



Simulating the Impact of Conservation Interventions on Runoff and Sediment Yield in a Degraded Watershed Using the WEPP Model

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ABSTRACT

Aim The present study aimed to use the WEPP model to simulate the impact of various conservation interventions on runoff and sediment yield and determine the optimum areal extent of a watershed to be treated economically.

Materials & Methods The study watershed (located in the Shivalik region of North-West India) was divided into various hillslopes and channels. The input files required to run the WEPP model were prepared for each hillslope and channel. The WEPP model was calibrated and validated by using monitored hydrological data (2015-2019). The impact of check dams and sedimentation basins, individually and in combination, on runoff, sediment yield, and sediment delivery ratio was simulated.

Findings The simulation results indicated that channel erosion is predominant in the watershed, and check dams are more efficient in controlling runoff and sediment yield than sedimentation basins. However, the coupled implementation of both interventions was much more effective than the individual implementation of each intervention. The simulated runoff and sediment yield decreased by 72% and 90%, respectively, with a significant reduction of about 95% in sediment delivery ratio (SDR) compared to the untreated watershed. The results further revealed that treating 66% of the watershed area with both the interventions can be considered as an optimum area that should be treated.

Conclusion In the absence of any recommendations for implementing management interventions in the Shivalik region of India, the results of the present study would serve as guidelines for treating degraded watersheds for their rehabilitation under limited financial resources.

Keywords Management Interventions; Micro-Watershed; Optimum Area; Sediment Delivery Ratio; Shivalik Foot-Hills

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Introduction

Soil erosion has become a severe challenge globally concerning its negative impact on soil health and agricultural productivity [1]. Soil erosion results in poor soil quality, loss of essential nutrients, and reduced water holding capacity [2]. The eroded soil contains three times more nutrients per unit weight than the remaining soil [3]. The nutrient depletion due to the mechanical action of water results in the physical and chemical degradation of soil (nutrient receding), which eventually not only leads to desertification [4] but also affects human health by polluting the soil, air, and water [5]. More than one billion hectares of area in the world are subjected to constant catastrophes of soil erosion [6]. Soil erosion results in an 8 billion Dollar loss to global GDP annually, which has reduced the crop yields by 33.7Tg (Teragrams) and increased water abstraction by 48 billion m³ [7]. In India, soil erosion accounts for a loss of 6600Tg, which accounts for wastage of 5.4 Tg of fertilizers with a valuation of US\$ 46.8 million [8]. Soil erosion has taken much toll on the landscapes of Asia, Africa, and South America, with an average bulk of 30-40Mgha⁻¹year⁻¹ [8]. Soil erosion has resulted in disastrous impacts, both on-site and off-site, on natural environmental setups in the form of sedimentation resulting in the siltation and pollution of inland waters, reduction in water quality, damage to turbines, and transport of chemical pollutants [9, 10]. About 15.5 Pg (Petagrams) of sediments are being deposited annually in the oceans [11].

In India, water erosion has affected about 111.26 million hectares of total geographical area (328.81 million hectares). The *Shivalik* foot-hills in northwest India are portrayed as one of India's eight major fragile ecosystems that are much susceptible to accelerated soil erosion [12]. This region produces considerable bulk of sediments as about 35-45% of rainfall goes as runoff during the monsoon season resulting in flash floods and downstream sedimentation. In some of the watersheds, soil erosion is as high as 244 Mg ha⁻¹ year⁻¹ [13]. The monsoon downpour entirely influences the *Shivalik* foot-hills, thus forecasting and estimation of runoff and sediment yield from a particular watershed is a fundamental precursor for the conservation of aquatic resources and boosting the agricultural productivity [14].

Under the changing climatic scenarios across the globe, the threat of soil erosion has increased manifold. The frequency and magnitude of soil erosion are expected to increase with future climate change [15]. The different processes involved in the impact of climate change on soil erosion by water are complex, which include the changes in rainfall amounts and intensities, the number of rainy days, nature of precipitation (rain, snow, etc.), evapotranspiration rates, plant residue decomposition rates, plant biomass production, soil microbial activity, and shifts in land use necessary to accommodate a new climatic regime [16]. To incorporate these processes, hydrological and climate models have become important tools to study the response of soil erosion to the changing climate [17].

In order to mitigate the impact of climate change on runoff and soil erosion, it is necessary to identify, design, and implement the conservation strategies, encompassing soil and water conservation measures and policies which strictly adhere to the scientific background and valid methodology [18]. Thus, quantification of runoff and spillage of topsoil needs to be addressed spatially and temporally to identify the best management practices/interventions at the watershed scale. However, manual monitoring of runoff and sediment yield in all the watersheds is almost difficult due to high expenditure, data procurement complexities, extensive requisite of land area, field staff, and requirements of automated apparatus. Moreover, funds to treat a watershed are not sufficient and remain a constraint in treating the whole watershed [19, 20]. Under these circumstances, interventions must be planned, preferably covering the most critical areas/hillslopes of a watershed, thereby treating as many numbers of watersheds as possible, partially, within the allocated budget.

To address these constraints, mathematical hydrologic models are viable tools for the computation of runoff and soil loss from individual hillslope and at the outlet of a watershed [21]. Many hydrologic models efficiently simulate runoff and sediment yield at the watershed scale. The ANSWERS [22], AGNPS [23], SHE [24], WEPP [25], EUROSEM [26], CREAMS [27], KINEROS2 [28] and LISEM [29] are a few among these models. However, selecting an appropriate model is a challengeable effort in terms of heterogeneity in environmental setups with

varying magnitudes for soil erodibility, runoff quantum, the sediment repository, and scale compatibility of parameters for up-scaling and down-scaling [30]. The Water Erosion Prediction Project model (WEPP) has been tested widely and found to be successful in the simulation of runoff and sediment yield from small watersheds with reasonable accuracy [31-36]. The present study aimed to use the WEPP model to simulate the impact of various conservation interventions/treatments on runoff and sediment yield and determine the optimum areal extent of a watershed to be treated economically. There is a dire need to conduct such a study as no such study has been conducted in the *Shivalik* region of North-West India, and the results of the present study would serve as guidelines for the policymakers to construct soil and water conservation structures in the region.

Materials and Methods

Description of the study area

The *Saleran* micro-watershed selected in the present study falls in the *Shivalik* foot-hills of Punjab in North-West India (Figure 1). It is situated between 31° 36' 18.32" N, 75° 58' 58.97" E and 31° 36' 45.40" N, 75° 59' 14.34" E (Figure 1). The watershed area is about 42ha, with elevation ranging from 342 to 416m above the mean sea level. The climate in the area is sub-humid. The average annual rainfall is about 1100mm, of which about 80% occurs during the monsoon season (June to September). The mean annual temperature is about 25°C with a maximum of 45°C in May and a minimum of 4°C in January. The soil texture of the watershed is sandy loam with sand and clay content of 85% and 6%, respectively. As far as land use is concerned, about 90% of the land area is covered by natural forests, and the rest is occupied by shrubland.

Hydrological data

The climatic data (rainfall, maximum temperature, minimum temperature, dew point temperature, sunshine hours, wind velocity, and wind direction) was collected for the last five years (2015-2019) from the agrometeorological observatory of the Punjab Agricultural University-Regional Research Station, Ballawal Saunkhri located at a distance of 200m from the study watershed. Rainfall charts for each rainfall event were analyzed to determine the different rainfall characteristics, viz. rainfall amount,

rainfall duration, average rainfall intensity, and peak rainfall intensity. Storm-wise runoff and sediment yield measurements were made at a gauging station located at the watershed outlet, maintained by PAU Regional Research Station, Ballawal Saunkhri. The daily runoff was recorded with the help of the stage level recorder installed over the Parshall flume (10ft). Runoff charts were analyzed to calculate the daily discharge (m^3s^{-1}) and were converted into runoff depth (mm) using the watershed area and duration of runoff. The sediment yield was measured as bedload and suspended load. The number of sediments collected in the siltation chamber just upstream of the Parshall flume was measured for each storm event and considered bed load. The suspended load was measured by collecting the runoff samples during the storm at regular time intervals and analyzing these samples in the laboratory.

WEPP model description

The WEPP is a physically-based runoff and soil erosion prediction model available with various interface programs, including a stand-alone Windows application and a geographic information system (GIS)-linked extension, GeoWEPP [37]. The model mathematically simulates the important physical processes related to surface runoff, soil erosion, and sediment transport and delivery. It computes spatial and temporal distributions of runoff, soil erosion, and deposition at the watershed level or on an individual hillslope so that suitable conservation measures can be selected/adopted for soil and water conservation [38].

Preparation of input files

The WEPP model requires four basic input files, viz., climate file, soil file, slope file, and land use management file, to simulate runoff and sediment yield. The watershed is divided into hillslopes and channels. The input files were prepared for each hillslope and channel. The WEPP model can be applied both at the watershed level as well as on the individual hillslope. The preparation of each input file is discussed below:

Climate file

The WEPP model has an in-built weather generator known as CLIGEN to prepare the climate file for its application. The model requires daily rainfall amount, maximum and minimum temperature, the ratio of time to rainfall peak/rainfall duration (t_p), ratio of maximum rainfall intensity and average rainfall

intensity (i_p), daily solar radiation, wind velocity, wind direction, and dew point temperature to prepare the climate input file. In the present study, these weather parameters were obtained from the agrometeorological observatory maintained by Punjab Agricultural University-Regional Research Station, Ballawal Saunkhri.

Soil file

The soil file in the WEPP model requires data on soil texture, organic matter, cation exchange capacity, inter-rill, and rill erodibility, critical shear, effective hydraulic conductivity, soil albedo, and initial saturation level [38]. Soil samples were taken from the study site (from 0-15cm and 15-30cm depths) and analyzed for obtaining the data required for the preparation of the soil input file. The percentage of sand, silt, and clay varied from 74.5 to 91.1, 5.6 to 17.4, and 3.3 to 8.1, respectively. The soil texture varied from sandy loam to loamy sand with the dominance of sand fraction, which may be ascribed to the siliceous parent material, position of soil in the landscape, and differential degree of weathering. Organic carbon (OC) varied between 0.17 to 0.59%, while the soil bulk density varied from 1.27 to 1.65Mgm⁻³ with no consistent distribution across the locations and depths. The inter-rill erodibility, rill erodibility, and critical shear were calculated using the equations available in the WEPP user summary [14].

Slope file

The slope map of the watershed was prepared with the help of the Alos Palsar Digital Elevation Model (Figure 2). The average slope of the watershed is 24.3%. The contour map of the watershed was imported into the WEPP interface as a background. The watershed was divided into 18 hillslopes and nine channels using the contour map having a contour interval of 5 m (Figure 2c).

Land use and management file

The land use and management file is structured into sections (collection of related data sets) includes the information section, plant growth section, operation section, initial condition section, management section, and others [39]. The management file builder contains many built-in cropping patterns and management practices, which can be easily brought into the data file to suit the prevailing conditions in each hillslope of the study watershed. In the present study, land use and management file were prepared for each

hillslope by importing the corresponding land use and management from the WEPP model database and edited suitably to match the conditions corresponding to each hillslope. It was assumed that the land use and management remained constant throughout the monsoon season as 90% of the land area is covered by natural forests.

Model calibration and validation

The WEPP model was calibrated and validated for the untreated *Saleran* watershed. Calibration was done to identify the parameters sensitive to the model output using the three-year hydrologic data (2015-2017), involving 28 runoff events. The validation was done using two-year data (2018-2019), involving 21 runoff events. The model performance was statistically analyzed by calculating the root mean square error (RMSE), correlation coefficient (r), mean bias error (MBE), and Nash-Sutcliffe model efficiency (η) [40]. The significance of the difference between the simulated and observed values of daily runoff and sediment yield were compared by Student's t-test at $p \leq 0.05$ using SAS 9.4 (SAS Institute Inc., Cary, NC, USA). The critically eroded hillslopes were identified for conservation treatment during the model validation based on the sediment yield at the individual hillslope.

Simulation of the impact of the conservation interventions

WEPP model provides an option to the user to implement different management interventions, including a culvert, drop spillway, emergency spillway, filter fence, perforated riser, rock-filled check dams, sedimentation basin, and straw bales in the watershed project. The user can select the impoundments/interventions of his own choice and edit its features and dimensions according to the location-specific conditions. Among all the available options, rock-filled check dams and sedimentation basins are the most feasible management interventions implemented in the study watershed. Hence, the validated WEPP model was applied to simulate the impact of watershed conservation interventions, namely (i) rock-fill check dams in series across the main drainage line, (ii) sedimentation basins equivalent to staggered trenches across the entire eroded hillslopes, and (iii) rock-fill dams and sedimentation basins in combination, in terms of runoff, sediment yield, and sediment delivery ratio, compared to that of the untreated watershed. The impact of these

conservation interventions was simulated on the entire watershed in terms of reduction in the runoff, sediment yield, and SDR through the number of models runs. The area under the conservation treatment was increased (scenario-1 to scenario-5) for every model run

starting with untreated watershed to completely treated watershed to determine the optimum areal extent of the watershed to be treated to get maximum benefit per unit of available financial resources.

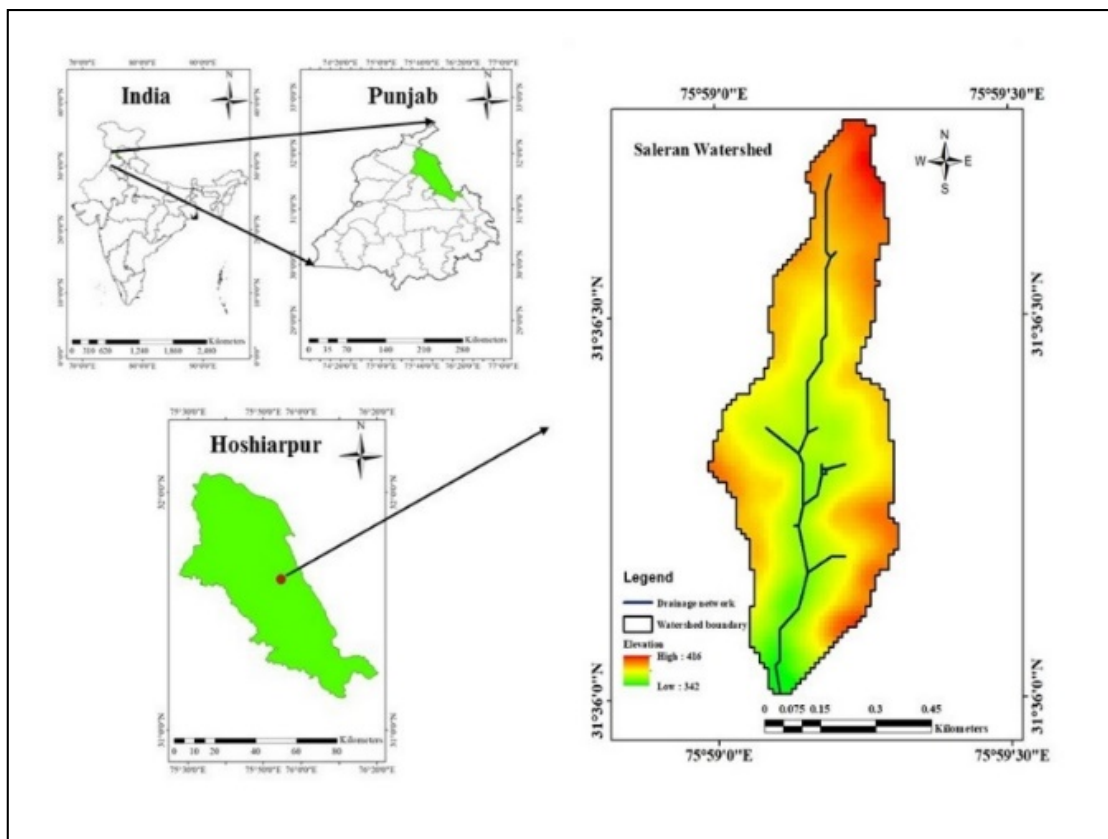


Figure 1) Location map of the study watershed

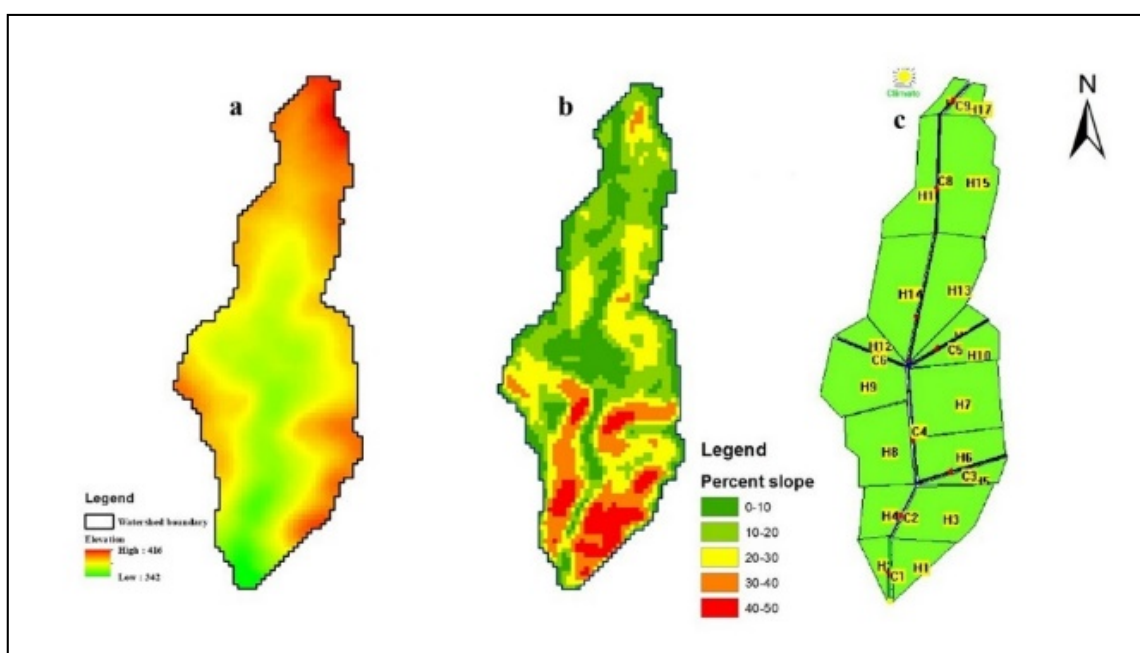


Figure 2 a) Digital elevation model **b)** slope map and **c)** hillslope and channel map of the study watershed.

Findings

Rainfall characteristics of studied rainfall events

During the study period (2015-2019), 49 runoff-producing rainfall events were recorded. The total rainfall received in 49 storms was about 2227mm, out of which 1056mm was received during the calibration period (2015-2017), and 1171mm was received during the validation period (2018-2019). The lowest and highest daily rainfall received during the study period was 12.0mm and 156.0mm. The average rainfall intensity of the rainfall events varied from 5.3 to 40.0mm/h, while as peak rainfall intensity varied from 12.0 to 88.0mm/h (Table 1).

Model calibration and sensitivity analysis for untreated watershed

Sensitivity analysis helps to identify the most influencing parameters which affect the model output. Sensitive parameters affect the model output by a large extent with a small change in their values. Hence the modeler must know the sensitive model parameters for successful model application. In the present study, the WEPP model was sensitive to the soil characteristics, including inter-rill erodibility, rill erodibility, critical shear, and hydraulic conductivity. The runoff was found sensitive to soil hydraulic conductivity, while sediment yield was sensitive to inter-rill erodibility, rill erodibility, critical shear, and hydraulic conductivity (Table 2). The sediment yield increased with an increase in the rill and inter-rill erodibility, whereas a negative correlation of sediment yield was observed with critical shear and soil hydraulic conductivity. As soil hydraulic conductivity increased, the infiltration rate increased, and the runoff amount decreased, which might have reduced the number of sediments reaching the watershed outlet as reported by various researchers [41-43]. Among these parameters, the highest sensitivity ratio was observed for rill erodibility (0.553), indicating the rill erosion is dominant in the study watershed. This could be due to the concentrated flow and high velocities in the rills, which result in higher soil erosion [14, 31]. The values of the calibrated parameters and the sensitivity ratio obtained during the calibration of the WEPP model are presented in Table 2.

The event-wise observed and simulated runoff and sediment yield and the corresponding rainfall during the model calibration period are given in Figures 3 and 4. The simulated values of

runoff and sediment yield are in close agreement with each other. The lower values of runoff and sediment yield are better simulated by the WEPP model than higher values which can be ascertained from the scatter plot diagram (Figure 5). The model's higher values of runoff and sediment yield are under-predicted because of the high rainfall events. Splash erosion results in the clogging of soil pores (known as the surface sealing phenomenon), reducing the infiltration, resulting in higher surface runoff. This phenomenon of surface sealing is not well-taken care of in the WEPP model [14]. Nearing [44] stated that the underprediction of the larger events is due to the limitation of the WEPP model in representing the random component of the observed data. The under-prediction of larger events by the WEPP model in forest watersheds has also been reported by several studies attributed to the under-estimation of subsurface lateral flows [45-47]. In order to increase the simulation accuracy of the WEPP model in forest watersheds, sub-surface flow parameters need to be calibrated more accurately [14]. The total observed and simulated runoff during the calibration period was 172.4mm and 167.5mm, respectively, with the corresponding values of sediment yield as 16.43Mg/ha and 14.32Mg/ha. During the calibration process, two extreme rainfall events (139 mm and 104 mm) were recorded, which significantly contributed to the total runoff and sediment yield. These events' runoff and sediment yield was about 48.92 and 35.23% of the total runoff and sediment yield, respectively. The model performance was tested with the help of statistical analysis (Table 3). The statistical comparison indicated a fairly good agreement between observed and simulated runoff and sediment yield data. The lower values of RMSE, MBE, and higher values of correlation coefficient and model efficiency indicate the accurate simulation of runoff and sediment yield by the WEPP model. The t-test also revealed a non-significant difference between observed and simulated runoff and sediment yield data during the calibration period at a 95% confidence level.

Model validation for untreated watershed

Model validation is a vital process that describes the ability of the model to simulate the runoff and sediment yield from the watershed. After obtaining the calibrated values of sensitive parameters during the model calibration,

validation was done by changing the climate file. All other input parameters were kept unchanged.

The event-wise runoff and sediment yield and the corresponding rainfall during the model validation period are given in Figures 6 and 7. The scatter plot diagrams show the good agreement between the observed and simulated runoff and sediment yield (Figure 8) except for a few points underpredicted by the model. The total observed and simulated runoff and sediment yield were found to be 140.2mm and 135.7mm, and 17.57Mg/ha and 16.66Mg/ha, respectively (Table 4). The highest runoff (42 mm) and sediment yield (3.7Mg/ha) was recorded for the rainfall event of 155.2mm (which occurred on 2019, 30 September). The low values of RMSE and MBE, and the high values of correlation coefficient and model efficiency, confirm that the model efficiently simulated runoff and sediment yield with reasonable accuracy (Table 4). Goodness-of-fit statistics for runoff and sediment yield simulation revealed no significant difference between the observed and simulated runoff, and sediment yield for the validation period are not significantly different at a 95% level of confidence.

The mean simulated soil loss from the drainage channels (13.33Mg/ha) is about three times from the hillslopes (4.16Mg/ha), amounting to total soil loss 17.7Mg/ha. This may be attributed to the fact that the amount and velocity of runoff in drainage channels are higher than that of the overland flow over the hillslopes and, hence has higher erosive force concerning higher transport velocity. This suggests that channel erosion is predominant in the watershed. Therefore, to control soil erosion in the watershed, the treatment of drainage lines should be given due priority. The annual sediment yield of different hillslopes within the

Saleran watershed varied from 1.40 to 7.62Mg/ha and divided into five classes/scenarios for the treatment, as shown in Table 5.

Simulation of the impact of the conservation interventions

In the WEPP model, any intervention can be selected as per requirement, and its features can be edited according to the location-specific conditions. In the present study, the rock-filled check dams and sedimentation basins in terms of staggered trenching were selected as the management interventions, and their impact was simulated in terms of reduction in the runoff, sediment yield, and sediment delivery ratio (SDR).

Impact of rock-filled check dams only

Eight rock-filled check dams were provided in series along the entire drainage lines of the watershed at an elevation difference of 5 m. The simulation results indicated that runoff and sediment yield decreased by 50% and 66.1%, respectively, due to the impoundment effect of check dams. Also, SDR decreased from 0.96 to 0.13 (Table 6). Check dams play a crucial role in reducing runoff and erosion, increasing water availability, and ensuring grazing stability in the watersheds [48]. Check dams are constructed in channels or gullies to trap the sediments within the channels [49]. Saghafian *et al.* [47] advocated applying the WEPP model to identify erosion and runoff sources in the watersheds and simulation of conservation practices for erosion control. Li *et al.* [50] testified the reduction in annual runoff and sediment load by 65.2% and 78.3%, respectively, over the 20 years due to the check dams. Yuan *et al.* [51] reported that check dams reduced the runoff volume peak runoff rate and sediment discharge by 58.6, 65.3, and 83.9%, respectively.

Table 1) Descriptive statistics of rainfall events recorded during the study period

Statistical Parameter	Rainfall (mm)					Average intensity (mm/h)					Maximum intensity (mm/h)				
	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019	2015	2016	2017	2018	2019
Range	123.6	52.0	29.0	102.7	135.5	20.5	31.0	34.0	28.8	27.6	56.0	73.0	66.0	68.0	56.0
Minimum	15.5	12.0	19.0	28.1	20.5	7.7	5.6	6.0	5.6	5.3	32.0	15.0	22.0	12.0	24.0
Maximum	139.1	64.0	48.0	130.8	156.0	28.2	36.6	40.0	34.4	32.9	88.0	88.0	88.0	80.0	80.0
Mean	67.1	35.5	32.1	56.0	64.0	17.7	15.0	16.5	22.2	17.9	57.1	44.1	47.9	55.5	55.4
Std. Deviation	44.0	22.9	10.1	27.2	46.7	6.7	11.2	9.5	9.1	13.9	24.2	27.0	21.8	20.9	21.0
Variance	1934.7	524.0	101.0	742.0	2176.4	45.0	125.9	91.1	82.9	192.4	586.5	729.6	477.1	438.6	439.6
Skewness	0.6	0.2	0.1	1.8	1.4	0.1	1.4	1.4	-0.5	0.4	0.4	0.4	0.8	-0.5	-0.3
Kurtosis	-0.6	-2.4	-1.3	3.6	2.3	-0.1	1.5	3.2	-0.5	-2.8	-2.5	-0.8	-0.7	-0.4	-1.4

Table 2) Sensitivity analysis of the calibrated parameters

Soil parameter	Calibrated value	Sensitivity ratio	
		Runoff	Sediment yield
Effective hydraulic conductivity (mmh^{-1})	4.62	-0.219	-0.189
Inter-rill erodibility ($\times 10^6 \text{ kgsm}^{-4}$)	5.52	0	0.327
Rill erodibility (sm^{-1})	0.0202	0	0.553
Critical shear (Nm^{-2})	2.50	0	-0.227

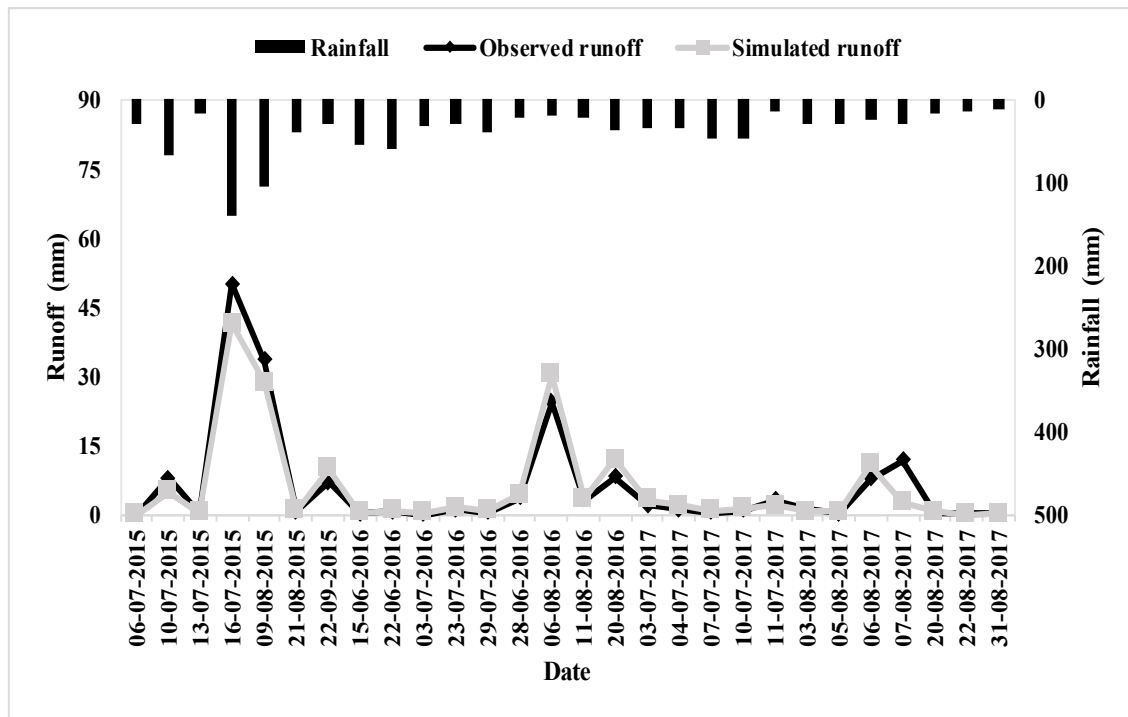


Figure 3) Observed and simulated storm wise runoff during model calibration

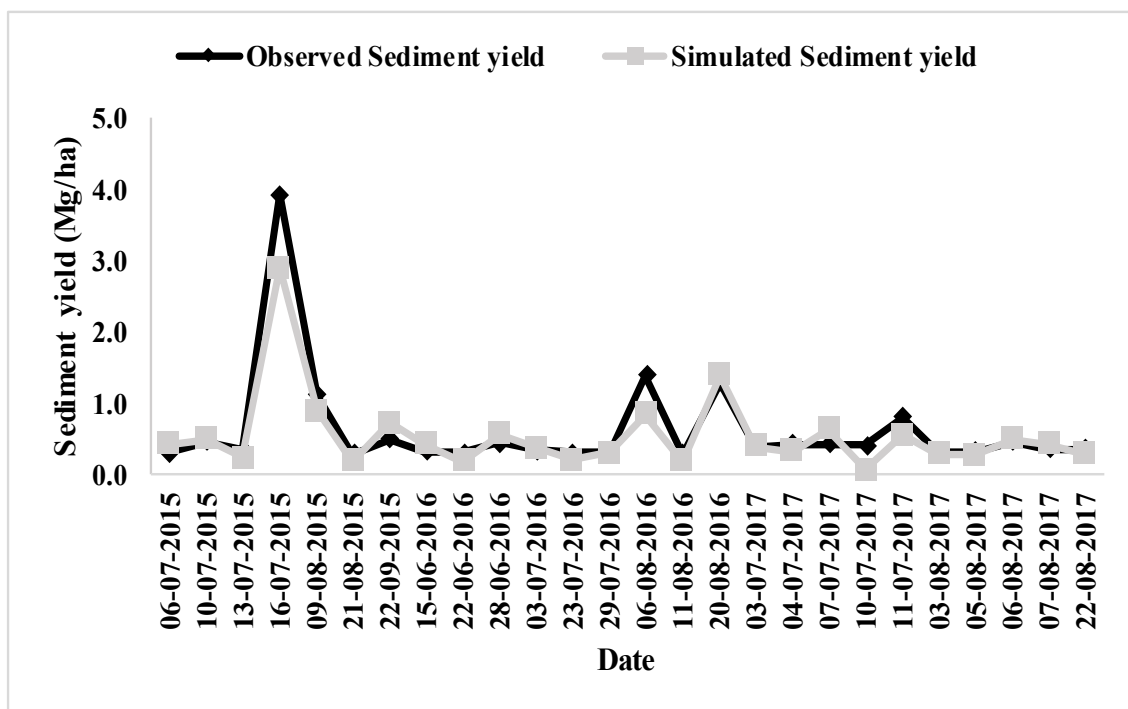


Figure 4) Observed and simulated storm wise sediment yield during model calibration

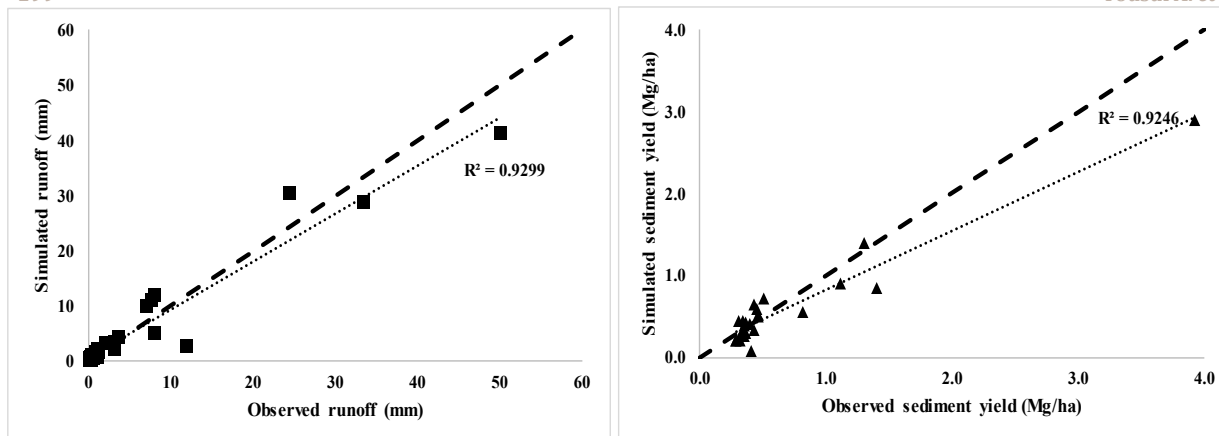


Figure 5) Comparison between observed and simulated runoff and sediment yield during model calibration

Table 3) Summary statistics for simulation of runoff and sediment yield during model calibration

Parameters	Runoff (mm)		Sediment Yield (Mg/ha)	
	Observed	Simulated	Observed	Simulated
Total	172.4	167.5	16.43	14.32
Root Mean Square Error		3.09		0.26
Mean Bias Error		1.80		0.16
Correlation coefficient (r)		0.964		0.962
Model efficiency (%)		90.57		86.72
t_{critical}		2.05		2.06
t_{calculated}		1.10		0.07

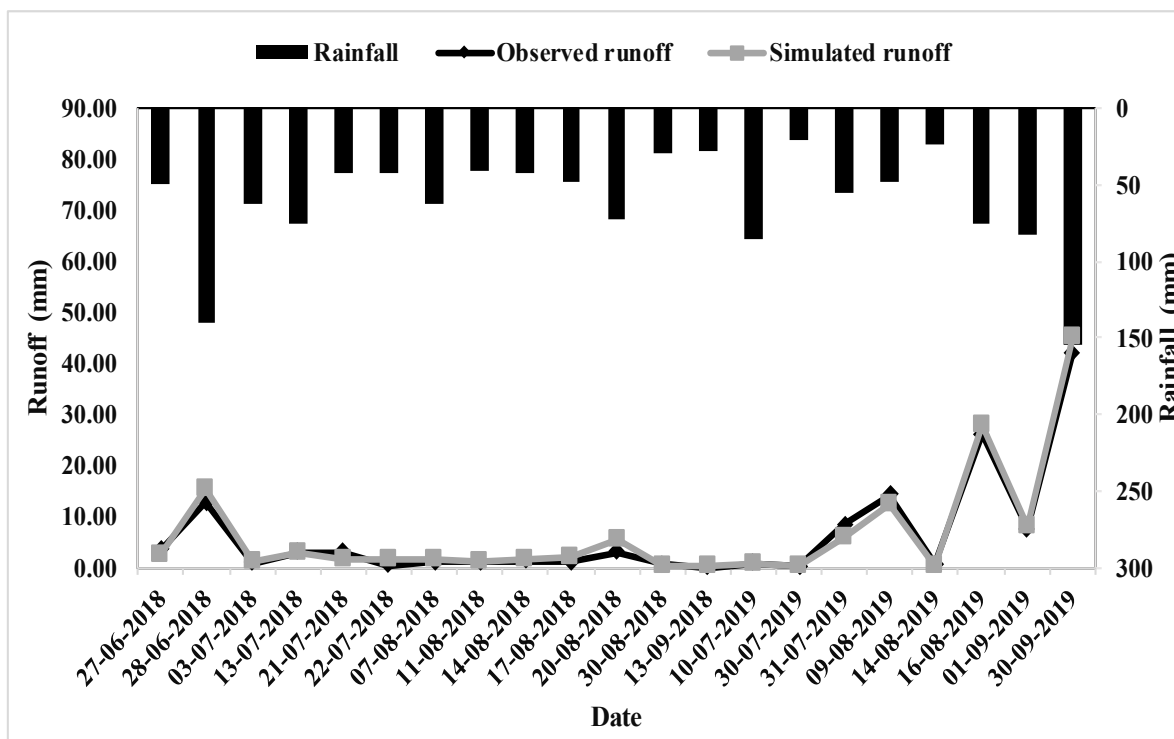


Figure 6) Observed and simulated storm wise runoff during model validation

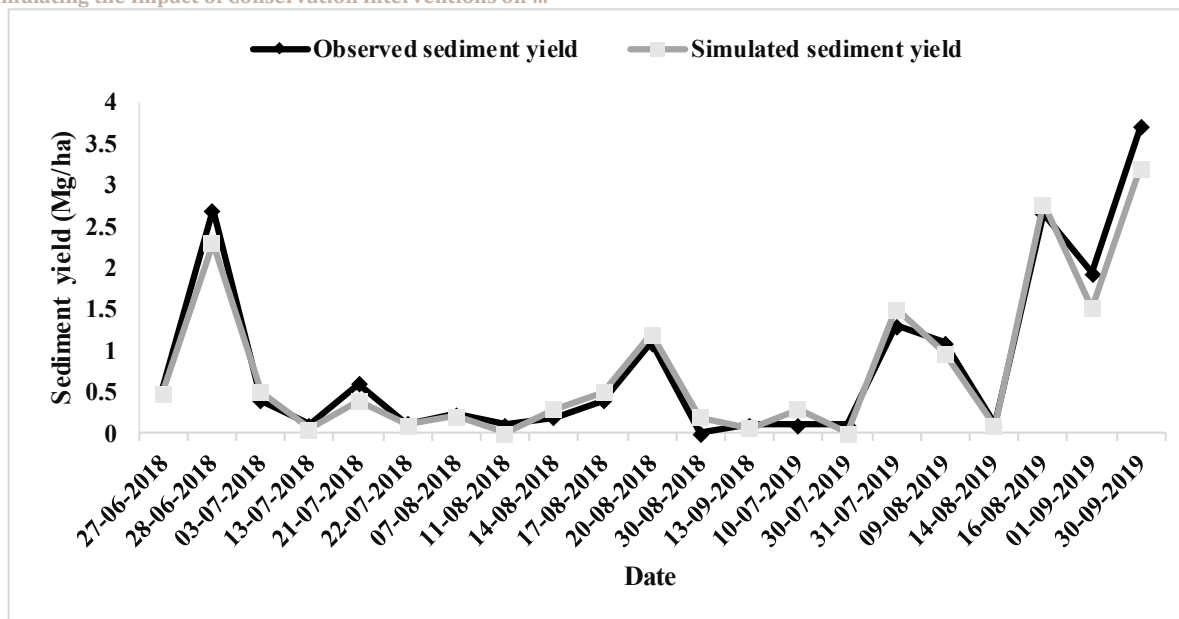


Figure 7) Observed and simulated storm wise sediment yield during model validation

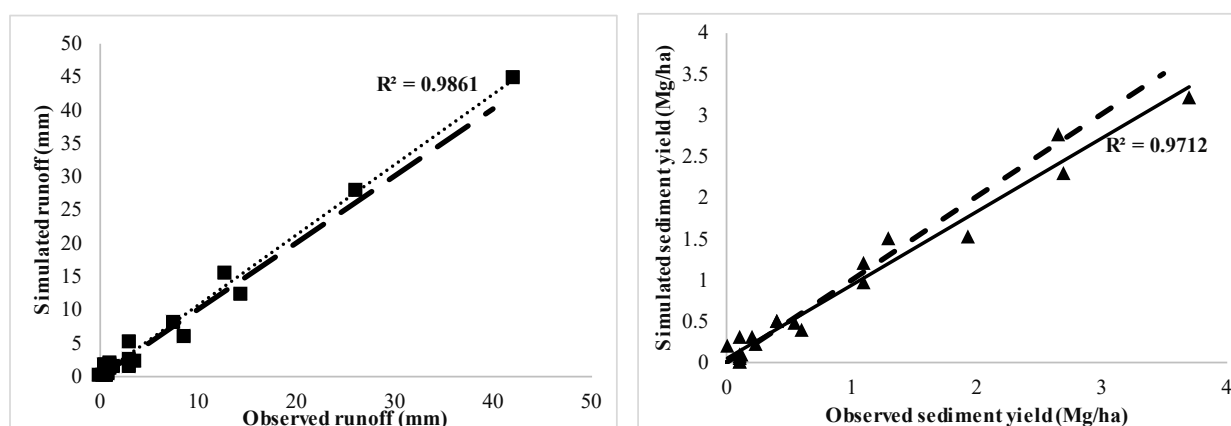


Figure 8) Comparison between observed and simulated runoff and sediment yield during model validation

Table 4) Summary statistics for simulation of runoff and sediment yield during model validation for untreated watershed

Parameters	Runoff (mm)		Sediment Yield (Mg/ha)	
	Observed	Simulated	Observed	Simulated
Total	140.2	135.7	17.57	16.66
Root Mean Square Error		1.49		0.20
Mean Bias Error		1.15		0.15
Correlation coefficient (r)		0.984		0.985
Model efficiency (%)		89.46		83.70
t _{critical}		2.09		2.09
t _{calculated}		0.61		0.09

Table 5) Scenarios for implementation of sedimentation basins/staggered trenches over the hillslopes

Scenario	Sediment yield range in the hillslopes (Mg/ha/year)	No. of hillslopes falling in the range	Area of hillslopes (ha)	Percent of watershed area
1	>7.0	2	10.0	23.5
2	>6.0	4	18.0	42.4
3	>5.0	6	27.8	65.6
4	>3.0	10	36.9	86.8
5	>1.0	18	42.0	100

Table 6) Impact of conservation interventions on watershed runoff and sediment yield

Parameters	Untreated Watershed	Treated with Rock-fill check dams only	Treated with sedimentation basins only	Treated with Rock-fill check dams + Sedimentation basins
Runoff (mm/year)	218.8	109.4	109.9	62.20
Sediment Yield (Mg/ha/year)	11.5	3.9	7.6	1.20
Sediment Delivery Ratio	0.96	0.13	0.35	0.05

Impact of sedimentation basins only

A sedimentation basin was considered equivalent to staggered trenching of the complete hillslope for soil and water conservation. In this study, the entire watershed area was treated with staggered trenching to prevent the flow of runoff and sediments to the drainage lines, and their impact was simulated. Simulation results (Table 6) indicated that due to the implementation of sediment basins/staggered trenching, runoff decreased by 50%, and sediment yield decreased by about 34%. The SDR value decreased from 0.96 to 0.35. The simulation results (Table 6) indicate that as compared to rock-fill check dams, the sedimentation basins/trenching seem to be equally efficient in controlling and conserving runoff in the watershed but less efficient in decreasing sediment yield and SDR. This may be due to the predominance of channel erosion in the watershed because structures such as rock-fill check dams (provided across the drainage line) result in better control of sediment yield than those located over the hillslopes.

Sedimentation basins have proven successful conservation interventions in controlling runoff and sediment yield [52-54]. Sedimentation basins reduced on-site as well as [55] and off-site sedimentation efficiently [56]. Sahoo *et al.* [57] reported that the sedimentation basins/staggered trenching resulted in a maximum reduction in runoff and sediment yield due to water storage in trenches and increased soil moisture to infiltration.

The combined impact of rock-fill check dams and sedimentation basins

The results simulating the combined impact of rock-fill check dams provided across the drainage lines and sedimentation basins over all the watershed hillslopes are shown in Table 6. The results indicate that the impact of the combined implementation of both interventions was much more profound than when implemented individually, which may be because these interventions cover the entire hydrologic system of the watershed. Runoff, sediment yield, and SDR decreased by 72%,

90%, and 95%, respectively, as simulated at the watershed outlet. The sedimentation basins and rock-fill check dams effectively control sheet erosion from the hillslopes and channel erosion. Hence, the coupled implementation of both interventions is quite effective in reducing/controlling watershed runoff and sediment yield.

Mekonnen *et al.* [49] recommended implementing check dams and sedimentation basins to trap the sediments generated within the watersheds. Check dams and sedimentation basins disconnect the sediment transfer pathways, thereby preventing off-site sedimentation [49]. The combined effect of soil and water conservation structures reduced the surface runoff by about 34% [58]. Sedimentation basins along with stone walls proved to be the best soil and water conservation structures in terms of reduction in runoff and soil loss [59]. Addisu and Mekonen [60] reported that sediment storage dams and check dams stored about 68900Mg of sediments in a watershed and thus played a great role in sequestering soil organic carbon. Mekonnen and Getahun [61] confirmed that the check dams combined with the sedimentation basins reduced the sediment yield by increasing the sediment deposition within the watersheds.

The optimum areal extent of treatment

In watershed management projects, it often becomes difficult to implement the selected management interventions in the entire watershed, mainly due to financial constraints [62, 63]. Under such situations, the conservation interventions can only be implemented on identified and prioritized hillslopes and drainage lines, where soil erosion is comparatively higher [64-66]. In this study, five different soil erosion scenarios and corresponding areal extent of the watershed to be treated with the best management intervention (BMI), i.e., the combination of rock-fill check dams and sedimentation basins, are given in Table 5. The impact of the BMI on runoff, sediment yield, and SDR under different erosion scenarios is presented in Figure 9.

The runoff, sediment yield, and SDR decreased

with an increase in the treatment area (Figure 9). Under scenario-1, scenario-2, scenario-3, scenario-4, and scenario-5, runoff reduced by 21.6, 57.5, 63.3, 67.4, and 71.6%, whereas sediment yield reduced by 33.8, 55.9, 73.3, 80.3, and 89.6%, respectively, as compared to the untreated watershed. Also, the SDR decreased from 0.96 of untreated watershed to 0.37, 0.19, 0.11, 0.08, and 0.05 under scenario-1, scenario-2, scenario-3, scenario-4 and scenario-5, respectively. The highest reduction in all three parameters was observed under scenario-5, where the entire watershed was treated. It was also observed from the simulated results that the reduction in sediment yield per unit of the treated area diminished with the increase in the treated area. It was 0.39Mg/ha per ha of the treated area when conservation interventions were implemented on 23.5% of the watershed area but reduced to 0.30Mg/ha for 65.5% treated area and 0.24Mg/ha when the entire

watershed was treated. The incremental decrease in sediment yield per unit of the treated area was maximum (0.39Mg/ha) when the minimum area (23.5%) was treated; after that, it decreased to its minimum value of 0.20Mg/ha at 65.6% treated area and remained same for 100% treated watershed. The percent decrease in sediment yield per unit of treated area decreased as the area under treatment was increased. It decreased at a rate of 3.38, 3.10, 2.63, 2.17, and 2.13% per ha at 23.5, 42.4, 65.6, 86.8, and 100%, respectively, of the treated area of the watershed. Under scenario-3, there is a considerable decrease in the runoff (63.3%), sediment yield (73.3%), and SDR (88.5%) concerning untreated watersheds. The scenario-3 is an economically viable option as it involves the implementation/construction of six sedimentation basins and three rock-filled check dams on the critically eroded hillslopes and channel segments, respectively.

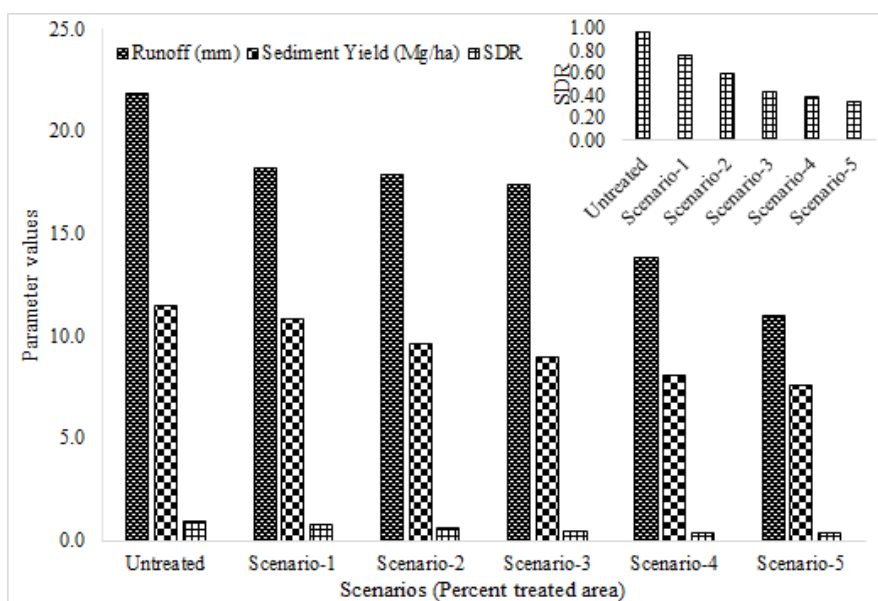


Figure 9) Impact of best management intervention under different erosion scenarios and areal extent of the watershed

Conclusion

In the present study, the WEPP model was calibrated and validated using hydrological data of five years (2015-19). The validated model was applied to simulate the impact of rock-filled check dams, sedimentation basins/trenching, and their combination on runoff, sediment yield, and SDR. The simulated results revealed that the check dams decreased the runoff, sediment yield and SDR by 50%, 66% and 86.4%, respectively. While sedimentation basins decreased runoff, sediment yield and SDR by 50%, 34% and 63.5%, respectively. The combined impact of

both the conservation interventions (check dams + sedimentation basins) was more effective than the individual intervention. The impact of conservation interventions diminished with the increase in the treated area and became relatively insignificant when the treated area exceeds 66% of the total watershed area (Scenario-3). Thus, implementation/construction of six sedimentation basins and three rock-filled check dams (scenario-3) to reduce runoff, sediment yield, and SDR by about 63.3, 73.3, and 88.5%, respectively, may be considered as the upper

limit of the area to be treated in a watershed as it is an economically viable option. Thus, in the absence of any concrete, practical recommendations for the *Shivalik* region, the results of this study would serve as guidelines for the treatment of degraded watersheds under limited available financial resources.

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