

Article

Streamflow and Sediment Yield Analysis of Two Medium-Sized East-Flowing River Basins of India

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Abstract: With increased demand for water and soil in this Anthropocene era, it is necessary to understand the water balance components and critical source areas of land degradation that lead to soil erosion in agricultural dominant river basins. Two medium-sized east-flowing rivers in India, namely Nagavali and Vamsadhara, play a significant role in supporting water supply and agriculture demands in parts of the Odisha districts of Kalahandi, Koraput and Rayagada, as well as the Andhra Pradesh districts of Srikakulam and Vizianagaram. Floods are more likely in these basins as a result of cyclones and low-pressure depressions in the Bay of Bengal. The water balance components and sediment yield of the Nagavali and Vamsadhara river basins were assessed using a semi-distributed soil and water assessment tool (SWAT) model in this study. The calibrated model performance revealed a high degree of consistency between observed and predicted monthly streamflow and sediment load. The water balance analysis of Nagavali and Vamsadhara river basins showed the evapotranspiration accounted for 63% of the average annual rainfall. SWAT simulated evapotranspiration showed a correlation of 0.78 with FLDAS data. The calibrated SWAT model showed that 26.5% and 49% of watershed area falling under high soil erosion class over Nagavali and Vamsadhara river basins, respectively. These sub watersheds require immediate attention to management practices to improve the soil and water conservation measures.

Keywords: river basin; SWAT; streamflow; sediment yield; critical source area

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1. Introduction

Soil erosion is a serious concern for land and water resources because it has a negative impact on soil fertility, agricultural production, and the quality of aquatic environment [1,2]. Soil erosion is caused by the interaction of physical and anthropogenic forces and erosion rates are affected by hydrology, climate, soil conditions, land use land cover changes and their interaction at the sub-watershed scale [3–5]. River basins are confronted with the most serious problems of land degradation and deterioration of water resources as a result of soil erosion [6]. Soil erosion from uplands deposits soil in riverbeds and reservoirs, causing flooding and reservoir capacity loss [7,8]. According to a Central Water Commission (CWC) report, the majority of the reservoirs in India are losing their storage capacity at a rate of 1% per year due to sedimentation [9]. Some tribal-inhabited areas in Andhra Pradesh, Odisha, Madhya Pradesh, Chhattisgarh, and Kerala have faced severe soil erosion as a result of shifting cultivation [10].

The majority of the rainfall in India occurs from June to October, with high intensity and widespread coverage. During these months, some rivers erupt with large floods, causing soil erosion. The eastern coastal belt along the Bay of Bengal (BoB), mainly Tamil Nadu, Andhra Pradesh and Orissa, is flooded by pre- and post-monsoon tropical cyclones

that form over the BoB [11,12]. According to Narayana and Babu [7] the average annual soil erosion rate in India is 16.35 t/ha/yr, which exceeds the permissible limit [13]. In India, 147 million ha of land is degraded, with water erosion accounting for 94 million ha [14]. Das [15] found that 12 major Peninsular Indian rivers contribute more than 1% of global river sediment flux.

Various studies were conducted in different regions of India using a modeling approach, field scale, and laboratory studies to have a comprehensive knowledge on soil erosion, sediment yield, and their impact on reservoirs and crop productivity [2,5,16–24]. Using experimental analysis, Vaithiyanathan et al. [16] noticed that the majority of sediment transport, more than 95% of the time, occurs during the monsoon period. Singh et al. [17] prepared a soil erosion rate map for India and they suggested severe soil erosion rates (>20 t/ha/yr) are found at the areas of Peninsular India. Prasannakumar et al. [18] found that the maximum soil loss was associated with a high slope length and steepness (LS) factor from degraded, deciduous forest and grasslands areas. Dutta and Sen [21] concluded that the highest annual sediment yield was associated with agricultural lands. Mahapatra et al. [22] concluded that 48.3% of the Uttarakhand state soil loss exceeds the permissible limit of 11.2 t/ha/yr. Himanshu et al. [20] used the SWAT model to evaluate the best management practices in the Marol watershed, India. In their study, the estimated average annual sediment yield was 12.2 t/ha/yr. Kolli et al. [24] concluded that sandy clay and red soils exported the highest sediment in the Kolleru catchment.

The aforementioned literature suggested that the amount of sediment yield within the basin varies depending on hydrology, climate, topography, land use change, and soil type [5,20,21,23]. Furthermore, soil erosion and sediment yield are not distributed evenly across the basins. As a result, sub-basin scale sediment yield analysis using a physically based distributed hydrological model is required for identifying accurate sediment source areas and controlling sediment yield through soil and water conservation practices. Many physically based hydrological models, such as VIC [25,26], ANSWERS [27], AGNPS [28], WEPP [29] and SWAT [30] have been in use over the past three decades to understand the hydrological processes. Roti et al. [31] reviewed the applicability of physically distributed models and concluded that the SWAT model outperformed AGNPS, ANSWERS and WEPP models [32–33] in both small and large areas [34]. Furthermore, with spatio-temporal variability of the hydrological process, SWAT produces acceptable results all over the world [35–41]. The majority of the recent studies used SWAT in conjunction with a geographical information system (GIS) interface for a variety of purposes, including modeling of runoff, soil moisture, sediment and water balance [19,21,42–44], climate change [45] and identifying critical source areas and evaluation of best management practices (BMPs) for sediments and nutrients [20,33,46] across the world. The aforementioned literature suggests that the SWAT model performance ranged from very good to satisfactory for the streamflow and sediment simulations.

The Nagavali and Vamsadhara river basins in India are vulnerable to frequent floods [11,39,47,48]. These basins are mainly dominated by agricultural activities and forest cover, which provide a livelihood for farmers in the Odisha districts of Kalahandi, Koraput and Rayagada, as well as the Andhra Pradesh districts of Srikakulam and Vizianagaram. The steep slopes towards the NE and NW part of the basins indicates fast runoff which causes soil erosion [12]. These river basins are particularly vulnerable to tropical cyclones caused by low-pressure depressions in the BoB. Cyclones such as the 1996 Andhra Pradesh cyclone, the 1999 Odisha cyclone, and other named cyclones such as Nilam, Laila, Phailin cyclone, Helen, Lehar, Hudhud, and Fani hit the Nagavali and Vamsadhara river basins between 1991 and 2019 [11,49]. Due to these cyclones, floods have occurred, which damaged the property, crops and affected the lives of many people [50]. Water stress in the Nagavali river basin in seasons other than the monsoon season has also been observed [43].

Based on the existing literature, both river basins are frequently flooded, resulting in soil erosion from upland areas and depositing in channels and reservoirs. Every year, the

erosion and deposition occur, resulting in a loss of reservoirs storage capacity loss. From 1977 to 2004, the Gotta barrage on the Vamsadhara river basin lost 61.43% of its live storage [9]. Long-term analysis of water balance components is required to reduce water stress over the basins during the dry season [43]. Several studies on soil erosion and sediment yield identified that all sub-basins within the basin have different characteristics and their response to anthropogenic and natural changes also differ [2,21,24]. There is a need for long-term water balance and sediment yield analysis as well as identifying erosion-prone areas for sediment yield and evaluating soil and water conservation practices using a biophysical model. The objective of this study was to implement a semi-distributed hydrological soil and water assessment tool (SWAT) to analyze the water balance components and identify sediment source areas for the Nagavali and Vamsadhara basins.

2. Materials and Methods

2.1. Study Area

The Nagavali and Vamsadhara rivers are two adjacent interstate medium-sized east-flowing river basins in southern Orissa and northern Andhra Pradesh, India (Figure 1), located between the Mahanadi and Godavari river basins.

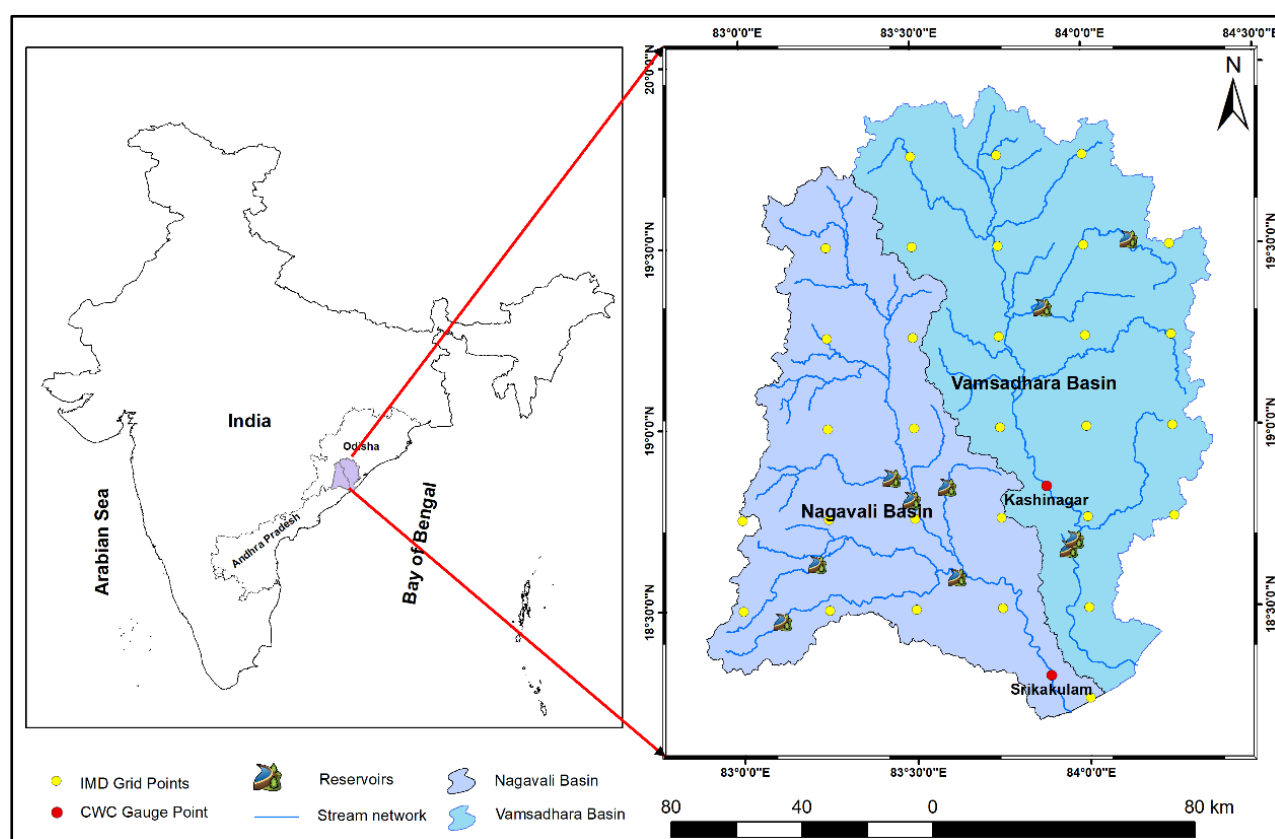


Figure 1. Map of the Nagavali and Vamsadhara river basins.

There are two types of climate in these river basins. The coastal area has a semi-arid climate, while the upper reaches have a dry sub-humid climate. The Nagavali river rises near the village of Lakshbahal in the Odisha. It travels 256 km and has a basin area of 9200 square kilometers before joining the BoB at Kallepalli village near Srikakulam. The major irrigation projects on the Nagavali river basin are Madduvalasa, Thotapalli barrage, and Janjavathi reservoirs, while the minor irrigation projects are Vengalarayasagar, Vottigedda, and Vegavathi (Peddagedda), as shown in Table 1.

Table 1. Details of existing reservoirs in the Nagavali and Vamsadhara river basins.

Reservoir Name	RES_EVOL (10 ⁴ m ³)	RES_ESA (Ha)	RES_PVOL (10 ⁴ m ³)	RES_PSA (Ha)	RES_Operational Year
Madduvalasa reservoir	9551	2673	9358	2405	2002
Thotapalli barrage	8503	1983	7105	1785	1908
Vottigedda reservoir	2713	440	2514	272	1976
Janjavathi reservoir	9628	2680	7855	2450	1978
Vengalarayasagar reservoir	4051	575	3646	518	1998
Vegavathi/Peddagedda reservoir	3038	294	2891	265	2003
Badnalla reservoir	5480	753	4932	678	1997
Harabhangi reservoir	11,116	1107	10,000	1000	1998

Note: RES_EVOL and RES_PVOL are the volumes of water needed to fill the reservoir to the emergency spillway and principal spillway, respectively. RES_ESA and RES_PSA are the reservoir surface areas when the reservoir is filled to the emergency spillway and principal spillway, respectively.

The details of reservoir volumes at emergency spillway and principal spillway, as well as their corresponding surface areas and reservoir operational years are obtained from the respective reservoir authorities and water body information system (WBIS) (<https://bhuvan-wbis.nrsc.gov.in/> (accessed on 16 July 2022)) maintained by the National Remote Sensing Centre (NRSC) Hyderabad.

The Vamsadhara river rises near Lanjigarh in Odisha and flows for 254 km before joining the BoB at Kalingapatnam in Andhra Pradesh. It has a basin area of 10,450 square kilometers. The average rainfall amount in the basin is 940.2 mm near the coast, 1551.6 mm in the northeast, and 1250.2 mm in the northwest [12]. The elevation range in the Vamsadhara river basin range from 10 m above MSL in the south near the coast to 1545 m in the northwest (hills near Bissam Cuttack). The Vamsadhara River basin is primarily influenced by cyclones caused by depressions in the BoB. Because of its narrow shape and hilly terrain, the Vamsadhara river basin is prone to flash floods. Table 1 shows the three reservoirs in the Vamsadhara river basin. The reservoirs of Badnalla and Harabhangi are located within the Kashinagar gauge station, while the Gotta barrage is located outside the gauge station.

2.2. Datasets

Below are detailed descriptions of the datasets that were used in this study:

2.2.1. Digital Elevation Model (DEM)

The Vamsadhara and Nagavali river basins are delineated using a 30 m × 30 m grid SRTM DEM obtained from USGS earth explorer (<https://earthexplorer.usgs.gov> (accessed on 16 July 2022)), as well as slope maps and a stream network. As shown in Figure 2a, the highest elevations in the Vamsadhara and Nagavali river basins are 1634 m and 1505 m, respectively. The drainage basin slope influences the contribution of surface runoff, infiltration, soil moisture, and ground water to the stream. Three slope bands (0–2%, 2–8% and more than 8%) are considered for both river basins.

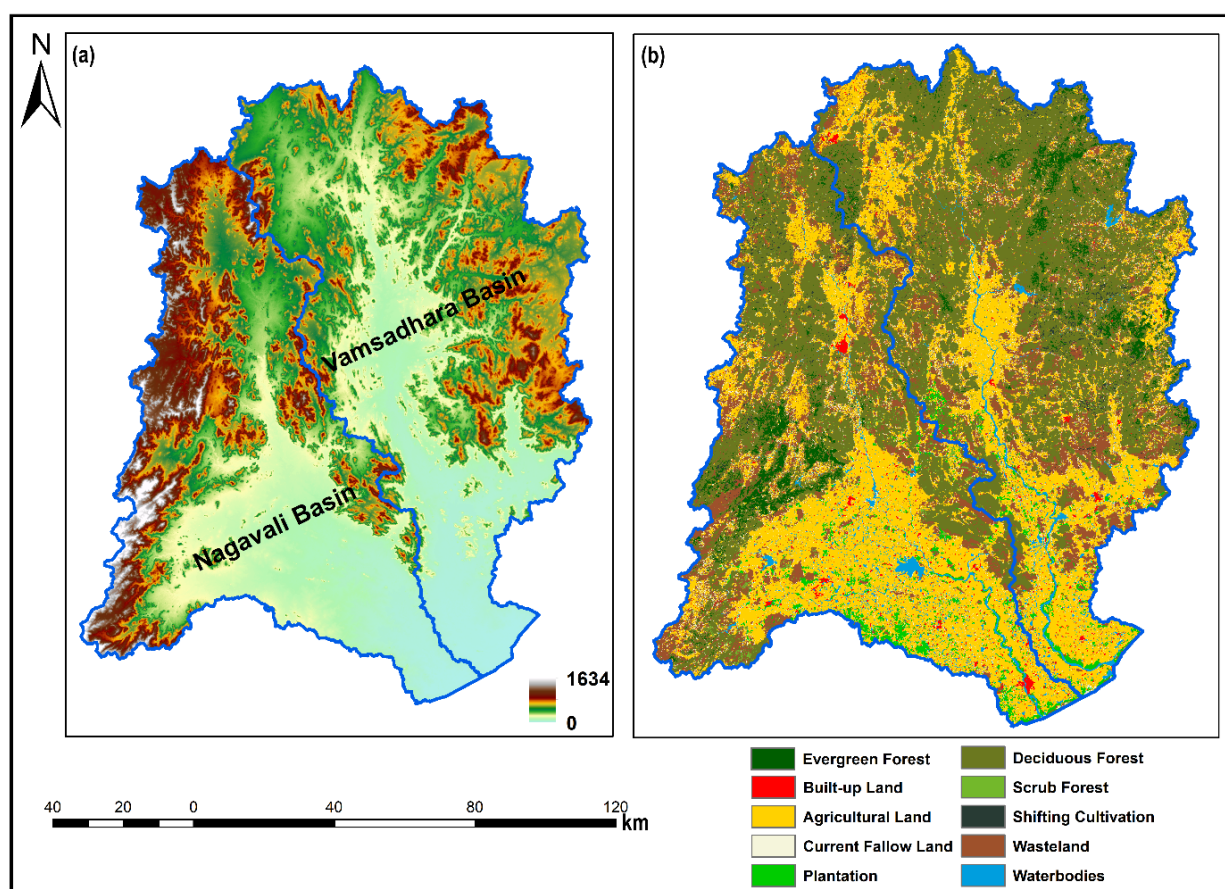


Figure 2. (a) DEM (b) LULC for the Nagavali and Vamsadhara river basins.

2.2.2. Land Use Land Cover (LULC)

The LULC data was obtained from NRSC Bhuvan (https://www.nrsc.gov.in/EO_LULC_Portals (accessed on 16 July 2022)) for the year of 2005 on a scale of 1:250 km as shown in Figure 2b. The LULC classification codes for the Nagavali and Vamsadhara river basins have been converted into SWAT land cover codes with 11 classes. Table 2 depicts the land use classification over the Nagavali and Vamsadhara basins. The LULC classification shows the major land use in the Nagavali river basin is agricultural lands (43%) and forest lands (34%) and over the Vamsadhara river basin major land is occupied by forests (52%) and agricultural lands (30%).

Table 2. Classification of land uses in the Nagavali and Vamsadhara basins.

S. No.	SWAT Code	Class Name	% of Area	
			Nagavali River Basin	Vamsadhara River Basin
1	RICE	Kharif crop	12.3	9.94
2	AGRL	Rabi crop	5.29	2.87
3	ORCD	Plantation	2.94	1.2
4	CRDY	Current fallow	12.21	7.63
5	AGRR	Double or Triple crop	10.22	7.67
6	FRSE	Evergreen forest	3.06	3.09
7	FRSD	Deciduous forest	29.34	46.65
8	RNGB	Degraded or Scrub-forest	1.53	1.44
9	BARR	Wasteland	19.05	17.23

10	WATR	Waterbodies	2.91	1.84
11	URBN	Built-up land	1.14	0.43

2.2.3. Soil Data

The soil map was obtained from the International Soil Reference and Information Centre (ISRIC) (<https://www.isric.org> (accessed on 16 July 2022)) with 1 km resolution. The soil textures of the basins include loam, sandy loam, sandy clayey loam, clayey loam, and clayey soil. The majority of the upper sub-basins in the Nagavali river basin is covered by sandy clayey soils, while the lower sub-basins is covered by loam soils. Clayey loam soils cover the majority of the Vamsadhara river basin.

2.2.4. Weather Data

Gridded daily rainfall [51] data ($0.25^\circ \times 0.25^\circ$) and $1^\circ \times 1^\circ$ gridded daily maximum and minimum temperature [52] datasets are collected from the Indian Meteorological Department (IMD) Pune (https://www.imdpune.gov.in/Clim_Pred_LRF_New/Grided_Data_Download.html (accessed on 16 July 2022)), India. Srivastava et al. [52] used a modified version of the Shepard's angular distance weighting algorithm for interpolating the station temperature data into 1° latitude $\times$ 1° longitude grids. The gridded temperature data was cross validated after development, and errors were estimated and less than 0.5°C were found. More details about the IMD gridded data are reported in [51,52]. The Nagavali river basin has 12 IMD rainfall grid points and the Vamsadhara river basin has 16 IMD rainfall grid points. Rao et al. [47] compared and found a good correlation of 0.79 between IMD gridded rainfall and gauge rainfall data. Over the Nagavali river basin the annual average rainfall for the period of 1901–2018 is 1230 mm, annual average maximum temperature for the period of 1951–2018 is 32.05°C and minimum temperature is 21.03°C . For the Vamsadhara river basin the annual average rainfall is 1260 mm, annual average maximum temperature is 32.21°C and minimum temperature is 21.27°C .

2.2.5. Hydrological Data

Streamflow data and sediment data available at Srikakulam gauge station for the Nagavali river basin and Kashinagar gauge station for the Vamsadhara river basin are used in the present study. Streamflow and sediment data was obtained from Central Water Commission (CWC), Mahanadi and eastern rivers organization, Bhubaneswar, Orissa. The maximum streamflow over the Nagavali river basin is $5624.74\text{ m}^3/\text{sec}$ recorded on 4 August 2006 and corresponding sediment load is 3.34 million tons. Over the Vamsadhara river basin the maximum streamflow is $7321.54\text{ m}^3/\text{sec}$ recorded on 7 August 2007 and corresponding sediment load is 1.97 million tons. The average annual streamflow is $79.22\text{ m}^3/\text{sec}$ and $82.1\text{ m}^3/\text{sec}$, annual average sediment load is 3.69 and 3.72 million ton over the Nagavali and Vamsadhara river basins. Figure 3 shows the inter-annual variability of rainfall and streamflow for the period of 24 years from 1991 to 2014.

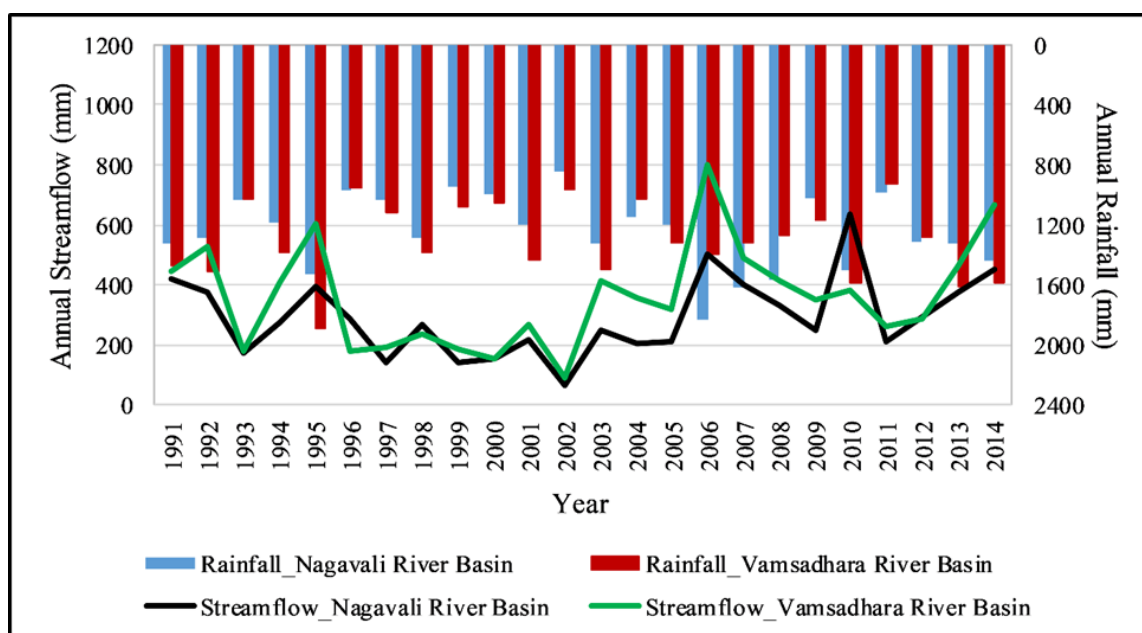


Figure 3. Annual rainfall and streamflow in the Nagavali and Vamsadhara river basins.

From Figure 3, it can be observed that over the Nagavali river basin the highest rainfall observed is 1832 mm in the year 2006, the lowest rainfall observed is 850 mm in 2002, and average rainfall is 1248 mm. Over the Vamsadhara river basin the highest rainfall is 1889 mm in the year 1995, the lowest rainfall is 926 mm in 2011, and average rainfall is 1303 mm. It was observed in both the river basins that 1995 and 2010 are flood years and the immediately following years of 1996 and 2011 are observed as drought years.

2.3. SWAT Model Setup

SWAT is a continuous, semi-distributed hydrologic model, developed by the U.S. Department of Agriculture [35,53–56]. SWAT simulates flow, sediment yield, and agricultural chemical yields from daily time steps to long term simulations.

In SWAT, to predict the sediment yield on a given day modified universal soil loss equation (MUSLE) was used as follows [57]:

$$SY = 11.8 \times (Q_{surf} \times q_{peak} \times A_{hru})^{0.56} \times C \times K \times P \times LS \times CFRG \quad (1)$$

Here, SY is the sediment yield (tons), Q_{surf} is the surface runoff volume (mm/ha), A_{hru} is area of HRU (ha), q_{peak} is peak runoff rate (m³/s), C is USLE cover and management factor, K is USLE soil erodibility factor, P is USLE support practice factor, LS is USLE topographic factor, $CFRG$ is coarse fragment factor and $Q_{surf} \times q_{peak} \times A_{hru}$ represents the runoff erosive energy variable. SWAT simulates the sediment yield in terms of total sediment loadings and the fraction of silt, clay and sand from sub-watershed.

Initially, to build the SWAT model, SRTM DEM, land use map and soil map were projected into common projection as WGS 1984 UTM 44N. The Nagavali river basin is delineated into 34 sub-basins and 2153 hydrological response units (HRUs) and the Vamsadhara river basin is 30 sub-basins and 2183 HRUs based on homogeneity of soil, land use, slope and 100 ha of threshold area using QSWAT on QGIS interface. The reservoir information, as shown in Table 1, has been updated into the SWAT model database. IMD precipitation, minimum and maximum temperature were given to the model to run simulations.

2.4. Model Performance Evaluation

Initially the SWAT model is calibrated and validated using the daily and monthly streamflow. The SWAT model performance is evaluated using coefficient of determination (R^2), Nash–Sutcliffe efficiency coefficient (NSE) [58] and percent bias (Pbias) [59].

$$NSE = 1 - \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i=1}^n (Y_i^{obs} - Y_{mean}^{obs})^2} \quad (2)$$

$$Pbias = \frac{\sum_{i=1}^n (Y_i^{obs} - Y_i^{sim}) \times 100}{\sum_{i=1}^n (Y_i^{obs})} \quad (3)$$

Here, Y_i^{obs} is the i^{th} observed data, Y_i^{sim} is the i^{th} simulated data, Y_{mean}^{obs} is the mean of observed data.

The optimal value of Pbias is 0, positive value represents the model bias towards underestimation and negative value denotes bias towards overestimation. The model performance was judged as satisfactory if NSE greater than 0.5 and Pbias is less than $\pm 25\%$ for monthly streamflow and less than $\pm 55\%$ for sediment simulations [60].

3. Results and Discussion

This study simulated streamflow and sediment yield, analyzed water balance components and identified critical source areas of erosion in the Vamsadhara and Nagavali river basins. The model was calibrated and validated by SWAT-CUP. The average annual water balance components and sediment yield analyses were performed sub-basin by sub-basin.

3.1. Calibration and Validation Analysis

The SUFI-2 algorithm in the SWAT-CUP [61] was used for model calibration, validation, and sensitivity analysis. The observed streamflow and sediments from Srikakulam and Kashinagar stations were used to calibrate and validate the SWAT model over Nagavali and Vamsadhara river basins (Figure 1). Based on observed streamflow data, the model simulated monthly streamflow for both basins for 29 years, from 1986 to 2014. The first five years of these 29 years were used as a model warm-up period for variable initialization. The following 15 years, from 1991 to 2005, were considered for calibration, and the remaining 9 years, from 2006 to 2014, were considered for validation. Observed sediment concentration data was available for 12 years, from 2002 to 2013 in grams per liter, and is converted to sediment load (tons per month). Data from 2002 to 2010 were used for calibration, and data from 2011 to 2013 were used for validation of sediment yield simulations.

3.1.1. Sensitivity Analysis

The SWAT model is a conceptual, semi-distributed model based on a number of parameters that vary significantly on a spatial and temporal scale. During the calibration period, sensitivity analysis was performed to identify the key parameters. For monthly streamflow simulations, 15 parameters were taken into account. The significance of sensitivity (P) and t -stat values were considered to identify sensitive parameters in Table 3. The parameters were more sensitive as the absolute t -stat values increase. P -values close to 0 indicating that the parameter is significant. The lower p -value and greater absolute t -stat value indicates higher sensitivity.

Table 3. Parameters that are sensitive in the Nagavali and Vamsadhara river basins.

S. No.	Parameter_Name	Nagavali River		Vamsadhara River	
		<i>p</i> -Value	t-Stat	<i>p</i> -Value	t-Stat
1	R_CN2.mgt	0.00	−8.74	0.00	−11.64
2	V_ALPHA_BF.gw	0.00	4.39	0.37	−0.90
3	A_GW_DELAY.gw	0.31	1.03	0.36	0.91
4	A_GWQMN.gw	0.41	0.83	0.00	6.23
5	V_GW_REVAP.gw	0.49	0.69	0.00	3.99
6	A_RCHRG_DP.gw	0.62	0.50	0.87	0.16
7	A_REVAPMN.gw	0.37	−0.90	0.35	−0.93
8	V_ALPHA_BF_D.gw	0.11	−1.61	0.23	−1.21
9	R_SOL_AWC.sol	0.87	0.16	0.01	−2.70
10	V_ESCO.hru	0.41	0.82	0.38	−0.88
11	V_CANMX.hru	0.09	1.69	0.10	1.64
12	V_CH_N2.rte	0.12	−1.55	0.54	−0.62
13	V_CH_K2.rte	0.02	−2.28	0.56	−0.58
14	V_CH_K1.sub	0.01	2.47	0.00	6.17
15	V_CH_N1.sub	0.55	0.59	0.12	1.55

Note: X_Parname.ext “X_” is a code to indicate the type of change to be applied to the parameter. If it is replaced by v_ it means the default parameter is replaced by a calibrated value, a_ means calibrated value added to the default value and r_ means the existing value is multiplied by (1+ calibrated value).

From Table 3, it is evident that CN2, ALPHA_BF, CH_K1, CH_K2, CH_N2, and CANMX are the most sensitive parameters for streamflow over Nagavali river basin and CN2, GWQMN, CH_K1, GW_REVAP coefficient, SOL_AWC, CH_K2 and CANMX are the most sensitive parameters for streamflow over Vamsadhara river basin. Because CN2 is the most sensitive and directly related to the runoff process in both river basins, changes in CN2 have a direct effect on streamflow and sediment yield. Table 4 represents the calibrated parameters and their fitted values over the Nagavali and Vamsadhara river basins for streamflow simulations, respectively. The parameters were described in detail in [54] and SWAT user manuals.

Table 4. Calibrated parameters and their fitted values for streamflow simulations.

S. No.	Parameter_Name	Min_Value	Max_Value	Fitted Values	
				Nagavali River Basin	Vamsadhara River Basin
1	R_CN2.mgt	−0.1	0.1	−0.088	−0.092
2	V_ALPHA_BF.gw	0	1	0.642	0.093
3	A_GW_DELAY.gw	−30	90	84.300	−11.1
4	A_GWQMN.gw	−1000	1000	5	−345
5	V_GW_REVAP.gw	0.02	0.2	0.053	0.172
6	A_REVAPMN.gw	−750	750	−498.75	123.75
7	V_ALPHA_BF_D.gw	0	1	0.45	0.687
8	A_RCHRG_DP.gw	−0.05	0.05	−0.019	−0.036
9	R_SOL_AWC.sol	−0.1	0.1	0.04	−0.029
10	V_ESCO.hru	0.3	0.6	0.53	0.58
11	V_CANMX.hru	0	20	0.45	9.35
12	V_CH_N2.rte	0.01	0.1	0.033	0.084

13	V__CH_K2.rte	0	100	74.75	24.25
14	V__CH_K1.sub	0	100	73.25	91.75
15	V__CH_N1.sub	0.01	0.3	0.19	0.15

3.1.2. Streamflow Simulation

The statistical results from calibration and validation showed a good agreement between observed and simulated monthly streamflow as presented in Table 5.

Table 5. Calibration and validation statistics.

River Basin	Gauge Station	Calibration				Validation			
		Period	R ²	NSE	Pbias	Period	R ²	NSE	Pbias
Monthly streamflow simulations									
Nagavali	Srikakulam	1991–2005	0.85	0.84	3.4	2006–2014	0.73	0.71	9.7
Vamsadhara	Kashinagar	1991–2005	0.82	0.8	−6.7	2006–2014	0.74	0.73	10.3
Monthly sediment simulations									
Nagavali	Srikakulam	2002–2010	0.86	0.85	−13.6	2011–2013	0.76	0.7	−14.3
Vamsadhara	Kashinagar	2002–2010	0.75	0.71	14.8	2011–2013	0.7	0.68	−42.8

The NSE values for the monthly streamflow of the calibration and validation period were 0.84 and 0.71 at Srikakulam station in the Nagavali river basin and 0.8 and 0.73 at Kashinagar station in the Vamsadhara river basin. The percentage bias (Pbias) for the calibration period was 3.4% for the Nagavali basin, indicating that it tends to under-predict, and −6.7% for the Vamsadhara basin, indicating that it tends to over-predict. During validation, Pbias is 9.7% and 10.3% in the Nagavali and Vamsadhara river basins, respectively. The model tends to under-predict for the Nagavali and Vamsadhara river basins during the validation period. The statistics for the SWAT model setup for Vamsadhara and Nagavali river basins are good when compared to standard model statistics [60]. Figures 4 and 5 show the observed versus simulated monthly streamflow at the Srikakulam and Kashinagar gauge stations over the Nagavali and Vamsadhara river basins, respectively.

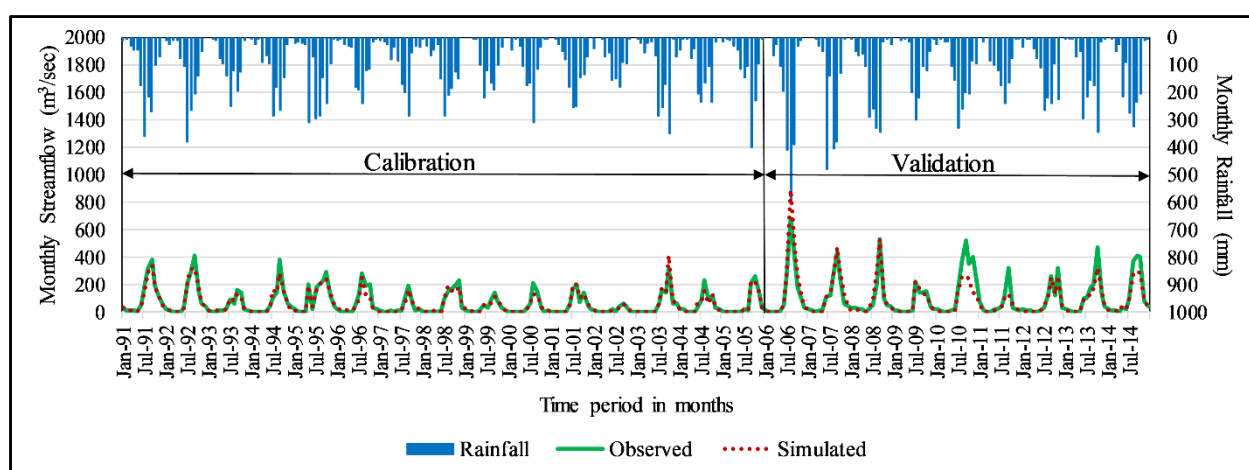


Figure 4. Observed versus simulated monthly streamflow during the calibration and validation period over the Nagavali river basin.

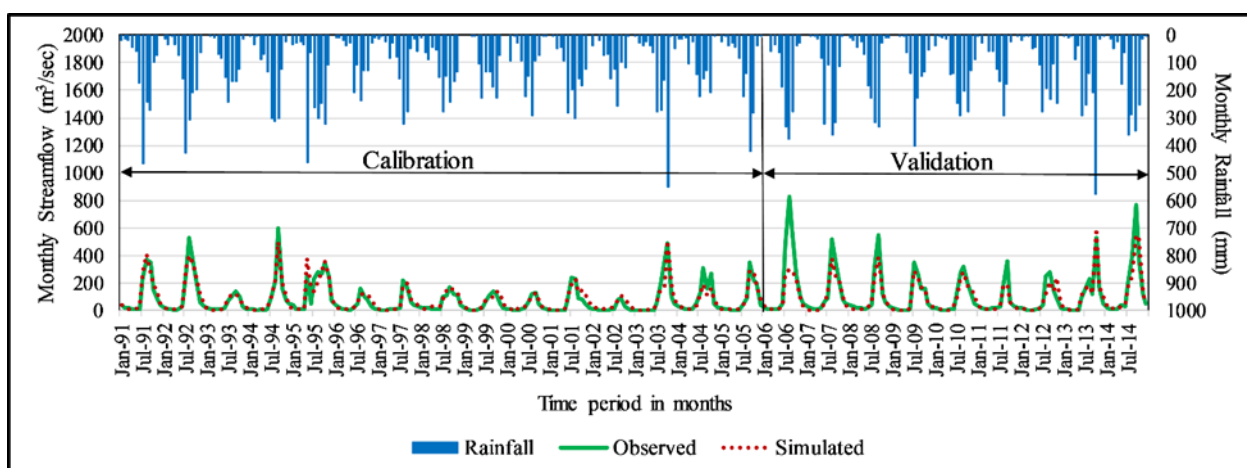


Figure 5. Observed versus simulated monthly streamflow during the calibration and validation period over the Vamsadhara river basin.

From Figures 4 and 5, it is evident that during the calibration and validation period, the time series plot of simulated streamflow reflects the precipitation pattern over the Vamsadhara and Nagavali river basins and matched well with the observed streamflow. In the Vamsadhara and Nagavali river basins, the largest quantity of streamflow occurred from June to October in every year.

3.1.3. Sediment Simulation

Following calibration of streamflow, the calibrated streamflow parameters were updated into the SWAT model, and sediment simulations were carried out. To reduce the high sediment yield from agricultural lands, manual calibration with landscape parameters influencing sediment yield from agricultural lands was performed first, followed by auto calibration [53,54]. Due to watershed uneven slope distribution, the initial LS factor (HRU_SLP and SLSUBBSN) is very high, resulting in an overestimation of sediment yield. Manual calibration was considered only for agricultural HRUs to reduce the sediment load with three landscape parameters [62] including USLE_P, HRU_SLP and SLSUBBSN.

To reduce sediment yield, the LS factors were reduced by replacing HRU_SLP (average slope steepness (m/m)) with 2% for agricultural HRUs and 0.5% for Rice crop HRUs and SLSUBBSN (average slope length (m)) with 75 m. These changes reduced the simulated sediment yield while limiting erosion from agricultural HRUs. The erosion process is influenced by the USLE_P (USLE equation support practice) factor, which is reduced from the default value of 1 to 0.5 for agricultural HRUs. Decreasing of USLE_P has a greater impact on sediment yield from agricultural HRUs. After adjusting these three parameters manually, the simulated sediment yield from agricultural HRUs is less than 1 t/ha/yr. Following manual adjustment of these three parameters, auto calibration was performed using the five parameters presented in Table 6.

Table 6. Calibrated parameters and their fitted values for monthly sediment simulation.

S. No.	Parameter_Name	Min_Value	Max_Value	Fitted Values	
				Nagavali River Basin	Vamsadhara River Basin
1	V__CH_COV1.rte	0	0.6	0.23	0.46
2	V__CH_COV2.rte	0	1	0.39	0.17
3	V__SPCON.bsn	0.0001	0.01	0.006	0.0068
4	V__SPEXP.bsn	1	1.5	1.12	1.08
5	R__USLE_K(..).sol	−0.2	0.2	−0.1	−0.09

As indicated in Table 5, the statistical findings between monthly observed and simulated sediment load obtained during calibration and validation revealed a good agreement for the Nagavali river basin and a satisfactory agreement for Vamsadhara river basin. For the calibration and validation periods, the NSE values for monthly sediment at Srikakulam gauge station for the Nagavali river basin were 0.85 and 0.7, respectively, and 0.71 and 0.68 at Kashinagar gauge station for the Vamsadhara river basin, respectively.

The percentage biases (Pbias) for the calibration and validation periods were -13.6% and -14.3% for the Nagavali basin and 14.8% and -42.8% for the Vamsadhara basin. The Pbias values for monthly sediment load show that the model tends to overpredict for the Nagavali river basin and underpredict during calibration, and overpredict during validation for the Vamsadhara river basin. The sediment load in the Nagavali and Vamsadhara river basins were overestimated due to basin barren and scant vegetation over the landscapes, topography and its complexity, and steep slopes, whereas 60% of the basins area was covered by steep slopes that are more than 8 degrees. Figures 6 and 7 show the observed and simulated monthly sediment load over the Nagavali and Vamsadhara river basins during the calibration and validation periods, respectively.

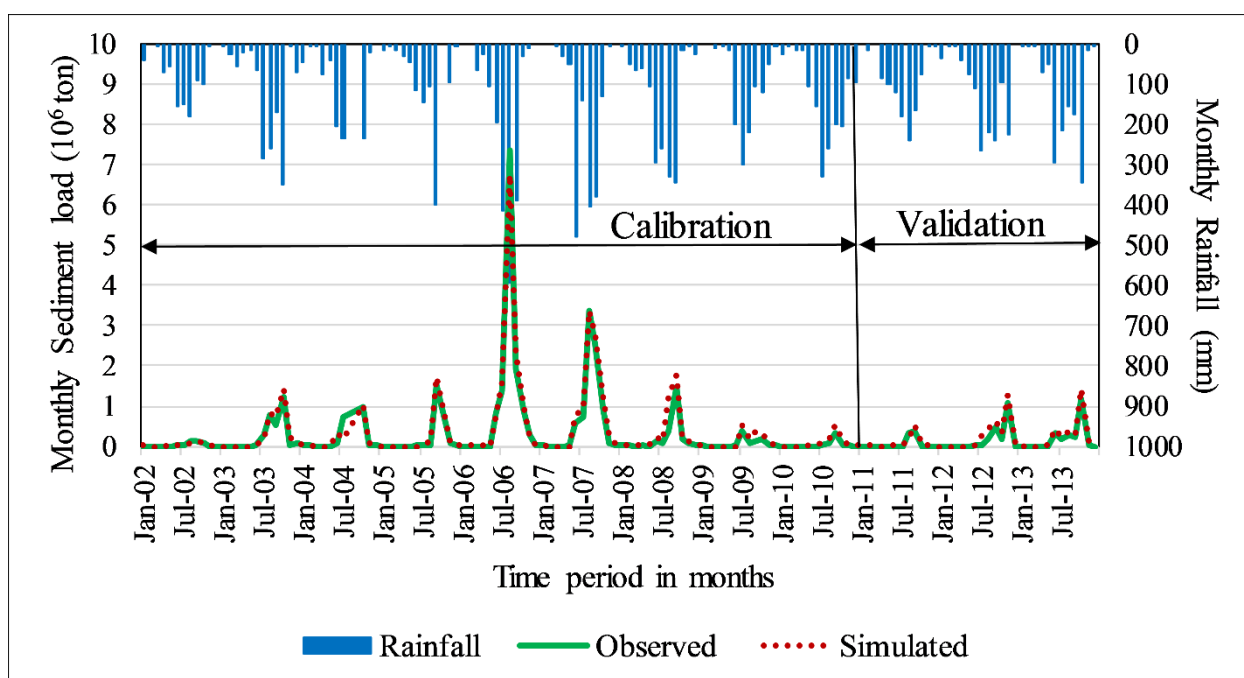


Figure 6. Observed versus simulated monthly sediment load during the calibration and validation period over the Nagavali river basin.

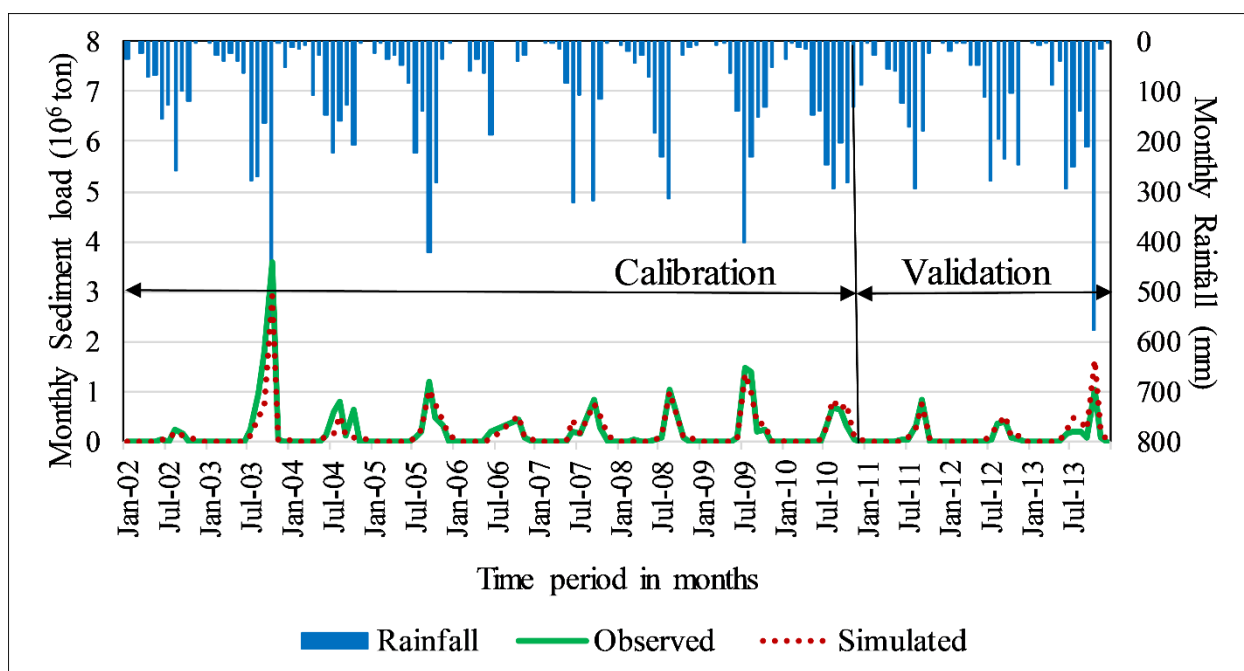


Figure 7. Observed versus simulated monthly sediment load during the calibration and validation period over the Vamsadhara river basin.

3.2. Water Balance of Nagavali and Vamsadhara River Basins

Analyzing and quantifying various elements of hydrological processes occurring within the basin is required for various water management scenarios. Precipitation, surface runoff, water yield, lateral runoff, and evapotranspiration are the primary components of water balance in the basin. The results of the calibrated model were examined in terms of the water balance components on a monthly basis from 1991 to 2014. The annual average rainfall amount in the Nagavali and Vamsadhara river basins is 1259 mm and 1332 mm, respectively. Figure 8a depicts the monthly water balance for the Nagavali and Vamsadhara river basins (b).

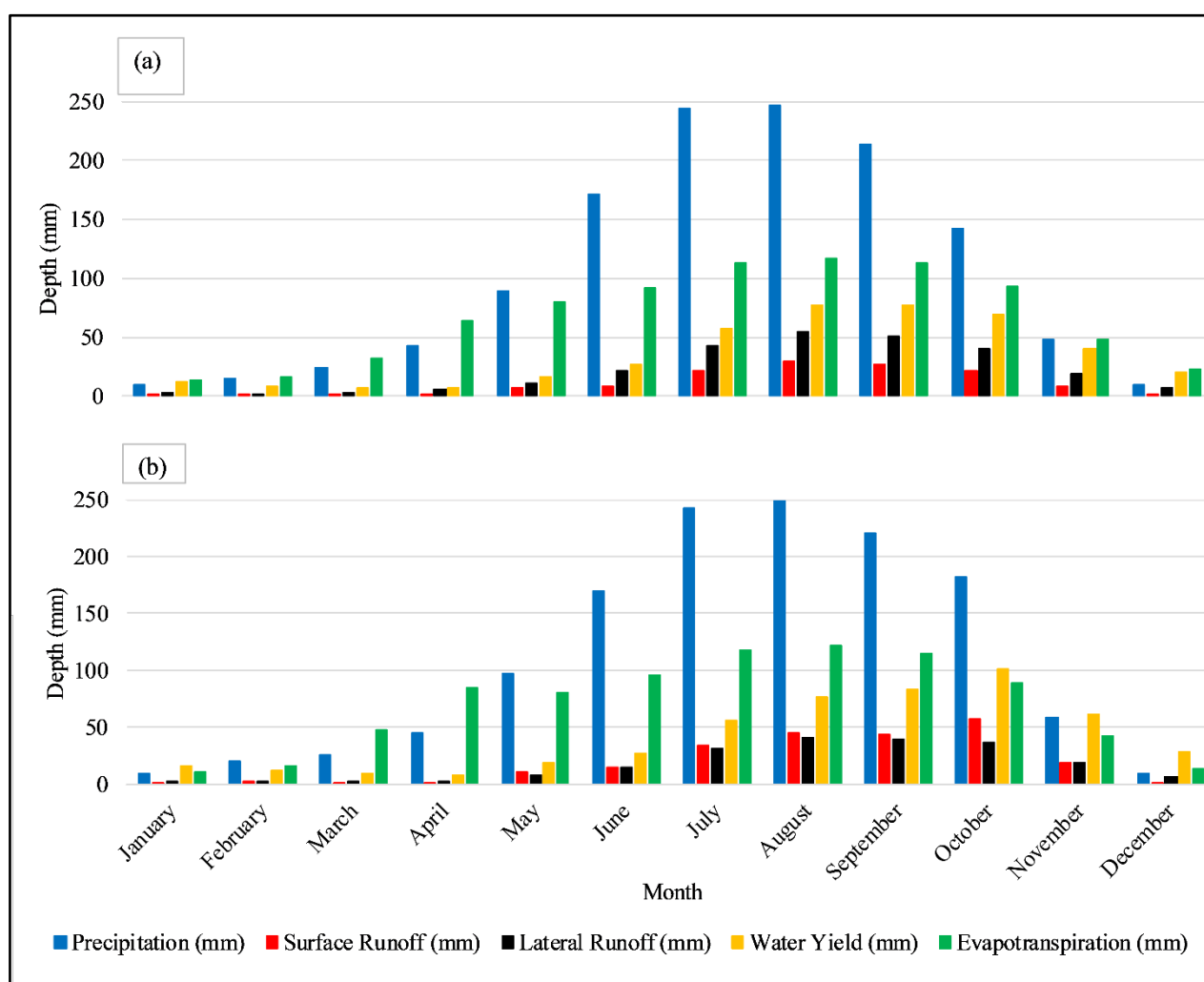


Figure 8. Mean monthly values of water balance components (a) Nagavali basin (b) Vamsadhara river basin.

During the monsoon season, 80% of the rainfall falls (June to October). Evapotranspiration contributes the most to water loss in both river basins, accounting for 63% of total water loss. The amount of water lost due to evapotranspiration is determined by the soil evaporation compensation factor (ESCO), the ET estimation method, and the leaf area index. Forest land and agriculture land cover the majority of the catchment area over the Nagavali and Vamsadhara river basins. As a result, evapotranspiration has a major impact on both river basin water resources. Because of the amount of plant growth, humidity, and wind velocities are high in these areas during monsoon and post monsoon months, evapotranspiration demands were higher in monsoon and post monsoon months than in pre monsoon months [43]. From Figure 8, in dry months, monthly evapotranspiration is estimated to be greater than total precipitation for both river basins. This is allowed because evapo-transpiration is a continuous process that occurs at varying rates during the day and night, regardless of precipitation, and the water for evapotranspiration comes from near-surface soil moisture. The depth of the plant root, which allows it to gather water via deeper soil layers, affects the rate of evapotranspiration [20]. Furthermore, because the SWAT model is a continuous model that accounts for changes in soil moisture content, it is easier to factor in the soil moisture content from the previous day. As a result, total precipitation in a given month may be less than total evapotranspiration in dry months. From the water balance analysis, there is a need for water-harvesting structures because both basins receive more than 80% of their rainfall during the monsoon season.

3.3. Spatial Distribution of Water Balance Components

The spatial distribution of average annual values of various water balance components was visualized to better understand the hydrological cycle over the Vamsadhara and Nagavali river basins. Figure 9 shows the spatial distribution of average annual precipitation, surface runoff, groundwater flow over the Nagavali river basin.

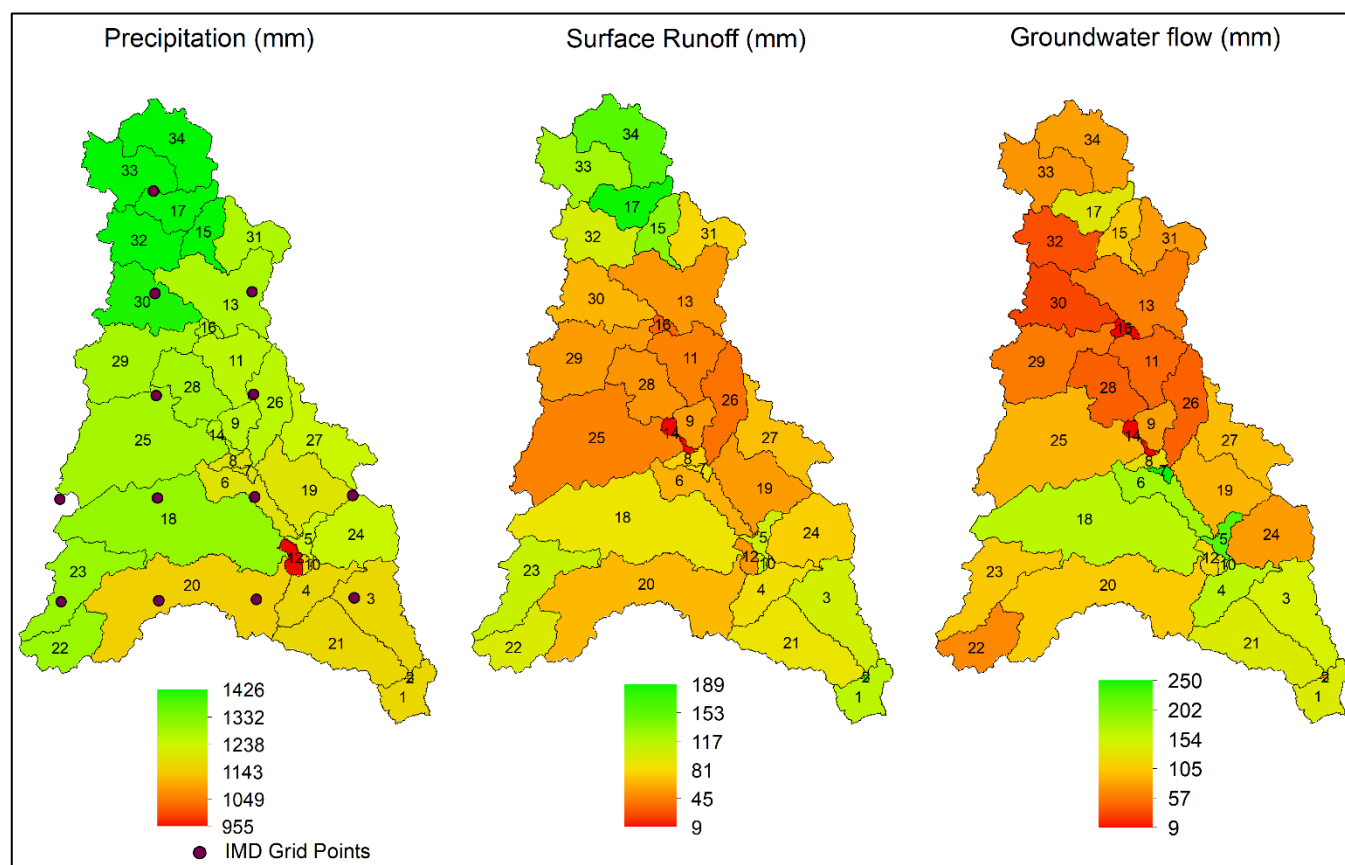


Figure 9. Spatial distribution of average annual precipitation, surface runoff and groundwater flow over the Nagavali river basin for the period of 24 years (1991–2014).

The upper sub-basins received the most precipitation over the Nagavali river basin, while the lower sub-basins received the least. Surface runoff ranges from 9 mm to 189 mm, with sub-basins 1, 2, 15, 17, 33 and 34 producing the most. The groundwater flow ranges from 9 mm to 250 mm, with sub-basins 5 and 7 producing the most groundwater flow. Figure 10 shows the spatial distribution of annual average evapotranspiration and its validation using the Famine Early Warning Systems Network Land Data Assimilation System (FLDAS) [63]. The SWAT model-simulated evapotranspiration varying from 698 mm to 1050 mm. Sub-basins 7, 10 and 12 contribute the most evapotranspiration, while lower sub basins with waterbodies and agricultural lands contribute the least. The FLDAS dataset, on the other hand, ranged from 825 mm to 1131 mm over the Nagavali river basin. The difference in Pbias between the SWAT simulated evapotranspiration and the FLDAS dataset is 15%.

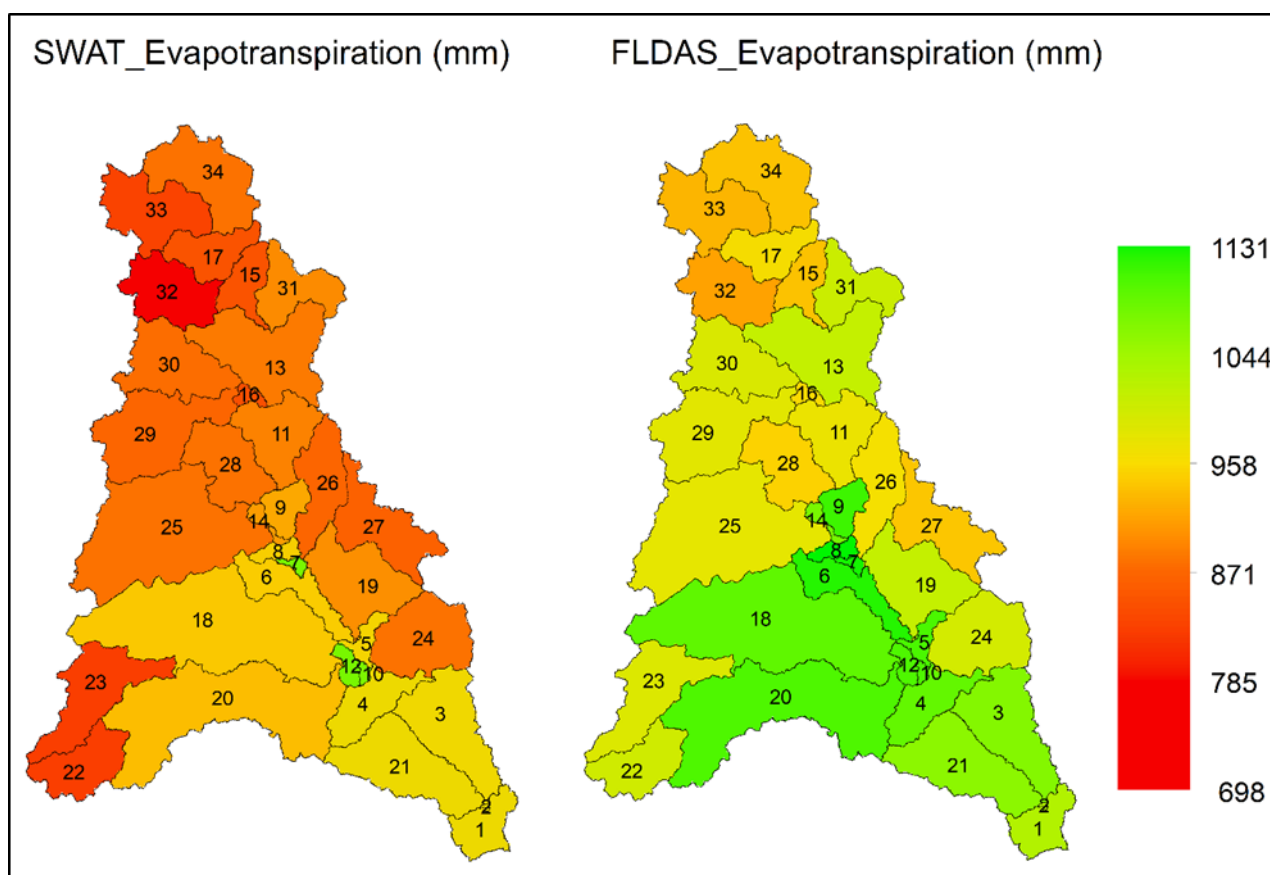


Figure 10. Spatial distribution of average annual evapotranspiration and its validation using FLDAS data over the Nagavali river basin for the period of 24 years (1991–2014).

The spatial distribution of average annual precipitation, surface runoff, and groundwater flow over the Vamsadhara river basin is depicted in Figure 11. The highest precipitation over the Vamsadhara river basin was 1410 mm in the upper sub-basins and the lowest was 1192 mm in the lower sub-basins. Surface runoff ranges from 43 mm to 172 mm, with sub-basins 8, 11, 12, 16, 25, and 29 producing the most. Groundwater flow ranges from 59 to 265 mm, with the majority of sub-basins contributing the most groundwater flow. Figure 12 shows the spatial distribution of average annual evapotranspiration and its validation using the FLDAS dataset. The SWAT simulated evapotranspiration varying from 730 mm to 941 mm, with sub-basins 2, 7 and 28 contributing the most. Whereas the FLDAS dataset ranged from 831 mm to 1075 mm over the Vamsadhara river basin. The difference in Pbias between the SWAT simulated evapotranspiration and the FLDAS dataset is 11%.

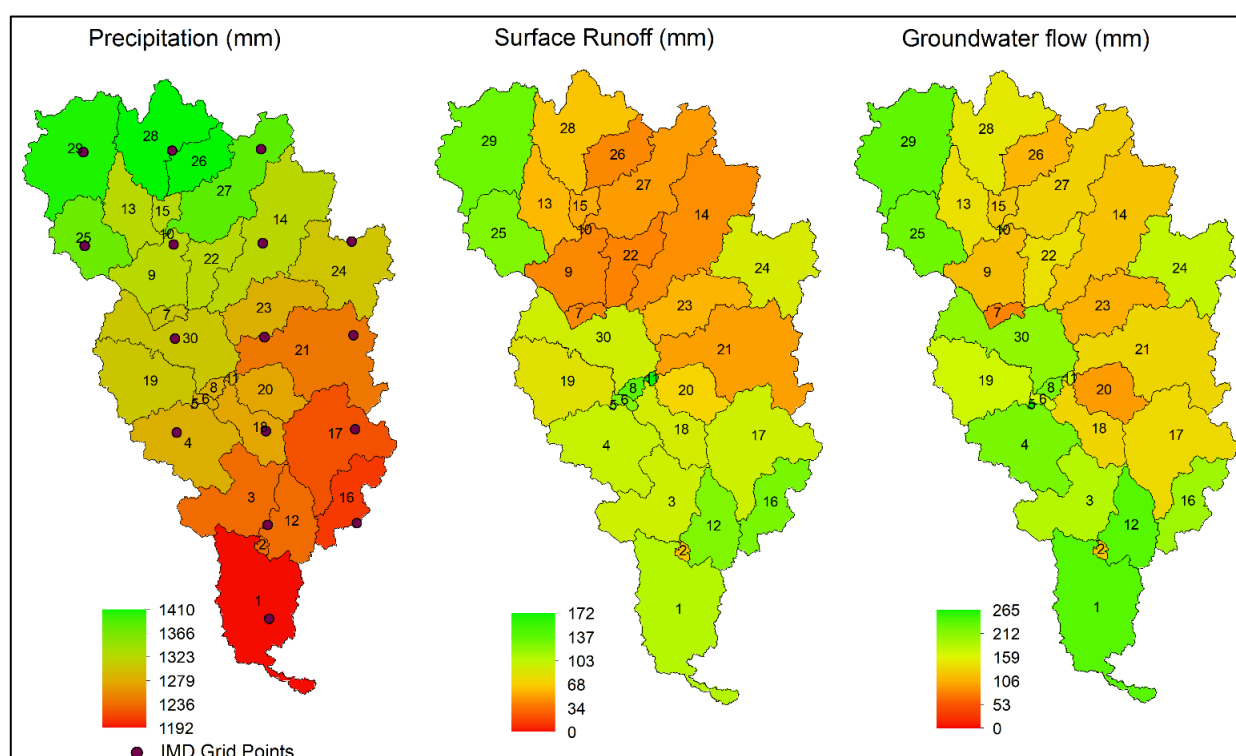


Figure 11. Spatial distribution of average annual precipitation, surface runoff and groundwater flow over the Vamsadhara river basin for the period of 24 years (1991–2014).

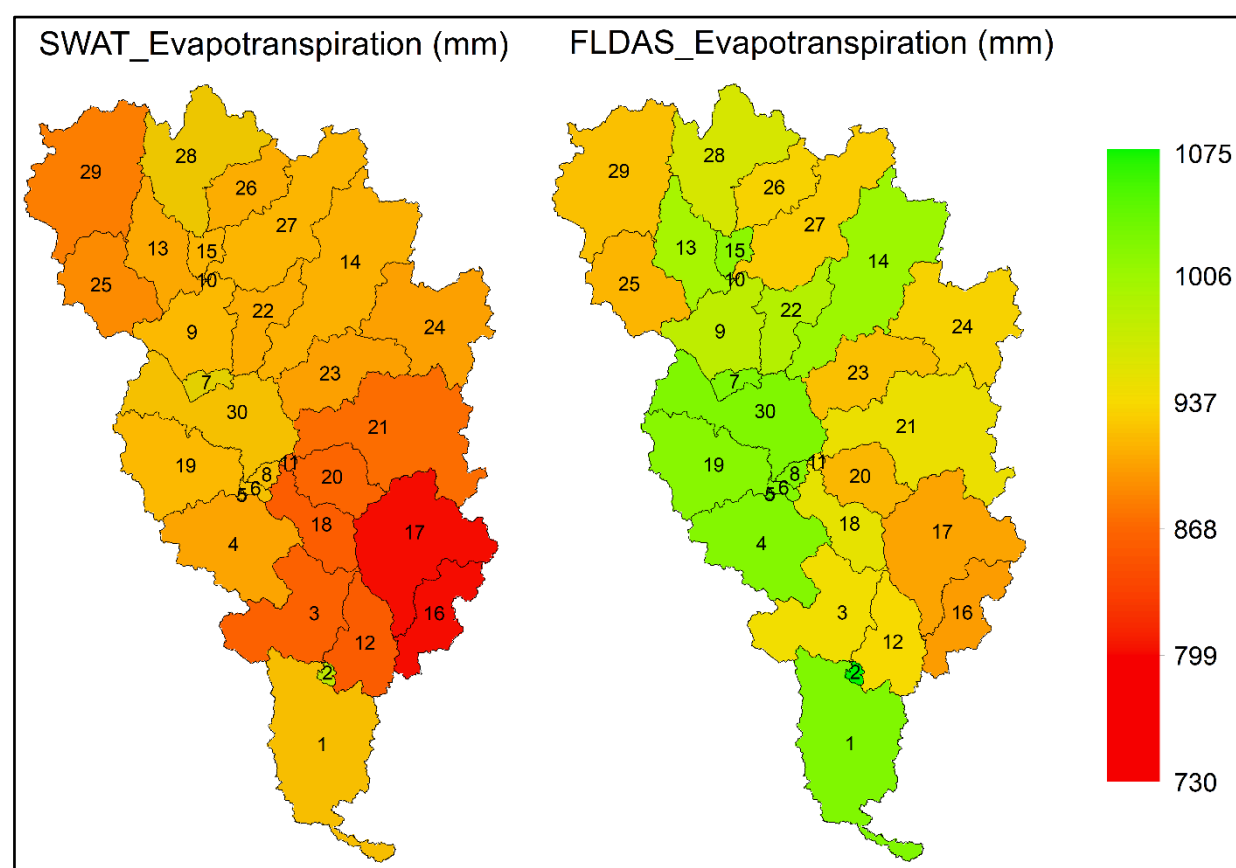


Figure 12. Spatial distribution of average annual evapotranspiration and its validation using FLDAS data over the Vamsadhara river basin for the period of 24 years (1991–2014).

Based on the spatial distribution of average annual hydrological components, it was concluded that the simulated precipitation over the basins for the period of 24 years from 1991 to 2014 showed a decreasing gradient from north to south and follows the altitude gradient over the two basins. Soil type and land use had the greatest influence on ground-water flow. The sub-basins with sandy soil and forest cover contributed the most ground-water flow. Sub-basins with bodies of water and agricultural lands with long-grown plants contribute the most evapotranspiration. The correlation between SWAT simulated evapotranspiration and the FLDAS dataset over the Nagavali and Vamsadhara river basins was 0.78.

3.4. Spatial Variability of Sediment Yield and Identification of Sediment Source Areas

The average trapping efficiency of sediment over the Nagavali and Vamsadhara river basins were identified as 77.65% and 67.59% by reservoirs. Table 7 shows the average annual sediment yield (t/ha/yr) for the two river basins divided into three classes for spatial representation and identification of critical source areas of sediment yield suggested by Singh [64] for Indian conditions [2,65]. The average annual sediment yield from the sub-basin is less than 5 t/ha/yr in the slight erosion class, 5–10 t/ha/yr in the moderate erosion class, and greater than 10 t/ha/yr in the high erosion class. The average annual sediment yield from sub-basins serves as the foundation for identifying critical sediment source areas [2,5,20]. This is useful for sub-watershed agricultural, structural, and watershed management planning.

Table 7. Areas subjected to various levels of soil erosion in the Nagavali and Vamsadhara basins.

S. No.	Sediment Yield (t/ha/yr)	Soil Erosion Class	Nagavali River Basin		Vamsadhara River Basin	
			Percent Area	Sub-Watershed Numbers	Percent Area	Sub-Watershed Numbers
1	0–5	Slight	24	1–7, 10, 12–14, 19, 21	13	5, 10, 21, 22, 26
2	5–10	Moderate	49.5	8, 9, 11, 16, 18, 20, 25, 26, 28–31	38	1, 2, 4, 7–9, 13–15, 27, 30
3	>10	High	26.5	15, 17, 22–24, 27, 32–34	49	3, 6, 11, 12, 16–20, 23–25, 28, 29

3.4.1. Nagavali River Basin

Figure 13a depicts the spatial distribution of average annual simulated sediment yield over the Nagavali river basin for 34 sub-basins.

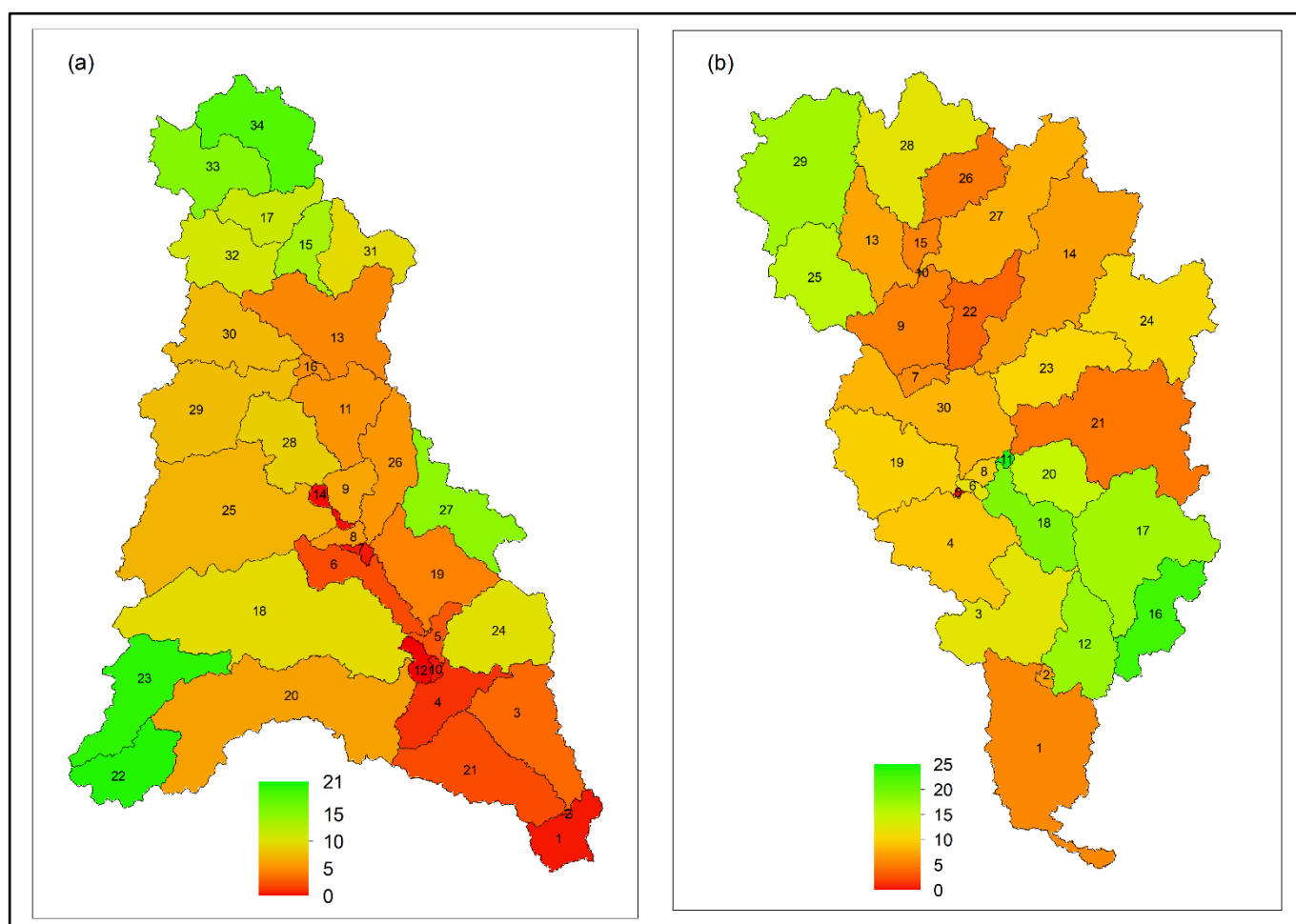


Figure 13. Spatial distribution of average annual sediment yield (t/ha/yr) (a) over the Nagavali river basin (b) over the Vamsadhara river basin for the period of 13 years (2002–2013).

Figure 13a shows that sub-basins 22, 23, and 34 have the highest sediment yield of 20.3 t/ha/yr. These sub-basins are characterized by moderate to steep slopes, and the majority of sub-basin areas are devoid of land use. Table 7 shows that 26.5% of the basin area is subject to high erosion (>10 t/ha/yr), with the corresponding sub-basins being 15, 17, 22–24, 27, 32, 33 and 34. These sub-basins are regarded as critical sediment source areas throughout the Nagavali river basin, and priority is given to them. In total, 49.5% of basin area is classified as moderate soil erosion (5–10 t/ha/yr) and 24% is classified as slight erosion (5 t/ha/yr). To reduce the severity of soil erosion caused by landscape and reservoir capacity loss, sub-basins with high sediment yields required immediate attention for soil conservation practices. The Nagavali river basin's average annual sediment yield was determined to be 7.18 t/ha/yr. In the Nagavali river basin, sub-basins with lower slopes and dense vegetation contribute a minor sediment yield. It has been observed that the lower portion of the basin produces a minor sediment yield.

3.4.2. Vamsadhara River Basin

Figure 13b depicts the spatial distribution of average annual simulated sediment yield over the Vamsadhara river basin for 30 sub-basins (b). Figure 13b shows that sub-basins 11 and 16 have the highest sediment yield of 24.8 t/ha/yr. These sub-basins, like the Nagavali river basin, have a moderate to steep slope, and the majority of the sub-basin areas are covered in wasteland. Table 7 depicts the Vamsadhara river basin, with 49% of the basin area falling into the high erosion class (>10 t/ha/yr), and the corresponding sub-basins being 3, 6, 11, 12, 16–20, 23–25, 28, and 29. These sub-basins are regarded as critical

sediment source areas throughout the Vamsadhara river basin, and priority is given to them. In total, 38% of basin area is subject to moderate soil erosion (5–10 t/ha/yr) and 13% is subject to slight erosion (5 t/ha/yr). To reduce the severity of soil erosion caused by landscape and reservoir capacity loss, the sub-basins contributing the most sediment yield required immediate attention to management practices. The average annual sediment yield of the Vamsadhara river basin, on the other hand, was found to be 10.7 t/ha/yr.

In both river basins, the majority of the sediment yield was contributed by wastelands with steep slopes ($> 8^\circ$), followed by fallow lands, degraded deciduous forest lands, and agricultural lands. Tribal peoples live along the river and rely on shifting cultivation for a living [12]. It could explain the high sediment yield from deciduous and degraded forest lands and wastelands.

According to average annual sediment yield analysis, the average annual sediment yield of the Nagavali and Vamsadhara river basins was found to be 7.18 and 10.7 t/ha/yr respectively, which is within the permissible limit of 11.2 t/ha/yr [13,22]. The sub-basin average annual sediment yield from the Nagavali and Vamsadhara river basins represents 26.5% and 49% of basin area contributing highest sediment yield, respectively, and the corresponding sub-basins are identified as critical sediment source areas. However, wastelands produced the highest sediment yield, followed by current fallow land, agricultural lands, degraded and deciduous forest lands with steep slopes in both river basins. According to Table 2, wastelands occupy 19.05% and 17.23% of the basin area of the Nagavali and Vamsadhara river basins, respectively. These lands are represented by hilly areas with less vegetation (scrub lands and barren lands), areas with mining activities, and areas where tribal communities previously practiced shifted cultivation.

4. Conclusions

The current study presented a SWAT model-based streamflow and sediment yield analysis of the Nagavali and Vamsadhara river basins, and critical sediment source areas were identified in order to recommend appropriate soil conservation measures at the sub watershed level. Sensitivity analysis reveals that the most sensitive parameters in both river basins are the initial SCS runoff curve number (CN2) and effective hydraulic conductivity in tributary channel alluvium (CH_K1). The obtained statistics over the Nagavali and Vamsadhara river basins range from very good to satisfactory, indicating the SWAT model's acceptance. The calibrated SWAT model simulated the streamflow generally, capturing peak flow events in close correlation with extreme precipitation, the model is influenced by both low and high precipitation events, resulting in under-predicted and over-predicted streamflow. From the water balance analysis evapotranspiration is the dominant process, accounting for 63% of the average annual rainfall over the basins. Evapotranspiration is attributed to plant growth, humidity and wind speed. The calibrated SWAT model produced an average annual sediment yield of 7.18 t/ha/yr for the entire basin and 10.7 t/ha/yr for the Nagavali and Vamsadhara river basins, which are classified as moderate and high soil erosion class, respectively. From the sub-basin average annual sediment yield analysis, 26.5% and 49% of basin area are classified as high erosion areas, over Nagavali and Vamsadhara river basins and these areas are characterized by steep slope of wasteland, followed by fallow lands, degraded, deciduous forests and agricultural lands and critical sediment source areas. These areas require immediate attention to management practices to improve the soil water conservation measures in the Nagavali and Vamsadhara river basins.

This study contributes to our understanding of water balance analysis, sediment yield analysis and identifying sediment source areas using the SWAT model. Furthermore, this research contributes to an understanding of climate change and the application of best management practices in the Nagavali and Vamsadhara river basins with identified sediment source areas. This study also provides the best calibrated parameters for using the SWAT model for real time flood forecasting. This study is expected to assist the

watershed planners and managers in implementing suitable soil and water conservation measures in both watersheds at the sub-basin scale.

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