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Assessing hydrological and water quality parameters in the Hathmati Watershed using the SWAT (Soil and Water Assessment Tool)

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ABSTRACT

The study is conducted on the Hathmati River, which is the principal tributary of the Sabarmati River, one of Gujarat's biggest rivers. Indicators of water quality such organic N, organic P, NO_3, NH_4, NO_2, total N, and total P were compared between the observed values in the watershed and the streamflow models. For monthly streamflow and monthly nitrate during the calibration period of 1999–2012, and for 0.87 and 0.56 for the validation period of 2013–2020, respectively, the Nash–Sutcliffe efficiency was 0.89 and 0.79. The measured water quality data at three locations in the watershed were largely compatible with their corresponding modeled values, while the agreement varied by nutrients. Using the parameters used to forecast the hydrological and water quality responses in the watershed region, the Soil and Water Assessment Tool model faithfully duplicated the hydrological and water quality conditions in this agricultural watershed. The results of the modeling indicated that nutrients are one of the key determinants with regard to the quality of the water, in accordance with the current land use and management practices in the watershed. Management practices should be implemented in order to reduce the nutrient load and meet the watershed's requisite water quality standards.

Key words: agriculture, management practices, nutrient hydrological model, water quality

1. INTRODUCTION

Compared to other land surfaces, agricultural land produces substantially higher levels of nitrogen and phosphorus. Numerous water bodies' water quality has significantly declined as a result of nutrient contamination from urban and agricultural sources (Howarth & Marino 2006; Howarth 2008; Dubrovsky *et al.* 2010; Kaushal *et al.* 2014). Fertilizers are an artificial source of nourishment. Runoff that is discharged directly may result in higher nutrient concentrations. Compared to other land surfaces, agricultural land produces substantially higher levels of nitrogen and phosphorus. Due to fertilizers used by farmers, the Hathmati River can be found at d/s with higher amounts of nitrogen and phosphorus. The majority of this growth was caused by an increase in the area under irrigated crops, which accounted for more than 80% of overall growth and increased fertilizer consumption (Department of Biotechnology 2018). In the previous 20 years, the area irrigated had grown from 2.06 million hectares (15.5%) to 4.39 million hectares (30.37%). The Hathmati Watershed is located in an area with excellent agricultural potential and extremely high nitrate content.

1.1. Research objective

The primary objective is to use hydrological modeling to provide a framework for watershed water quality. The Soil and Water Assessment Tool (SWAT) model, which is founded on physical principles, is used in this study. Setting up a framework for hydrological and water quality modeling, verifying and calibrating the model, and creating different scenarios can all help achieve this goal.

1.2. Significance of the study

The model configuration used in this paper can be used to assess the likelihood of nutrient and sediment runoff in the Hathmati River Basin. Because the existing model has been calibrated for hydrology and nutrient yield analysis strongly relies on SWAT's ability to simulate hydrological events, it can determine the consequences of changes in land use and land cover in the basin. Given that agriculture has a significant impact on this basin, crop management data can be submitted to the model to determine how different crops affect the basin's water quality. The SWAT model has been applied in a number of studies to mimic the best management practices in various watersheds throughout the globe (Bracmort *et al.* 2006; Parajuli *et al.* 2008; Xie 2015). Such models can aid watershed managers in making better judgments and managing their watersheds more successfully because non-point source problems are more common in basins where agriculture is the main activity.

2. THE STUDY AREA

2.1. Hathmati Watershed

The research focuses on the Hathmati River regime, which is one of the major tributaries of the Sabarmati River in the Indian state of Gujarat. The Sabarkantha district's Hathmati watershed, with an area of 1,317.41 km^2 and coordinates of 23°30′49″N and 72°49′29″E, is chosen as the study area. From the Gujarat Malwa Hills, it rises. It reaches Sabarmati after following a 98-km route close to the village of Ged, 20 km southwest of Himmatnagar in the Sabarkantha district (Figure 1).

The research region is covered by Topo sheets Nos. 46-A-13, 46-A-14, 46-E-01, 46-E-02, 46-E-05, and 46-E-06 from the Survey of India (SOI). The river in this study has a length of 98 km, and its entire course has a little incline. Agriculture is the main land use. Loam to sandy soils makes up the soil cover near the Sabarkantha district, and a rain gauge station is situated near the village of Bhiloda. Bodoli and Guhai are two major tributaries of the Hathmati with catchment sizes of 119 and 505 km^2, respectively. The annual rainfall is 780–890 mm. The yearly rainfall coefficient of variation over the basin is quite large and ranges from 42 to 65% (Dave *et al.* 2012). The average maximum and lowest temperatures are 38 and 16 °C, respectively.

2.2. Data collection

The digital elevation model with a 30 m resolution produced by CARTOSAT-1 was used to obtain the geometric data for the Hathmati River. State Water Data Centre, Gandhinagar, Gujarat, has provided daily rainfall, climatic (minimum, maximum, relative humidity, and average wind speed), hourly sunshine, and water quality data. SWDC has provided weather and climatic data for two stations. SOI Toposheets, satellite data, and other auxiliary data were used to construct a number of thematic maps. These maps were produced at a 1:12,500 scale.

A wide range of spatial data, including Digital Elevation Model (DEM), Land Use Land Cover (LULC), soil maps made from Cartography and Satellite - 1 (CARTOSAT-I), Shuttle Radar Topography Mission (SRTM), BHUVAN, and Indian Remote Sensing 1-D (IRS-ID), Linear Imaging Self-Scanning Sensor-4 (LISS IV) satellite data and prepared in ArcGIS 10.5 with a resolution of 30 m, as well as a number of collateral data, including weather files (from 1999 to 2020) gathered from rain gauge stations and climate stations, make up the study's data. The source of the data used in this paper is indicated in Table 1.

3. METHODOLOGY

To simulate the quality and quantity of surface water and groundwater and to predict the environmental effects of land use, land management practices, and climate change, the SWAT, a small watershed to the river basin-scale model, is employed. The SWAT is often utilized to assess non-point source pollution control, regional watershed management, and soil erosion prevention and control (https://swat.tamu.edu).

The SWAT model, which is free software in the public domain, is actively supported by the USDA Agricultural Research Service. This hydrology model incorporates all the hydrological information, including precipitation, surface runoff, subsurface runoff, return flow, groundwater flow, infiltration, deep percolation, transmission losses, evaporation, transpiration, weather information, storage in ponds and reservoirs, crop growth and irrigation, reach routing, fertilizer and pesticide loading, and water transfer. It is possible to use the SWAT as a watershed hydrological transfer model.

The SWAT is a continuous time model that executes on a daily time step at the basin scale. An agricultural activity's timing over the course of a year (such as crop rotation, planting and harvest dates, irrigation, fertilizer, and pesticide application rates and timing) as well as the long-term consequences on important management basins is both forecasted by this type of model. In areas where agriculture is the main land use, it can be used to simulate the water and nutrient cycles at the basin scale. It can also be used to assess the environmental

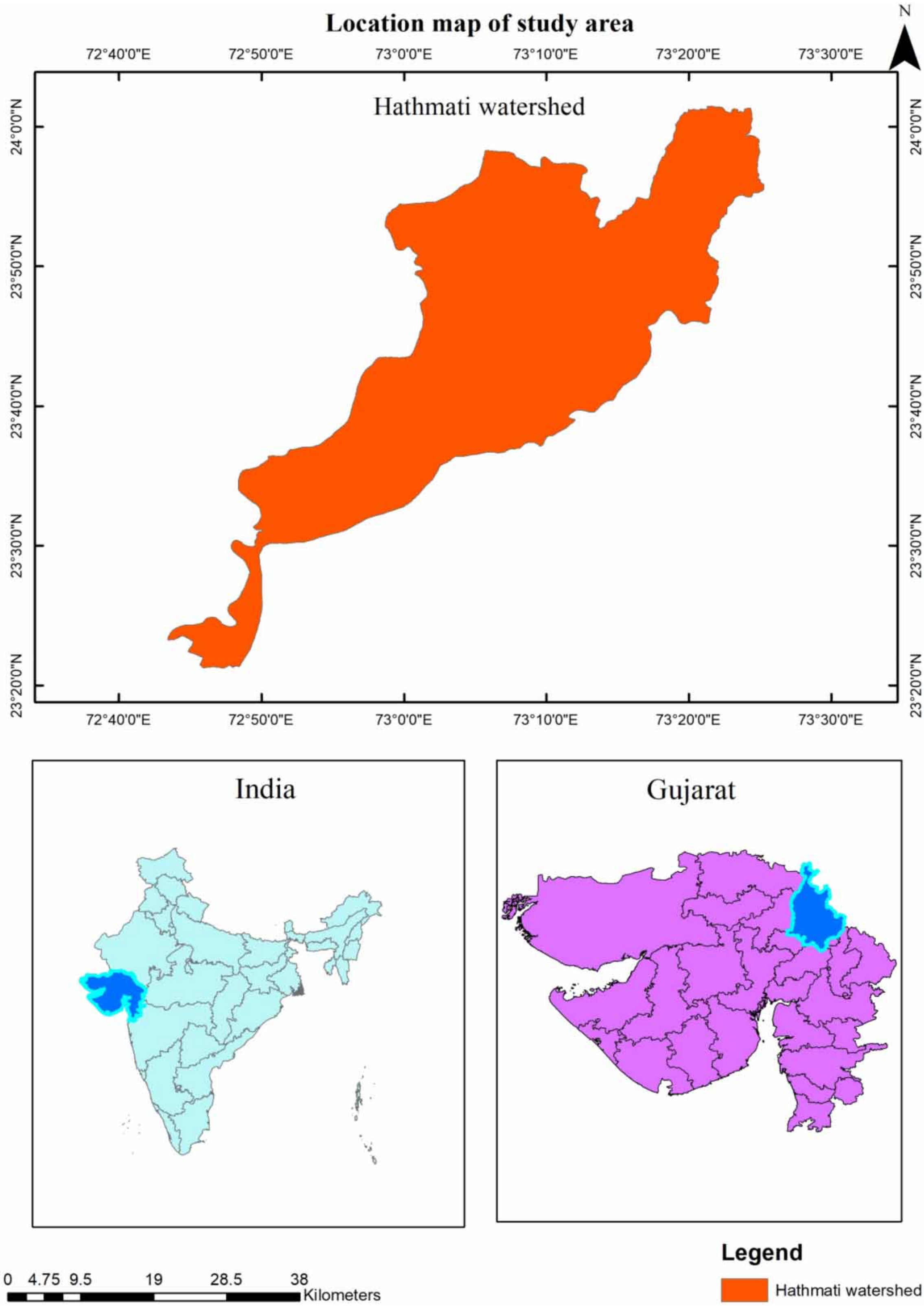

Figure 1 | Hathmati River Watershed, Gujarat, India.

effectiveness of different management approaches and best management practices. Sub-basins are first defined using topographic criteria in SWAT's two-level disaggregation system, and they are then further discretized using elements like land use and soil type. The SWAT simulation that was performed for this study uses it to

Table 1 | Data collection

Sr. No.	Type	Location	Year
1	Daily rainfall data	Bhiloda, Mankadi	2001–2016
2	Climatic (minimum temperature, maximum temperature, relative humidity, average wind speed) data	Bhiloda, Mankadi	2001–2016
3	Hourly sunshine	Bhiloda, Mankadi	2002–2016
4	Water quality	Himmatnagar, Khandhol, Mankadi	2002–2016

Source: State Water Data Centre, Gandhinagar.

set up and run the simulation. For simulation utilizing the SWAT, input data including DEM, LULC map, and soil map are supplied. The stages needed for modeling are shown in Figure 2.

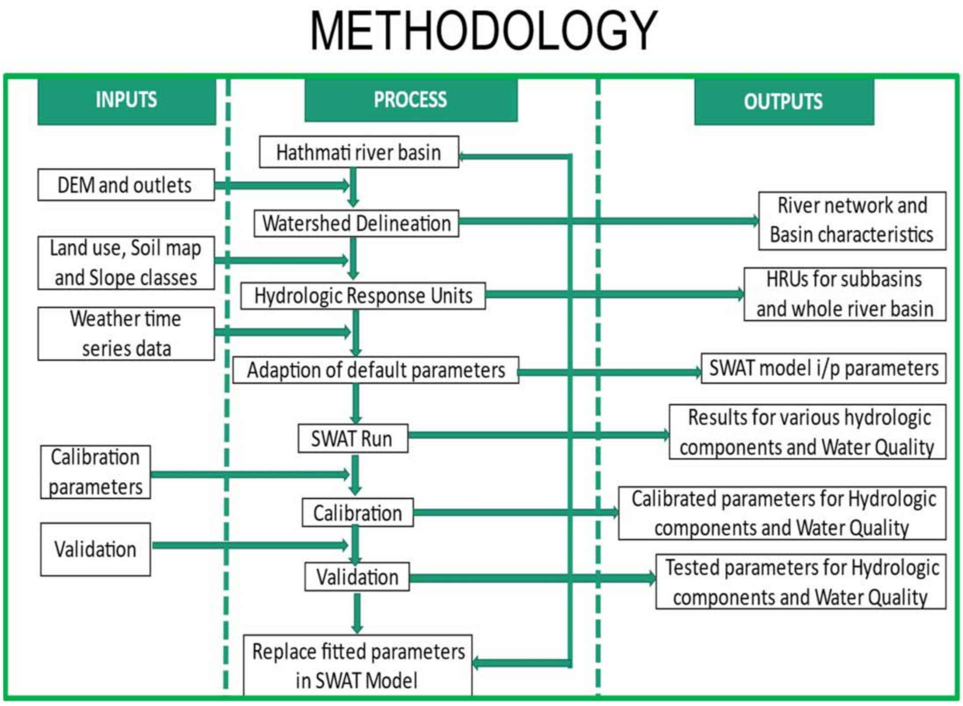

Figure 2 | Methodology.

3.1. Model calibration and validation

Iteratively modifying model parameters to obtain close agreement between observed and predicted streamflow and nitrate levels is called calibration. The calibrated model must be used for a considerable amount of time in order to be considered valid, and during that time, the consistency of the predicted and actual values must be reevaluated. Good agreement during the validation period suggests a high degree of model calibration precision. The SWAT is a process-based simulation model; therefore, most of its parameters are based on data that are readily available in the real world. Santhi *et al.* (2001) and Neitsch (2005) both give thorough explanations of the SWAT model calibration procedures and definitions of the various calibration parameters.

3.1.1. Streamflow

Calibration and validation of the simulated annual, monthly, and daily streamflow were performed (output of the sub-basin 13) using the real streamflow measured at the Bhiloda Station. Numerous statistics, including the mean, mean relative error (D), standard deviation, coefficient of determination (r^2), and Nash–Sutcliffe efficiency

(NSE), were used to assess the agreement between the anticipated and observed values. For daily streamflow, Santhi *et al.* (2001) state that agreement is deemed satisfactory if $r^2 > 0.5$ and NSE > 0.4. The initial step in calibrating the model was to do a sensitivity analysis for the watershed. The purpose of the sensitivity analysis was to identify the factors that had the greatest influence on the watershed's streamflow, surface runoff, and baseflow.

3.1.2. Water quality

Similar to many watersheds, data on water quality monitoring for the Hathmati River watershed were only available for specific dates when stream-water samples were taken. The water quality was calibrated so that the simulated amounts of parameter concentrations matched the levels of those contaminants that were detected. In contrast to the simulated values from the SWAT model, which were the daily average values during the simulation period, these monitoring measures solely represented the instantaneous levels observed on sampling days. Latin-Hypercube and One-Factor-At-a-Time (LH OAT) sampling is combined in the sensitivity analysis approach to give a global sensitivity analysis for a large number of parameters with a limited number of model runs. The SWAT includes 26 streamflow parameters, 6 sediment parameters, and 9 nutrient parameters. Model-sensitive parameters can be assessed using a multiple regression analysis. The significance of parameter sensitivity is dictated by the value of p, and the sensitivity can be assessed using the t-test. The importance and sensitivity increase with the distance between p and 0. When the value of p is less than or equal to 0.05, a model parameter is said to be sensitive. The significance of SWAT sensitive characteristics varies with respect to terrain, soil types, and land use. The study found that SWAT model's 15 hydrological parameters and its 13 sediment and nutrient parameters were responsive. Find the parameters that are most responsive to the observed values of interest. Usually, this knowledge can be gleaned from the literature. Surface runoff and nitrate were both used as variables in the model calibration, and a total of 28 sensitive parameters were selected (Koo *et al.* 2020a, 2020b).

4. RESULTS AND DISCUSSION

4.1. Streamflow calibration and validation

The model has been validated for the flow duration from January 2013 to December 2020 after being calibrated from January 1999 to December 2012 with a 3-year warm-up phase. The correlation coefficient (r^2) and the NSE test (Nash & Sutcliffe 1970) have both been used to compare simulated and observed flow. The output of the model demonstrated a good match between the estimated flow and the observed flow. Table 2 displays the correlation coefficient and NSE values.

Table 2 | Model performance for streamflow

	Years	No. of simulations	Variable	R^2	NS	Mean_sim (Mean_obs)	StdDev_sim (StdDev_ obs)
Calibration	2002–2012	50	FLOW_OUT_13	0.90	0.89	1.39 (1.77)	2.74 (2.85)
Validation	2013–2020	50	FLOW_OUT_13	0.91	0.87	1.01 (0.96)	1.69 (1.47)

As demonstrated in Table 3, the NSE and R-values more than 0.80 denote very strong correlation between the observed and simulated discharge (Evans 1996). In conclusion, the model successfully simulates the flow. In general, as shown in Table 3, fundamental statistics for comparing the simulated and observed streamflow over the validation period show that there is good agreement between the two. Figures 3–5 show the daily, monthly, and yearly calibration of flow, respectively.

Figures 6–8 indicate daily, monthly, and yearly validation of streamflow.

4.2. Water quality calibration and validation

During the calibration period of 2002–2012, NO_3 concentrations were measured 51 times, and during the validation period of 2013–2020, NO_3 concentrations were measured 29 times. The correlation coefficient and NSE values are presented in Table 4.

Figures 9 and 10 indicate monthly and yearly calibration of nitrate. Daily calibration of nitrate is not possible due to lacking of data.

Figures 11 and 12 indicate monthly and yearly validation of Nitrate.

Table 3 | SWAT input parameters and final calibrated values for the Hathmati River Watershed

Sensitivity rank	SWAT parameter	SWAT parameter description	Unit	Range	Absolute value
1	CN2	Curve number	–	30–98	87.290001
2	ALPHA_BF	Baseflow recession constant	day^{-1}	0–1	0.670000
3	GW_DELAY	Delay time for aquifer recharge	days	0–500	650
4	GWQMN	Depth of water required for return flow in the shallow aquifer	mm	0–5,000	650
5	SOL_AWC	Available water capacity of the soil layer	mm	0–1	0.89
6	ESCO	Compensation factor for soil evaporation	–	0–1	0.17
7	SURLAG	Lag coefficient for surface runoff	–	0.05–24	13.2225
8	USLE_P	USLE equation support practice factor	–	0–1	0.49
9	CH_COV1	Channel erodibility factor	–	0.05–0.6	0.4625
10	CH_ERODMO	Channel erodibility factor	–	0–1	0.95
11	SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	Ton/m^3	0.0001–0.01	0.002179
12	SPEXP	Exponent in the sediment transport equation	–	1–1.5	1.085000
13	AI0	Ratio of chlorophyll a to algal biomass	μg g	10–100	82.900002
14	RS1	Local algal settling rate at 20 °C	m/d	0.15–1.82	0.300300
15	MUMAX	Maximum specific algal growth rate	day^{-1}	1–3	2.30
16	RHOQ	Local algal respiration rate at 20 °C	day^{-1}	0.05–0.5	0.459500
17	NPERCO	Nitrate percolation coefficient	–	0–1	0.130000
18	AI1	Fraction of algal biomass that is nitrogen	mg	10–100	91.900002
19	RS4	Local settling rate for organic nitrogen at 20 °C	day^{-1}	0.001–0.1	0.093070
20	BC1	Rate constant for the biological oxidation of ammonia nitrogen at 20 °C	day^{-1}	0.1–1	0.919
19	RS4	Local settling rate for organic nitrogen at 20 °C	day^{-1}	0.001–0.1	0.093070
20	BC1	Rate constant for the biological oxidation of ammonia nitrogen at 20 °C	day^{-1}	0.1–1	0.919
21	BC2	Rate constant for the biological oxidation of nitrite to nitrate at 20 °C	day^{-1}	0.2–2	1.766
22	BC3	Local rate constant for the hydrolysis of organic nitrogen to NH + at 20 °C	day^{-1}	0.2–0.4	0.274
23	PPERCO	Phosphorus percolation coefficient	$10\ m^3/Mg$	10–17.5	17.425001
24	PHOSKD	Phosphorus soil partitioning coefficient	m^3/Mg	100–200	115
25	GWSOLP	Soluble phosphorus concentration in the groundwater flow	mg P/L	0–1,000	430
26	AI2	Fraction of algal biomass that is phosphorus	mg P/mg alg biomass	0.01–0.02	0.0149
27	RS5	Local settling rate for organic phosphorus at 20 °C	day^{-1}	0.001–0.1	0.0149
28	BC4	Local rate constant for organic phosphorus mineralization at 20 °C	day^{-1}	0.01–0.7	0.00595

4.3. Water quality effects

For a basin average, the average sediment yield is exceptionally high that is more than 10 metric tons per ha. The maximum sediment output in at least one HRU is greater than 50 metric tons per ha. The HRU no. 7 sub-basin 4 with forest land use and loamy skeletal soil yields the best value. Large amounts of organic nitrogen are present in

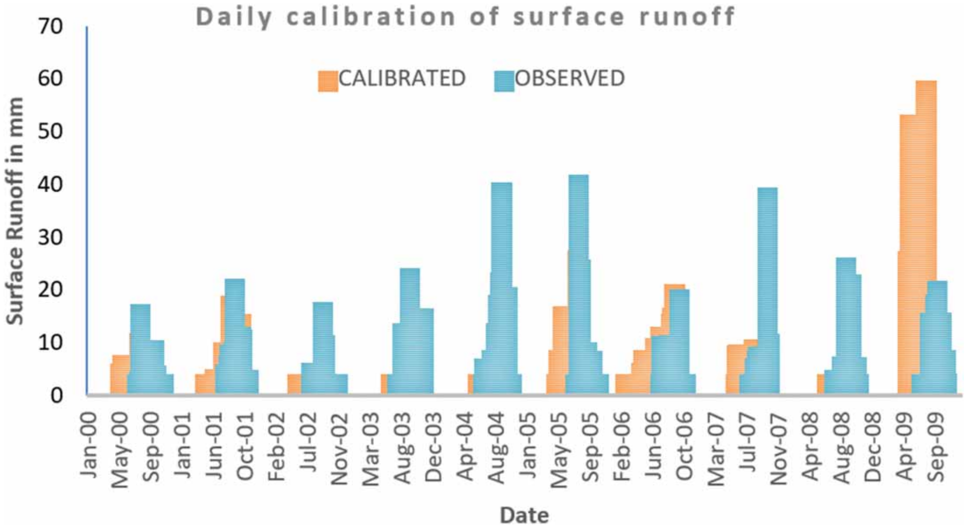

Figure 3 | Daily calibration of surface runoff.

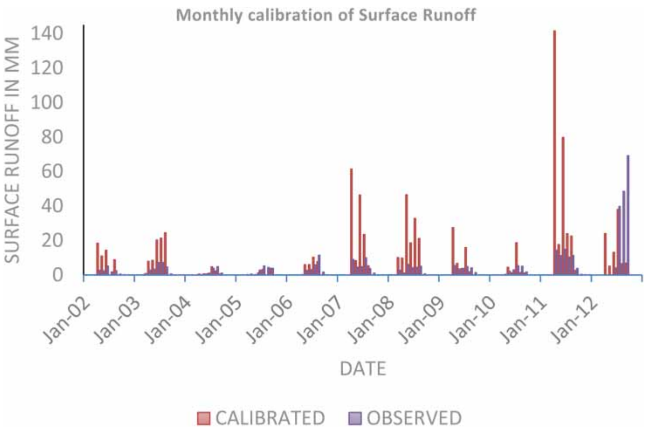

Figure 4 | Monthly calibration of surface runoff.

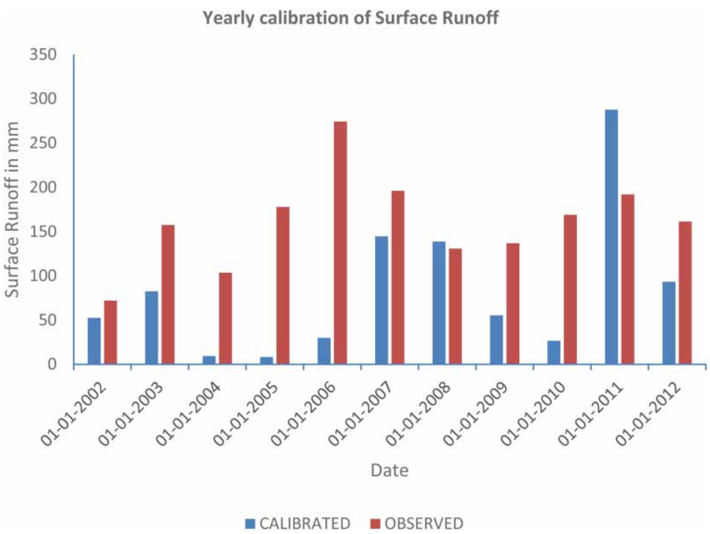

Figure 5 | Yearly calibration of surface runoff.

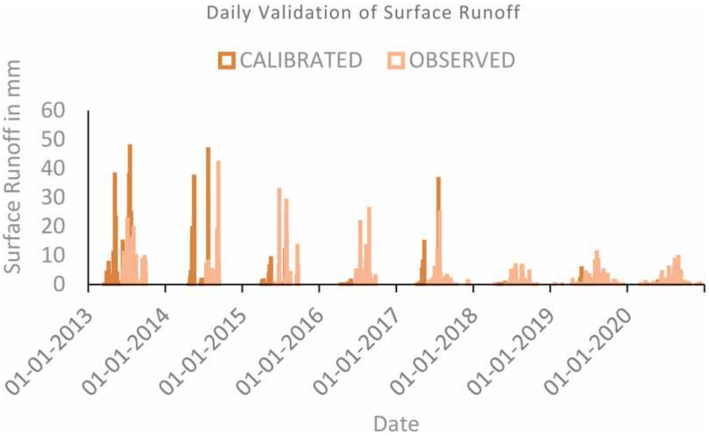

Figure 6 | Daily validation of streamflow.

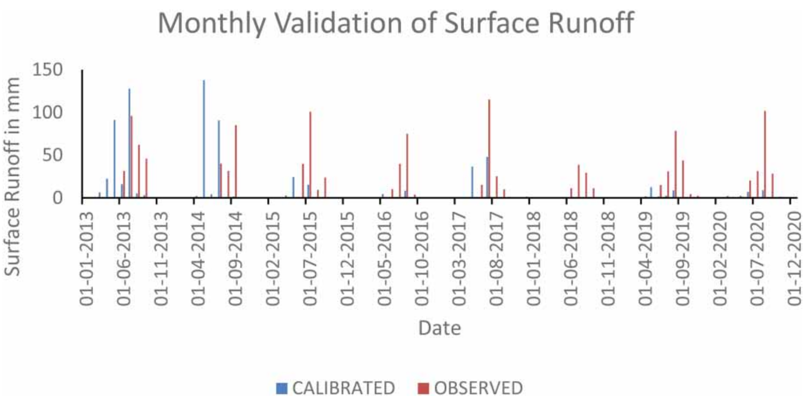

Figure 7 | Monthly validation of streamflow.

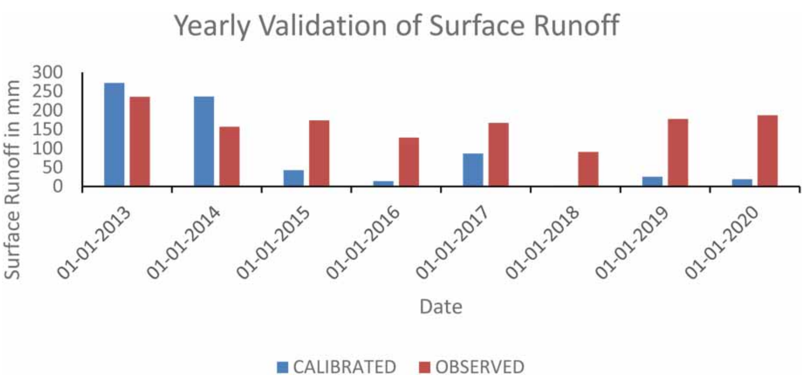

Figure 8 | Yearly validation of streamflow.

soils as organic matter. Large variations between the initial and end nitrogen contents may signify the simulation used too much fertilizer. Crops can use half of the nitrogen that is applied. There is a significant organic and mineral phosphorus reserve in the soil.

Over fertilization with either commercial or manure phosphorus sources during the simulation frequently results in a significant rise in the mineral phosphorus content. This implies that the concentration of phosphorus in runoff will similarly rise during the simulation period since nitrogen losses are an important part of the

Table 4 | Model performance for nitrates

	Years	No. of simulations	Variable	R^2	NS	Mean_sim (Mean_obs)	StdDev_sim (StdDev_ obs)
Calibration	2002–2012	50	NO3_OUT_13	0.98	0.79	7,288.38 (5078.95)	20,868.20 (14936.51)
Validation	2013–2020	50	NO3_OUT_13	0.99	0.56	4,292.88 (2934.80)	13,389.95 (8212.58)

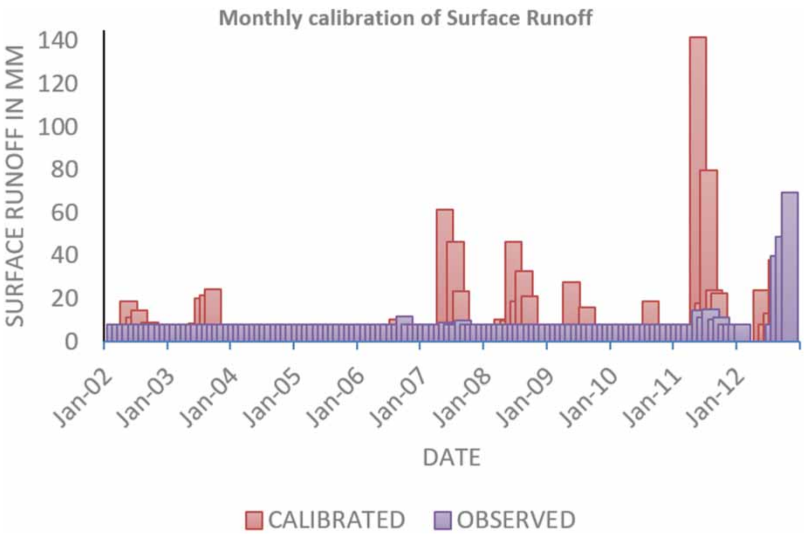

Figure 9 | Monthly calibration of nitrate.

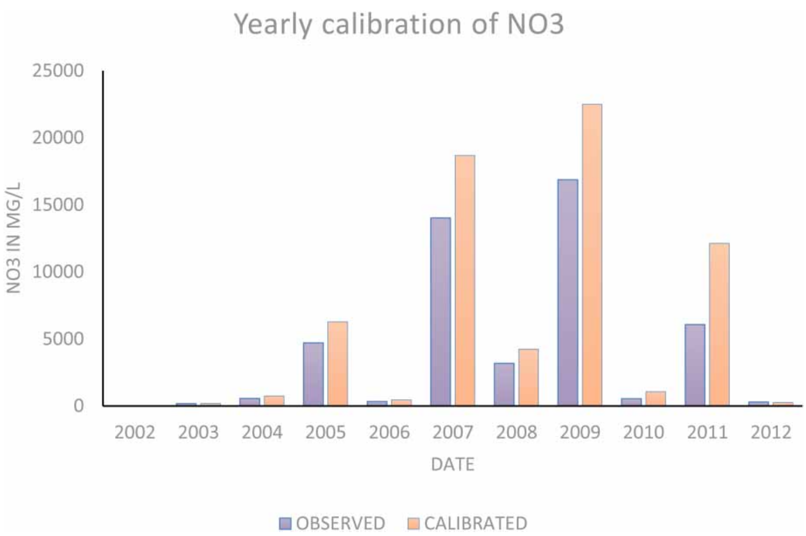

Figure 10 | Yearly calibration of nitrate.

Hathmati watershed. The information presented here pertains to losses from the landscape surface that is sent to reaches. Crops lose more than 40% of the applied nitrogen in total. Surface runoff nitrate losses could be lower. Both the solubility ratio for nitrogen and phosphorus in runoff and the soluble phosphorus losses in surface runoff are low. Moreover, 38% of the applied fertilizer leaches nitrate, signaling a problem that needs to be fixed.

5. RESULTS AND DISCUSSION

The study demonstrates how streamflow and water quality data from the Bhiloda Gauge Station from 1999 to 2012 were used to calibrate the SWAT model. The default settings for each parameter in the model were used.

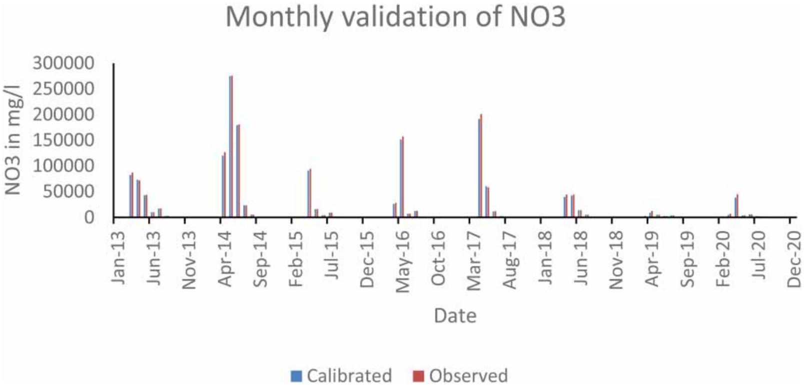

Figure 11 | Monthly validation of nitrate.

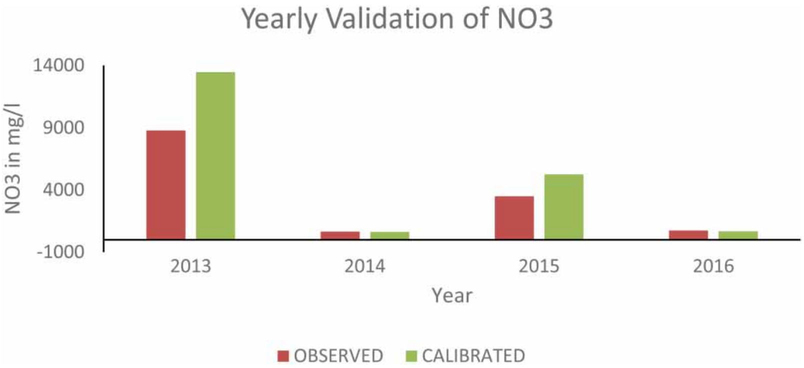

Figure 12 | Yearly validation of nitrate.

The calibrated model was then put to the test with information on streamflow and water quality gathered by SWDC, Gandhinagar, at the Bhiloda Station from 2013 to 2020 as well as information on water quality gathered by SWDC, Gandhinagar, at four other locations within the Hathmati Watershed. Goodness-of-fit statistics demonstrated that the simulation of streamflow and nitrate was successful. The SWAT model has generated accurate estimates of streamflow and nitrate; however, the variability of streamflow has been overestimated. Streamflow has been underestimated during high-flow events and overestimated during low-flow occurrences. Simulated values of NH_4, organic N, organic P, NO_2, NO_3, total nitrogen, and total phosphorus were matched with measurements of water quality. The degree of closeness between actual and simulated values happened as a result of different processes for sediment, nitrogen, and phosphorus losses in soil and streams (Heathwaite *et al.* 2000). The calibrated–validated SWAT model was used to mimic the hydrology and water quality features of the watershed. The water-balance analysis found that more over 45% of the annual precipitation was lost through evapotranspiration. In both wet and dry years, surface runoff had the biggest impact on streamflow. Baseflow made for around 80% of the average annual streamflow.

6. CONCLUSION

The analysis of the framework for preserving water quality and the provision of a tool to aid in decision-making are the main objectives of this research. Surface flow and nitrate concentrations in watersheds can both be simulated by the model. Additionally, it has the capacity to model how nitrate concentrations and surface flow affect several aspects of nutritional water quality. The hydrograph comparisons between the observed and modeled flow revealed parallels, provided a strong fit for the regression curve, and illustrated the viability of using model scenarios in areas with sparse data. Modeled NO_3^- had some seasonal changes but was typically consistent in size and dispersion. The major sources of unpredictability may be viewed as internal model parameter settings and algorithmic deficiencies in handling the complexity of an agricultural watershed. This evaluation of the modeling process and model's hydrologic basis in actual hydrology have resulted in a further warning that no mathematical model can be taken as reality because there will always be flaws because watersheds are complex systems whose behavior cannot be completely replicated in a simulation model. This thesis showed that the SWAT model may be utilized to analyze tiny watersheds. In addition to confirming watershed studies and serving as a forecasting tool for decision-making, it will provide agricultural farm owners and policymakers with a useful tool that will support best practices in agriculture and the environment. The study presented here shows that it is possible to rebuild the time series of nitrate and discover geographic correlations of components for the Hathmati River using input data on discharge, land use, and pollution sources. With the help of this, it is possible to calculate the water quality for different watershed areas on any given day during the simulation period. These data can be used to provide suggestions for an improved monitoring system. They can also be utilized to make educated guesses about the nitrate content of periods and places that are not actually observed. The SWAT model, which was used to examine the effects of irrigated agriculture, is well-suited for predicting nitrate concentrations. Irrigated farmland is by far the main source of nitrate contamination in the river. It is appropriate for a situation in which there are few data sources and minimal prior environmental monitoring activity. On the other hand, there are some problems with the chosen approach as well. We are unsure as to whether the nitrate is a result of specific irrigation management methods, if it is related to the soil, or if it is brought on by other environmental causes. It assumes that all irrigation perimeters would behave similarly and only provide an empirical estimate of the amount of nitrate exported when baseflow and overland flow are combined. The validation of the model results for the Hathmati Watershed was good. Another significant problem in the study was the paucity of the validation data available. It is difficult to judge the usefulness of the recommended model with so few observations. It is possible to utilize the model to produce monitoring suggestions if we assume that it appropriately depicts the spatiotemporal behavior of nitrate concentration.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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