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Quantitative Assessment of Soil Erosion in the Hathmati Watershed using the SWAT

Bhagyesh C. Contractor[1, *], Dr. Bhavin G. Buddhdev[2]

[1]Ph.D. Research Scholar, Gujarat Technological University, Ahmedabad; [2]Assistant Professor, Applied Mechanics Department, Vishwakarma Government Engineering College, Ahmedabad, Gujarat

*Corresponding Author:

Email: bccphd@gmail.com; Phone: +91-9904773040 (Bhagyesh C. Contractor)

ABSTRACT:

Soil erosion is a critical environmental issue that significantly impacts agricultural productivity and water quality. Soil erosion estimation is often difficult due to the complexity of many factors such as climate, land uses, topography, and human activities. In this research paper, the Soil and Water Assessment Tool (SWAT) model is used to estimate surface runoff and soil erosion and to prioritize the most degraded sub-watersheds to adopt the appropriate soil conservation measures in Hathmati Watershed having a total basin area of 1421.91 sq. km. of Sabarmati River basin of India. SWAT model involves many components such as hydrology, meteorological conditions, soil temperature, crop growth, nutrients, pesticides, soil erosion, sediment yield, and agricultural management practices. Meteorological data, topography, land use land cover (LULC), soil characteristics, and climate data were integrated into the SWAT model to estimate soil erosion over a period. This hydrogeological model is set up for a span of 20 years, i.e. from the year 2001 to 2020. The model result shows that the soil erosion rate ranges from 10 to 40 ton/ha/year in the Hathmati watershed. The soil erosion rates more than 40 t/ha/year is observed in the year 2005, 2006, 2007, 2009, 2010, and 2014 due to high rainfall intensity and changes in LULC pattern. The SWAT model indicates that differences in soil erosion rates within the Hathmati Watershed are mainly caused by differences in Rainfall Patterns, Land use land cover type, and gradient slope. Application of the SWAT model demonstrated that the model provides a useful tool to predict surface runoff and soil erosion and can successfully be used for prioritization of soil erosion-prone areas over semi-arid watersheds.

Key Words: Surface Runoff, Soil Erosion, Hydrogeological Modeling, Soil and Water Assessment Tool (SWAT), Soil & Water Conservation, Sustainable Land Management (SLM)

1. INTRODUCTION:

In recent decades, soil erosion by water has emerged as a significant global issue due to the declining ratio of natural resources to population and the effects of climate change. (Terranova et al. 2009). Soil Erosion is the disintegration and removal of topsoil due to the combined effect of rainfall and surface runoff affecting the soil's nutrition level, thereby affecting any region's agricultural productivity. The global average rate of soil erosion is estimated to be around 12 to 15 tons per hectare per year (Biggelaar et al., 2003; Buraka et al., 2022), resulting in a soil loss of approximately 0.96 to 1.2 millimeters from the land surface annually (Food and Agriculture Organization, 2019). In India, out of a total land surface of 328.8

million hectares, 94 million hectares are affected by water-induced soil erosion, 16 million hectares by acidification, 14 million hectares by flooding, 9 million hectares by wind erosion, 6 million hectares by salinity, and 7 million hectares by a combination of these factors (Bhattacharyya et al., 2015). In a developing country like India, where agriculture is the backbone of the economy, the impact of soil loss, particularly, the loss of top fertile soil, has a huge effect on agricultural output, land use intensity, and cropping patterns, all of which have significant environmental and economic consequences (Rajbanshi and Bhattacharya, 2020). In addition to reducing agricultural productivity, soil erosion leads to increased siltation in rivers, reservoirs, and wetlands, causing disasters such as floods and droughts that threaten the ecology of affected areas (Jamal et al., 2022).

Soil erosion is influenced by various factors, such as soil types, the intensity of rainfall, topographic conditions, and human land use activities (Makhdumi et al., 2023). Soil physical properties play an important role in holding the soil particles together viz., weaker soil types comprised of silty and sandy soil are more prone to erosion as the soil lacks the strength to bind the soil particles together owing to high runoff rate, while clayey soil is less prone to soil erosion (Ghosh et al., 2022). Land use and land cover changes such as alteration in agricultural practices, clearing of the forest, etc. have accelerated the rate of soil erosion (Guo et al., 2019). Numerous research studies have found that soil loss is primarily caused by water erosion, which is exacerbated by improper land use and management practices, including unscientific tillage and agricultural methods (Bhatt et al., 2020).

Soil erosion estimation is one of the greatest challenges in natural resources and environmental planning. Computer simulation models are becoming increasingly popular in predicting soil loss for various land use and management practices. In order to forecast runoff, flooding, soil erosion and nutrient transport to agricultural watersheds under different conditions, various hydrological models such as ANSWERS (Beasley and Huggins, 1980); CREAMS (Knisel, 1980); EPIC (Williams et al., 1985); TOPMODEL (Beven and Kirkby, 1979); SHE (Abbott et al., 1986); IHACRES (Jakeman and Hornberger, 1993); AGNPS (Young et al., 1987); SWARB (Williams et al., 1985); IHDM (Calver and Wood, 1995); SWM (Crawford and Linsely 1966) and SWAT (Soil and Water Assessment Tool) (Arnold et al., 1996) have been established. The Soil and Water Assessment Tool (SWAT) is used because of its numerous features and components that simulate water balance, surface runoff, soil erosion loss, and land management techniques. The SWAT model applies to large watersheds and is intended for ungauged watersheds (Neitsch et al. 2002b). The SWAT model is widely used for soil erosion modeling in watersheds, under different conditions, including semi-regions. This study describes the use of SWAT in identifying hydrological response units (HRUs), development of the land use/land cover (LULC) maps, simulation of SWAT model using SUFI-2 algorithm for runoff simulation as well as soil erosion estimation for hydrological modeling of Hathmati Watershed of Sabarmati River Basin.

2. MATERIALS AND METHODS:

Study Area

The Hathmati River is a Left bank tributary of Sabarmati River. It rises in Southwest foothills of the Rajasthan range in Gujarat State and flows in South West direction for a distance of 122 km to meet the Sabarmati on its left bank. This tributary drains an area of about 1500 sq km. The two main tributaries of Hathmati are Bodoli and Guhai having a catchment area of 119 and 505 sq. km respectively. The Hathmati

River watershed has been selected for the study and the location map developed using ArcGIS is shown in Figure-1.

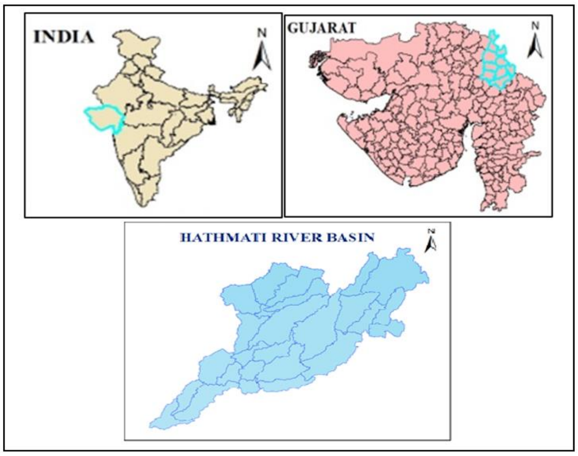

Figure 1: Location Map of the Hathmati River Basin

Hathmati river basin has a tropical monsoon climate with three seasons, the monsoon (kharif, between late June to October), the cooler rabbi (November to February) which is dry except for occasional rain in November and in the coastal region, and the hot summer season (March to mid-June). The rainfall occurs almost entirely in monsoon months (June to September) with an average annual rainfall of the basin of about 860 mm with significant regional variations.

In this study, various spatial data like the Digital Elevation Model (DEM). Land Use Land Cover (LULC) map, Soil classification map are generated from CARTOSAT-I, SRTM, BHUVAN and IRS~ID LISS III satellite data and prepared in ArcGIS on 1:12500 scale with the resolution of 30m and several collateral data like meteorological data, weather data, river gauging data for a span of 20 years (from 2001 to 2020) have been collected. The details of weather/raingauge stations fall in the study area are shown in Table 1.

Table 1: Details of Weather/Raingauge Stations

Sr. No.	Weather Station Name	Latitude	Longitude	Elevation
1	Badoli	23° 49' 30"	73° 04' 31"	217 m
2	Bhiloda	23° 47' 00"	72° 56' 30"	230 m
3	Mankadi	23° 41' 30"	73° 09' 40"	195 m
4	Khandiol	23° 42' 00"	73° 03' 00"	185 m

Soil and Water Assessment Tool (SWAT)

The Soil and Water Assessment Tool (SWAT) was developed by the United States Department of Agriculture (USDA) Agricultural Research Service ((Arnold et al. 1996; Srinivasan et al. 2004) to simulate the land phase of the hydrologic cycle as well as the impact of land management practices on water, sediments in watersheds in daily time steps.

SWAT model is a semi-dispersed watershed scale persistent time display with day-by daytime step. The SWAT model involves many components such as hydrology, meteorological conditions, soil temperature, crop growth, nutrients, pesticides, sediment yield, and agricultural management practices (Bhagyesh et al. 2024, Byakod et al. 2017). The hydrological components of the SWAT model are based on the following water balance equation.

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw})$$

Where SWt is the final water content, SW_0 is the initial soil water content of the day i, t is the time in days, R_{day} is the amount of precipitation on day i, Q_{surf} is the amount of surface runoff on day i, E_a is the amount of evapotranspiration on day i, W_{seep} is the amount of water entering the vadose zone from the soil profile on day i and Q_{gw} is the amount of return flow on day i (mm of H2O).

SWAT simulates surface runoff volumes and peak runoff rates for each HRU using daily or sub-daily rainfall amounts using a modification of the soil conservation service curve number (SCS-CN) method or the Green & Ampt infiltration method (Neitsch et al. 2005), respectively. In the curve number method, the curve number varies non-linearly with the moisture content of the soil profile, reaching its lowest value when the soil profile approaches the wilting point and increasing to nearly 100 as the soil approaches saturation. The surface runoff is calculated using following equation:

$$Q = \frac{(R - 0.2S)^2}{R + 0.8S} \qquad R > 0.2S$$

$$Q = 0 \qquad R \leq 0.2S$$

Where, Q is the daily surface runoff (millimeters), R is the daily rainfall (millimeters) and S is a retention parameter.

The retention parameter, ‘S’ varies among watersheds because soils, land use, management, and slope all vary, and with time because of changes in soil water content. The parameter ‘S’ is related to Curve Number (CN) by the following SCS equation

$$S = 254 \left(\frac{100}{CN} - 1\right)$$

The following Modified Universal Soil Loss Equation (MUSLE) is used to estimate Soil Erosion and sediment yield for each HRU (Williams and Berndt 1977):

$$SE = 11.8 * (Q_{surf} \,.\, q_{peak} \,.\, Area_{hru})^{0.56} * K_{USLE} * P_{USLE} * C_{USLE} * LS_{USLE} * C_{FRG}$$

Where, SE is soil erosion load (metric tons), Q_{surf} is surface runoff volume (millimeter of water per hectare), q_{peak} is peak runoff rate (cubic meter per second), $Area_{hru}$ is HRU area (hectare), K_{USLE} is soil erodibility factor, P_{USLE} is support practice factor, C_{USLE} is cover and management factor, LS_{USLE} is a topographic factor, and C_{FRG} is the coarse fragment factor.

Sediment deposition and degradation are the two dominant channel processes that affect sediment yield at the outlet of the watershed. Whether channel deposition or channel degradation occurs depends on sediment loadings from upland areas and the transport capacity of the channel network. If the sediment load in a channel segment is larger than its sediment transport capacity, channel deposition will be the dominant process. Otherwise, channel degradation occurs over the channel segment. The SWAT model estimates the transport capacity of a channel segment as a function of the peak channel velocity (Manel Mosbahi et al. 2012).

SWAT Input Parameter

The Soil and Water Assessment Tool (SWAT) is a comprehensive, semi-distributed river basin model designed to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large, complex watersheds. For soil erosion estimation, the SWAT model requires various types of input data categories including (i) Climate data like precipitation, temperature, solar radiation, wind speed and relative humidity, (ii) Topographic data like Digital Elevation Model (DEM), (iii) Land Use/Land Cover (LULC) maps, (iv) Soil types and soil properties, (v) River gauging data. These data collectively enable the SWAT model to accurately simulate the processes within the watershed that influence soil erosion.

SWAT Model Setup

a) Watershed Delineation

The first step in setting up the SWAT model on any study area is the physiographic analysis based on catchment topography. A watershed is a hydrological unit from which runoff resulting from precipitation flows past a single point into a large stream, river, lake, or pond. Watershed delineation is performed in ArcGIS 10.8 software. A Digital Elevation Model (DEM) of 90m resolution for Hathmati Watershed was downloaded from Unites State Geological Survey (Earth Explorer)/Shutter Radar Topographic Mission (SRTM- http://srtm.csi.cgiar.org). Using this DEM, watershed delineation has been done using the ArcSWAT interface. The watershed delineation map using ArcSWAT is generated and it is shown in Figure 2:

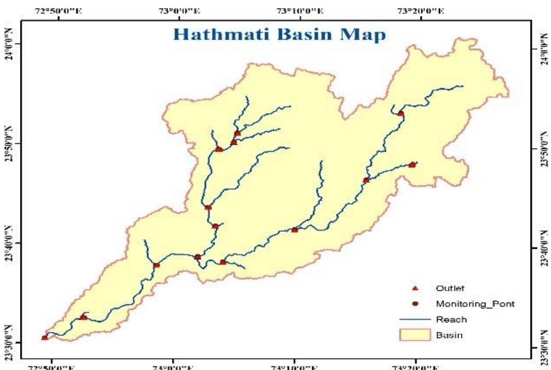

Figure 2: Watershed Delineation Map

Table 2 shows the details like area, stream length, Basin length and elevations of the Hathmati watershed.

Table 2: Details of Hathmati Watersheds

Total Watershed Area:	1421.91 Sq. km
Total Basin Length:	369.12 km
Total Stream length:	234.69 km
Minimum Elevation:	81.00 m
Maximum Elevation:	669.00 m
Mean Elevation:	236.76 m

b) Land Use/Land Cover (LULC) Map

Land cover data shows the extent of a region covered by forests, wetlands, impervious surfaces, agriculture, and other land and water types. LULC map for the study area has been prepared using Landsat Satellite image downloaded from USGS Earth Explorer. Land use pattern of the study area was carried out by standard methods of analysis of remotely sensed data and interpretation of satellite data. The study area comprised various land use and land cover (LULC) classes, including WATR-Water Bodies (3.30%), AGRL-Agricultural Land (52.89%), WETF-Fallow Land (6.30%), URBN-Urban Land (3.35%), BARR-Barren Land (3.85%), FRSE-Shrub Land (1.84%), FRST-Forest Land (28.29%), and WETL-Vegetation Patches (0.18%). Figure 3 represents the LULC map of the study area.

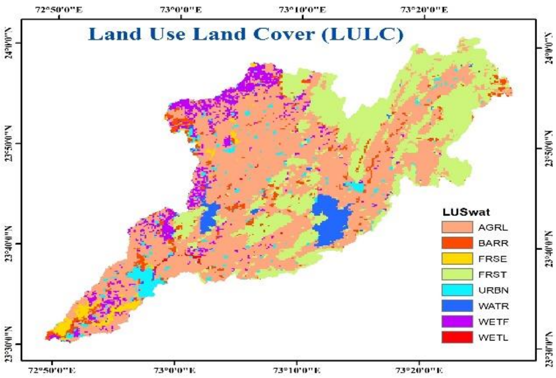

Figure 3: Land Use Land Cover (LULC) Map

c) Soil Map

Soil Classification is derived from a Digital Soil Map of the World developed by Food & Agriculture Organization (FAO). A total of 12 Soil IDs have been demarcated in the study area. All the Soil Groups are covered up with Coarse Soil (8.23%), Coarse Loamy Soil (18.84%), Fine Soil (52.49%), Fine Loamy (5.58%), Loamy Soil (0.54%), and Loamy Skeletal Soil (14.32%). Figure 4 represents the Soil map of the study area.

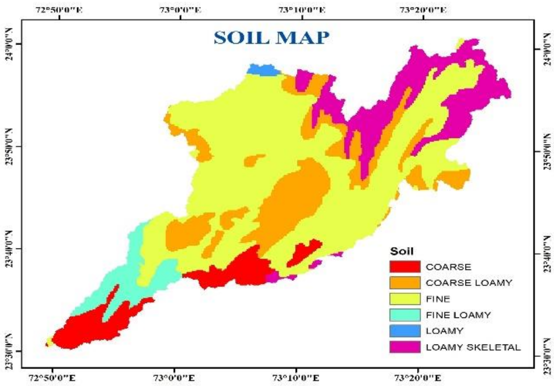

Figure 4: Soil Map

d) Slope Map

The slope is a crucial factor in watershed prioritization. Steeper slopes tend to generate greater runoff, reduce infiltration, and consequently lead to increased soil erosion. Slopes are categorized according to the criteria outlined in the Integrated Mission for Sustainable Development (IMSD) document. Figure 5 represents the Soil map of the study area. Table 3 lists the various slope classifications that are discovered and their geographic distribution in the study area.

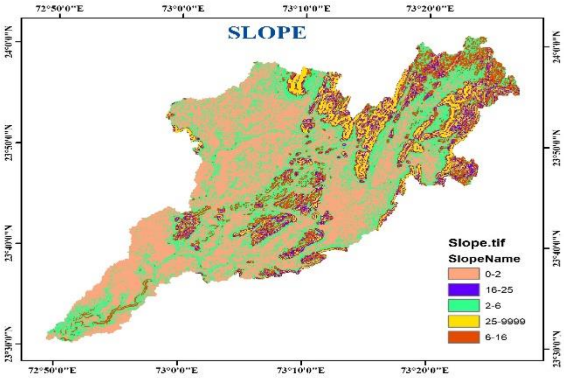

Figure 5: Slope Map

Table 3: Slope Classifications

Slope Class	Slope Class Limit (%)	% Area Covered	Slope Classification
1	0 – 2	45.31	Level
2	2 – 6	28.00	Undulating
3	6 - 16	13.99	Rolling
4	16 - 25	5.71	Hilly
5	25 - 9999	6.99	Steep

e) Hydrological Response Units (HRUs) Definition

Hydrologic Response Units (HRUs) are fundamental components in the Soil and Water Assessment Tool (SWAT) that represent unique combinations of land use, soil type, and slope within a watershed. The land use, soil, and slope data layers are integrated with ArcSWAT to create a composite map for HRUs. Threshold values for land use, soil, and slope have been set to determine the level of detail for HRU creation. These HRUs are crucial for simulating the hydrologic and environmental processes at a fine spatial resolution. The model suggests 30 HRUs to delineate each sub-basin in the current study up to the outlet point using the current data available. Figure 6 represents the HRUs' definitions of the study area.

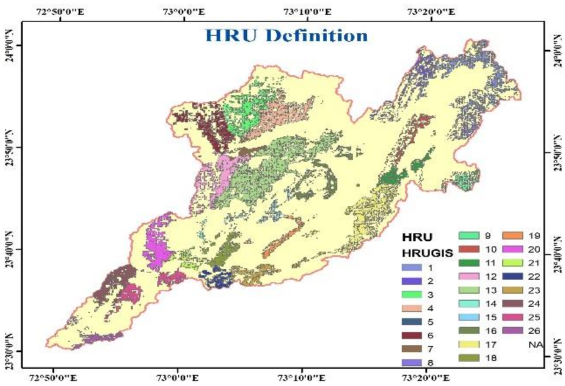

Figure 6: Hydrologic Response Units (HRUs) Definitions

f) Weather Data Generation

After the HRU distribution is done, the meteorological data for the watershed simulation is combined. The basin is given the locations of the weather stations and the various meteorological data such as rainfall, temperature, relative humidity, solar radiation and river gauging data, etc., The SWAT model can be performed using weather information such as measured rainfall, relative humidity, temperature, wind speed, and solar radiation.

g) Model Run

Once the HRUs are defined and the weather data is generated, the model simulation is conducted. All the model's collateral data are incorporated in a predetermined format. In addition, ArcSWAT offers a simulation option for any collateral data if the observed values are not accessible. This SWAT model run on a monthly basis over a span of 20 years, from 2001 to 2020. The model produced several output tables, such as hru, rch, sub, output, etc.

3. RESULTS AND DISCUSSIONS:

The SWAT model result shows that the soil erosion rate ranges from 10 to 40 ton/ha/year in the Hathmati watershed. The soil erosion rates more than 40 t/ha/year is observed in the year 2005, 2006, 2007, 2009, 2010, and 2014 due to high rainfall intensity and changes in LULC pattern. The estimated value of surface runoff and soil erosion rates from the SWAT model for 20-year periods are shown in Table 4.

Table 4: Estimated value of Surface Runoff and Soil Erosion from SWAT Model

Year	Surface Runoff (m^3/sec)	Soil Erosion (ton/ha)
2001	5.26	17.79
2002	3.22	11.71
2003	9.39	32.42
2004	4.95	18.69
2005	16.93	59.58
2006	42.79	158.90
2007	19.98	49.77
2008	7.28	21.38
2009	12.70	54.23
2010	12.70	44.11
2011	17.21	34.54
2012	11.70	23.44
2013	15.38	30.6
2014	21.04	49.48
2015	12.58	28.92
2016	6.95	17.01
2017	13.46	33.56
2018	0.95	1.71
2019	8.29	22.56

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2020	8.71	18.25

The annual soil erosion estimated from the SWAT model for the entire Hathmati watershed is presented in Figure 7. The highest soil erosion (158.90 ton/ha) was estimated in 2006 when rainfall was 1640.55 mm. The lowest soil erosion (1.71 ton/ha) was estimated in 2018 when rainfall was 442 mm. A correlation between rainfall characteristics and soil erosion has been observed in most of the years. Generally, an increase in rainfall leads to a corresponding increase in soil erosion. An average soil erosion was estimated as 36.43 ton/ha/year for the Hathmati watershed.

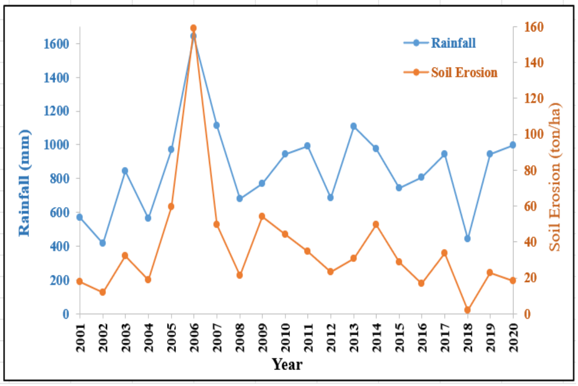

Figure 7: Estimated Annual Soil Erosion from SWAT model

The model calibration was conducted using the available yearly rainfall records for a span of 20 years i.e. from 2001 to 2020. The comparison between the observed and model-simulated rainfall values indicated that they are in a fair degree of agreement. Figure 8 shows the Comparison between observed and simulated yearly rainfall for model calibration.

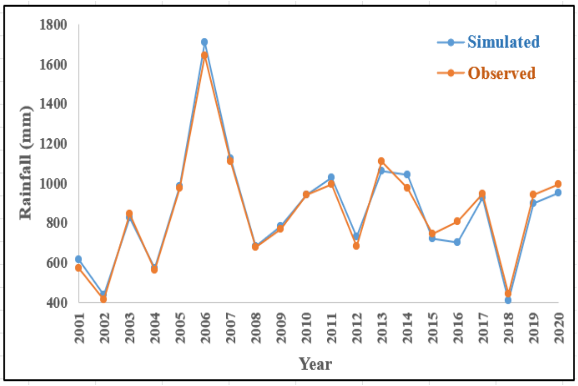

Figure 8: Comparison between observed and simulated yearly rainfall

The validation of soil erosion is not possible due to the lack of measured data. The correlation coefficient (R^2) between surface runoff and soil erosion is calculated as 0.9467 and is statistically significant; this relationship is represented by a power function as shown in Figure 9. It was almost impossible to compare our results with those obtained by others who worked in semi-arid climate conditions as the soil and the land cover are not similar.

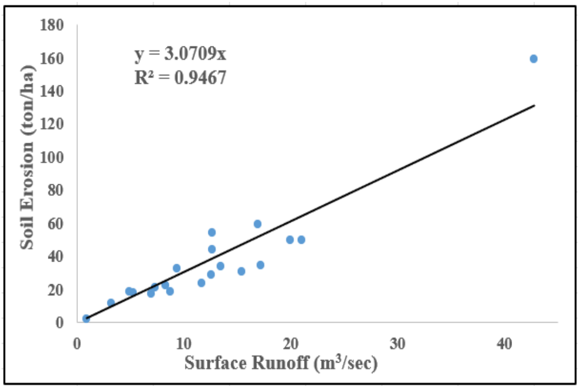

Figure 9: Relationship between simulated soil erosion and simulated surface runoff

4. CONCLUSIONS:

This study aimed to estimate surface runoff generation and soil erosion rates for the Hathmati watershed of the Sabarmati river basin by applying the SWAT model. The results demonstrate that the SWAT model, combined with satellite remote sensing and geographical information systems, provides useful tools for estimating surface runoff and soil erosion. The simulated values of the rainfall matched the observed rainfall. The SWAT model indicates that differences in soil erosion rates within the Hathmati Watershed are mainly caused by differences in Rainfall Patterns, Land use land cover type, and gradient slope. Runoff and soil erosion are positively related to land cover in the catchment. Greater forest cover generally results in less runoff and soil loss. This indicates that the model is effective for identifying and prioritizing vulnerable sub-catchments. The model represents the correlation coefficient (R^2) between surface runoff and soil erosion is very strong positive ($R^2 = 0.9467$) and statistically significant. The SWAT model is widely recommended for investigating the impacts of LULC, climate change, and soil erosion in watersheds and river basins.

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