in RRB.

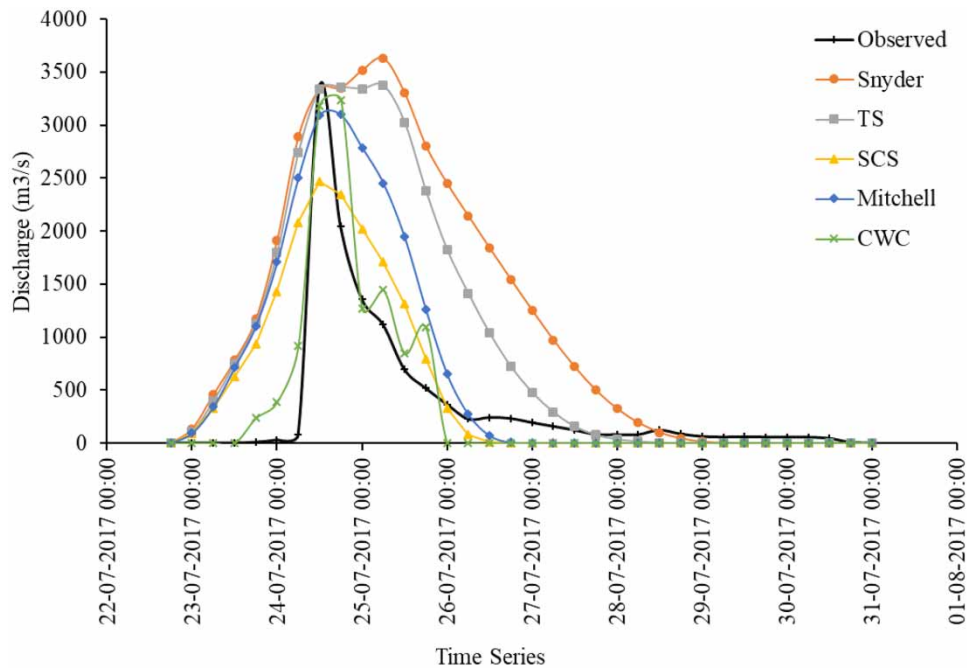


Figure 6 | Direct runoff hydrograph of all methods for RRB.

of C_t and C_p was to get simulated discharge closer to the observed discharge. For SW1, the values of t_p , t_b and Q_p were 13.88 h, 104.65 h and 77.39 m³/s. For SW2, the values of t_p , t_b and Q_p were 10.27 h, 93.82 h and 92.01 m³/s. For SW3, the values of t_p , t_b and Q_p were 10.05 h, 93.15 h and 64.43 m³/s. Established UH and SUH ordinates were used to develop the storm hydrograph with actual precipitation over the basin. Prajapati & Subbaiah (2005) had also compared the different SUH models and identified Snyder as the best suitable method due to having the highest efficiency (88.03%) for the Rawat Sagar Basin.

Taylor and Schwarz (TS) method

No big streams or other unusual features in the basin are shown in the existing toposheet. Therefore, the specified method can be applied without modification. The values of A, L and L_c were taken from the SOI toposheet for all

sub-watersheds (Table 5). The average slope (S_e) of the main flow path was determined from Equation (12). The values of S_e were 0.0035, 0.00344 and 0.00226 for SW1, SW2 and SW3 respectively. The t_p (h) and Q_p (m^3/s) were calculated for all the sub-watersheds using the TS formula (Equations (12)–(16)). First of all, Q_p was obtained in ft^3/s . Then, it was converted into m^3/s for comparison with other methods. For SW1, the values of t_p and Q_p were 11.75 h and $74.46 m^3/s$. For SW2, the values of t_p and Q_p were 12.98 h and $87.52 m^3/s$. For SW3, the values of t_p and Q_p were 16.14 h and $59.98 m^3/s$. The UH was completed by t_b , W_{50} , W_{75} , and Q_p . The values of t_b were 64.07, 70.80 and 88.05 for SW1, SW2 and SW3, respectively. Velez & Botero (2011) had estimated the time of concentration and the lag time using different empirical methods at San Luis Creek Basin, Manizales, and concluded that the TS method also gave similar results to Snyder's method.

Soil conservation service (SCS) method

In this method, first, S (in percentage) and CN were determined. The values of S were 0.35, 0.34 and 0.23 for SW1, SW2 and SW3, respectively. After much trial-and-error process, the values of CN were fixed for all the sub-watersheds. The t_p (h), t_b (h) and Q_p (m^3/s) were calculated for all the sub-watersheds using the TS formula (Equations (18)–(22)). For SW1, the values of t_p , t_b and Q_p were 17.18 h, 45.86 h and $53.74 m^3/s$. For SW2, the values of t_p , t_b and Q_p were 11.48 h, 30.64 h and $63.91 m^3/s$. For SW3, the values of t_p , t_b and Q_p were 12.80 h, 34.18 h and $38.89 m^3/s$. Salami *et al.* (2009) had also evaluated different SUH methods for the development of storm hydrographs for eight rivers in south-west Nigeria. They summarised that the SCS method was best due to the lowest percentage difference for the study area.

Mitchell's method

Equations (23) and (24) are used generally for the calculation of t_L . But in this study, t_p was not known so Equation (24) was used for the calculation of t_L . The values of t_L were 13.13, 11.44 and 9.07 for SW1, SW2 and SW3, respectively. The t_p (h), t_b (h) and Q_p (m^3/s) were calculated for all the sub-watersheds using the TS formula (Equations (23)–(27)). For SW1, the values of t_p , t_b and Q_p were 16.13 h, 43.06 h and $102.57 m^3/s$. For SW2, the values of t_p , t_b and Q_p were 14.44 h, 38.55 h and $81.50 m^3/s$. For SW3, the values of t_p , t_b and Q_p were 12.07 h, 32.21 h and $55.32 m^3/s$. Patel & Thorvat (2016) had worked on the different SUH methods at the Upper Kumbhi Basin and the Dhamani Basin, Maharashtra, India. They found that Mitchell's method was provided with a percentage error of 11.361% (still within the range of error) for the study area.

Central water commission (CWC) method

The t_p (h), t_b (h) and Q_p (m^3/s) were calculated for all the sub-watersheds using the CWC formula (Equations (28)–(36)). The results indicate that the UH parameter values are determined with the CWC method. The relation of these parameters with basin characteristics is presented in Tables 5 and 6. For SW1, the values of t_p , t_b and Q_p were 4.15 h, 13.90 h and $118.95 m^3/s$. For SW2, the values of t_p , t_b and Q_p were 3.79 h, 13.07 and $103.48 m^3/s$. For SW3, the values of t_p , t_b and Q_p were 2.85 h, 10.62 h and $95.10 m^3/s$. Reddy *et al.* (2019) had worked on the different SUH methods for flood estimation at the ungauged catchments of the west coast of Karnataka, India. They identified that the CWC is also a suitable method for the study area.

Efficiency criteria

In this part, all the methods were evaluated through eight efficiency criteria, and bold text shows the best result for the efficiency criteria (Table 7).

Pearson coefficient (r)

This is the statistical test that quantifies the statistical relationship between two continuous variables. It is based on covariance. It gives the magnitude as well as the direction of the relationship (Equation (37)). It ranges between +1 and -1, where +1 is a total positive correlation, 0 is no correlation, and -1 is a total negative correlation. Pearson coefficients for Snyder, TS, SCS, Mitchell and CWC methods were 0.69, 0.74, 0.76, 0.77 and 0.89, respectively. The best Pearson coefficient was achieved for the CWC method because it is closer to 1, and the worst Pearson coefficient was achieved for Snyder's method because it is nearer to 0.

Correlation coefficient (r^2)

According to Bravais Pearson, it is the squared value of the Pearson coefficient. It can also be expressed as the squared ratio of covariance to multiplying with the standard deviation (Equation (38)). The range lies between 0

Table 7 | Efficiency criteria for all SUH methods

Efficiency criteria	Methods				
	Snyder	TS	SCS	Mitchell	CWC
r	0.69	0.74	0.76	0.77	0.89
r^2	0.47	0.54	0.58	0.59	0.79
E	-2.39	-1.32	0.38	-0.15	0.59
d	0.60	0.69	0.85	0.80	0.92
KGE	-0.06	0.03	0.55	0.24	0.52
MAE	870.75	656.43	323.16	438.15	243.33
$RMSE$	1,268.79	1,050.20	543.40	737.80	427.11
$NRMSE$	3.62	3.00	1.55	2.11	1.14

Bold values indicate best result for the efficiency criteria.

and 1. A zero value indicates no correlation at all, and a value of one means perfect correlation. One of the major disadvantages is that it quantifies only dispersion. A model which has systematic dispersion all the time will give a good r^2 value (≈ 1). Correlation coefficients for Snyder, TS, SCS, Mitchell and CWC methods were 0.47, 0.54, 0.58, 0.59 and 0.79 respectively. The best correlation coefficient was achieved for the CWC method because it is closer to 1, and the worst correlation coefficient was achieved for Snyder's method because it is nearer to 0.

Nash-Sutcliffe efficiency (E)

This was proposed by Nash & Sutcliffe (1970). It is defined as one minus the ratio of the sum of the squared difference between observed and predicted values to the variance observed values (Equation (39)). The range lies between 1 and $-\infty$. A value of one indicates a perfect fit for observed and predicted values. The biggest drawback is that the differences between observed and predicted values are determined as squared. So similar to r^2 , E is not very sensitive to systematic dispersion. Nash-Sutcliffe efficiency for Snyder, TS, SCS, Mitchell and CWC methods was -2.39, -1.32, 0.38, -0.15 and 0.59. The best Nash-Sutcliffe efficiency was achieved for the CWC method because it is nearer to 1, and the worst Nash-Sutcliffe efficiency was achieved for Snyder's method because of the maximum negative value.

Index of agreement (d)

It was proposed by Willmott (1981) to overcome the insensitivity of r^2 and E. It is the ratio of mean square error to the potential error (Equation (40)). The denominator represents the largest value that the squared difference of each pair can attain. The numerator is very sensitive to high values and insensitive for low values. The range of d is 0 (no correlation) to 1 (perfect fit). The Index of agreement for Snyder, TS, SCS, Mitchell and CWC methods was 0.60, 0.69, 0.85, 0.80 and 0.92. The best Index of agreement was achieved for the CWC method because it is nearer to 1, and the worst Index of agreement was achieved for Snyder's method because it is nearer to 0.

Kling-Gupta efficiency (KGE)

This was proposed by Gupta *et al.* (2009). It provides a diagnostically interesting decomposition of the E (and hence MSE), which helps to study the relative importance of its different components like correlation, bias, and variability (Equation (41)). The range lies between 1 and $-\infty$. A value of one indicates a perfect fit for the observed and predicted values. KGE for Snyder, TS, SCS, Mitchell and CWC methods was -0.06, 0.03, 0.55, 0.24 and 0.52. The best KGE was achieved for the SCS method because it is nearer to 1, and the worst KGE was achieved for Snyder's method because of the negative value.

Mean absolute error (MAE)

This is the most straightforward measure of prediction correctness. MAE is straightforward, as the name recommends, the mean of the absolute errors. The absolute error is the absolute difference between the predicted and the observed value (Equation (42)). MAE expresses how big an average error can be expected from the prediction without considering their direction. The MAE can range from 0 to ∞ . A value of zero indicates a perfect fit for the observed and predicted values. MAE for Snyder, TS, SCS, Mitchell and CWC methods were 870.75, 656.43, 323.16, 438.15 and 243.33. Compared with each other, the best MAE was achieved for the CWC method because it is nearer to 0, and the worst MAE was achieved for Snyder's method because of the maximum value.

Root mean square error (RMSE)

The RMSE is a frequently used specific metric between the predicted values and the observed values. These individual differences are also called residuals, and they are aggregated in a single predictive power measure by the RMSE (Equation (43)). RMSE measures the error level between two sets of data. The RMSE can range from 0 to ∞ . A value of zero indicates a perfect fit for the observed and predicted values. RMSE for Snyder, TS, SCS, Mitchell and CWC methods were 1,268.79, 1,050.20, 543.40, 737.80 and 427.11, respectively. Compared with each other, the best RMSE was achieved for the CWC method because it is nearer to 0, and the worst RMSE was achieved for Snyder's method because of the maximum value.

Normalized root mean square error (NRMSE)

The NRMSE enables the comparison of models with distinct scales. Therefore, the NRMSE can be interpreted as a fraction of the overall range, which the model typically resolves (Equation (44)). The NRMSE can range from 0 to ∞ . A value of zero indicates a perfect fit for the observed and predicted values. The NRMSE for Snyder, TS, SCS, Mitchell and CWC methods was 3.62, 3.00, 1.55, 2.11 and 1.14. The best NRMSE was achieved for the CWC method because it is nearer to 0, and the worst NRMSE was achieved for Snyder's method due to the maximum value.

Compound factor (CF) model

The CF was used to assess all methods' priority ranks, determined by Equation (45). From this group of methods, the first rank was assigned to the method having the lowest CF and so on. Further, the CF ranked these methods into 1–5. The CFs for Snyder, TS, SCS, Mitchell and CWC methods were 5, 4, 2.13, 2.75 and 1.13. So, the rankings for Snyder, TS, SCS, Mitchell and CWC methods were 5, 4, 2, 3 and 1, respectively. According to the ranking, the method of CWC is the best suitable method for predicting runoff for the RRB because of the minimum CF value (Table 8). The hydrograph shape of CWC is similar to the observed hydrograph. The peak time difference between observed and CWC is also minimum (Figure 5). So, due to these all factors, the CWC method is best for RRB for SUH generation.

Table 8 | Ranking of SUH methods using CF model

Efficiency criteria	Methods				
	Snyder	TS	SCS	Mitchell	CWC
r	5	4	3	2	1
r^2	5	4	3	2	1
E	5	4	2	3	1
d	5	4	2	3	1
KGE	5	4	1	3	2
MAE	5	4	2	3	1
$RMSE$	5	4	2	3	1
$NRMSE$	5	4	2	3	1
CF	5	4	2.13	2.75	1.13
Ranking	5	4	2	3	1

CONCLUSIONS

In the present study, the optimum number of RGS was determined. The empirical methods were used to establish the relationship between several variables that synthesise unit hydrograph for the RRB. Two RGS already existed, which was not sufficient. Indian Standard 4987:1994 suggests that two more RGS are required for carrying out meaningful rainfall analysis. This study also illustrates the CF-based ranking of methods. The CF is minimum (1.13) and maximum (5.0) for the CWC and Snyder methods. Minimum CF indicates the highest ranking. The simulated hydrograph shape is similar to the observed hydrograph shape, the peak time difference between observed and simulated is minimum and the CF value is also minimum for CWC method. This study recommended using the CWC method, which is found to be the most appropriate SUH method for the RRB. The computed flood discharges could be used as the primary input in the

hydraulic model, which is seldom available along the semi-arid river basin. This study will help in the planning of flood mitigation and water conservation measures for data-scarce regions. The lack of flood data is a basic limitation for hydrological studies and hydrologic modelling in this study area. In fact, many past floods have not been recorded by hydrometric stations. So, this analysis is only subjected to the 2017 flood event. The present study can be further refined by considering more catchments of varying sizes and geomorphologic conditions.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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First received 27 July 2021; accepted in revised form 19 November 2021. Available online 1 December 2021