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A scenario-based analysis of selected best management practices for reduced sediment and nutrient yield in the watershed located in the Shivalik hills, India

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ABSTRACT

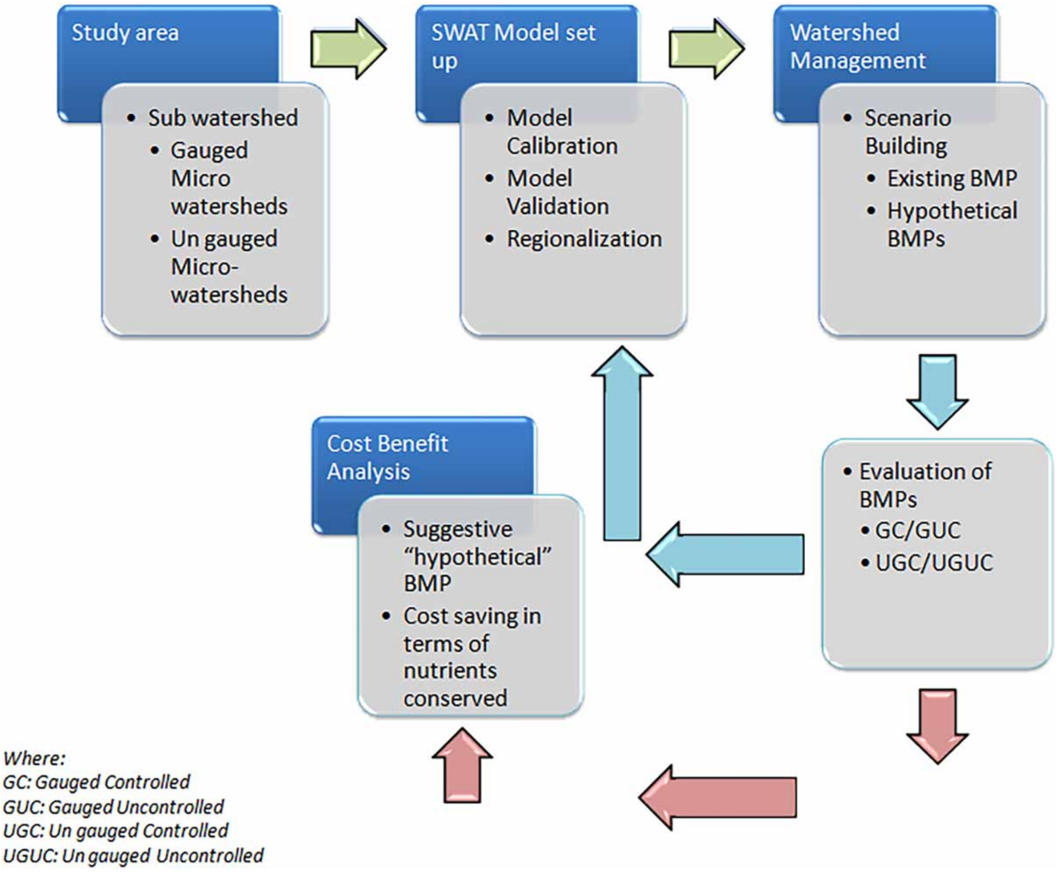
In this study, an attempt has been made to evaluate the best management practices (BMPs) in a poorly degraded and economically fragile watershed area in Shivalik hills, Northern India. A scenario-based approach was followed to evaluate the existing BMPs and a few hypothetically implemented BMPs based on SWAT modeling. A regionalization approach was adopted for calibrating the SWAT model for ungauged micro-watersheds within the study area. After successful calibration, soil and water assessment tool (SWAT) model was simulated for several BMPs that are in practice such as Check dams, vegetation and fencing so as to learn about their effectiveness in controlling sediment and nutrient yield. Other hypothetically installed BMPs, such as contouring, terracing, grassed waterways and filter strips were also evaluated in untreated micro and sub-watersheds. The cost–benefit analysis of these hypothetical BMPs revealed that the average reduction in nutrients was maximum for grassed waterways and minimum for terracing. Overall, the scenario-based analysis revealed that conservation practices, in the otherwise degraded watershed, can prove to be beneficial for sustainability of its natural resources.

Key words: BMPs, cost–benefit analysis, nutrients, sediment yield, soil erosion, SWAT modeling

HIGHLIGHTS

- SWAT model calibration for gauged and ungauged microwatershed using regionalization technique.
- Evaluating the effectiveness of in-place best management practices in controlling sediment yield and a few nutrient parameters causing nonpoint pollution during rainfall season.
- Cost–benefit analysis of the hypothetically designed and implemented best management practices in conserving nutrient loss using SWAT simulations.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Runoff-induced soil erosion and its subsequent disposal into the river network through watershed outlets is a serious and continuous global environmental problem affecting the quality of water, soil and land resources (Bhattacharyya *et al.* 2015; Pandey *et al.* 2021). It is the process by which surface soil is entrained from one place and accumulates in a new location due to the impact of rainfall and runoff. The soil erosion and its transportation process cause degrading surface soil quality, a regime problem in the stream channels, a decrease in the capacity of stream channels, lakes and reservoirs by deposition of sediments, and an increase in the costs of maintaining water conveyance structures. It is, therefore, required to take some preventive measures to save this runoff and control erosion during the rainy season. The best management practices (BMPs) are strategies for conserving soil and water, as well as social and cultural activities, that have been identified as effective and feasible ways of reducing and controlling runoff-induced sediment and nutrient transport in a watershed (Debo & Reese 2003). Evaluating the efficacy of a BMP by collecting monitoring data from the fields is both expensive and time consuming especially for large watersheds with varying land use and soil features. In this regard, watershed models stand out as valuable tools as they have the capability to analyze watershed processes and their interactions, as well as simulate BMPs at a relatively low cost and without investing the time required to install and monitor BMPs in the field (He 2003; Liu *et al.* 2017). According to Khalid *et al.* (2016), SWAT is a well-established, physically based distributed model among other hydrological models to analyze the effectiveness of land management practices and BMP implementation in large and complex watersheds (Chaubey *et al.* 2010; Tyagi *et al.* 2014). As a result, the SWAT model has emerged as one of the popularly used river basin scale models for hydrologic and environmental evaluations. However, the performance of a BMP is basically affected by several factors, which differ significantly from location to location within any watershed. Therefore, it is difficult to develop a particular set of BMPs that is best for all watersheds (Maeda *et al.* 2018). Rather, it is necessary to determine the existing condition of the watershed and choose BMPs that will be effective to control the sediment and nutrient transport within the basin and have reasonable implementation and maintenance costs.

Sushanth *et al.* (2019) assessed critical erosion-prone areas in Patiala-ki-Rao watershed using geographic information system (GIS) and water erosion prediction project (WEPP) models. The results of their study showed that built-up, agriculture and fallow lands with high slopes and sand content are more prone to soil erosion. Simulating the sediment yield (SY) at hillslope level provided an idea about the critical erosion-prone areas within the watershed, and thus appropriate management strategies can be planned for the sustainable livelihoods of the inhabitants in the watershed. Yousuf *et al.* (2021) used the WEPP model to simulate the impact of check dams and sedimentation basins on runoff and SY. They concluded that channel erosion is predominant in the watershed and check dams are more efficient in controlling runoff and SY than sedimentation basins. However, the coupled implementation of both interventions was much more effective than the individual implementation of each intervention.

For a small watershed Patiala-Ki-Rao in Shivalik Hills in Northern India, which is selected for the present study, a few BMPs are already in place as ongoing research. These BMPs have been institutionalized because one of the biggest concerns in the watershed is its erodible nature, which becomes prominent during monsoon season. A large portion of monsoon rainfall (35–45%) is lost as runoff in the torrents causes large-scale erosion in the area. A survey has revealed that 90% of the villagers have agriculture as their primary occupation and the key constraints on agriculture production in these villages are deep groundwater, shortage of surface water, low water & nutrient holding capacity of the soil, degraded and undulating lands and poor socio-economic conditions of the residents. It has been found that large amounts of rainwater go as runoff in a small duration and create erosion and flooding in lower-lying areas, resulting in water loss and land degradation. Along with the eroded soils, pesticides and fertilizers from the agricultural lands are also transported and find their way into the natural streams causing deterioration of downstream water quality Therefore, a soil and water conservation plan is needed in the area, in which management decisions are based on physical principles and scientific concepts. However, before implementing management practices, it is also necessary to assess their effectiveness in controlling soil loss and nonpoint source (NPS) pollutants such as nutrients. Therefore, a methodology is needed to evaluate the effectiveness of the various soil water conservation measures in the selected watershed. The present paper thus attempts to (1) evaluate the impact of different BMPs as well as a few hypothetically implemented BMPs on reducing SY and nutrients loss using SWAT model and, (2) evaluate the most efficient BMPs using cost–benefit analysis (CBA) to reduce the input cost for sustainable watershed management.

2. MATERIALS AND METHOD

2.1. Study area

The selected study area is situated between 30° 47′ North and 76° 48′ East at lower left and 30° 50′ North and 76° 52′ East at upper right. It is at a mean elevation of 477 m above the mean sea level with an area of 14.96 km^2. The upper Patiala-Ki-Rao watershed, as it is called, gets its name from the stream (Patiala-Ki-Rao) that flows through it. The stream originates from the dense forests of the Shivalik hills in the north of Chandigarh, located in Northern India, as shown in Figure 1(a) and 1(b). The water flows in tributaries only during the monsoon season from July to September. The area has a semi-arid climate and rainfall is the primary source of water in the region. The average annual rainfall varies from 850 to 1,250 mm. The rains are inconsistent and more than 80% of high-intensity and short duration rains occur during the monsoon months (Sharma & Bhardwaj 2017). Geologically Shivalik hills are made up of poorly consolidated sand stone and conglomerates, which are the solidified waste of the mighty Himalayas. One of the biggest concerns in the watershed is its erodible nature which becomes prominent during monsoon season. Runoff-induced soil erosion and loss of soil fertility are two major concerns in the watershed. The entire area is ecologically degraded and is one of the most backward areas of the Shivalik hills. The watershed was delineated and processed to consist of two main sub-watersheds named (SW-I and SW-II). The sub-watershed SW-II was further retained to depict four micro-watersheds named (MW-I, MW-II, MW-III and MW-IV) as shown in Figure 1. The area of these sub-watersheds and micro-watersheds are given in Table 1. A few BMPs are already in place to control runoff and soil loss in four gauged adjacent micro- watersheds nested within the selected ungauged sub-watersheds. However, studies on the efficacy of these BMPs in controlling erosion and nutrient loss are not reported.

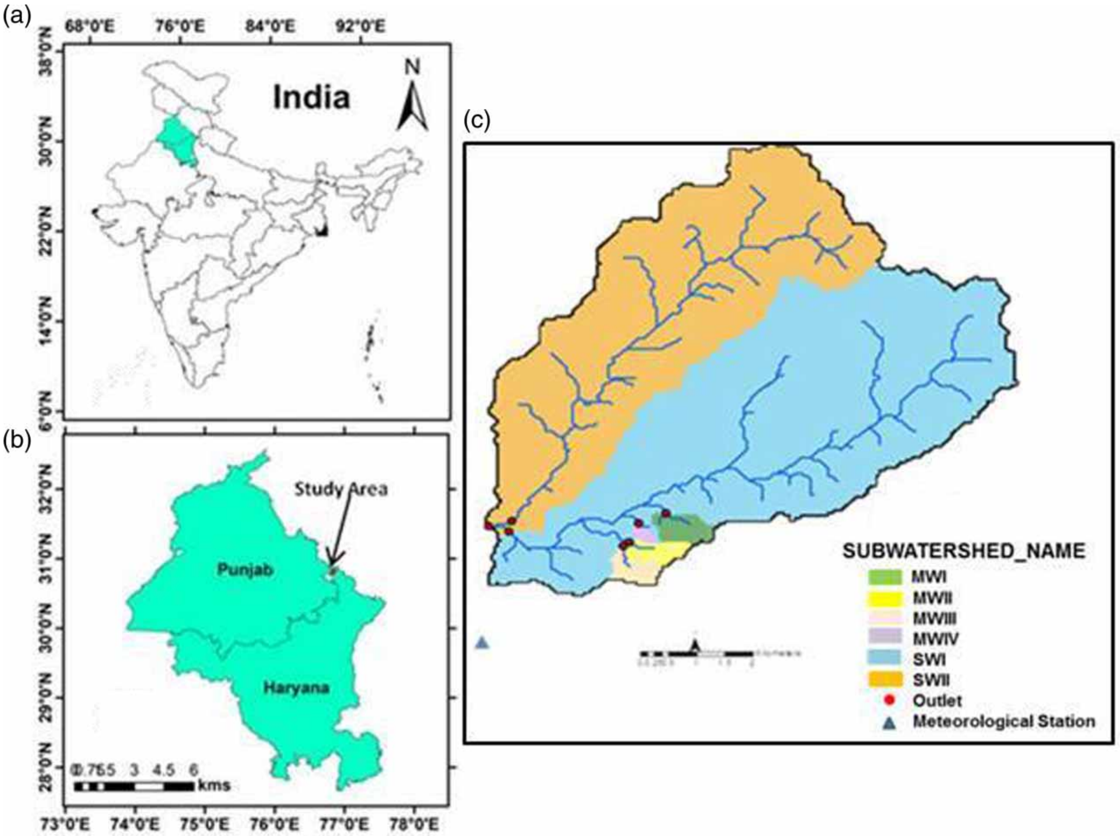


Figure 1 | (a, b) Location map of study area, (c) sub-watersheds and gauged micro-watershed of selected watershed.

Table 1 | Area of selected watershed, sub-watersheds and microwatersheds

S. No.	Name of watershed	Area (km^2)
1.	Selected upper Patiala-Ki-Rao Watershed (W)	14.96
2.	Sub-watershed-I (SW-I)	8.27 (excluding four gauged micro-watersheds)
3.	Sub-watershed-II (SW-II)	6.27
4.	Microwatershed-I (MW-I)	0.15
5.	Microwatershed-II (MW-II)	0.12
6.	Microwatershed-III (MW-III)	0.11
7.	Microwatershed-IV (MW-IV)	0.036

2.2. SWAT model set up and its calibration

SWAT is a continuous-time, physically based, semi-distributed river basin or watershed scale model (Arnold *et al.* 1998). It is a watershed hydrological transport model comprising weather, surface runoff, return flow, percolation, evapotranspiration, transmission losses, pond and reservoir storage, crop growth and irrigation, groundwater flow, reach routing, nutrient and pesticide loading, and water transfer components (Ronco *et al.* 2017). The model works on hydrological response units (HRUs) and hydrological processes are simulated by using water balance equation.

In order to configure the SWAT model for the study area, several input files need to be prepared beforehand in a format accepted by the model. These input files include digital elevation model (DEM) data, land use, soil slope and weather data. Six land use categories were identified in the study area, i.e., forest, shrubland, agriculture, river/water bodies, roads and residential. The major land use category is forest and the soil table consisted of three soil classes. The classes specified in these tables are defined in the default SWAT database. The classification of the slope was based on the DEM used during watershed delineation and classified into five classes: from 0 to 5, 5 to 20, 20 to 35, 35 to 45 and 45 to 99.99. These datasets were linked to the SWAT datasets. All the three loaded layers were overlaid to create hydrologic response units. The total number of HRUs created in the process was 182. The observed records for weather variables were collected from a meteorological station located near the watershed. Weather data for the period 2004–2015, i.e., 12 years, were collected from this meteorological station. The study watershed was divided into two sub-watersheds and four micro-watersheds as shown in Figure 1(c) and 1(d), respectively. Outlets were selected for the whole watershed and for two main sub-watersheds, above the confluence of two tributaries, where water samples were collected for qualitative analysis. In addition to these, four outlets of gauged micro-watersheds were also selected where runoff gauging stations are located. During the simulation, a 3-year warm-up period was given to establish the initial soil water conditions. The total simulation period was set to run from 2004 to 2015 (i.e., 12 years). Hence, a 9-year period of hydrologic variables was simulated for the study watershed excluding the warm-up period. The model was initially run by using default model parameters for the simulation of stream flow and SY, following which sensitivity analysis was performed to identify the sensitive model parameters. In order to find the best parameter set for the model, the Sequential Uncertainty Fitting-2 (SUFI-2) approach within SWAT Calibration and Uncertainty Programs (SWAT-CUP) was used. The best-fitted parameter values obtained from SWAT-CUP were incorporated into the SWAT database for simulations of discharge and SY at monthly time steps. Keeping in view the availability of limited observed data of stream flow and SY of gauged micro-watersheds, the model was used to simulate the stream flow and SY. At the same time, based on the parameter set selected for gauged micro-watersheds, stream flow and SY at the outlets of ungauged watersheds and sub-watersheds were also simulated using the technique of regionalization. In this technique, the parameter set is considered as transferable, as watersheds with similar characteristics exhibit similar hydrological behavior and, therefore, the transformation of parameters is plausible (Bardossy 2007). The spatial proximity and physical similarity approach was carried out by transferring parameters from a donor microwatershed to the receiver ungauged watershed and sub-watersheds as suggested by Parajka *et al.* (2005) and Patil & Stieglitz (2011). Transformation of hydrological parameters was plausible as the outlets of gauged micro-watersheds were located downstream and quite close to the outlets of selected ungauged watersheds with almost similar characteristics (climate, soil, etc.). The area ratio method was used to compare the stream flow and sediments at the outlets of ungauged watersheds, sub-watersheds and gauged micro-watersheds. In this method, the estimation of stream flow of an ungauged watershed is determined by multiplying the measured flow at the nearby reference gauged watershed by the area ratio of the ungauged to gauged watersheds (Archfield & Vogel 2010; Gianfagnaa *et al.* 2015) given in the following Equation:

$$Q_{\text{ungauged}} = Q_{\text{gauged}} \times \frac{\text{Area}_{\text{ungauged}}}{\text{Area}_{\text{gauged}}} \tag{1}$$

The first 5 years (2007–2011) of the 9-year period were used for calibration, and the subsequent 4 years (2012–2015) were used for model validation. The model was calibrated by using the values of 20 sensitive parameters that were identified during the sensitivity analysis. The model was calibrated for stream flow and SY simultaneously for four gauged micro-watersheds from 2007 to 2012 at a monthly time step. The performance evaluation was done on the basis of three performance indices: coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE) and Percentage Bias (PBIAS), where NSE was used as the major objective function. It was observed in the study that, among all the four gauged micro-watersheds, micro-watersheds-IV predicted better results for stream flow and SY. The R^2, NSE and PBIAS values for the microwatershed-IV were 0.94, 0.91 and 13.9 for the calibration period and 0.92, 0.90 and 9.5 for the validation period, respectively, for stream flow. Whereas for SY, the R^2, NSE and PBIAS values were 0.92, 0.88, and 27.8 for calibration period and 0.88, 0.80 and 28.4 for validation period, respectively. The statistical analysis clearly predicts that the model performance for both calibration and validation for monthly stream flow and SY was good as per performance rating criteria of hydrological models (Premanand *et al.* 2018). Therefore, the predicted flow and SY of the best-chosen microwatershed-IV was used to validate the stream flow and SY for selected ungauged watershed and sub-watersheds.

3. WATERSHED MANAGEMENT AND SCENARIO BUILDING

In the present study, the SWAT model has already been calibrated and validated for stream flow and SY for the selected area and for the four gauged micro-watersheds. The data on water quality in terms of nutrients were not available for the selected watershed. In a similar condition, literature provides several studies (e.g., refer Nelson *et al.* 2006; Barlund *et al.* 2007; Abouabdillah *et al.* 2014; Smith *et al.* 2014; Himanshu *et al.* 2019; Busico *et al.* 2020; Abu-Zreig & Hani 2021) where efficiency of management practices on variables other than the variable for the model is calibrated due to the lack of observed data. Hence, although sediment is the pollutant of concern in the study area, the effectiveness of management practices on nutrients was also evaluated to test the SWAT model's applicability in evaluating the efficacy of management decisions. The simulated SY and nutrients, i.e., organic nitrogen (ON), nitrate as nitrogen (NO_3), total nitrogen (TN), organic phosphorus (OP) and total phosphorus (TP) for micro-watersheds with BMPs were compared to micro-watersheds and sub-watersheds without BMPs to evaluate the efficiency of BMPs in reducing the sediments and nutrients entering into the stream water.

3.1. Evaluation of existing BMPs

As given in Table 2, check dam, vegetation and fencing are applied in the micro-watersheds-I (MW-I) and in microwatershed-II (MW-II). Fencing has been applied to microwatershed-III (MW-III). In microwatershed-IV (MW-IV), no control measures are used so far. To lower the channel gradient, temporary loose boulder check dams are built on the drainage line of micro-watersheds-I (MW-I). The loose boulder check dam is composed of locally available stones, as shown in Figure 2. These check dams were constructed in the upstream area of microwatershed-I (MW-I) to reduce runoff velocity and settling of sediments. These small, temporary structures across a stream are constructed using gravel, straw rolls, sandbags or fiber blocks (Hassanli & Beecham 2013; Sami Al-Janabi *et al.* 2020). Generally, check dams can also be introduced when it is impractical to line the stream or permanent flow-control practices (Khonkaen & Jie-Dar 2011). These are often constructed such that the crest of a dam is level with the toe of the upslope dam. Vegetation is done to reduce soil erosion by planting and improving the soil structure of concerned areas. To prevent erosion, the roots of plants, such as grass, bind the soil particles together. It also aids in reducing the effect of rainfall and preventing soil particle detachment.

The SY data in kg/hectare, as observed during the year 2007–2015, are available for all four micro-watersheds. The graphical representation of observed data of suspended SY as shown in Figure 3 predicts that management practices have an effective role in controlling soil loss. The untreated microwatershed-IV is found to have more suspended SY compared to all other the three gauged micro-watersheds. The maximum SY is observed to be 20,727.98 kg/hectare during the year 2008 for untreated microwatershed-1V and for a similar year, the SY was observed to be 13,513.95, 13,354.52 and 15,703.05 for MW1, MW2 and MW3, respectively, indicating the role of management practices in controlling the soil loss. The average percentage reduction of SY measured over a period of 9 years was 37.2, 41.42 and 40.81 in microwatershed-I, microwatershed-II and microwatershed-III, respectively, as compared to untreated microwatershed-IV. The results are suggestive of the usefulness of adopting appropriate management practices in the Shivalik region for the purpose of rejuvenating and conserving natural resources in the future.

3.1.1. Scenario building for BMP evaluation

Water quality parameters under two different scenarios with the combinations of the gauged-controlled (GC)/gauged-uncontrolled (GUC) and the ungauged-controlled (UGC)/ungauged-uncontrolled (UGUC) microwatersheds and sub-watersheds were simulated using SWAT to assess the impact of management practices. Among four gauged micro-watersheds MW-I, MW-II and MW-III implemented with BMPs as given in Table 2 are controlled micro-watersheds, whereas gauged microwatershed MW-IV and ungauged sub-watersheds SW-I and SW-II are uncontrolled microwatersheds and sub-watersheds where no control measure is implemented to control

Table 2 | Existing BMPs in different microwatersheds

S. No.	Name of microwatershed	Existing BMPs
1.	MW-I	Check dam, vegetation, fencing
2.	MW-II	Vegetation, fencing
3.	MW-III	Fencing

Figure 2 | Check dams at the drainage line of microwatershed-I.

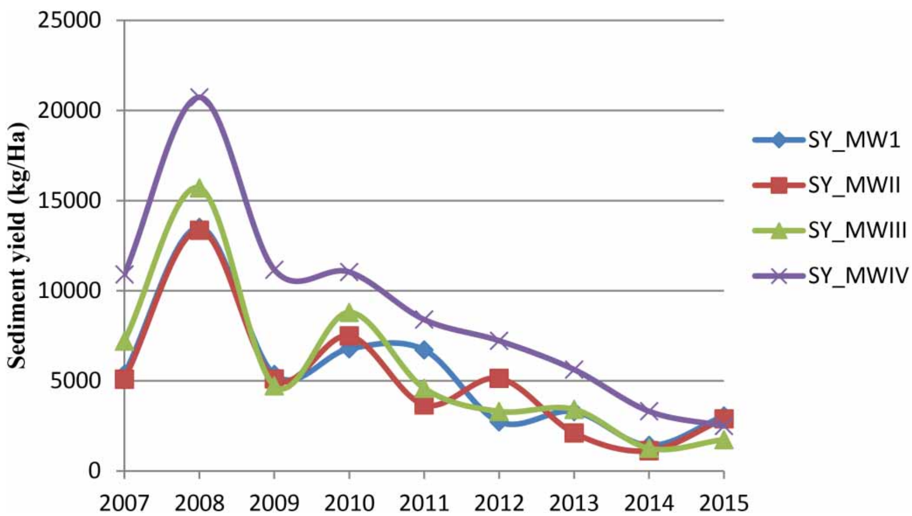


Figure 3 | Variation of observed sediment yield (SY) for four gauged micro-watersheds.

the runoff and pollutants. The existing BMPs were evaluated by directly changing the parameter (USLE_P) within the calibrated SWAT model. The effectiveness of existing BMPs analysed by comparing the outputs of sediment and nutrient yield under these two scenarios. In either of the two scenarios, simulated monthly sediment and nutrient loads were compared.

Scenario 1: GC/GUC

In the first combination, two gauged microwatersheds nested within the selected ungauged watershed were chosen and compared. The gauged microwatershed-I was applied with engineering, vegetation and fencing gauged and microwatershed-IV was not implemented with any control measure.

Scenario 2: UGC/UGUC

In the second combination, the selected ungauged sub-watershed with no control measures was compared with microwatershed-I (MW-I), where control measures are applied and hypothesized as ungauged.

3.2. Evaluation of a few hypothetically implemented BMPs

In the selected watershed, check dam, plantation and fencing are the existing BMPs used to control runoff, soil loss and NPS pollution. Evaluation of these BMPs predicted their effectiveness to control runoff, soil loss and NPS pollution using SWAT model. Taking into account the efficacy of existing BMPs, some potential BMPs were hypothetically simulated to check their effectiveness. In this study, the impacts of contouring, terracing, grassed waterways and filter strip were hypothesized to check their effectiveness in reducing sediment and nutrient yield. The study thus aims to evaluate the impact of these soil and water conservation interventions prior to their application in the watershed to develop sustainable irrigation strategies. SWAT was run on a monthly basis from 2004 to 2015 (excluding the initial 3 years from 2004 to 2006 as a warm-up period). The BMPs, i.e., contouring, terracing, filter strips, and grass waterways, were hypothetically implemented using the scheduled management operations (.ops) file. The impacts of these BMPs were evaluated by compiling monthly SY, ON, nitrate as nitrogen (NO_3-N), TN, OP and TP losses for all the 9 years.

3.2.1. Scenario building for hypothetical BMPs

The simulated monthly loadings for sediment and nutrients when no BMPs were implemented were used as the baseline loading conditions to which the simulated loads from hypothetically implemented BMP scenarios were compared. The monthly load difference between a hypothetically implemented BMP scenario and the baseline scenario was used to determine the load reduction achieved by BMP implementation. The effectiveness of hypothetically implemented BMPs was carried out by comparing the monthly SY, ON, nitrate as nitrogen (NO_3), TN, OP, and TP under these two scenarios as:

Scenario 1 (Baseline scenario): The baseline simulation was considered when no BMP was applied in the watershed.

Scenario 2 (Hypothetically implemented BMPs Scenario): In this scenario, simulations were modeled hypothetically by implementing management practices to quantify the impact of contouring, terracing, filter strips, grass waterways on sediment and nutrient loadings.

4. RESULT AND DISCUSSIONS

4.1. Analysis with existing BMPs

The simulated monthly SY and nutrient loads were compared from 2007 to 2015 to evaluate the efficiency of management practices in minimizing NPS pollutants in terms of nutrients. The simulated water quality variables, i.e., ON, nitrate as nitrogen (NO_3), TN, OP and TP were compared to evaluate the impact of management practices. Comparisons under these two scenarios were made on a percentage reduction basis of these water quality variables by comparing the percentage change in the microwatershed where BMPs exist to the untreated microwatershed as in Table 3. It is clear from the results that in micro-watersheds and sub-watersheds where management practices did not exist, the percentage of sediment load and the nutrient load was high as compared to treated micro-watersheds. The SY as shown in Figure 4(a) and 4(b) predicts that SY during June to September varied from 0.01 to 9.8 tons/hectare for GC micro-watersheds, and from 0.644 to 18.01 tons/hectare for GUC microwatershed, which clearly indicates that controlled micro-watersheds deliver less sediment as compared

Table 3 | Percentage reduction of suspended sediments and nutrients with the application of existing BMPs in selected watershed

		Parameter					
S. No	**BMP scenario**	**Sediment yield**	**Organic nitrogen (ON)**	**Nitrate (NO_3)**	**Total nitrogen (TN)**	**Organic phosphorus (OP)**	**Total phosphorus (TP)**
1.	Gauged-controlled (GC)/gauged-uncontrolled (GUC)	80.5%	72.4%	63.4%	71.6%	49.4%	73.9%
2.	Ungauged-controlled (UGC)/ungauged-uncontrolled (UGUC)	75.8%	48.5%	36.1%	50.2%	49.3%	48.6%

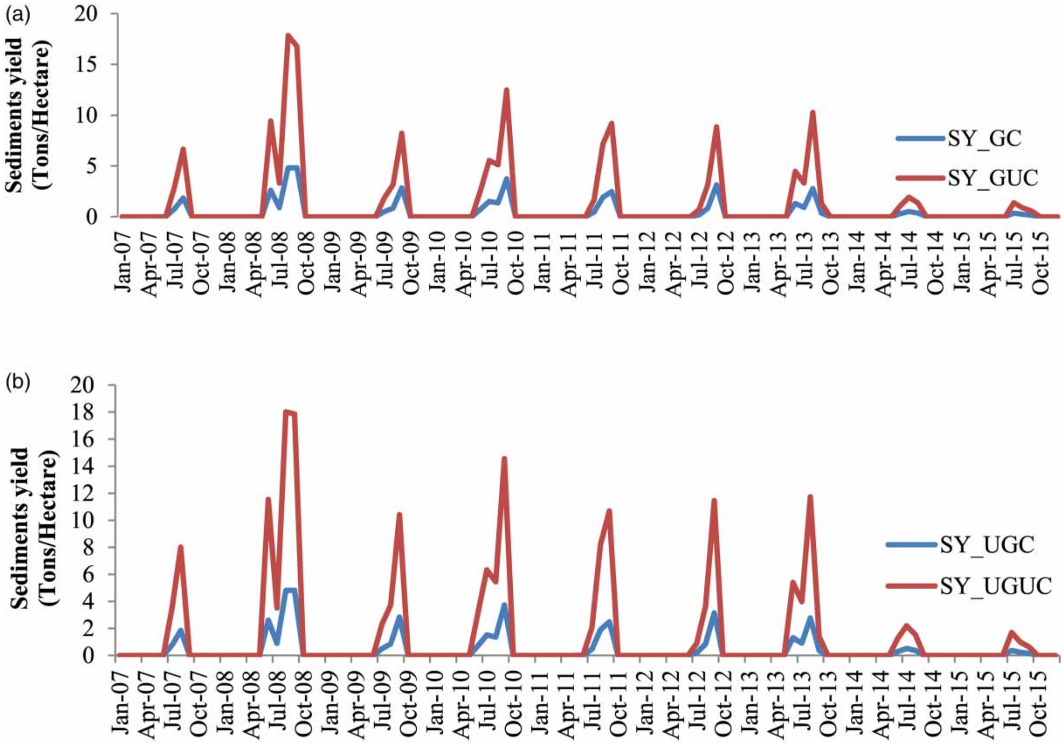


Figure 4 | (a) Monthly simulated sediments yield for gauged-controlled/uncontrolled watersheds. (b) Monthly simulated sediment yield for ungauged-controlled/uncontrolled watersheds.

to uncontrolled micro-watersheds. It was also observed that the sediment delivery was more during August and September as compared to June and July. Figure 5(a) and 5(b) shows the variation of TN (monthly) as simulated under two scenarios for existing BMPs. As observed from the figures, the magnitude of TN expressed as a total of ON and nitrates is higher for ungauged conditions compared to controlled scenarios in micro-watersheds and sub-watersheds. A similar observation is made from the variation of total phosphorous over the years 2007–2015 as in Figure 6(a) and 6(b).

The results of SY and nutrient load percentage reduction with the BMP application are shown in Table 3 for the two selected scenarios. The study shows the effectiveness of management practices when existing BMPs were evaluated. The results predicted that the percentage of suspended sediment and the nutrient load was low in the micro-watersheds where management practices were implemented compared to untreated micro-watersheds and sub-watersheds.

4.2. Analysis with hypothetical BMPs

Model simulation results with the application of management practice over baseline simulation predicted relative effectiveness and identified the management practices that should be more effective in the study watershed. The results obtained from baseline simulation were compared to the outcomes obtained when soil and water conservation methods (BMPs) were used. The efficacy of integrating different conservation methods was calculated by computing the percentage change in the model outputs when such conservation measures are implemented, as given in the following equation:

$$\text{Effectiveness of BMP} = \left(\frac{\text{Baseline simulation} - \text{Simulation after BMP implementation}}{\text{Baseline simulation}}\right) \times 100 \tag{2}$$

The percentage sediment and nutrient reduction with the hypothetical application of contouring, terracing, grassed waterways and filter strips at the outlet of selected ungauged watershed as shown in Table 4 predicts that contouring and terracing reduced the average sediments yield by 49.9%, while grassed waterways reduced the average sediments by 75.9% and filter strips reduced the average sediments by 11.23% from baseline

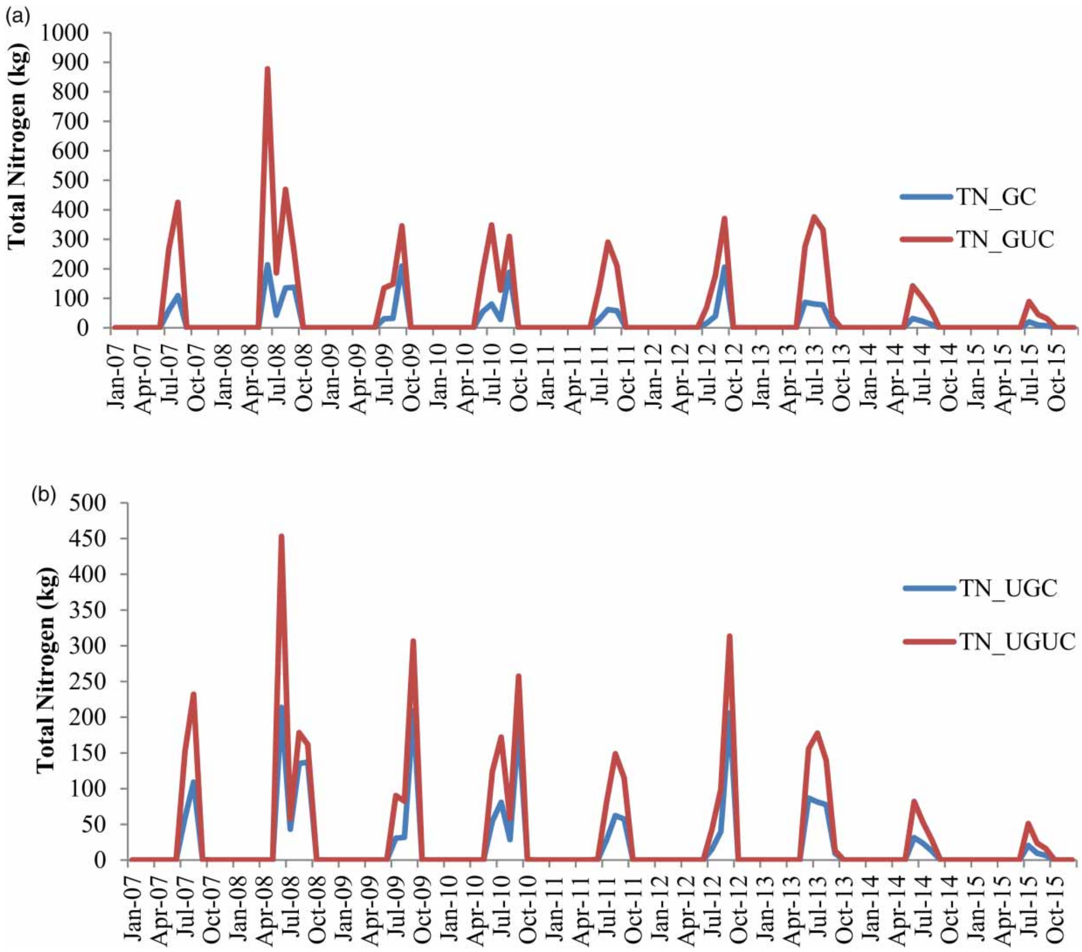


Figure 5 | (a) Monthly simulated total nitrogen for gauged-controlled/uncontrolled watersheds. (b) Monthly simulated total nitrogen for ungauged-controlled/uncontrolled watersheds.

simulation. Whereas, the percentage average decrease in TN and TP with the implementation of contouring, terracing and grassed waterways was 34.12, 29.97, 94.6, 40.13, 35.76, and 98.1%, respectively.

The results of the present study clearly predict that grassed waterway is the most effective BMP for managing sediments and nutrients entering into the stream. It was also observed that filter strips have the least significant impact on reducing sediments and nutrients whereas contouring and terracing also resulted in a decline in sediments and nutrient yield in the selected watershed. These estimates can help the decision-makers to determine how effective these BMPs might be when implemented in the untreated and ungauged watershed. Taking into account the effectiveness of the selected BMPs, soil water conservation techniques can be planned in such a way as to control land degradation, and improve water availability and crop production by implementing them the most economically acceptable way.

4.3. Cost–benefit analysis

It is clear from the evaluation of existing and hypothetical BMPs implementation that the percentage of suspended sediment and the nutrient load was high in the micro-watersheds and sub-watersheds where management practices were not applied, as compared to treated micro-watersheds. The study indicated that conservation practices are needed in the selected watershed to reduce soil erosion and nutrients for the sustainability of the selected watershed on the basis of priority. Furthermore, before implementing conservation practices, there is a need to evaluate the most efficient BMPs using CBA to reduce the input cost and resources.

The effect of BMPs on the average monthly nutrient yield is simulated by the SWAT model. If the soil's nutrients are depleted, it will be necessary to use more chemical fertilizers to keep the soil fertile (Bartik 1988; Hamilton 1994; Tiezzi 2002). It is, therefore, possible to evaluate the worth of BMPs in terms of the cost of additional chemical fertilizers needed by farmers if BMPs are not used. Equation (3) shows that if farmers do

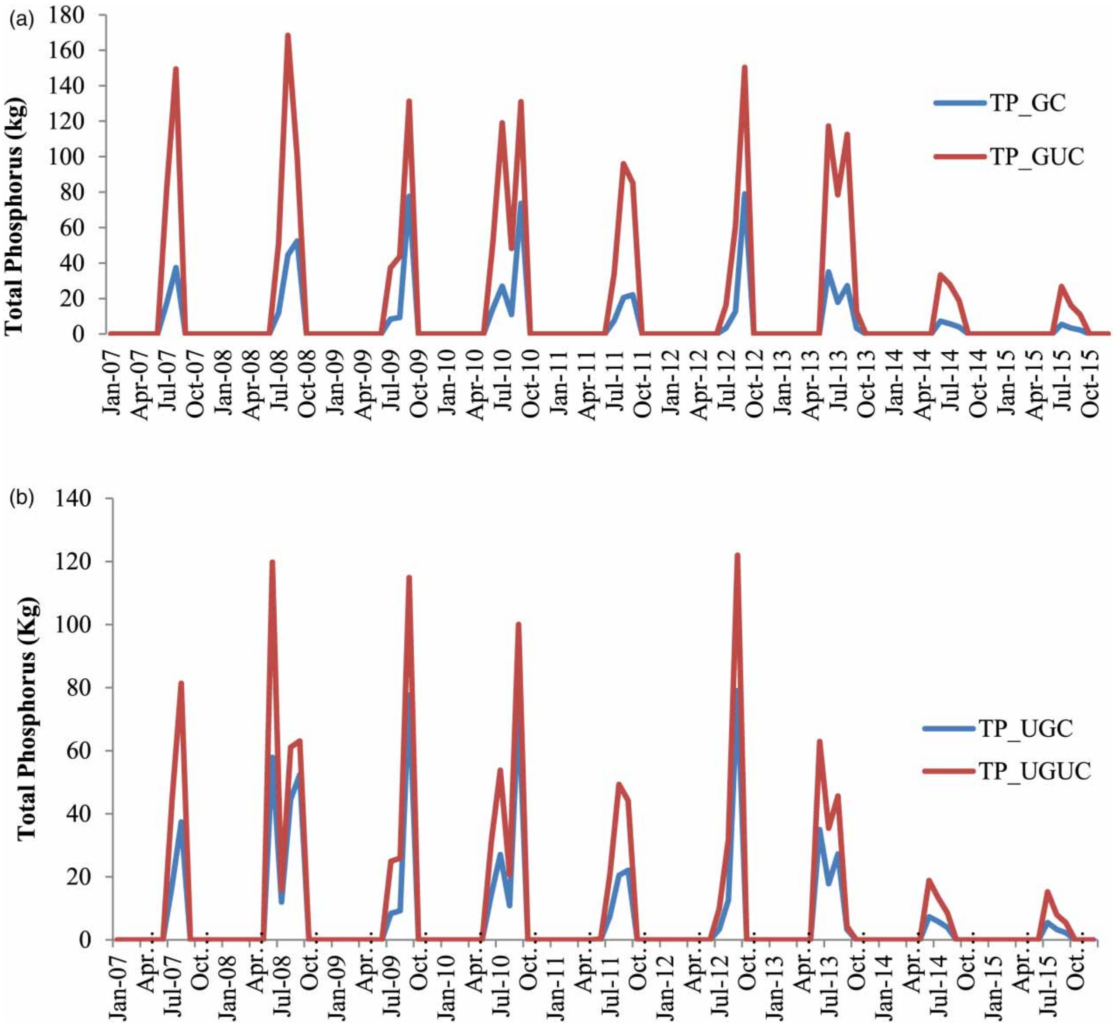


Figure 6 | (a) Monthly simulated TP for gauged-controlled/uncontrolled watersheds. (b) Monthly simulated TP for ungauged-controlled/uncontrolled watersheds.

Table 4 | Percentage reduction of sediments and nutrients with the hypothetical implementation of BMPs in selected watershed

		Parameter					
S.No.	**BMP scenario**	**Sediments yield**	**Organic nitrogen (ON)**	**Organic phosphorus (OP)**	**Nitrate (NO_3)**	**Total nitrogen (TN)**	**Total phosphorus (TP)**
1.	Contouring	50%	44.5%	41.0%	4.5%	34.1%	40.1%
2.	Terracing	49.9%	43.7%	36.5%	4.8%	30.0%	35.8%
3.	Grassed waterways	76%	98.4%	98.3%	56.5%	94.6%	98.1%
4.	Filter strip	11.3%	7.6%	5.6%	0.0%	0.0%	0.0%

not use BMPs, the formula is as follows:

$$E_m = T_m \times S_m \times P_m \quad (3)$$

where E_m is the loss of TN or TP, T_m is the total nutrient loss of agricultural nonpoint source pollution in the selected watershed, S_m is the coefficient of TN or TP that is converted to fertilizer usually used by local farmers

Table 5 | Estimated cost of the nutrients conserved with the hypothetical implementation of conservation practices

S. No.	Parameter	BMP	Average reduction (kg/ha)	Cost of reduced nutrient (Rs)
1.	Total nitrogen (TN)	Contouring	10.9	87.0
		Terracing	4.00	32.0
		Grassed waterways	220.0	1,760.0
		Filter strip	0.0	0.0
		Total	234.8	1,878.5 (approximately. 25.4 USD)
2.	Total phosphorus (TP)	Contouring	3.68	92
		Terracing	1.8	45
		Grassed waterways	80.9	2,022.5
		Filter strip	0	0
		Total	86.38	2,159.5 (approximately.29.1 USD)

and P_m is the price of fertilizer. The benefits can be calculated based on how much nutrition the BMPs can preserve.

In the present study, the reduction of sediment and nutrients yield with the hypothetical application of BMPs was simulated. The results predicted that the most effective BMP is the grassed waterways followed by contour farming, terracing and filter strips to reduce the intrusion of sediments and nutrients into the stream. However, the implementation of terracing is labour-intensive and expensive as compared to contouring, and the simulated results also predicted that contouring was more effective in reducing sediment and nutrients as compared to terracing, as shown in Table 4. Therefore, grass waterways and contouring are more effective and economical in reducing the soil and nutrient loss among the four hypothetical BMPs evaluated for the selected watershed. Whereas to calculate the amount of TN and total phosphorous (TP) that gets reduced with the application of these BMPs in monetary terms, the average retail prices of the commonly used fertilizers urea and Di-Ammonium Phosphate (DAP) used by local farmers were obtained through market surveys. The price for the elemental forms of nitrogen and phosphorus was calculated, and from the calculated average prices of elemental nitrogen and phosphorus, input costs per nutrient for inorganic fertilizer were assessed. However, the actual cost for inorganic fertilizer will be somewhat higher than that of the elemental nutrients due to manufacturing and transportation.

In the absence of conservation practices, approximately 234.81 kg/ha of TN and 86.38 kg/ha of TP were required to replenish the nutrient loss. It was estimated that around 54.48 USD would be spent to replace the lost macronutrients nitrogen (N) and phosphorous (P) with the inorganic fertilizers, as shown in Table 5. The on-site cost of erosion would, however, be higher than this estimate. This is because the cost of macro nutrient potassium (K) (not simulated in SWAT model), the cost of conserving soil and water and the cost of compensating for the reduced crop production have not been included in this analysis. These losses lead to substantial environmental degradation. The consequences of the ensuing soil erosion along with nutrients decrease soil productivity, which makes crop production unsustainable.

5. CONCLUSIONS

The Upper Patiala-Ki-Rao watershed in Shivalik hills located in Northern India is economically poor land area that is degrading over a period of time. This is because of its highly erodible nature, loss of soil fertility and non-point pollution during the monsoon months when its rivulets carry the seasonal flow. A few BMPs are already in place to control runoff and soil loss in four gauged micro-watersheds nested within the selected ungauged sub-watersheds. However, the study on the efficacy of these BMPs in controlling erosion and nutrient loss is not reported. Hence, in an attempt to propose sustainable watershed measures, a scenario-based evaluation of BMPs was performed. The SWAT model was first calibrated and validated for sub-watersheds that are gauged following which the model was also calibrated for ungauged sub-watersheds using the area ratio method of regionalization. Once calibrated, the effectiveness of existing BMPs, such as check dams, plantation and vegetation, in four gauged micro-watersheds was predicted. Taking into account the efficacy of existing BMPs, some potential hypothetical BMPs, such as contouring, terracing, grassed waterways and filter strips were also simulated. Based on CBA, it was concluded that the grassed waterways and contouring were found to be effective and economical in reducing sediments and nutrients among the four hypothetical BMPs. The results predicted that the percentage of suspended sediment and the nutrient load was low in the micro-watersheds where management practices were implemented compared to untreated micro-watersheds and sub-watersheds. In the absence of conservation techniques, 234.81 kg/ha of TN and 86.38 kg/ha of TP were required to restore nutrient loss. The cost of replacing the lost macronutrients N and P with inorganic fertilizers was calculated to be 55 USD. The study indicated that conservation practices are needed in the selected watershed to reduce soil erosion and nutrients for the sustainability of the selected watershed.

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.

REFERENCES

Abouabdillah, A., White, M., Arnold, J. G., De Girolamo, A. M., Oueslati, O., Maataoui, A. & Lo Porto, A. 2014 Evaluation of soil and water conservation measures in a semi-arid river basin in Tunisia using SWAT. *Soil Use and Management* **30** (4), 539–549.

Abu-Zreig, M. & Hani, L. B. 2021 Assessment of the SWAT model in simulating watersheds in arid regions: case study of the Yarmouk River Basin (Jordan). *Open Geosciences* **13** (1), 377–389.

Archfield, S. A. & Vogel, R. M. 2010 Map correlation method: selection of a reference streamgage to estimate streamflow at ungaged catchments. *Water Resources Research* **46** (10), W10513.

Arnold, J. G., Srinivasan, R., Muttiah, R. S. & Williams, J. R. 1998 Large area hydrologic modeling and assessment part 1: model development. *Journal of the American Water Resources Association* **34** (1), 73–89.

Bardossy, A. 2007 Calibration of hydrological model parameters for ungauged catchments. *Hydrology and Earth System Sciences* **11** (2), 703–710.

Barlund, I., Kirkkala, T., Malve, O. & Kamari, J. 2007 Assessing SWAT model performance in the evaluation of management actions for the implementation of the Water Framework Directive in a Finnish catchment. *Environmental Modelling & Software* **22** (5), 719–724.

Bartik, T. J. 1988 Evaluating the benefits of non-marginal reductions in pollution using information on defensive expenditures. *Journal of Environmental Economics and Management* **15** (1), 111–127.

Bhattacharyya, R., Ghosh, B. N., Mishra, P. K., Mandal, B., Rao, C. S., Sarkar, D., Das, K., Anil, K. S., Lalitha, M., Hati, K. M. & Franzluebbers, A. J. 2015 Soil degradation in India: challenges and potential solutions. *Sustainability* **7**, 3528–3570.

Busico, G., Colombani, N., Fronzi, D., Tazioli, A. & Mastrocicco, M. 2020 Evaluating SWAT performance to quantify the stream-flow sediment yield in a highly urbanized basin. *Environmental Sciences Proceedings* **2** (5), 1–6.

Chaubey, I., Chiang, L., Gitau, M. W. & Mohamed, S. 2010 Effectiveness of best management practices in improving water quality in a pasture-dominated watershed. *Journal of Soil and Water Conservation* **65** (6), 424–437.

Debo, T. N. & Reese, A. J. 2003 *Municipal Storm-Water Management*, 2nd edn. CRC Press, Springer, Boca Raton, FL.

Gianfagnaa, C. C., Johnsona, C. E., David, G., Chandler, A. & Hofmann, C. 2015 Watershed area ratio accurately predicts daily streamflow in nested catchments in the Catskills, New York. *Journal of Hydrology: Regional Studies* **4**, 583–594.

Hamilton, K. 1994 Green adjustment to GDP. *Resources Policy* **20** (3), 155–168.

Hassanli, A. M., Beecham, S., 2013 Criteria for optimizing check dam location and maintenance requirements. In: *Check Dams, Morphological Adjustments and Erosion Control in Torrential Streams* (Cones-Garcia, C. & Aristide-Lenzi, M. eds). Nova Science, Inc, Hauppauge, NY, pp. 11–31.

He, C. 2003 *Integrated Watershed Management-Principles and Practice*, 2nd edn. Wiley, New Jersey.

Himanshu, S. K., Pandey, A., Yadav, B. & Gupta, A. 2019 Evaluation of best management practices for sediment and nutrient loss control using SWAT model. *Soil and Tillage Research* **192**, 42–58.

Khalid, N. F., Din, A. H. M., Omar, K. M., Khanan, M. F. A., Omar, A. H., Hamid, A. I. A. & Pa'suya, M. F. 2016 Open-source digital elevation model (DEMs) evaluation with GPS and LiDAR data. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences* **2016** (42), 299–306.

Khonkaen, P. & Jie-Dar, C. 2011 The application of check dams construction to watershed management: a case study in the north of Thailand. *Journal of Soil and Water Conservation* **43** (1), 111–122.

Liu, Y., Engel, B. A., Flanagan, D. C., Gitau, M. W., McMillan, S. K. & Chaubey, I. 2017 A review on effectiveness of best management practices in improving hydrology and water quality: needs and opportunities. *Science of the Total Environment* **601**, 580–593.

Maeda, P., Chanse, V., Rockler, A., Montas, H., Shirmohammadi, A. & Wilson, S. 2018 Linking stormwater best management practices to social factors in two suburban watersheds. *PLOS ONE* **13** (8), e0202638.

Nelson, R. G., Ascough, J. C. & Langemeier, M. R. 2006 Environmental and economic analysis of switchgrass production for water quality improvement in northeast Kansas. *Journal of Environmental Management* **79** (4), 336–348.

Pandey, S., Kumar, P., Zlatic, M., Nautiyal, R. & Panwar, V. P. 2021 Recent advances in assessment of soil erosion vulnerability in a watershed. *International Soil and Water Conservation Research* **9** (3), 305–318.

Parajka, J., Merz, R. & Bloschl, G. 2005 A comparison of regionalisation methods for catchment model parameters. *Hydrology and Earth System Sciences* **9** (3), 157–171.
Patil, S. & Stieglitz, M. 2011 Hydrologic similarity among catchments under variable flow conditions. *Hydrology and Earth System Sciences* **15** (3), 989–997.
Premanand, B. D., Satishkumar, U., MaheshwaraBabu, B., Parasappa, S. K., Dandu, M. M., Kaleel, I., Rajesh, N. L. & Biradar, S. A. 2018 QSWAT model calibration and uncertainty analysis for stream flow simulation in the Patapur micro-watershed using sequential uncertainty fitting method (SUFI-2). *International Journal of Current Microbiology and Applied Sciences* **7** (4), 831–852.
Ronco, P., Zennaro, F., Torresan, S., Critto, A., Santini, M., Trabucco, A., Zollo, A. L., Galluccio, G. & Marcomini, A. 2017 A risk assessment framework for irrigated agriculture under climate change. *Advances in Water Resources* **110**, 562–578.
Sami Al-Janabi, A. M., Ghazali, A. H., Yusuf, B., Sammen, S. S., Afan, H. A., Al-Ansari, N., Shahid, S. & Yaseen, Z. M. 2020 Optimizing height and spacing of check dam systems for better grassed channel infiltration capacity. *Applied Science* **10** (11), 3725.
Sharma, R. & Bhardwaj, S. 2017 Effect of mulching on soil and water conservation – a review. *Agricultural Research Communication Centre* **3**, 311–315.
Smith, C. M., Williams, J. R., Nejadhashemi, A., Woznicki, S. A. & Leatherman, J. C. 2014 Cost-effective targeting for reducing soil erosion in a large agricultural watershed. *Journal of Agricultural and Applied Economics* **46** (4), 509–526.
Sushanth, K., Kumar, R. & Bhardwaj, A. 2019 Soil mapping of Patiala-Ki-Rao watershed in Shivalik foothills using GIS. *International Journal of Agricultural Science and Research* **9** (2), 1–8.
Tiezzi, S. 2002 Environmental defensive expenditures and households behaviour in Italy. *Applied Economics* **34** (16), 2053–2061.
Tyagi, J. V., Rai, S. P., Qazi, N. & Singh, M. P. 2014 Assessment of discharge and sediment transport from different forest cover types in lower Himalaya using soil and water assessment tool (SWAT). *International Journal of Water Resources and Environmental Engineering* **6** (1), 49–66.
Yousuf, A., Bhardwaj, A. & Prasad, V. 2021 Simulating the impact of conservation interventions on runoff and sediment yield in a degraded watershed using the WEPP model. *Ecopersia* **9** (3), 191–205.

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