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Simulation of runoff and sediment yield from a forest micro watershed in *Shivalik* foothills using WEPP Model

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ABSTRACT

The Water Erosion Prediction Project (WEPP) watershed model has been applied to simulate storm wise runoff and sediment yield from a small forest watershed having an area of 1.85 ha located in *Shivalik* foothills. Sensitivity analysis of the model was performed to identify the most critical parameters. The model was calibrated and validated using observed data pertaining to 52 storms (1982-2004) for the watershed. The watershed was divided into 29 hill slopes and 18 channels. Climate file was generated by CLIGEN software using observed meteorological data. Soil, slope and land use management files were prepared for each hills lope and channel. The model simulated storm runoff with percent error of 7.01 and 6.78, RMSE of 1.40 and 4.60 mm, and model efficiency of 94 and 87%, respectively and for simulation of sediment yield, the percent error was 5.01 and 4.96, RMSE was 0.41 and 0.66 mm, and model efficiency was 86.56 and 82.78%, respectively for the calibration and the validation periods. All the simulation statistical parameters are well within the acceptable limits and that shows reasonable accuracy of the model in simulating storm runoff and sediment yield. These results further indicate the suitability of the WEPP model for its future application in small forest watersheds of *Shivalik* foothills.

1. INTRODUCTION

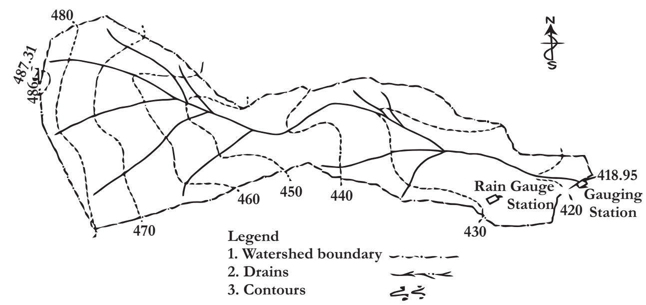
Land degradation due to soil erosion is a major threat to agricultural sustainability in *Shivalik* foothills falling in the states of Punjab, Haryana, Himachal Pradesh and Jammu and Kashmir in Northwest India that cover an area of 2.14 m ha (Yadav, 2015; Kumar, 2016). The extent of degraded land in this area was 194 km^2 in 1852, 2000 km^2 in 1939, and it increased to 20,000 km^2 in 1981 (Patnaik, 1981). The bank erosion is major cause of land degradation, leading to deteriorated drainage systems, which ultimately govern natural calamities in terms of floods, and nonpoint source pollution (Rao *et al.,* 2013). In the state of Punjab, an area of 5.38 lakh ha which falls in the *Shivalik* foothills and locally known as Kandi area, is considered to be one of the eight most degraded and fragile agro-ecosystems of the country. In the monsoonal country like India, high intensity rains during the monsoon season cause severe erosion in croplands which leads to sedimentation of the downstream water bodies (Rao *et al.,* 2015). Erratic distribution of rainfall, small landholdings, lack of irrigation facilities, heavy biotic pressure on the natural resources, inadequate vegetative cover, heavy soil erosion, landslides, declining soil fertility and frequent crop failures resulting in scarcity of food, fodder and fuel are the characteristics of this region. Annual rainfall in the area varies from 800 to 1200 mm. A large portion of monsoon rainfall (35-40%) goes as runoff in the torrents originating from the *Shivalik* foothills (Bhardwaj and Rana, 2008). The annual erosion rate in the *Shivalik* foothills is more than 80 Mg $ha^{-1}yr^{-1}$ and in some watersheds, it is as high as 244 Mg $ha^{-1}yr^{-1}$ (Bhatt *et al.,* 2012; Bhardwaj and Kaushal, 2009). Such rates of soil erosion often cause pollution and sedimentation downstream as well as reducing the depth of soil available for future agricultural production (Arya *et al.,* 2010). This clearly shows that some form of soil conservation or soil protection policy is needed urgently in this area for which it is essential to quantify runoff and sediment yield in the study area.

Use of mathematical hydrological models to quantify runoff and sediment yield for designing and evaluating alternate land use and best management practices in a watershed is one of the most viable options, since it is very often impractical or impossible to directly measure soil loss on every piece of land, and the reliable estimates of the various hydrological parameters including runoff and sediment yield for remote and inaccessible areas are tedious and time consuming by conventional methods. There are several models available to estimate runoff and sediment yield from a watershed. The EPIC, ANSWERS, CORINE, ICONA, MIKE SHE, CASC2D, AGNPS, CREAMS, SWAT and WEPP are a few among these models (Bhardwaj and Kaushal, 2009). Any model used for computing potential soil loss from an area deals with a large number of parameters concerning vegetation, management practices, soil, topography and climate. Performance of a model depends upon the number of parameters it is considering for runoff and soil loss computation (Amore *et al.,* 2004). The WEPP model is a process-based erosion model that computes spatial and temporal distributions of soil loss and sediment deposition from overland flow on hill slope and soil loss and sediment deposition from concentrated flow in small channels (Flanagan and Nearing, 1995). The model has been used successfully around the globe (Yu and Rosewell, 2001; Amore *et al.,* 2004; Pieri *et al.,* 2007; Baigorria and Romero, 2007; Shen *et al.,* 2009; Shen *et al.,* 2010) for simulating runoff and soil loss from different land use and crop management practices. A few studies have been conducted in India for quantification of runoff and sediment yield using WEPP model (Pandey *et al.,* 2008; Ramsankaran *et al.,* 2009; Singh *et al.,* 2009), but none in the *Shivalik* foothills. Thus, the present study was undertaken keeping in view the need to evaluate the performance of WEPP model for simulating runoff and sediment yield from small watersheds in *Shivalik* foothills for its future application in the area.

2. MATERIALS AND METHODS

Study Area

The selected watershed is located at 76°51'E longitude and 30°44'N latitude in *Shivalik* foothills region under Central Soil and Water Conservation Research farm, Mansa Devi, Panchkula (Haryana). The watershed area is 1.85 ha having mean elevation of 370 m above msl. The area has a sub-humid type of climate. The average annual rainfall is 1100 mm, of which 80% is received during monsoon season only. The rainfall is highly erratic and occurrence of high intensity rainfall is a common feature. The soil texture of the micro-watershed is sandy loam with pH ranging from 6.3 to 8.5 and low to medium organic carbon content. This forest watershed has been under protection since 1956. The watershed is equipped with 0.75 m deep, 90°V-shaped sharp crested weir at the outlet of the watershed. Fig. 1 shows the topographic map of the study watershed. *Acacia catechu, Dalbergia sissoo, Lantana camara* and bhabbar grass (*Eulaliopsis binnata*) are the dominant trees, shrub and grass species of the watershed.



(Source: ICAR-IISWC, Research Centre, Chandigarh)

Fig. 1. Topographic map of the study watershed

WEPP Model Description

The WEPP model represents a new erosion prediction technology that is based on fundamentals of stochastic weather generation, infiltration process, runoff generation and flow, soil physics, vegetation, hydraulics, and erosion mechanics (Nearing *et al.,* 1990). The WEPP watershed model is an extension of the WEPP hill slope model. The model has the capabilities for estimating spatial and temporal distributions of runoff and soil loss *i.e.* net soil loss for an entire hill slope or for each point on a slope profile can be estimated on a daily, monthly or average annual basis (Flanagan and Nearing, 1995). It simulates rainfall excess using Green-Ampt Mein-Larson infiltration equation. Surface runoff routing is based on either kinematic wave representation in single event mode with approximate solution or simplified regression equations. The erosion processes representation in the model is limited to sheet and rill and erosion occurring in channels where detachment is due to hydraulic shear. Three soil erodibility parameters namely inter-rill erodibility (Ki), rill erodibility (Kr) and critical hydraulic shear (τ_c) along with effective hydraulic conductivity (Ke) have been considered in the model. Three stages of erosion *i.e.* detachment, transport and deposition are quantified using rill-inter-rill concept of describing sediment detachment. The model accommodates the spatial and temporal variability in topography, surface roughness, soil properties, crops, and land use conditions on hill slopes. The model allows linkage of hill slope profiles to channels and impoundments. Runoff and sediment from one or more hill slopes can be routed through channels in a small watershed. Almost all of the parameter updated for hill slopes is duplicated for channels. In channels, the model simulates sediment detachment, transport and deposition using a steady state solution of the sediment continuity equation. Impoundments such as farm ponds, terraces, culverts, filter fences and check dams can be simulated to remove sediment from the flow (Flanagan and Livingston, 1995; Flanagan and Nearing, 1995; Pandey *et al.,* 2008; Flanagan *et al.,* 2012; Elliot, 2013; Saghafian, 2015).

Model Inputs

The major inputs to WEPP model are a climate data file, a slope data file, a soil data file, and a cropping/management data file. Applying WEPP in a watershed application also requires additional input files which provide information on channel and impoundment characteristics as well as watershed configuration. The climate files for the WEPP model for 52 rainfall events in a single storm mode were prepared using the CLIGEN program. The CLIGEN is a stochastic weather generator that produces daily time series of precipitation, temperature, dew point, wind, and solar radiation for a single geographic point, based on average monthly measurement for the period of climatic record. Daily observed precipitation, maximum and minimum temperature for the years from 1982 to 2004 were used in CLIGEN software to generate climatic data *i.e.* duration of precipitation, ratio of time to rainfall peak/rainfall duration, ratio of maximum rainfall intensity and average rainfall intensity, daily solar radiation, wind velocity, wind direction and dew point temperature.

The watershed was divided into 29 hill slopes and 18 channels. The soil, slope and management files were prepared for all hill slopes and channels. The soil file was prepared in the WEPP windows interface. Soil characteristics for sandy loam soil of the study watershed (Yadav *et al.,* 2005) namely, albedo, initial saturation level, inter-rill erodibility, rill erodibility, critical shear, hydraulic conductivity *etc.* were estimated using the empirical equations as described in the WEPP user summary (Flanagan and Livingston, 1995).

The distance-elevation data was generated segment-wise for each hill slope from the topographic map of the watershed (Fig. 2). The slope of each hill slope segment was calculated using the following formula (Yousuf, 2014):

$$\textit{Percent slope, } s = \frac{E_2 - E_1}{L} \times 100$$

Where, E_2 = elevation of lower point (m), E_1= elevation of higher point (m) and L = segment length (m). Slope profile is plotted between distance and elevation. In the model, the slope file builder has the added advantage of allowing the user to graphically preview the slope profile.

The land management input file contains all the information needed by the WEPP model related to plant parameters (rangeland plant communities and cropland annual and perennial crops), tillage sequences and tillage implement parameters, plant and residue management, initial conditions, contouring, subsurface drainage, and crop rotations. The management file builder contains a large number of built in cropping pattern and management practices, which can be easily brought into our data file to suit the prevailing conditions of *Shivalik* foothills on each overland flow elements within a hill slope.

Sensitivity Analysis

Sensitivity analysis is important to know those parameters which affect the output of the model to a larger extent with slight variation in their values. The hydrological models are most sensitive to weather and soil parameters (Nearing *et al.,* 1990; Baffaut *et al.,* 1997). Generally, weather parameters are recorded manually or by precisely calibrated automatic weather stations and chances of error in the measurement are very less. Therefore, sensitivity analysis of weather parameters is omitted. Thus, in this study, sensitivity analysis was carried out with respect to soil parameters only. The model's sensitivity to an input parameter was determined by varying parameter value within acceptable range, while keeping other parameters constant, and comparing the corresponding values of predicted runoff and sediment yield. The soil input parameters considered for sensitivity analysis were effective hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear. The values of these parameters were varied by ±50% of the average soil values (Flanagan and Livingston, 1995) so as to be within acceptable range (Pandey *et al.,* 2008; Singh *et al.,* 2011; Bhardwaj and Kaushal, 2009) during the analysis. To quantify the impact of change in the values of input parameters on the outputs, the following relative sensitivity equation (McCuen and Snyder, 1983) was used:

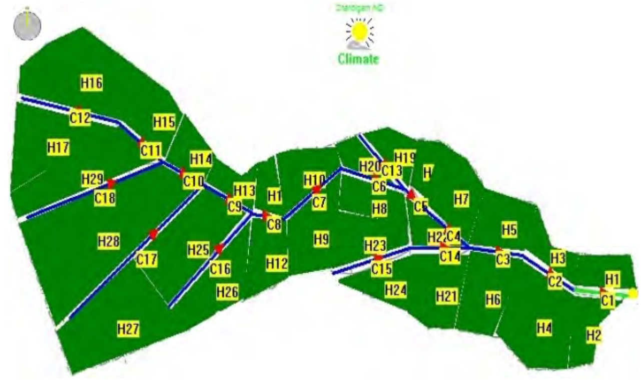


Fig. 2. Delineated hillslopes and channels in the watershed

$$S_r = \frac{(P_2 - P_1)/P_{12}}{(I_2 - I_1)/I_{12}}$$

Where, I_1 and I_2 are the smallest and largest values of the input parameters used, I_{12} is the average of I_1 and I_2; P_1, P_2 and P_{12} are the corresponding values for the output.

WEPP Model-Calibration and Validation

Precise calibration of the model is essential for accurate simulation results (Pieri *et al.,* 2007). For the study watershed, data of 52 storms was available (1982 to 2004), out of which 22 storms (1982-91) were used for calibration and 30 storms (1993-2004) were used for validation of the model. The manual calibration based on trial-and-error procedure (Sorooshian and Gupta, 1995) was used in the study. Previous studies on the WEPP model (Nearing *et al.,* 1990, Bhuyan *et al.,* 2002, Pandey *et al.,* 2008, Singh *et al.,* 2011) indicated that the model is very sensitive to soil input parameters in simulation of runoff and sediment yield. Hence, soil parameters such as: effective hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear were considered for calibration in the present study. The values of parameters were chosen within the prescribed range. Several simulations were performed adjusting the parameters values until the deviation between observed and simulated data became minimum. After calibration proper validation is equally essential for model testing before it could be used for simulation under field conditions. During validation, the performance of the calibrated model was judged without any change in the data of input files except the climate file.

Statistical Analysis

WEPP model output was statistically analyzed using various statistical parameters such as mean, standard deviation, percent error, Root Mean Square Error (RMSE), correlation coefficient and model efficiency (Nash and Sutcliffe, 1970). Also the Student's t-test in SAS software (version 9.4) at 95% significance level (Gupta and Kapoor, 2002) was performed to compare the means of simulated and measured values of daily runoff and sediment yield.

3. RESULTS AND DISCUSSION

Sensitivity Analysis

The results of the sensitivity analysis of the WEPP model have been summarized in Table 1. In the simulation of both the runoff as well as sediment yield, model is sensitive to hydraulic conductivity. This may be because of the fact that the amount of runoff produced due to a particular rainfall event would depend upon the type of soil and hence the rate at which rain water moves vertically downward in the soil. As this vertical movement is low, runoff generated would be high and vice versa. Further, sediment transport capacity is directly proportional to the amount of runoff generated. Therefore hydraulic conductivity of soil is the most important model parameter in the simulation of runoff and sediment yield.

In the simulation of sediment yield, results of the sensitivity analysis further indicate that model is most sensitive to the rill erodibility followed by inter-rill erodibility, hydraulic conductivity and critical shear. Since soil resistance to detachment by raindrop impact determines inter-rill erodibility (Ki), and soil resistance to detachment by concentrated flow determines rill erodibility (Kr), higher sensitivity of the model to rill erodibility may be due to the fact that rilling process is dominant in high slope and high rainfall condition that exist in the study watrershed. The model considers rill erosion as a function not only of rill erodibility but also of sediment carrying capacity of flow. High rainfall on steep slopes generate large amount of runoff depleting quickly with high velocity. Under these conditions, sediment transport capacity of runoff flow is not limiting even if inter-rill erosion contributes fair amount of sediment load to the flow. Critical shear stress also has influence on the model response for sediment yield as indicated by its sensitivity ratio. Erosion is considered to occur when hydraulic shear stress of flow exceeds the critical shear stress of the soil. In the erosion process, detachment of soil particle is a function of critical shear stress of soil. Therefore, influence of critical shear stress on erosion is quite obvious. Similar results were reported in previous studies by Baffaut *et al.* (1997); Bhuyan *et al.* (2002); Pandey *et al.* (2008); Singh *et al.* (2011).

Table: 1
Sensitivity ratios of different parameters

Parameter	Average value of the soil parameter	Range of test value		Sensitivity ratio	
		-50%	+50%	Runoff	Sediment yield
Ke (mm h^{-1})	9	4.5	13.5	-0.434	-0.316
Ki (10^6 Kg s m^{-4})	6.5	3.25	9.75	0	0.398
Kr (s m^{-1})	0.0204	0.0102	0.306	0	0.783
τc (N m^{-2})	2.5	1.25	3.75	0	-0.219

Ke: Effective hydraulic conductivity; Ki: Inter-rill erodibility; Kr: Rill erodibility, τc: Critical shear

Simulation of Runoff

The parameters to which the model output was sensitive were first calibrated and adjusted for model as described in the materials and methods section. The storm wise observed and simulated runoff hydrograph for the calibration and validation periods are shown in Fig. 3 and Fig. 4, respectively. Both the Figures show that the trend of simulated values closely match the trend of the observed values for both the calibration and validation periods. The total measured and simulated values of runoff for the calibration period were 119.09 and 118.85 mm, and the corresponding values for the validation period were 347.62 and 331.47 mm, respectively. There was a simulation error of 0.20% for calibration period and 4.64% for validation period, which is quite low, keeping in view the complex nature of the runoff process. Scatter plots for the daily measured as well as simulated

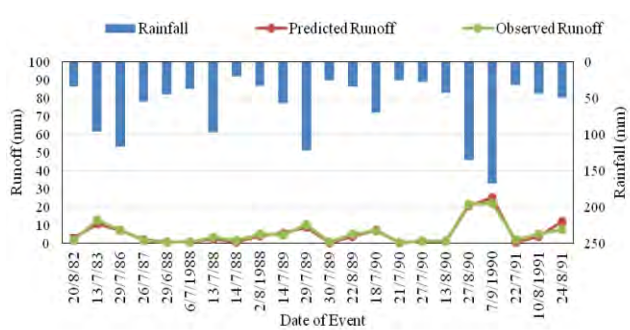


Fig. 3. Measured and simulated daily runoff hydrograph for model calibration

runoff for the calibration and validation are given in Fig. 5 and Fig. 6. It is observed that most of the data points are evenly distributed about the 1:1 line.

The results of statistical analysis are presented in Table 2. The RMSE of 1.40 and 4.60 mm, percent error 7.01 and 6.78, model efficiency of 94 and 87%, respectively for the calibration and the validation period indicate reasonably accurate simulation of surface runoff by the model. Also, goodness-of-fit statistics for simulation of runoff revealed that the means of observed and simulated runoff for the calibration and validation periods are not significantly different at 95% confidence level. Although, a few high magnitude events are under-predicted, yet overall performance of the model is quite satisfactory. The value of the RMSE for validation period (4.60 mm) is much higher

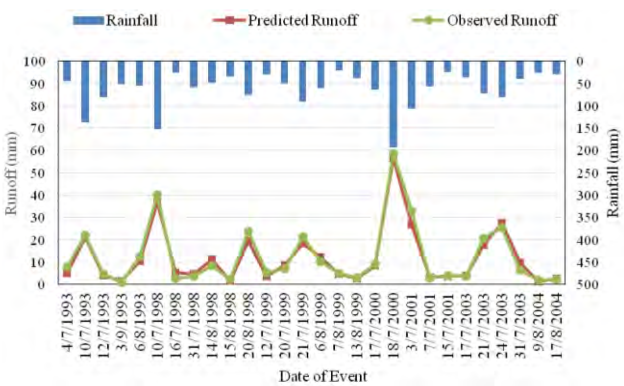


Fig. 4. Measured and simulated daily runoff hydrograph for model validation

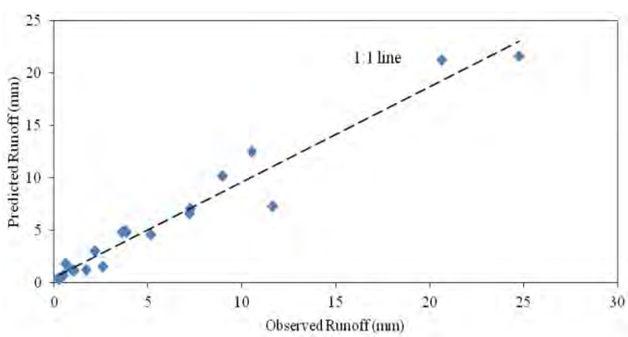


Fig. 5. Comparison between measured and simulated daily runoff for model calibration

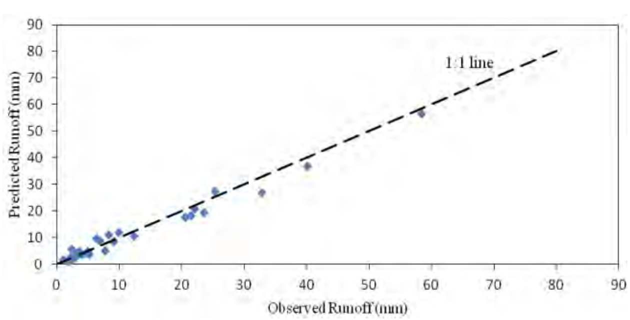


Fig. 6. Comparison between measured and simulated daily runoff for model validation

than that for calibration period (1.40 mm). This may be due to the fact that most of the storms in the calibration period were of small size as compared to those during the validation period. Out of the 22 storms considered for calibration only 2 storms (9%) were of magnitude greater than 15 mm. However, during the validation period there were 8 storms (27%) out of 30 storms whose magnitude was greater than 15 mm. That may be the reason for higher value of RMSE for the validation period.

Simulation of Sediment Yield

The measured and simulated values of sediment yield for the calibration and validation periods are shown in Fig. 7 and Fig. 8, respectively. From the Figures, it is observed that the trend of simulated values matches closely match the trend of the measured values for both the calibration and validation periods. The total measured and simulated values of sediment yield for the calibration period were 14.91 and 13.08 Mg ha^{-1}, respectively and the corresponding values for the validation period were 26.94 and 26.90 Mg ha^{-1} for the validation period. The percent error in the simulation of total sediment yield is only 0.15%, which is quite low. Also, the model simulated mean sediment yield per storm perfectly for the validation period. Scatter plots for the daily measured as

Table: 2
Statistical analysis of measured and simulated daily runoff

Parameter	Runoff (mm)			
	Calibration period		Validation period	
	Measured	Simulated	Measured	Simulated
Mean	5.40	5.42	12.42	11.83
Std. Dev.	6.02	6.45	13.46	12.44
Maximum	21.65	24.75	58.43	56.41
Total	119.09	118.85	347.62	331.47
RMSE (mm)	1.40		4.60	
Percent error	7.01		6.78	
Corr. Coeff.	0.97		0.91	
Model efficiency	94%		87%	
t-calculated	0.01		0.53	
t-critical	2.08		2.08	

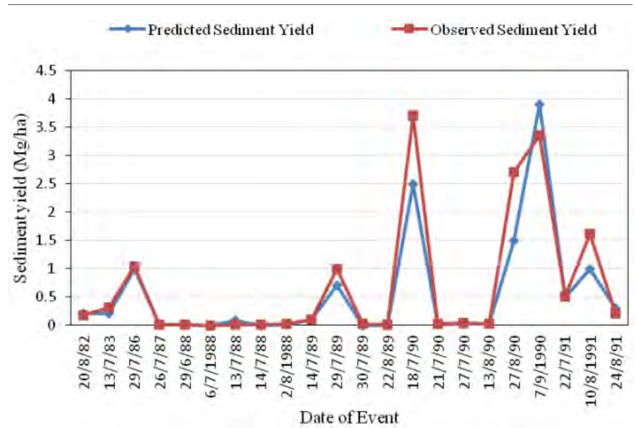


Fig. 7. Measured and simulated sediment yield for model calibration

well as simulated runoff for the calibration and validation are given in Fig. 9 and Fig. 10, respectively. It is observed that most of the points are evenly distributed about the 1:1 line.

The summary statistics of the results is presented in Table 3. Goodness-of-fit statistics for simulation of sediment yield revealed that means of observed and simulated sediment yield for the calibration and the validation periods are not significantly different at 95% confidence level as t-calculated is less than t-critical for both the periods. Also, the RMSE of 0.41 and 0.66 mm, percent error 5.01 and 4.96, model efficiency of 86.31 and 82.78%, respectively for the calibration and the validation period indicate reasonably accurate simulation of sediment yield by the model.

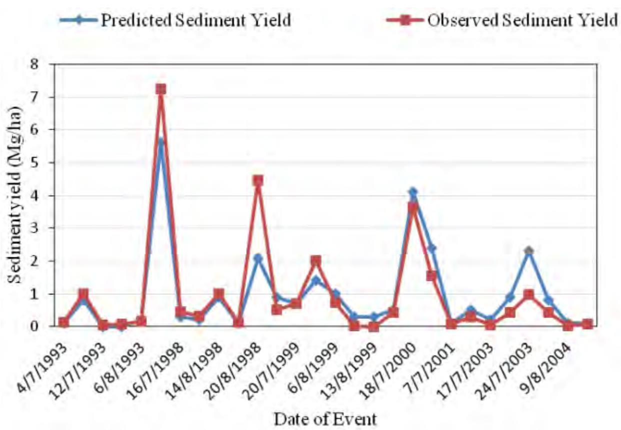


Fig. 8. Measured and simulated sediment yield for model validation

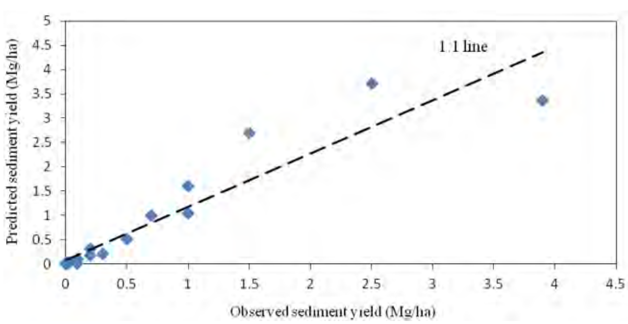


Fig. 9. Comparison between measured and simulated sediment yield for model calibration

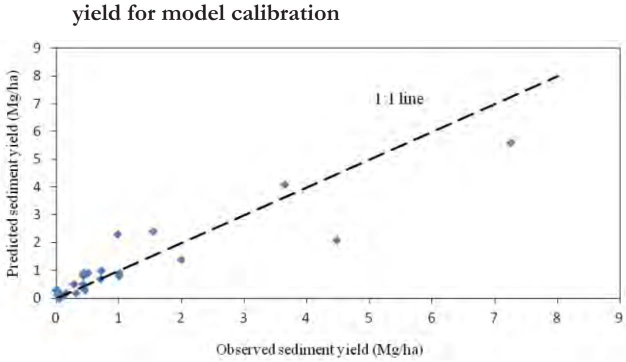


Fig. 10. Comparison between measured and simulated sediment yield for model validation

Table: 3
Statistical analysis of measured and simulated sediment yield

Parameter	Sediment yield (Mg ha^{-1})			
	Calibration period		Validation period	
	Measured	Simulated	Measured	Simulated
Mean	0.67	0.59	0.96	0.96
	0.59	0.96	0.96	
Std. Dev.	1.11	1.01	1.60	1.28
Maximum	3.71	4.20	7.25	5.60
Total	14.91	13.08	26.94	26.90
RMSE (Mg ha^{-1})	0.41		0.66	
Percent error	5.01		4.96	
Corr. Coeff.	0.94		0.91	
Model efficiency	86.31%		82.78%	
t-calculated	0.22		0.03	
t-critical	2.05		2.05	

The discussion above shows that WEPP model has the capability to simulate storm based runoff and sediment yield from small watersheds with reasonable accuracy. However, smaller events are more closely predicted by the model as compared to events of higher magnitude. This fact is corroborated by the lower values of RMSE, and higher correlation coefficient and modeling efficiency for calibration period as compared to validation period in simulating both the runoff and sediment yield, keeping in view that most of the storms in the calibration period were of small size as compared to those during the validation period. Out of the 22 storms considered for calibration, 20 storms were of magnitude less than 15 mm and during the validation period there were 8 storms out of 30 storms whose magnitude was less than 15 mm. Higher magnitude events are not that well simulated by the model may be because of the fact that runoff and soil erosion processes are highly complex phenomena and are affected by interaction among the characteristics of rainfall, soil, slope, land use and conservation measures. During the larger rainfall events, splash erosion process becomes dominant and affects the infiltration capacity of soil by sealing the pores and formation of crust on soil surface. The role of surface sealing on runoff generation and sediment production is quite obvious. Also, magnitude of randomness in higher events may be large. Such phenomena may not have been well represented in the model and needs improvement.

4. CONCLUSIONS

The present study was carried out to evaluate the physically based WEPP model for simulation of runoff and sediment yield from a small 1.85 ha forest watershed in *Shivalik* foothills in north-west India. The results of the study indicate that the model is highly sensitive to hydraulic conductivity while simulating runoff whereas it is sensitive to hydraulic conductivity, rill erodibility, inter-rill erodibility and critical shear while simulating sediment yield. Hence, the model should be calibrated precisely for these sensitive parameters. The model has the capability to simulate storm based runoff and sediment yield from a small watershed with reasonable accuracy. However, model simulates smaller storms better as compared to larger storms. Overall, the WEPP model performed well for simulation and quantification of runoff and sediment yield and hence, can be used with confidence in the area.

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