Hydrologic Impact Evaluation of Land Use and Land Cover Change in Subbasins of Tapi River Using SWAT Model

Ankur Sharma, Ruchi Khare, Mahendra Kumar Choudhary, and Vishnu Prasad

Abstract The current research is based on the comparative analysis conducted using land-use maps of 2005 and 2015. SWAT simulations are undertaken on a monthly time scale to estimate runoff for associated rainfall. The coefficient of correlation (R^2) and Nash–Sutcliffe efficiency (NSE) for rainfall and the accompanying runoff for the calibration period of 10 years (1988–97) are determined to be 0.99 and 0.99 respectively at Gidhade station and 0.95 and 0.9 for Sarangkheda station. And for the next 7 years (1998–2004) of the validation period, values of R^2 and NSE are 0.99 and 0.99 and 0.99 and 0.98 for Sarangkheda and Gidhade stream gauge stations. The above-mentioned results are comparatively similar for both land-use maps for 2005 and 2015. Based on model predictions, it is found that the annual surface runoff reduced marginally while the evapotranspiration increased, while baseflow and deep aquifer recharging remain unchanged. The surface runoff has decreased by 3.23% in the ten years, water in shallow aquifer returning to root zone has lowered by 0.34%, and evapotranspiration has increased by 1.07%. In terms of land-use classes, there has been a significant increase in rangeland and a decline in agricultural land.

Keywords Watershed modeling · SWAT model · Landuse/landcover (LULC) change · Rainfall–runoff

A. Sharma (✉) · R. Khare · M. K. Choudhary · V. Prasad
Department of Civil Engineering, Maulana Azad National Institute of Technology, Bhopal 462003, India
e-mail: ankursharma1912@gmail.com

R. Khare
e-mail: ruchikhare@manit.ac.in

M. K. Choudhary
e-mail: mkchoudhary@manit.ac.in

1 Introduction

In recent years, research has focused on the hydrological impact of land-use change, significantly regarding rainfall–runoff response [3]. This is because the dynamics of the rainfall–runoff process are driven by LULC change in combination with rainfall, properties of soil and terrain. LULC impacts on the processes of hydrology occur quickly as compared to soil and elevation, allowing researchers to investigate their direct impact [7]. Drought, flooding, landslides, and extreme soil erosion are becoming more common worldwide, particularly in the tropics and are influenced by climate change, and anthropogenic activities mainly LULC modification are also an important factor [6]. Due to the effects of this change on watershed, it is crucial to study this interaction between environment and human beings.

Several studies have already been conducted worldwide to examine the effect of LULC change on water balance parameters at the sub basin scale [10]. In past years, the assessment of LULC alterations has gained importance in providing options for land developments and forecasting environmental consequences at small scales [2]. Previous and current LULC change scenarios were used in hydrological models to find out the response of water balance in the catchments [13]. The impact of changes in land-use on runoff characteristics varies by location.

Land use management has changed streamflow patterns, deep and shallow aquifer recharge, surface and sub-surface runoff, and return flow, among other factors, with various environmental consequences [8]. As a result, it is essential to look into the impact of LULC changes on runoff characteristics in the area of interest, especially if the area has any unique features. This paper uses a Tapi river sub-basins case study to examine the effects of LULC alterations on streamflow. Sub-watershed runoff and water yield were computed and compared for a similar period.

2 Study Area and Data Source

2.1 Sub Basins of Middle Tapi River Basin

The Tapi basin covers 65,145 km^2 or approximately 2% of the country's entire geographic area. It originates in the Madhya Pradesh district of Multai and ends in the Arabian Sea near Surat. Apart from supporting various residential water supply schemes, industry, and hydropower in its watershed, the Tapi River is a crucial source of irrigation and acts as a significant part in the agricultural economies of Maharashtra and Gujarat. However, the river basin used in this study has an area of 17,684.99 km^2, starting Savkheda Station till Ukai Dam, as shown in Fig. 1. Since the basin is at the middle part of the basin, observed discharge data at savkheda has been used as the inlet discharge data for the study.
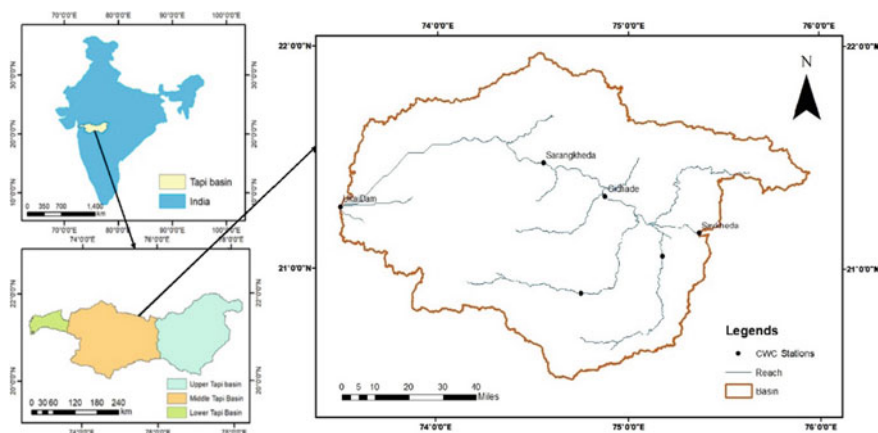
Fig. 1 Index map of the study area

3   Data Collection

3.1   Digital Elevation Model (DEM)

The watershed was delineated and additional topographic processing was done using a digital elevation model (DEM) SRTM DEM with 30 m resolution obtained from the USGS.

3.2   Land Cover/Land Use (LULC)

The bare surface was obtained using two land-use maps created by India's National Remote Sensing Centre (NRSC) in 2005 and 2015 (1:250,000). Unless their location agreed with the location of the bare surface generated from NRSC LULC data, all fallow land found from satellite images was classed as agricultural land. The final land-use data is divided into six categories, included in the SWAT2012 database. Water (or WATR in SWAT), general agricultural (AGRL), shrub grassland (RNGB), barren surface (BARR), forest (FRSD), and urban (URMD) settlements were the six types of settlements.

3.3   Soil Data

Meteorological data resolution substantially impacts streamflow and sediment load modeling, and a fine spatial resolution soil map will improve the model's prediction

accuracy. The National Bureau of Soil Survey and Land Use Planning provided the soil map for this investigation (NBSS&LUP). Initially, the complete area was digitized manually in ArcGIS using state-wise soil maps in JPG format. Then, a separate excel file was prepared for the corresponding soil series properties according to the required format. And finally, both were imported to ArcSWAT. According to the Middle Tapi Basin, the soil map (30 arc-second raster resolution) was projected to WGS1984 UTM Zone 43 N using the raster re-projection tool in ArcGIS.

3.4 Weather Data

Meteorological data is one of the most crucial information required by the SWAT model. The SWAT model typically requires at least two observed metrological data to acquire proper runoff, namely daily rainfall data and temperature data. In contrast, the other metrological parameters can be simulated by the SWAT model utilizing a weather generator. Rainfall data for 24 different stations in the basin was received from the Indian Meteorological Department (Pune) for this study. IMD also provided temperature data (maximum and minimum) in a grid format ($01° \times 01°$). Other climatic characteristics, such as solar radiation, relative humidity, and wind speed, were simulated using the SWAT model and weather generator.

3.5 Streamflow Data

SWAT is a model that simulates the effects of land use and management on water, agricultural chemical yields, and sediments of watersheds that are not gauged [11]. Even with the lack of data for calibration and validation, the model is run and implemented. However, calibration and validation are still required in hydrologic modeling investigations. The Central Water Commission (Surat) provided the rainfall data needed for this investigation. The most powerful instrument for calibrating and validating the model's performance is discharge data. In the present work, daily discharge data for the period from 1988 to 2004 including three separate stations, namely Gidhade, Sarangkheda, and Savkheda, were used.

4 Materials and Methods

4.1 SWAT Model

The Soil and Water Assessment Tool was developed by the USDA's Agricultural Research Service in Texas. There are mainly two ways to categorize SWAT:

1. It can be classed as a deterministic model based on input and uncertainty.
2. It can also be classed as a semi-distributed model based on spatial representation of the watershed.

SWAT considers a variety of physical processes to represent surface runoff and sediment in a watershed. Examples of physical processes include evapotranspiration, evaporation, infiltration, prospective and actual evapotranspiration, lateral flow, and groundwater contribution. Because sediment, pesticides, and nutrients are delivered through streamflow from upland watersheds, the accuracy of sediment, pesticide, and nutrient prediction is dependent on the precision of hydrologic cycle prediction [5]. The hydrology simulation in the SWAT model can be divided into two essential parts: (1) land and (2) routing phases of the hydrological cycle. This model allows its user to estimate the relative influence of climate, soil, management, and vegetation changes (Arnold and Allen 1998).

4.2   Selection of Input Parameters

The SWAT model was parameterized with land-use inputs for two time periods using parameter ranges which were assigned during calibration of the model (Table 1). With the NSE results in hand, there is a solid case to be made for employing the discovered parameters as an input to model study for the complete watershed over a more extended period to analyze the basin's response to land-use change [4, 12].

Table 1 SWAT parameters were used in model calibration

Parameter	Description	Initial range	Calibrated value
r__CN2.mgt	SCS runoff curve number	−0.3 to 0.3	−0.285
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for "revap" to occur (mm)	50–150	52.5
v__ESCO.bsn	Soil evaporation compensation factor	0.6–0.9	0.7875
r__SOL_K().sol	Saturated hydraulic conductivity	−0.6 to 0.3	−0.5325
r__SOL_AWC().sol	Available water capacity of the soil layer	0–0.6	0.405
v__GW_REVAP.gw	Groundwater "revap" coefficient	0.1–0.25	0.20125
v__ALPHA_BF.gw	Baseflow alpha-factor (days)	0–0.4	0.39
v__SURLAG.bsn	Surface runoff lag time	0.1–1.5	1.255
v__HRU_SLP.hru	Average slope steepness	0.001–0.01	0.004325
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0.003–0.01	0.008775

5 Results and Discussions

5.1 Calibration and Validation

SWAT simulation covered 20 years from 1985 to 2004 using SWAT-CUP. This software (Calibration and Uncertainty Procedures) has been prepared in order to calibrate the data outputs from SWAT simulations [1]. The process of calibration was carried out using 1988 to 1997 streamflow data, and it was validated using the remaining data from 1998 to 2004. Calibration of the model using identified set of parameters and their corresponding values has improved the model prediction capability. Firstly, the procedure was implemented for the model prepared using land-use data of the year 2005, which improved the precalibrated model at Sarangkheda station, *NSE* right from 0.91 to 0.99 and R^2 from 0.97 to 0.99. The procedure also enhanced the performance of uncalibrated model at Gidhade station, *NSE* from 0.89 to 0.95 and R^2 from 0.94 to 0.95.

Compared to prior SWAT modeling studies, these calibrated values are relatively high. Secondly, the same calibration and validation process was implemented for the model prepared using land-use data of the year 2015. And, hence again same results were drawn, i.e., at Sarangkheda station, *NSE* is 0.99, and R^2 is 0.99, and at Gidhade station, *NSE* is 0.95 and R^2 is 0.95. Furthermore, based on the criterion, NSE greater than 0.5 and values R^2 of above 0.5 are regarded as "acceptable and satisfactory" [9].

The improvement can be seen in the calibration plot shown in Fig. 2 where it can be seen that there is a marked improvement in line fitting, especially for baseflow. Validation also yields good simulation results, both using land-use data of 2005 and 2015, at Sarangkheda station, *NSE* is 0.99, R^2 is 0.99, and at Gidhade station, *NSE* is 0.99, and R^2 is 0.98. Several factors can influence the model's performance. In this case, we are using observed discharge data at Savkheda station as an inlet point, tremendously increasing the model performance. Due to which similar calibration and validation results have been observed both for LULC of 2005 and 2015.

5.2 Land Use/Land Cover (LULC) Change

The SWAT model was parameterized with few more land-use inputs for the two time period using parameter settings identified during calibration of the model (Table 1). With the NSE results in place, there is a solid case to be made for employing the discovered parameters as input to the model for the complete watershed over a more extended period to analyze watershed balance components to the change in land use. From 2005 to 2015, the LULC change in the Tapi River's Middle watershed indicated an increase in grassland and water but a decline in the forest, barren, and available agricultural land, which can be observed in Fig. 3.

The LULC alteration resulted in a 2.4 mm reduction in annual surface runoff (Table 3) not only decrease in the runoff but also in revaporization from shallow
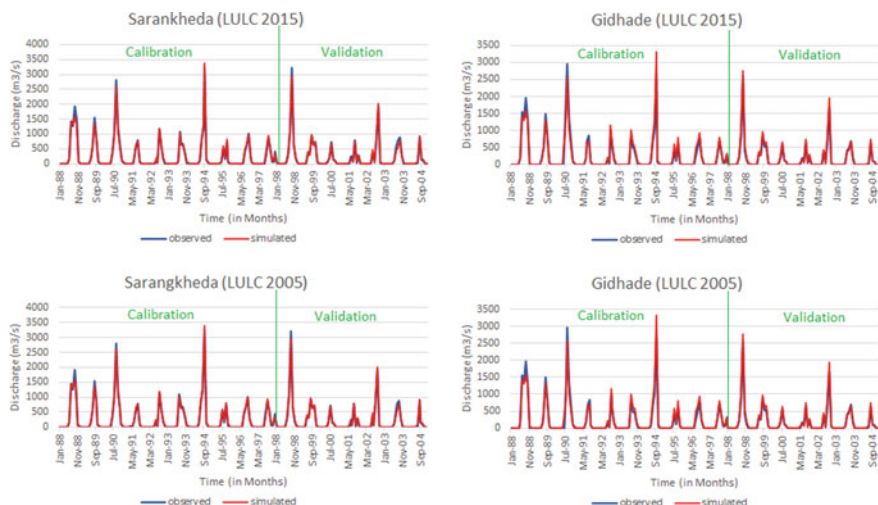
Fig. 2 Discharge versus time series plot of at Sarangkheda and Gidhade stations both using land cover maps of 2005 and 2015

aquifer cab noted by an annual value of 1.05 mm. Moreover, evapotranspiration has increased by 3.7 mm per year, whereas percolation and deep aquifer recharge have remained constant. In addition, the base is also unaltered. While the percentage cover of urban land remained unchanged for both periods, the percentage cover of agricultural land decreased by 3.9% (Table 2). There was also a major increase in the percent cover of grasslands, while the percent cover of barren land declined by 1.1%. There is a slight rise in the water-covered area and a decrease in the forest area.

Increased evapotranspiration and decreased shallow aquifer revaporization are direct results of grasslands, while barren lands decreased. In addition, in 10 years, the reduction in surface runoff results from a combination of land-use changes, including changes in evapotranspiration, percolation, and agricultural cover. These reactions are ruled by the same hydrologic principles that influence LULC's linkages with surface runoff, infiltration, evapotranspiration, percolation, and deep aquifer recharge.

6 Conclusions

The following conclusions can be drawn from the preceding research:

1. This study found that LULC change impacts the hydrologic responses of Middle Tapi Basin watersheds regarding water quantity and hydrologic occurrence timing. According to model simulations, annual surface runoff declined as evapotranspiration increased, also base flow and deep aquifer recharge remained steady.
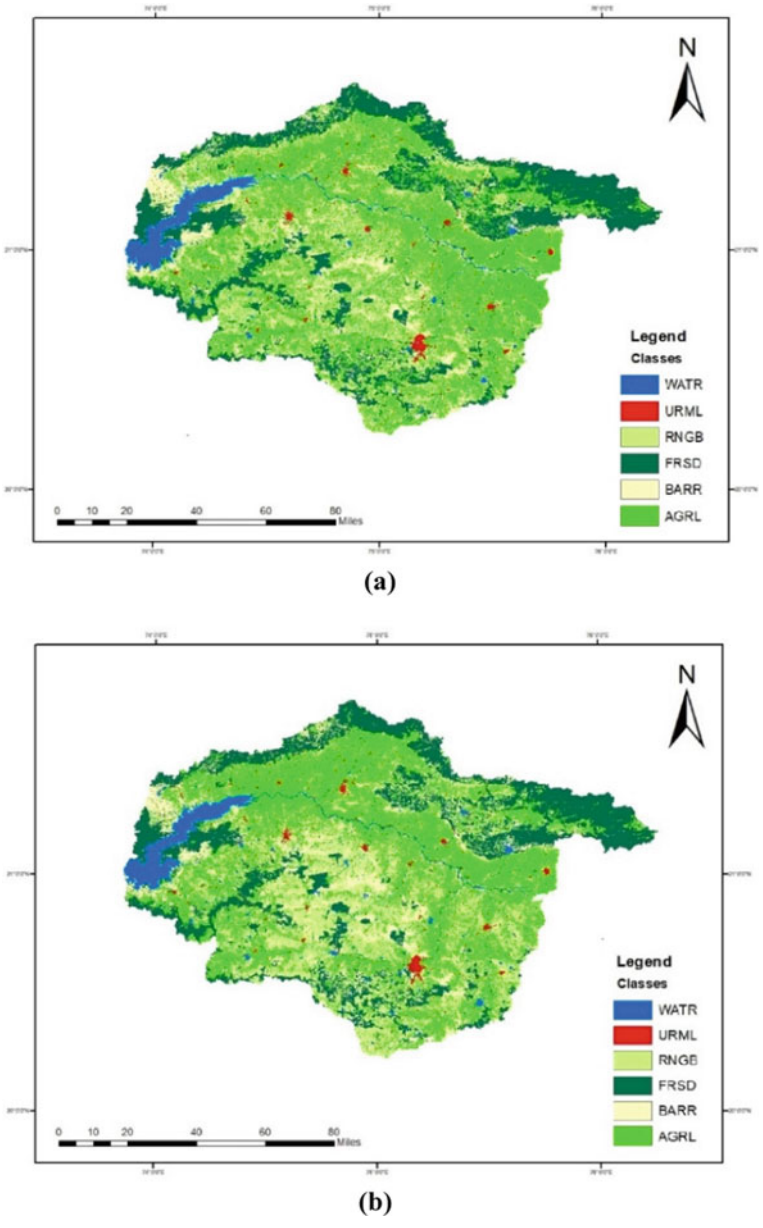
Fig. 3 Land use/land cover (LULC) maps **a** 2005 and **b** 2015 for the watersheds of Middle Tapi

Table 2 Percent area of LULC classes for 2005 and 2015 with its relative changes

LULC classes	LULC code	2005 Percent cover (%)	2015 percent cover (%)	The difference in percent cover (2015–2005)
Urban	URML	1.54	1.54	0
Agricultural	AGRL	42.12	38.19	−3.92
Grassland	RNGB	18.69	23.93	5.23
Forest	FRSD	21.01	20.93	−0.07
Barren	BARR	11.98	10.91	−1.07
Water	WATR	4.66	4.91	0.25
Total	-	100	100	0

Table 3 Water balance for the 2005 and 2015 LULCs

Hydrologic variables	LULC 2005		LULC 2015	
	mm	%	mm	%
Surface runoff	4.95	7.0815	47.9	6.8526
Baseflow	0.37	0.053	0.37	0.053
Revap shallow aquifer	302.1	43.219	301.0	43.069
Deep aquifer recharge	2.88	0.412	2.88	0.412
Evapotranspiration	344	49.213	347.7	49.742
Precipitation	699	100	699	100

As per land-use classes, there is a modest decline in agricultural land and a high increase in grassland.

2. Below-mentioned three hydrological variables show the following changes in terms of percentage. Surface runoff has decreased by 3.23% in the ten years from 2005 to 2015, water in shallow aquifer which were returning to root zone has lowered by 0.34%, and evapotranspiration has increased by 1.07%.

3. It was discovered that the model's performance in terms of NSE and R^2 does not change significantly for both LULCs. One of the critical reasons for strong model performance for both LULCs could be the use of observed discharge data at Savkheda as an inlet.

4. tWater sustainability involves research based on a hydrological change in response to changes in land-use patterns, and hence, efforts must be made to bridge information gaps and provide a decision-making support system for this critical ecosystem.

Survey and Land Use Planning (NBSS & LUP) for providing the necessary data to conduct the present study.

References

1. Abbaspour KC, Rouholahnejad E, Vaghefi S, Srinivasan R, Yang H, Klove B (2015) A continental-scale hydrology and water quality model for europe: calibration and uncertainty of a high-resolution large-scale SWAT model. J Hydrol 524:733–752
2. Aghsaei H, Mobarghaee Dinan N, Moridi A, Asadolahi Z, Delavar M, Fohrer N, Wagner PD (2020) Effects of dynamic land use/land cover change on water resources and sediment yield in the Anzali wetland catchment, Gilan, Iran. Sci Total Environ 712 Article 136449
3. Amini A, Ali T, Ghazli A, Akib S (2011) Impacts of land-use change on streamflows in the Damansara Watershed, Malaysia. Arab J Sci Eng 36(5):713–720
4. Arnold JG, Allen PM (1998) Estimating hydrologic budgets for three Illinois watersheds. J Hydrol 176:57–77
5. Briones RU, Ella VB, Bantayan NC (2016) Hydrologic impact evaluation of land use and land cover change in Palico Watershed, Batangas, Philippines using the SWAT model. J Environ Sci Manag 19(1):96–107
6. Hurkmans R, Terink W, Uijlenhoet R, Moors EJ, Troch PA, Verburg PH (2009) Effects of land use changes on streamflow generation in the Rhine basin. Water Resour Res 45(6):W06405
7. Miller SN, Kepner WG, Mehaffey MH, Hernandez M, Miller RC, Goodrich DC, Kim DK, Heggem DT, Miller WP (2002) Integrating landscape assessment and hydrologic modeling for land cover change analysis. J Am Water Resour Assoc 38:915–929
8. Ni X, Parajuli PB, Ouyang Y, Dash P (2021) Assessing land-use change impact on stream discharge and stream water quality in an agricultural watershed. J Catena 198 Article 105055. https://doi.org/10.1016/j.catena.2020.105055
9. Santhi C, Arnold JG, Williams JR, Dugas WA, Srinivasan R, Hauck LM (2001) Validation of the SWAT model on a large river basin with point and nonpoint sources. J Am Water Resour Assoc 37(5):1169–1188
10. Sanyal J, Densmore L, Carbonneau P (2014) Analysing the effect of land-use/cover changes at sub-catchment levels on downstream flood peaks: a semi-distributed modeling approach with sparse data. CATENA 118:28–40
11. Srinivasan R, Xiaoming Z, Jeffrey GA (2010) SWAT Ungauged: hydrological budget and crop yield predictions in the Upper Mississippi River Basin. Am Soc Agric Biol Eng 53(5):1533–1546
12. Zhang X, Xinxiao Y, Sihong W, Wenhong C (2008) Effects of changes in land use and land cover on sediment discharge of runoff in a typical watershed in the Hill and Gully Loess Region of Northwest China. Front For China 3(3):334–341. https://doi.org/10.1007/s11461-008-0056-1
13. Zhu C, Li Y (2014) Long-Term hydrological impacts of land use/land cover change from 1984 to 2010 in the Little River Watershed, Tennessee. Int Soil Water Conserv Res 2(2):11–21. https://doi.org/10.1016/S2095-6339(15)30002-2