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Rainfall-runoff estimation of an ungauged Nanjannad watershed in Nilgiris district of Tamil Nadu using WEPP model

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ABSTRACT

The rainfall and runoff relationship is a key factor in assessing the water availability in the watershed. The amount of water available is estimated for watershed interventions and proper watershed planning. It is difficult to establish the rainfall and runoff relationship in the ungauged hill watersheds. The water erosion prediction project (WEPP) model is well established globally for the estimation of runoff. Hence, an attempt has been made to estimate the runoff and also to derive the relationship between rainfall and runoff in the Nanjannad hill watershed of the Nilgiris district of Tamil Nadu State, India. A climate file is been generated using the CLIGEN software using the observed meteorological data, slope data, soil data and management files are being prepared for accurate results. The monthly and annual rainfall and runoff analysis over the period of 7 years (2015-2021) has shown that the month of May has received the maximum rainfall (1606 mm) and maximum runoff (449 mm). The rainfall variation in the watershed is between 880 mm and 1859 mm. The maximum rainfall (1859 mm) and maximum runoff (519.3 mm) occurred in the year 2021. The statistical analysis reveals a positive correlation ($R^2 = 0.77$) between the rainfall and runoff. The runoff varies from 0.72 Mcm to 2.25 Mcm (16.75% to 27.92%). The maximum runoff obtained is 2.25 Mcm (27.92%) and the average runoff in the watershed is obtained at 1.36 Mcm (21.71%). Hence, it is suggested that, watershed interventions can be planned to manage the 22 to 28% annual rainfall and the rainfall and runoff relationship for watershed planning can be considered as 0.22 to 0.28.

1. INTRODUCTION

Conservation of the soil and water resources is a major concern these days. The threat posed by the available resources has grown as the population has grown. So, proper utilisation of the resources for the proper planning of water management strategies is required. The estimation of runoff in the watershed will give us a better idea of the construction of the structures. The Nanjannad watershed is located in the Nilgiris hills, where the estimation of runoff by gauging is difficult and costly as it is located in the mountain region.

Water availability estimation will be able to determine the amount of available water for watershed management planning and development (Manivannan *et al.,* 2021). The estimation of runoff is done using the water erosion prediction project (WEPP) model. It is a process-based model to predict runoff, soil erosion, and sediment delivery from fields, farms, forests, rangelands, construction sites, and urban areas (Nearing *et al.,* 1989). Hydrological models are used for the prediction of hydrological responses in various watersheds and by which we can have a better understanding of the impacts of these practises (Tripathi *et al.,* 2003; Johnson *et al.,* 2003; Li *et al.,* 2008; Ahn *et al.,* 2011, Sudhishri *et al.,* 2016). Different hydrological models have been updated and number of parameters required for each model varies according to the mathematical method used for finding the runoff (Miller *et al.,* 2002; Shrestha *et al.,* 2009; Devia *et al.,* 2015). Data from eight natural runoff plots were chosen, the WEPP input files for soil, slope, climate, and crop management were compiled based on measured data, it was found that runoff was somewhat overpredicted for small rainfall events and low-runoff years, but underpredicted for strong storms and high-runoff years (Zhang *et al*., 1996). Distributed parameter models is being used mainly for the low slope conditions (Agliardi *et al.,* 2003; Camici *et al.,* 2011; Qu *et al.,* 2022).

WEPP model estimation of the surface runoff during the summer was found to be realistic, it has been found that increased infiltration capacity due to more soil slope, soil effective hydraulic conductivity for frozen soil were problematic during winter events (Lundekvam *et al*., 2006). The performance was tested by predicting daily runoff and sediment output using data from previous monsoon seasons. The coefficient of determination (R^2 = 0.86-0.91) shows that the watershed runoff is accurately modelled (Pandey *et al.,* 2008). The model determined where and when runoff occurred, as well as potential depositing sites. The model performance was investigated using WEPP model runoff results, which were compared to the monthly data collected from the sample watershed. The index of agreement was 0.99, indicating that the model predictions produced good results (Yuksel *et al.*, 2008). The WEPP model is used for the estimation of runoff successfully worldwide (van Lier *et al.,* 2005; Raclot and Albergel, 2006; Choudhury *et al.,* 2022) and also in India (Pandey *et al.,* 2009; Akbari *et al.,* 2015; Kumar *et al.,* 2021; Sushanth and Bhardwaj, 2019; Kar *et al.,* 2022).

Nanjannad watershed is a Hill watershed in the Ooty, which is at a high elevation of 2100 m from mean sea level, there are high chances of runoff and variation in slope which causes erosion. So, there is a need to estimate the runoff and to develop better criteria for soil and water conservation. The present study was conducted to predict the runoff in the Nanjannad hill watershed using the WEPP hill slope model and also to derive the relationship between rainfall and runoff, which will be useful for the watershed interventions for proper planning of the watershed.

2. MATERIALS AND METHODS

Study Area

In the present study, the Nanjannad watershed in Udghamndalam is used for the rainfall runoff analysis. The watershed is located between 11˚20'0"N to 11˚22'30"N latitude and 76˚37'30"E to 76˚40'0"E longitude as mentioned (Fig.1). Nanjannad watershed is in the Nilgiris hill ranges, the area of the watershed is 434 ha. The watershed has a high elevation, which results in cold temperatures and frequent precipitation. In the watershed region, day temperatures range from 22.1°C in the summer to 5.1°C in the winter. The temperature drops below 0°C at times during the night. Soil types present in the watershed include lateritic soil, red sandy soil, red loam, black soil, alluvial soil, and colluvial soil. Black soils form in valleys where water-

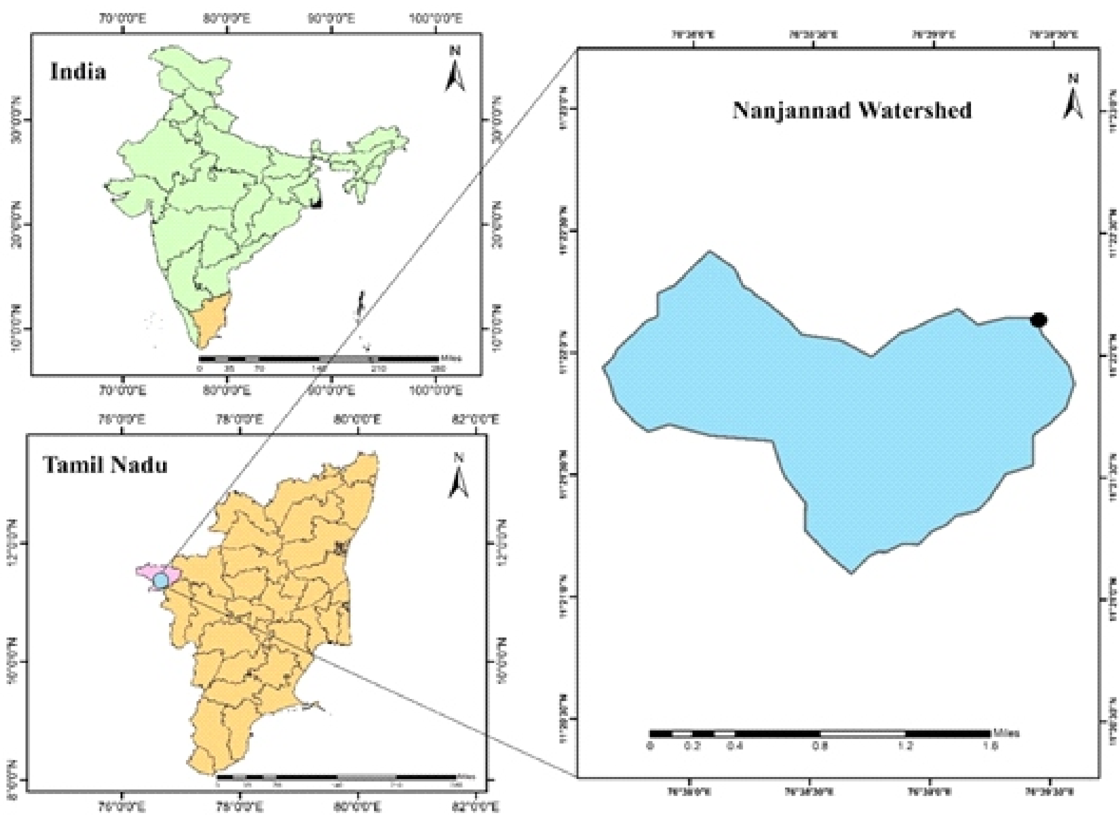

Fig. 1. Nanjannad Watershed map

logging is widespread during the monsoon season (Manivannan *et al.,* 2021). Agriculture patterns differ from valley floor to hilltop, with a wide range of farming kinds and management techniques. The main crops farmed in the Nanjannad watershed area are potato, carrot, cauliflower, cabbage, beetroot, and radish (Karthik *et al.,* 2022). Soil samples are taken in the watershed and the analysis is done at different depths to find out the percentages of sand, silt and clay. The Nanjannad watershed's land use and land cover studies indicated that vegetation dominates the watershed region, as shown in Table 1, with shrubs and hill tops. A GIS is used for the extraction of the watershed and also for the extraction of the slope map of the Nanjannad watershed. The ASTER digital elevation model (DEM), which is downloaded and used for the extraction of the slope map (Fig. 2). Watershed drainage map indicating 4th order stream as highest order (Fig. 3). Watershed areas are delineated using the DEM and a prepared slope map using Arc-GIS 10.3 software.

Water Erosion Prediction Project (WEPP)

The WEPP is a new generation runoff prediction system that can be used for environmental planning and evaluation, as well as soil and water conservation (Weltz *et al.,* 2020). The model is a collection of computer programs, implements a distributed parameter, continuous simulation, and erosion prediction model. The approach, which accounts for both geographic heterogeneity in topography, soil properties, and land use situations, was developed to anticipate runoff impacts from agricultural management practises in small agricultural watersheds (Verma *et al.,* 2010).

Table: 1
Land use pattern in Nanjannad watershed

S.No.	Land use pattern	Percentage (%)
1.	Forest	33.4
2.	Water bodies	18.8
3.	Vegetation	38.1
4.	Barren land	9.7

Preparation of Input files for WEPP

Preparation of input files forms the basis of any hydrologic model (Brunner, 2012). Climate, soil, slope, and management data are the main input files for the WEPP that simulates runoff. With the exception of the climate input file, where a Programme named CLIGEN is offered in the model and may be used to generate data series of any length, input file builders are supplied in the model for other input data files.

Estimation of Runoff in WEPP

Infiltration based parameters as bulk density, which indicates the pore volume of the soil, gives the information on various variables as it reflects the overall pore volume of the soil. The effective hydraulic conductivity of the WEPP model is an important parameter for estimating infiltration and runoff. The inter-rill erodibility parameter measures soil resistance to separation due to raindrop impact. The rill erodibility parameter measures the soil resistance to detachment by concentrated rill flow. The WEPP model manual

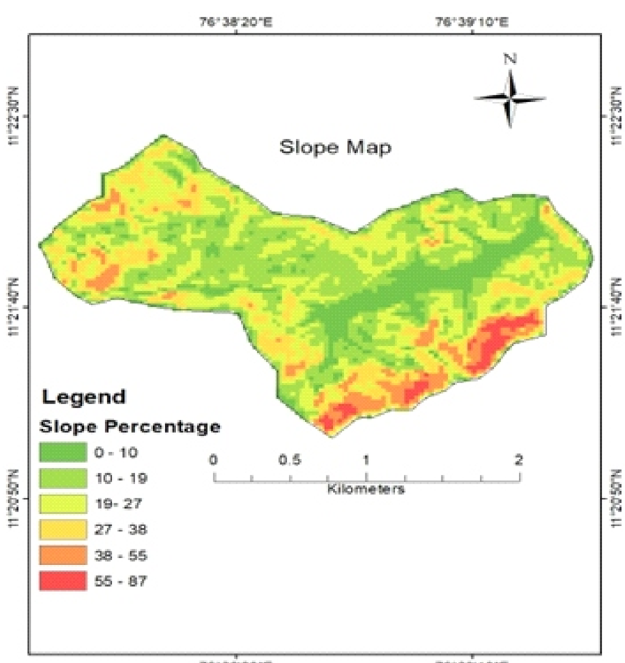

Fig. 2. Slope map of the Nanjannad watershed

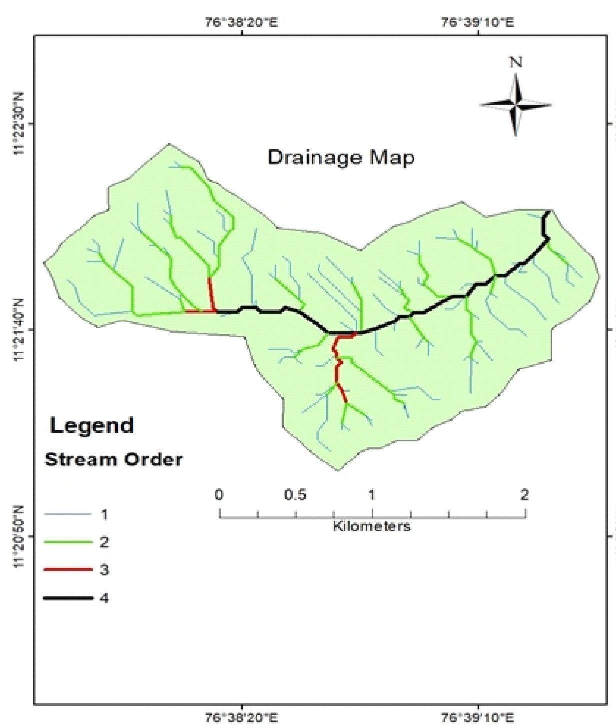

Fig. 3. Drainage Map of Nanjannad watershed

offers detailed statistical descriptions of channel hydrological processes. The procedures employed in the research are stated in the below equations (Flanagan and Nearing, 1995). The modified Green and Ampt infiltration equation, termed as the "Green-Ampt Mein-Larson" model, is used to compute runoff. It can be stated numerically as follows:

$$f_i = \frac{Fi - Fi - 1}{ti - ti - 1}$$

Where, f_i = average infiltration rate (m s^{-1}), i = time interval at current, I - 1 = time interval previous, F = cumulative infiltration depth (m), and t = time (s).

The kinematic wave model transforms the temporal distribution of rainfall intensity into a time intensity distribution of runoff or a quantity of peak flow using the estimated technique. The surplus volume of rainfall is calculated in combination with infiltration estimates as follows:

$V_i = R_i - F_i$ $for\ r_i > f_i\ and\ F_i < S_p$; $V_i = V_{i-1}$ $for\ r_i \leq f_i and\ F_i < S_p$; $V_i = R_i$ $for\ F_i \geq S_p$

Where, V = cumulative rainfall excessive depth (m), R = cumulative rainfall depth (m), F = infiltration depth (m), i = current time interval, i -1 = previous time interval, and Sp = upper limit of water storage (m) in the top two soil layers.

The potential flow modelling approach causes the runoff transformation in the WEPP watershed model. The governing equations is the kinematic equation for flow on a plane as follows:

$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = V$ and depth-discharge relationship as:

$$q = a\,h^m$$

Where, h = depth of flow (m), q = discharge per unit width ($m^2 s^{-1}$), a = coefficient of depth and discharge, m = exponent of depth and discharge, and x = distance from the top of the plane (m).

Water balance and also the percolation component were developed in WEPP to estimate soil moisture content in the root zone and evapotranspiration loss throughout the simulation time utilising input from the climate, infiltration, and crop growth aspects (Savabi and Williams, 1995). Infiltration, runoff, soil evaporation, plant transpiration, and seepage are all hydrologic actions in WEPP. All the parameters of the WEPP model are calculated and used for the estimation of the runoff, The runoff estimated are tabulated and used for the analysis and deriving the rainfall-runoff relationship.

Statistical Analysis

The Pearson correlation, sometimes known as Pearson's r, is a prominent statistic for analysing how strongly relationships exist between two variables. The correlation coefficient (r) is a dimensionless numeric statistic that ranges from -1 to 1 (Kim *et al.,* 2015). As a result, the correlation value determines the importance of the correlation. A correlation value of 0 indicates there is no linear relationship between the two variables. Whereas if the coefficient is 1 or very close to 1, the two variables are positively correlated (Marsman and Wagenmakers *et al.,* 2018). The correlation coefficient is found out using the formula.

$$r = \frac{\sum_{i=1}^{n}(\mathrm{xi} - \mathrm{x})(\mathrm{yi} - \bar{\mathrm{y}})}{\sqrt{\Sigma(\mathrm{xi} - \bar{\mathrm{x}})^2 \Sigma(\mathrm{yi} - \bar{\mathrm{y}})^2}}$$

Where, r is correlation coefficient, x_i and y_i values of the single variables. x and cy mean values of data. In the present research, Pearson correlation coefficient is used to correlate the rainfall and runoff of the present watershed.

3. RESULTS AND DISCUSSION

Rainfall and runoff values are analysed over the last seven years between 2015 and 2021. The runoff is estimated using the hill slope model in the water erosion prediction project (WEPP). Close examination of all the runoff values reveals that the runoff is majorly dependent on the amount of rainfall and that the runoff is mainly produced for the larger events, as the small rainfall events that occurred in January, February, and March did not produce any runoff in the as shown (Fig. 4). Similar kind of result is observed and stated various authors (Ram Sankaran *et al.,* 2009, Singh *et al.,* 2011, Fang *et al.,* 2012). The maximum rainfall occurred in the month of May with about 1606 mm and the maximum runoff also occurred in the month of May with about 449.62 mm of all the seven years. The lowest rainfall (27.67 mm) and runoff occurred in the month of Feb (Fig.4).

Yearly rainfall and runoff over the seven years reveals that the maximum rainfall occurred in the year 2021 (1859 mm). A similar amount of rainfall is observed in South Korea, ranging from 1859 to 1873 mm (Jang *et al.,* 2015). The maximum runoff also occurred in the year 2021, about 519 mm (Fig. 5). The values of the runoff and rainfall over the seven years reveal that the runoff in certain months *i.e.*

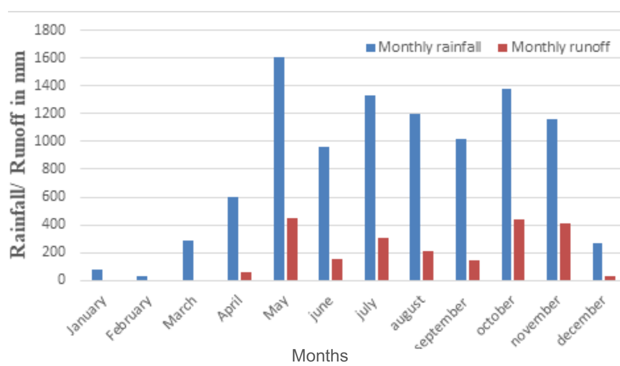

Fig. 4. Monthly Rainfall and Runoff (2015-2021)

May, Oct and Nov is higher where there are high rainfall events as indicated in Fig. 5.

The trend in the rainfall variation over the seven years (2015-2021) was analysed and the yearly and cumulative departures were found. The trend in the yearly and cumulative departure gives how much variation has been there over the years (Sarala and Lakshmi, 2015; Matomela *et al.,* 2019). The departure of values from the mean clearly reveals that there is a lot of variation in the rainfall over the years, as from 880 mm to 1859 mm, The variation is shown in the yearly and cumulative departure over these years (Fig. 6).

The rainfall and runoff in the Nanjannad watershed over the last seven years show that the runoff to rainfall ratio ranges from 16.75% to 27.92%. The runoff to rainfall ratio reveals that how much amount of the rainfall is contributing towards runoff. The lowest ratio of 16.75% was observed in the year 2017 and the highest runoff to rainfall ratio of 27.92% was observed in the year 2021. A similar ratio of 22% to 27.5% of runoff to rainfall ratio is observed (Sheng *et al.,* 2009). So, by the WEPP model runoff process, we can say that in the year 2021, a greater number of the high rainfall events occurred, which gave the highest runoff in that year. The estimation of runoff volume is used for the estimation of the amount of water that is available for better water management strategies. The average value of the runoff in the Nanjannad watershed is observed to be 1.36 Mcm, which implies 21.71% (Table 3) of runoff to rainfall ratio. The runoff to rainfall values in the watershed implies the amount of rainfall contributing to the runoff in the watershed.

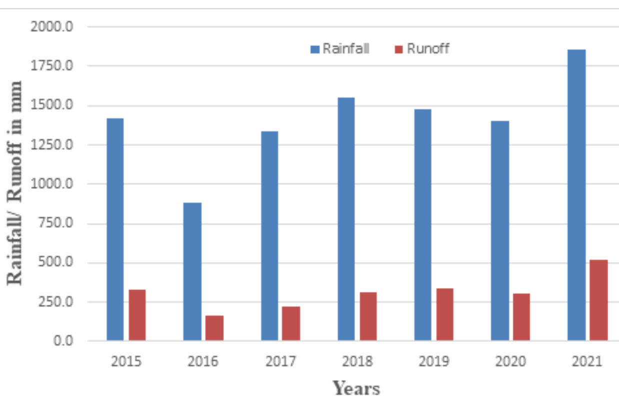

Fig. 5. Yearly Rainfall and Runoff (2015-2021)

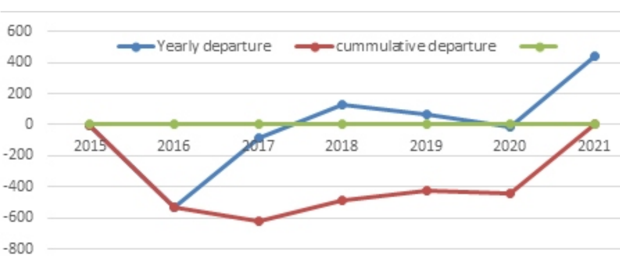

Fig. 6. Yearly and Cumulative departure of the rainfall over 7 years (2015-2021)

The linear relationship between the rainfall and runoff is derived using the scatter diagram (Fig. 7). The correlation coefficient (R^2) is observed to be 0.77, which implies a positive correlation between the rainfall and runoff. Similar kinds of values were obtained as 0.77 in the sub basin of the river Jhelum (Archer, 2009) and 0.78 in the runoff modelling (Soulsby, 2011). The study was conducted in the ungauged watershed where the verification of the observed runoff was not possible. The obtained result is found to be satisfactory in terms of the stability and also the wide adoptability of the WEPP model.

4. CONCLUSIONS

The study derives the rainfall and runoff relationships in the Nanjannad watershed. Estimation of runoff using manual methods like gauging is time consuming and costly, and the establishment of gauging in these mountain ranges is difficult. So, estimation of runoff using empirical models and deriving the rainfall and runoff relationship is a better way to understand the water availability in the Nanjannad hill watershed. The rainfall and runoff analysis of monthly and yearly analysis are analysed over the last 7 years (2015-

Table: 3
Annual rainfall-runoff depth and volume of Nanjannad watershed

Year	Rainfall (mm)	Runoff (mm)	Runoff volume		% Runoff to Rainfall
			Runoff volume (m^3)	Runoff volume (Mcm)	
2015	1416.4	331.3	1438029	1.43	23.40
2016	882.8	168.0	729298	0.72	19.03
2017	1334.6	223.5	970203	0.97	16.75
2018	1550.5	311.7	1352639	1.35	20.10
2019	1480.8	340.2	1476281	1.47	22.97
2020	1401.4	305.4	1325549	1.32	21.79
2021	1859.6	519.3	2253632	2.25	27.92
Sum	9926.2	2199.5	9545630		
Average	1418.03	314.21	1363661	1.36	21.71

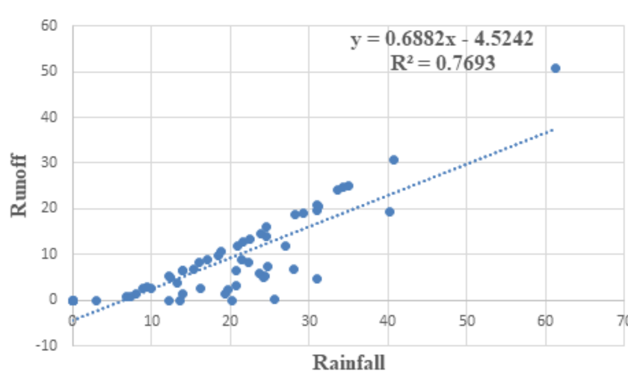

Fig. 7. Rainfall and runoff relationship

2021) using the WEPP model, and the results indicate that the maximum rainfall occurred in the month of May (1606 mm) and the runoff also occurred in the month of May (449 mm). The maximum rainfall and runoff events suggest that the runoff in the Nanjannad regions mainly depends on the amount of rainfall that occurred. The keen observation of results states that the months of Jan, Feb, and March have little rain but the runoff is not generated. It implies that the WEPP model is producing the runoff in the events that are having high storm events. The rainfall varied between 880 mm and 1859 mm in these years. The variation in the years is clearly stated in the yearly and cumulative departures over these years, which implies how the rainfall has varied over the years. The maximum rainfall (1859 mm) and maximum runoff (519.3 mm) were observed in the year 2021. The correlation coefficient (R^2 = 0.77) revealed a positive correlation between the rainfall and runoff over these years. The average runoff over these years is obtained as 1.36 Mcm (21.71%) and the maximum runoff obtained is 2.25 Mcm (27.92%). Accordingly, we can suggest that the, watershed interventions and also the planning can be done for 22 to 28% of the annual rainfall, and the rainfall and runoff relationship for the watershed planning is considered from 0.22 to 0.28. The WEPP model has proved to be the most efficient for the ungauged hill watersheds for prediction of runoff. Hence, the WEPP model is recommended for the estimation of the water availability in the ungauged mountain watersheds.

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