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Estimation of Catchment Parameters of Snyder's Synthetic Method for Water Resources Planning and Flood Management in Sri Lanka

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Abstract: Snyder's synthetic unit hydrograph method is widely recognized for synthesizing unit hydrographs. This paper illustrates a study demonstrating how to estimate catchment parameters using Snyder's synthetic method for hydro-meteorological stations maintained by the Irrigation Department and its application to Sri Lanka. Updated Snyder's Unit Hydrograph parameters, including coefficient accounting for flood wave and storage condition (C_p) and coefficient representing variations of catchment slop and storage (C_t) for 15 river gauge stations spread across the island, have been presented in this paper. The C_p values vary from 0.22 to 0.7, and the C_t values vary from 0.48 to 5.76. Updating the Snyder parameters is a long-term requirement, and these values can be used to update the previous values estimated in 1980.

Keywords: Snyder’s method, Unit hydrograph, Direct runoff hydrograph

1. Introduction

The demand for water is continuously increasing as population and development increase. More and more water resource development needs to be implemented to conserve existing water sources and face the increasing demand and problems that may arise [1]. Similarly, floods constitute one of the most devastating natural disasters and have a negative impact on socio-economic infrastructure in many countries. An area of debate is how to deal with the effects of climate change on the hydrological cycle and, in particular, precipitation, the statistical properties and seasonality of runoff, and the resulting discharge into rivers [2]. In order to deal with the increasing demand and the impacts of climate change in the future, infrastructure for water resource management has to be developed. The flood hydrograph is the most essential component of water-related structural design. A hydrograph is the graph of runoff measured at the stream-gauging station with time[3]. The most common approach is creating a design flood hydrograph utilizing historical flow data accessible over a more extended period. Precipitation and runoff data are needed to develop the hydrograph of a basin or watershed unit. However, this data is only available in some parts of the world. In most of the areas, these data are not available [3]. Due to the lack of gauging stations, this condition is frequent along many rivers and streams worldwide.

Hence, hydrological engineers have employed synthetic means to produce a flood hydrograph to address this issue in ungauged watersheds. The concept of the synthetic unit hydrograph may be traced back to the 1930s, which was developed to synthesize the Unit Hydrograph (UH) using watershed parameters rather than rainfall-runoff data[4].
The runoff is classified as direct runoff and base flow based on the time delay between the precipitation and the runoff. Direct runoff hydrograph (DRH) is developed via unit hydrograph. A unit hydrograph is a direct runoff hydrograph produced by one unit of constant intensity and uniform rainfall falling evenly across the catchment. The unit hydrographs in synthetic hydrographs are developed using empirical equations with regional validity that relate the hydrograph features to the basin characteristics.

Unit hydrographs have been created using synthetic approaches and there are a number of Synthetic Unit Hydrograph (SUH) techniques

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that have been used in ungauged catchments to develop UH[5]. In 1932, Sherman introduced the first version of the unit hydrograph theory. Since then, Snyder's method[6], Taylor and Schwarz's model, Soil Conservation Service (SCS) method, Time-Area (Clerk in 1945), and Gray's methods are some of the popular SUH approaches used to develop UH[5]. In 1938 Snyder developed a set of empirical equations for SUH in large numbers of catchments in the Appalachian Highland of the eastern United States[4], [6], [7], [8]. The SUH method has better acceptability for ungauged basins[7]. Snyder's Synthetic Unit Hydrograph (SSUH) is based on the characteristics of a standard UH.

Sri Lanka is an island in the Indian Ocean, south of India. Sri Lanka is prone to annual flooding due to high rainfall intensities enhanced by cyclones from the Bay of Bengal. Due to the location of Sri Lanka in the Indian Ocean between the Bay of Bengal and the Gulf of Mannar, the pressure variations with high winds develop heavy rainfalls[9]. As seasonal rains, there are two monsoonal and two inter-monsoonal showers of rain in a year, namely, the First inter-monsoon (FIM), Southwest monsoon (SWM), Second inter-monsoon (SIM), and Northeast monsoon (NEM)[9]. For design purposes and flood forecasting, unit hydrograph theory is realistically applied in generating flood hydrographs caused by heavy rainfall in watersheds for ungauged basins of Sri Lanka. Catchment parameters for Snyder's method were developed in early 1980 by the Irrigation Department of Sri Lanka for 20 river basins[10], [11], [12].An update has yet to be made since then. Land use patterns and climate factors have changed drastically. Accordingly, Snyder's Unit Hydrograph parameters have to be updated.

River Basin Management has gained importance in managing floods and improving water resources to generate income through agriculture and hydropower. Despite Sri Lanka having 103 significant river basins, only 20 have been gauged. As most of the gauged basins are found in the wet zone, most of the basins in the country are ungauged. Hence, synthetic methods have to be utilized for estimating unit hydrographs (subsequently design, flood hydrographs) for water-related structural design. From 1989 to date, the Irrigation Department of Sri Lanka has constructed more than 15 major reservoirs and has used the Snyder method to estimate flood hydrographs.

This study used Snyder's synthetic unit hydrograph method to derive unit hydrographs for existing river gauges and then estimated Snyder's synthetic unit hydrograph parameters. This paper provides a prominent method for developing catchment parameters for SSUH.

2. Study Area

There are about 40 river gauging stations maintained by the Irrigation Department. However, in this study, only 15 hydrological stations were selected to estimate the Snyder parameters. These hydrometeorological stations were selected by considering the data availability required for calculating the lag coefficient (Ct) which depends on the catchment properties and peak flow coefficient (Cp) which depends upon the catchment characteristics. The locations of hydrological stations are shown in Figure 1.

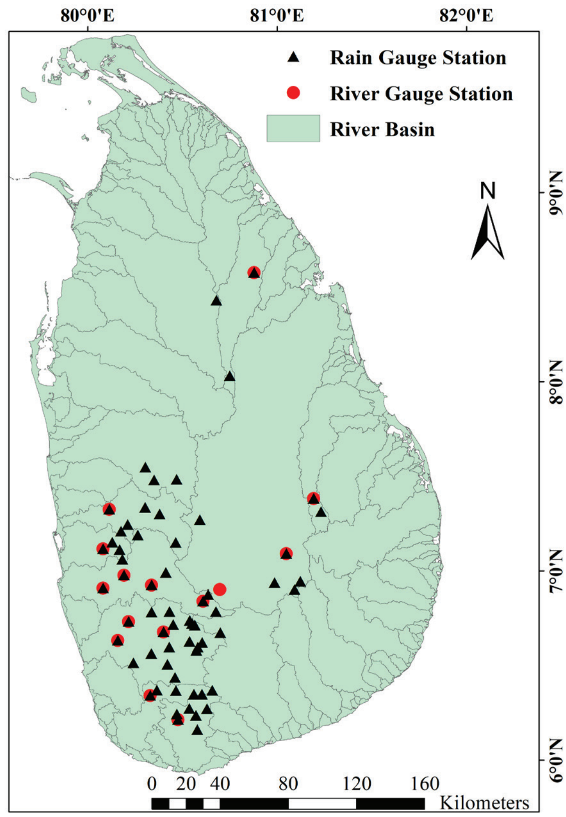

Figure 1 – Locations of the River Gauge and Rainfall Stations

3. Materials and Methods

The data used for the study were SRTM Digital Elevation Model (DEM) data and historical river flow data obtained from 15 river gauges. These river flow data were the extreme events recorded during the last 42 years (1980-2022). The event duration was selected considering the duration of each extreme event. The study area's SRTM Digital Elevation Model data was downloaded, and hydraulic data were extracted using the spatial analyst tools of ArcGIS. Precipitation and hydrological data were acquired from the Hydrology and Disaster Management Division of the Irrigation Department, Sri Lanka.

In this study, Hourly rainfall data corresponded to hourly discharged data of selected gauging stations, and daily rainfall of other nearest gauging stations of the same duration was used to obtain observed DRH. Thiessen polygon analysis was used to determine the areal significance to point rainfall of the catchment for modeling the basins. In addition, the catchment area, length of the longest water stream (L), and distance along the main stream from the gauging station to the point close to the catchment centroid (Lc) were calculated using Arc GIS software. Initial rainfall data was screened using the method adopted by Iresh (2020)[13].

Then, the flood hydrograph was created using available discharge data to separate the base flow and obtain observed DRH. The base flow was separated using the straight-line method. For more details on base flow separation, the reader may read Gonzales et al. (2009)[14]. To obtain the derived DRH, we must multiply the UH coordinates into effective rainfall. DRH and Effective Rainfall Hyetograph (ERH) are graphs that represent the rainfall and river flow of the same flood event.

The area of ERH multiplied by the catchment area gives the total volume of direct runoff, which is the same as the area of DRH. With the use of available data, DRH was derived. The index was calculated using the observed total rainfall and effective rainfall[15].

$$\text{Ø}_{\text{Index}} = \frac{\text{Losses}}{\text{Time}} \quad \ldots (1)$$

Hourly effective rainfall during the storm was estimated using the recorded rainfall for the respective event. The DRH has been derived using UH ordinates. In this study, rainfall excess in each 1-hour duration is operated upon the unit hydrograph successively to get the various DRH curves. The ordinates of these DRHs are lagged to obtain the proper time sequence. They were collected and added at each time element to obtain the required net DRH due to the storm[15].

Let U1, U2, U3, and U4 be ordinates of UH, and R1, R2, and R3 are the magnitude of the excess rainfall for the 1-hour time step. The corresponding ordinates of the DRH Q_1, Q_2, $Q_3$to Q_7 can be obtained[15].

$$Q_0 = 0 \quad \ldots (2)$$

$$Q_1 = R1.U1 \quad \ldots (3)$$

$$Q_2 = R2.U1+R1.U2 \quad \ldots (4)$$

$$Q_3 = R3.U1+R2.U2+R1.U3 \quad \ldots (5)$$

$$Q_4 = 0+R3.U2+ R2.U3+ R1.U4 \quad \ldots (6)$$

$$Q_5 = 0+0+ R3.U3+ R2.U4 \quad \ldots (7)$$

$$Q_6 = 0+0+0+ R3.U4 \quad \ldots (8)$$

$$Q_7 = 0 \quad \ldots (9)$$

In late 1960, Synder's parameters for 21 gauging sites were estimated by Ranthunga and Jayaratna; according to their study, they modified the formulas for the Sri Lankan catchments. Snyder's formulas are given in the following equation for unit hydrograph.

$$T_p = C_t*(L\ L_c)^{0.3} \quad \ldots (10)$$

where,

T_p is Basin lag (hours),C_t is Model parameter,L is the length of the longest stream (km), L_c is the distance along the main stream from the gauging station toa point close to the catchment centroid (km).

$$Q_n = \frac{C_p x\ 2.78\ x\ A}{T_n} \quad \ldots (11)$$

where;

Q_p=Peak discharge of unithydrograph(m^3s^{-1})

A=Catchment area (km^2)

C_p=Model parameter

As previously mentioned[15], base length of UH (T) is given by;

$$T = \frac{B+CxT_p}{24}\text{days} \quad \ldots (12)$$

For the Sri Lankan Catchments,

B = 0.77

C = 2.92

T_p = Basin lag in hours

Width of the UH (W) is given by,

$$W_{50\%} = 5.87(Q_p/A)^{-1.08} \text{ (hours)} \quad \ldots (13)$$

This method compared the observed (DRH) and the DRH derived using SSUH. The two DRHs were compared for several C_p and C_t values. Hence, the two graphs were validated using the Nash Sutcliffe Efficiency (*NSE*) statistical index. Step by step methodology adopted for this study is given in Figure 2.

3.1 Nash Sutcliffe Efficiency (*NSE*)

Nash-Sutcliffe Efficiency (*NSE*) is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance [16]. This research used *NSE* to validate the results by comparing the corresponding synthetic DRH with the observed DRH for specific flood events.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(OBS_i - SIM_i)^2}{\sum_{i=1}^{n}(OBS_i - \overline{OBS})^2} \quad \ldots (14)$$

$OBSi$ = Observation value
$SIMi$ = Forecast value
$\overline{OBS}$ = Average of observation values

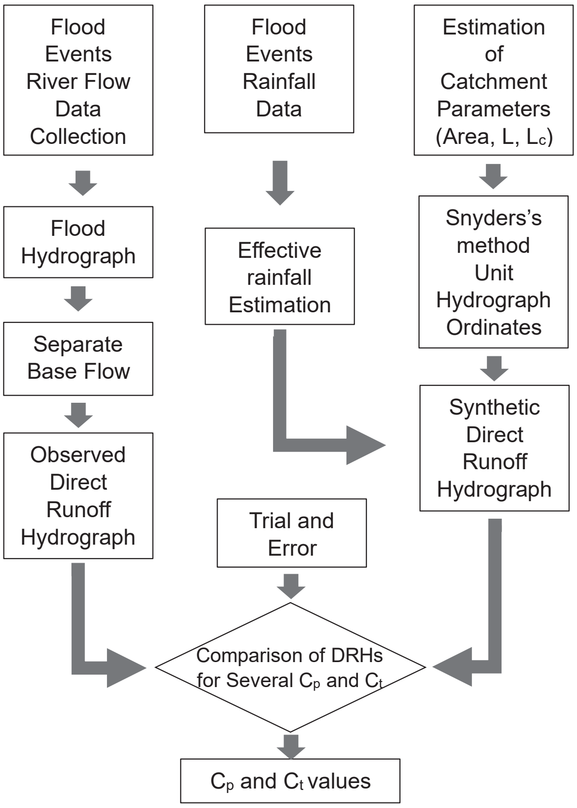

Figure 2 – Methodology Flow Chart

Table 1 – Hydrological Stations Used for the Study

Station no	Hydrological Station	Value of C_p	Value of C_t
1	Pitabeddara	0.7	1.4
2	Calidoniya	0.41	1.55
3	Thaldena	0.43	0.48
4	Horowpathana	0.3	3.75
5	Giriulla	0.42	1.03
6	Dunamale	0.48	5.76
7	Deraniyagala	0.3	1.35
8	Glencourse	0.42	2.2
9	Hanwella	0.35	2.5
10	Kalawellawa	0.42	5
11	Ellagawa	0.3	4.5
12	Rathnapura	0.3	2.75
13	Padiyathalawa	0.4	0.96
14	Norwood	0.22	1.2
15	Thawalama	0.27	1.9

4. Results and Discussion

The research has been done for 15 gauging stations in Sri Lanka to estimate Snyder's parameters for those catchments. Since most of the data is available in the wet zone of the country, it would be more suitable if this study could be done covering the entire country. According to the results, the C_p value varies from 0.22 to 0.7, and the C_t value varies from 0.48 to 5.76. The summary of the results is shown in Table 1. However, only the flood hydrograph of the May 2021 flood event at Hanwella and the comparison between the graphs obtained from DRH using Snyder's method and the observed DRH are shown in Figures 3 and 4 for conciseness. In this case, *NSE* is 95%. Also, the *NSE* values for all selected stations were between 70%-95%. The constants C_t and C_p vary over a wide range and from basin to basin, and may not be equally suitable for all basins. The synthetic hydrograph base length is always greater than or equal to a day, hence, Snyder's method is suitable for fairly large basins (for Sri Lankan condition, area greater than 200 km^2).

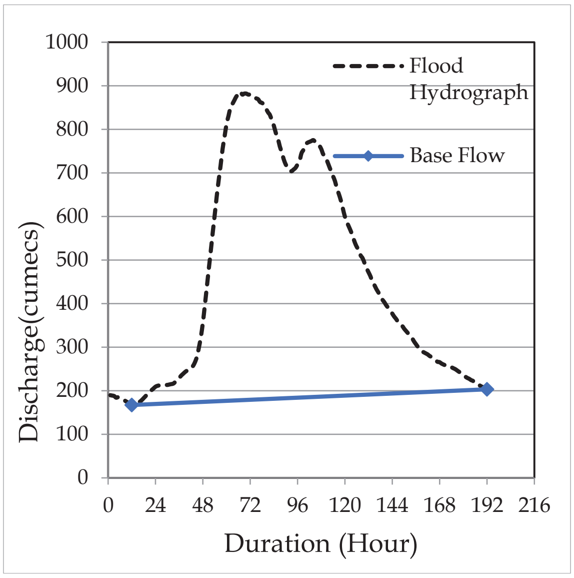

Figure 3 – Flood Hydrograph and Base Flow Separation

5. Conclusion

The stations presented in this paper differ from those used in the 1980s. According to the data availability, present research work has been done for 15 gauging stations in Sri Lanka. Results were also different from the previous study because the physical characteristics of the catchments were changed from the 1980s to 2022. The highest C_t values in the Western Slope region yield greater basin lag and consequently greater diffusion. Similarly, the southern part of the island gives higher C_p values meaning, greater peak flow and consequently less diffusion. However, these findings will be useful for the design engineers to carry out their design by using updated Snyder's C_t and C_p values.

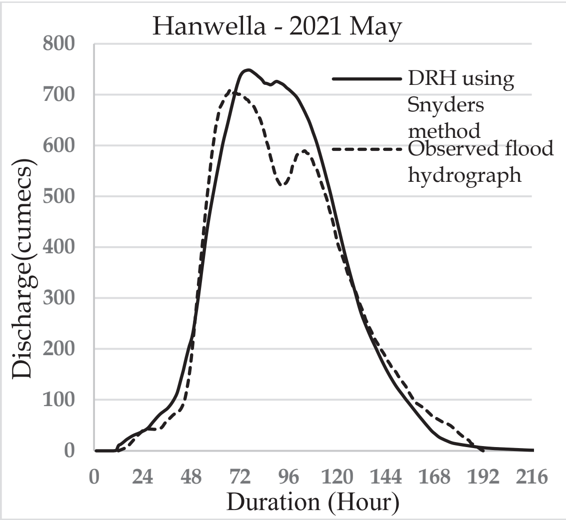

Figure 4 – Comparison of DRH with Observed Hydrograph

The results can be further improved if the hourly rainfall data is available for all nearby rainfall stations and if more stations can be accommodated for study, especially for the northern and northwestern parts of the country. Also, these factors should be considered in the future modification of water allocation, application of distribution technologies, and decision-making concerning water resource management in the dry zone of Sri Lanka.

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