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Development of synthetic peak runoff hydrographs for the Asa river, Ilorin, Nigeria using Snyder and SCS methods

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Abstract

Hydrological design in ungauged tropical basins is challenging due to limited streamflow data. This study developed synthetic unit and storm hydrographs for the Asa River watershed in Ilorin, Nigeria, using the Snyder and Soil Conservation Service (SCS) methods. Rainfall depths for 25-, 50-, 75-, and 100-year return periods were estimated using Gumbel's Extreme Value Type I distribution. Rainfall excess was computed with the SCS Curve Number method using a CN value of 75 based on watershed soil and land-use characteristics. Design storm hydrographs were generated through discrete convolution. Peak discharges from the SCS method ranged from 780.75 to 1043.60 m^3/s, while Snyder's method produced values between 627.63 and 848.69 m^3/s. Analysis of variance (ANOVA) showed no significant difference between the methods at the 5% level ($p = 0.0546$). Although the SCS method produced higher peak discharges, both approaches are suitable for estimating design floods in medium-sized ungauged tropical watersheds.

Keywords: Design storm analysis; Flood hydrograph modelling; Rainfall–runoff simulation; Tropical watershed; Ungauged basin.

1. Introduction

Reliable estimation of design flood hydrographs is fundamental for the planning and design of hydraulic structures such as dams, culverts, bridges, spillways, and urban drainage systems. However, many watersheds in developing countries remain ungauged or poorly monitored, limiting the availability of long-term discharge records required for conventional frequency analysis.

Synthetic unit hydrograph techniques provide an alternative approach for estimating peak runoff and storm hydrographs in such basins [1]; [2]. Among the most widely applied methods are the Snyder synthetic unit hydrograph and the Soil Conservation Service (SCS) dimensionless hydrograph approach. These methods estimate watershed response characteristics using measurable geomorphological parameters such as basin area, channel length, slope, and lag time.

Despite their extensive use, comparative evaluation of Snyder and SCS methods under tropical watershed conditions remains limited [3]; [4], particularly for medium-sized basins in West Africa. The Asa River watershed in Ilorin, Nigeria, represents a typical ungauged tropical basin experiencing increasing urbanization and hydrological alteration.

The objectives of this study were to:

(i) develop synthetic unit hydrographs using Snyder and SCS methods;

(ii) generate design storm hydrographs for selected return periods; and

(iii) evaluate statistical agreement and uncertainty between both methods.

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2. Materials and Methods

2.1. Study area

The Asa River flows through Ilorin, Kwara State, Nigeria, in a south–north direction, forming a natural divide between eastern and western parts of the city. The watershed lies between latitudes 8°24′N – 8°36′N and longitudes 4°10′E – 4°36′E. The basin area is 647.14 km^2, with a main channel length of 41.62 km, centroid length of 7.97 km, and average channel slope of 0.0025 mm^{-1}.

Figure 1 shows a map of Nigeria, with Kwara State and the study area highlighted. Figure 2 shows the Asa River's catchment area. The watershed serves domestic, agricultural, and industrial water needs.

2.2. Materials

Some of the major materials/data used for the study are presented in Table 1.

2.3. Methodology

2.3.1. Data collection

Rainfall data were obtained from meteorological stations, while watershed characteristics such as drainage area, slope, and land use were derived from GIS datasets.

Table 1: Materials/Data used in the study

S/N	Material/Data	Description	Purpose in the Study
1	Historical Rainfall Data	Annual maximum rainfall records for the study area sourced from NIMET and station data (point data).	Used for rainfall frequency analysis and estimation of design storm depths
2	Topographic Map / Digital Elevation Model (DEM)	Elevation data of the Asa River watershed carried out using SRTM with spatial resolution (30 m × 30 m).	Used for watershed delineation and determination of basin slope
3	Land Use/Land Cover Data	Information on vegetation, urban areas, and agricultural land adopted Landsat of spatial resolution (30 m × 30 m).	Used for determination of watershed characteristics and Curve Number
4	Soil Type Data	Hydrologic soil group classification of the watershed sourced from FAO and local survey with variable/map scale resolution.	Used to determine the SCS Curve Number (CN) value
5	Watershed Morphometric Parameters	Basin area, channel length, and basin slope	Required for Snyder and SCS unit hydrograph development
6	SCS Curve Number Tables	Standard hydrologic tables from the SCS method	Used to estimate rainfall excess from total rainfall
7	Gumbel Distribution Tables	Statistical tables for Extreme Value Type I distribution	Used for estimating rainfall for different return periods
8	Snyder Unit Hydrograph Parameters	Basin lag coefficient and peaking coefficient	Used to generate the Snyder synthetic unit hydrograph
9	SCS Dimensionless Unit Hydrograph	Standard hydrograph parameters developed by SCS	Used to develop SCS unit hydrograph
10	Hydrologic Computation Tools	Software such as Microsoft Excel or statistical packages	Used for data processing, analysis, and hydrograph generation
11	Discrete Convolution Method	Mathematical approach for hydrograph computation	Used to generate storm hydrographs from rainfall excess

Figure 1: Location of the Asa river watershed in Ilorin, Nigeria.

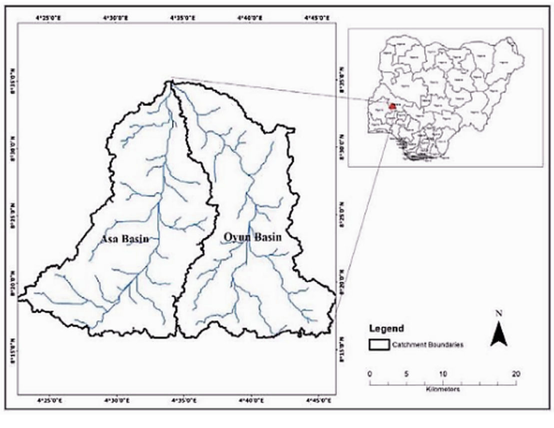

Figure 2: Map of Nigeria showing the river Asa catchment area.

2.3.2. Rainfall frequency analysis

Annual maximum daily rainfall data were analysed using Gumbel's Extreme Value Type I distribution. Gumbel's distribution has been widely used for extreme rainfall frequency analysis [5]; [6].

The rainfall magnitude (R_T) corresponding to return period (T) was estimated as:

$$R_T = \bar{R} + K_T \sigma \quad (1)$$

where $\bar{R}$ is mean annual maximum rainfall, σ is standard deviation, and K_T is the frequency factor.

Estimated rainfall depths are stated in Table 2 for the return periods of 25-, 50-, 75- and 100-year respectively.

Table 2: Estimated rainfall depth for different return periods

Return Period	Rainfall (mm)
25-year	137.13
50-year	151.09
75-year	159.15
100-year	164.85

2.3.3. Rainfall excess estimation

The SCS Curve Number method has global acceptance for event rainfall-runoff estimation [7]. Rainfall excess was computed using:

$$Q_d = \frac{(P - 0.2S)^2}{(P + 0.8S)} \tag{2}$$

where Q_d is direct runoff (mm) and P is rainfall depth (mm), and

$$S = \frac{25400}{CN} - 254 \tag{3}$$

A Curve Number (CN) value of 75 was adopted based on dominant soil hydrologic group B and mixed land-use conditions within the watershed.

2.3.4. Snyder synthetic unit hydrograph

Snyder's method remains a benchmark synthetic hydrograph approach in ungauged watersheds [8]. Snyder's method estimates basin lag time (T_L), peak discharge (Q_p), and base time (T_b) using empirical relationships:

$$T_L = C_t(L \cdot L_c)^{0.3} \tag{4}$$

$$Q_p = \frac{C_p A}{T_p} \tag{5}$$

where $C_t = 1.6$ (lag coefficient), $C_p = 0.62$ (peak coefficient), A is basin area (km^2), L is main channel length (km), and L_c is centroid length (km).

2.3.5. SCS synthetic unit hydrograph

The SCS dimensionless hydrograph method estimates peak discharge and has been validated in multiple climates [9]:

$$Q_p = \frac{0.208A}{T_p} \tag{6}$$

$$T_P = T_L + \frac{D}{2} \tag{7}$$

$$T_L = 0.6T_c \tag{8}$$

Time of concentration was estimated using Kirpich's equation:

$$T_c = 0.0195L^{0.77}S^{-0.385} \tag{9}$$

where Q_p is peak discharge (m^3 s^{-1}), A is basin area (km^2), Q is direct runoff (mm), and T_p is time to peak (h).

2.3.6. Hydrograph development

Storm hydrographs were generated using discrete convolution:

$$Q_n = \sum_{i=1}^{n} R_i U_{n-i+1} \tag{10}$$

where R_i is incremental rainfall excess and U is unit hydrograph ordinate.

2.4. Statistical evaluation

Peak discharge estimates were compared using analysis of variance (ANOVA) at $\alpha = 0.05$. Additional performance metrics included Nash–Sutcliffe efficiency (NSE), root mean square error (RMSE) and percent bias (PBIAS). Uncertainty was assessed using 95% confidence intervals.

2.4.1. Nash–Sutcliffe efficiency (NSE)

$$\text{NSE} = 1 - \frac{\sum(Q_{\text{obs}} - Q_{\text{sim}})^2}{\sum(Q_{\text{obs}} - \bar{Q}_{\text{obs}})^2} \tag{11}$$

where Q_{obs} is reference peak discharge (SCS), Q_{sim} is Snyder peak discharge, and $\bar{Q}_{\text{obs}}$ is mean SCS peak discharge. NSE values range from $-\infty$ to 1, with values > 0.5 indicating satisfactory model performance [10].

2.4.2. Root mean square error (RMSE)

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum(Q_{\text{obs}} - Q_{\text{sim}})^2} \tag{12}$$

RMSE measures the average magnitude of error in the same unit as discharge (m^3/s).

2.4.3. Percent bias (PBIAS)

$$\text{PBIAS} = 100 \times \frac{\sum(Q_{\text{sim}} - Q_{\text{obs}})}{\sum Q_{\text{obs}}} \tag{13}$$

Positive values indicate underestimation, while negative values indicate overestimation.

2.4.4. Uncertainty analysis

The quantification of variability in peak discharge estimates was computed for both Snyder and SCS peak flows across the four return periods at 95% confidence intervals (CI):

$$\text{CI} = \bar{Q} \pm t_{\alpha/2,\, n-1}\frac{s}{\sqrt{n}} \tag{14}$$

where $\bar{Q}$ is mean peak discharge, s is standard deviation, $n = 4$ (number of return periods), and $t_{0.025,\,3} = 3.182$.

3. Results and discussion

3.1. Peak discharge estimates

Peak discharge results are presented in Figure 3 (comparative SCS vs. Snyder hydrograph for the four return periods). Figures 4–7 show hydrographs for individual return periods.

The SCS method consistently produced higher peak discharge values than Snyder's method (Figures 3–7). The SCS method produced peak discharges between 780.75 and 1043.60 m^3 s^{-1}, while Snyder's method yielded values from 627.63 to 848.69 m^3 s^{-1}. Peak discharge increased consistently with return period for both methods. This difference can be attributed to the SCS dimensionless hydrograph shape, which tends to generate sharper and more concentrated peak responses compared to Snyder's empirically derived lag-based formulation. The differences between Snyder and SCS peaks have also been documented in other watersheds [11]; [12].

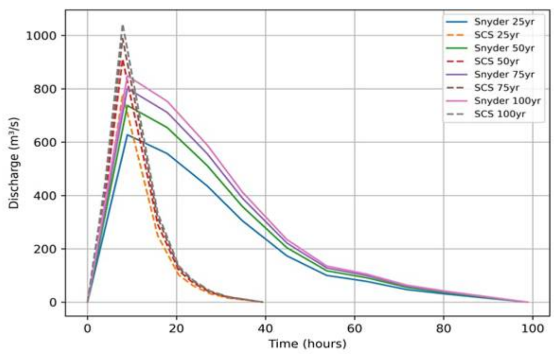

Figure 3: Comparison of peak discharge estimates from Snyder and SCS methods (25-yr to 100-yr events).

3.2. Statistical comparison of Snyder and SCS methods

The ANOVA results showed $F = 5.676$, $p = 0.0546$. There is no statistically significant difference between the two methods at the 5% level since $p > 0.05$. However, the SCS method yielded consistently higher peak values, indicating a more conservative design estimate. Application of ANOVA for hydrograph method comparison is supported by statistical hydrology literature [13].

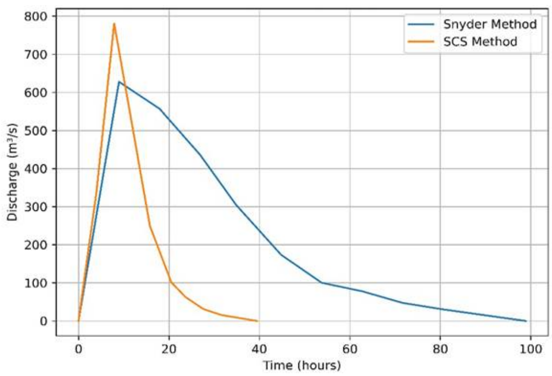

Figure 4: Comparative storm hydrographs for SCS and Snyder approach (25-yr return period).

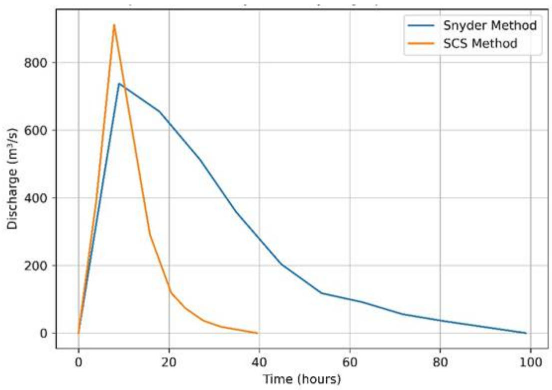

Figure 5: Comparative storm hydrographs for SCS and Snyder approach (50-yr return period).

3.3. Hydrological implications

The increasing peak discharge with return period confirms expected hydrological behaviour. High peak discharge sensitivity to land use and storm characteristics has been widely reported [14]; [15].

The relatively short time-to-peak observed suggests rapid runoff concentration, likely influenced by moderate basin slope and increasing urbanization.

For infrastructure design, the SCS method may provide safer estimates for flood protection structures due to its higher peak predictions.

3.4. Statistical validation of peak discharges at different return periods

The ANOVA results indicated no statistically significant difference between methods ($F = 5.68, p = 0.055$). Performance metrics obtained for NSE, RMSE and PBIAS are shown in Table 3 using peak discharge values for 25-, 50-, 75-, and 100-year return periods.

According to hydrological model performance standards [10]: NSE > 0.75 is ranked as very good and |PBIAS| between 15–25% is ranked as good.

Thus, the Snyder method demonstrates very good predictive performance relative to SCS, despite producing consistently lower peak values.

The advanced performance indicators further confirm strong agreement between the two methods. The high Nash–Sutcliffe Efficiency (0.94) suggests excellent consistency in peak discharge trends across return periods. However, the negative |PBIAS| value (-18.43%) indicates systematic underestimation by the Snyder method relative to SCS. RMSE (150.64 $m^3 s^{-1}$) reflects moderate absolute deviation relative to peak magnitude.

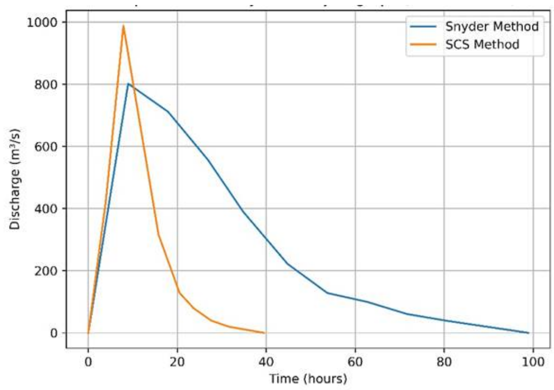

Figure 6: Comparative storm hydrographs for SCS and Snyder approach (75-yr return period).

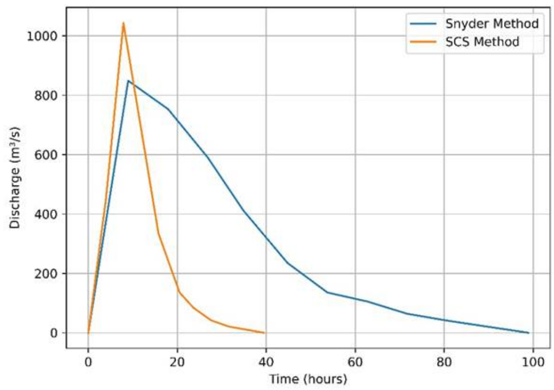

Figure 7: Comparative storm hydrographs for SCS and Snyder approach (100-yr return period).

This behaviour aligns with previous studies reporting that SCS hydrographs typically generate sharper and higher peak responses due to their dimensionless structure and concentration assumptions.

Table 3: Statistical results for validation

Metric	Statistical Value
NSE	0.94
RMSE	150.64 $m^3 s^{-1}$
PBIAS	-18.43

3.5. Uncertainty analysis of peak discharge

Uncertainty analysis as shown in Table 4 further indicates moderate responsiveness of peak discharge to Curve Number variation, emphasizing the hydrological importance of land-use and soil parameterization. Such sensitivity behaviour is consistent with event-based rainfall-runoff modelling frameworks commonly applied in ungauged tropical basins.

The confidence intervals show partial overlap between Snyder and SCS peak discharge ranges, reinforcing the ANOVA result ($p = 0.0546$) that no statistically significant difference exists at the 5% level. However, the consistently higher upper bound of the SCS interval indicates a more conservative flood estimate. This improves statistical robustness beyond single-point comparisons.

Table 4: Uncertainty results of the estimated peak discharges

Method	Mean ($m^3\ s^{-1}$)	Std. Dev.	95% CI ($m^3\ s^{-1}$)
Snyder	753.91	96.54	600.21 – 907.61
SCS	931.64	113.63	750.94 – 1112.34

3.5.1. Sensitivity Analysis of Curve Number

Peak discharge response was evaluated for the 100-year return period as shown in Table 5. A $\pm 5\%$ variation in CN resulted in approximately $\pm 7.5\%$ variation in peak discharge. This demonstrates moderate sensitivity to watershed storage assumptions, importance of accurate land-use and soil classification, and the need for site-specific CN calibration when possible.

The SCS method exhibits predictable, near-linear sensitivity behaviour, consistent with established hydrological modelling studies.

Table 5: Sensitivity analysis of estimated peak discharge (SCS Method)

CN Value	Peak Discharge (m^3/s)	% Change
71.25	967.82	-7.26%
75	1043.60	Base
78.75	1124.15	$+7.72\%$

4. Conclusions

Synthetic unit hydrographs for the Asa River watershed were successfully developed using Snyder and SCS methods. Design storm hydrographs for 25-, 50-, 75-, and 100-year return periods were generated using rainfall frequency analysis and rainfall excess computation.

Although the SCS method produced consistently higher peak discharge values, statistical analysis indicated no significant difference between the two methods at the 5% level. Both methods are therefore suitable for flood estimation in medium-sized ungauged tropical watersheds.

The study provides a practical framework for hydraulic structure design and flood risk management in data-scarce environments.

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