Journal of Hydrology 405 (2011) 261–276

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Simulation of runoff and sediment yield from a hilly watershed in the eastern Himalaya, India using the WEPP model

R.K. Singh [a,*], R.K. Panda [b], K.K. Satapathy [c], S.V. Ngachan [a]

[a] ICAR Research Complex for NEH Region, Umiam, Meghalaya 793 103, India
[b] Agricultural and Food Engineering Department, Indian Institute of Technology, Kharagpur, West Bengal 721 302, India
[c] National Institute of Research for Jute and Allied Fibres, 12 Regent Park, Kolkata 700 040, India

ARTICLE INFO

Article history:
Received 2 December 2009
Received in revised form 15 March 2011
Accepted 18 May 2011
Available online 17 June 2011
This manuscript was handled by L. Charlet, Editor-in-Chief, with the assistance of P.J. Depetris, Associate Editor

Keywords:
WEPP model
Hilly watershed
Runoff
Sediment
Management strategies

SUMMARY

A study was undertaken to develop appropriate vegetative as well as structural measures to control sediment yield from a 239.44 ha small multi-vegetated watershed in high rainfall and high land slope conditions of eastern Himalayan range in India using a physically based distributed parameters Water Erosion Prediction Project (WEPP) model. The model was calibrated and validated using field-measured data pertaining to 86 storms of monsoon season 2003 and 98 storms of 2004. The daily simulated runoff and sediment yield of the Umroi watershed for the calibration and validation periods were found to match with their measured counterparts at 95% significance level as shown by the Student's *t*-tests. The model simulated daily runoff quite well as corroborated by reasonably high Nash–Sutcliffe simulation coefficients of 0.94 and 0.87, low root mean square errors of 1.42 and 1.77 mm, and low percent deviations of −1.71 and −3.01, respectively for calibration and validation periods. The performance of the model for simulating daily sediment yield was also quite good with Nash–Sutcliffe simulation coefficients of 0.95 and 0.90, root mean square errors of 0.08 and 0.09 Mg ha^{-1} and percent deviations of 3.05 and −5.23, respectively for calibration and validation periods. Subsequently, the calibrated and validated model was used to simulate vegetative (crop, level of fertilization and tillage) and structural (rock-fill check dam and trash barrier) measures and combinations of vegetative and structural control to evaluate their impacts on runoff and sediment yield reduction. Simulations of different vegetative management scenarios indicated that replacing traditional *bun* agriculture and upland paddy crop with maize, soybean, and peanut would reduce sediment yield by 18.68, 29.60 and 27.70%, respectively. Field cultivator and drill-no-tillage systems have the potential to reduce sediment yield by 13.14 and 21.88%, respectively as compared to the existing practice of spading and country plough. Installation of 8 check dams and 18 trash barriers in the drainage line was predicted to reduce sediment yield from the Umroi watershed substantially with reduction of 54.67%. Simulations of combinations of management practices indicted that soybean and peanut in upland situations with field cultivator or drill-no-tillage system, and structural control in the drainage line has potential to make agriculture sustainable in the Umroi watershed with sediment yield reduction up to 78.40%. The results of the study indicate that the WEPP model can be successfully used for developing conservation management practices in high rainfall and high slope conditions of eastern Himalaya.

1. Introduction

Food security and environment protection are the most challenging task the world is facing today. Land and water resources are important components of environment. Degradation of the quality of these resources will affect the quality of the environment. Major portion of the food consumed by human being comes from the land. Due to demographic pressure land use is intensified and erosion prone area is brought under subsistence agriculture leading to land degradation.

Soil erosion is an irreversible phenomenon causing land degradation and deterioration of surface water quality. It is caused due to inappropriate land use and poor management. Soil degradation is responsible for making 0.3–0.8% of the world's arable land unsuitable for agricultural production every year and an additional 200 million ha of cropped area would be required over the next 30 years to feed the increasing population (den Biggelaar et al., 2004; Lafond et al., 2006). Therefore, this precious finite resource must be safeguarded against all kinds of degradation and deterioration for sustainability of agricultural production and environment protection.

* Corresponding author. Tel.: +91 364 2570276 (O), 2570109 (R); fax: +91 364 2570213/2570355.
E-mail address: rksingh_ars@yahoo.com (R.K. Singh).

0022-1694/$ - see front matter © 2011 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2011.05.022

In India, out of the total geographical area of 329 million ha, approximately 145 million ha of the total land resource is subjected to various degrees of wind and water erosion, which cause a loss of 5.3 million Mg of soil every year. In eastern Himalayan region of India, soil erosion by water is a major factor causing land degradation. About one third area of the region suffers from various forms of land degradation problems (Sehgal and Abrol, 1994). Practice of traditional slash-and-burn agriculture on steep slopes, intense rainfall, undulating and sloppy land surface compounds the problem many folds. About 386 900 ha area in the region is affected by shifting cultivation and as high as 76.6 Mg ha^{-1} yr^{-1} of soil is lost due to this system of farming (Satapathy, 1996). Eighty percent area is under threat of moderate to severe erosion.

To combat the threat of land degradation, we need to understand physical process of erosion in relation of topography, land use and management. Watershed being a natural drainage unit should form the basis for planning various land uses and conservation measures to optimize the use of soil and water resources to increase and sustain agricultural production. In order to develop a comprehensive plan for soil and water conservation, it is essential to estimate runoff and soil loss resulting from different crop and structure-based management practices.

Among the available tools for soil erosion assessment, simulation models are quite important because appropriate models can be used to evaluate a variety of management scenarios without costly and time consuming field tests (Pieri et al., 2007). In recent past a trend of testing and using physical process based runoff and soil erosion prediction models both at field as well as at watershed scales has gained momentum. These physical process based models, often with an explicit attempt to describe runoff and erosion processes, are better equipped to evaluate the impacts of management interventions and help make management decisions aimed at preserving land productivity and environment quality (Yu and Rosewell, 2001). Before application, such models need to be properly calibrated and validated using measured hydrologic data of the watershed. Lack of reliable field-measured data for calibration and validation of models is the major limitation for their application. Runoff and soil loss data can be obtained through field measurements and watershed attributes could be derived using remotely sensed data and digital elevation model of the watershed (Amore et al., 2004; Baigorria and Romero, 2007).

In hilly watersheds spatial and temporal variability in terms of soil, land use/land cover, topography, rainfall and biotic interventions are large. The runoff, sediment, fertilizers, pesticides and other pollutants, resulting from the agricultural activities cause deterioration of quality of surface and ground water. Methods for identification of sources of pollutants and their quantification are essential for their control. Distributed parameter watershed models are applicable for this type of assessment. Review of literatures revealed that CREAMS (Knisel, 1980), ANSWERS (Beasley et al., 1982), SWRRB (Arnold et al., 1990), AGNPS (Young et al., 1989), EPIC (Sharpley and Williams, 1990) and SWAT (Arnold et al., 1998) are probably the most important models and widely used worldwide for hydrologic and pollutants transport modeling. The main erosion components of these models are based on concepts originally formulated in the Universal Soil Loss Equation (USLE) model (Wischmeier and Smith, 1978), which relate the total amount of soil loss to six factors: rainfall erosivity, soil texture, slope length and grade, soil cover and conservation practice. Runoff components of these models use the SCS–CN method to predict runoff (Bingner, 1990; Schröder, 2000). Among these models only SWAT, AGNPS and ANSWERS are the distributed parameters physically based watershed scale models mostly used for low slope conditions (Arnold et al., 1998; Bingner et al., 1992; Schröder, 2000).

Any model used for computing potential soil loss from an area must deal with a large number of parameters concerning vegetation, management, soil, topography and climate (Amore et al., 2004). Performance of a model depends upon number of parameters it is considering for runoff and soil loss computation based on scientific theory. Performance of such model may not differ much on different scales. Topography and nature of rainfall are quite dominant parameters in generation of runoff and soil erosion particularly in hilly watersheds. Water Erosion Prediction Project (WEPP) is one such process based model developed for estimating soil loss, and selecting catchment's management practices for conservation planning for field and small catchments (Flanagan and Nearing, 1995; Lane et al., 1997). The model was used successfully world wide (Yu and Rosewell, 2001; Huang et al., 1996; Amore et al., 2004; Pieri et al., 2007; Baigorria and Romero, 2007; Shen et al., 2009; Shen et al., 2010) including India (Pandey et al., 2008) for estimating runoff and soil loss from different land use and crop management practices. Performance of the WEPP model was compared with the ANSWERS (Bhuyan et al., 2002), EPIC (Bhuyan et al., 2002), and SWAT (Shen et al., 2010). They found that the performance of the WEPP model was at par with the ANSWERS and better than the EPIC and SWAT in simulating different management scenario for reduction of sediment yield.

However, for Indian conditions only one study could be found on use of the WEPP (Pandey et al., 2008) in literature. They calibrated and validated the WEPP model using the historical hydrologic data of a small agricultural watershed with medium slope conditions and receiving annual rainfall up to 1300 mm. In the study, they performed calibration and validation of the model and no measures were suggested to control sediment loss. Although the WEPP model has been used at many locations worldwide including India but none of the study was conducted under high rainfall and high slope conditions of eastern Himalaya and simulation of structural measures using the WEPP model. Rainfall and slope are very dominant in erosion process in the region where in addition to the vegetative measures structural measures are also needed to control runoff and soil loss. The present study was undertaken to test the applicability of the WEPP model in a hilly watershed of eastern Himalayan region of India with the following objectives:

1. To perform calibration, validation and sensitivity analysis of the WEPP model for simulating the runoff and sediment yield.
2. To develop vegetative as well as structure based management practices to control soil loss from the hilly watershed.

2. Study area description

For the present study, Umroi watershed in the eastern Himalayan region of India was selected. The watershed is located in Umsning block of Ribhoi district of Meghalaya state of India and lies between 91°57′31″ and 91°58′37″ E longitude and 24°42′32″ and 24°43′42″ N latitude. Location of the study area is shown in Fig. 1. The watershed area is 239.44 ha and its elevation ranges from 900 to 1240 m above the mean sea level. The land surface is made up mostly of Precambrian metamorphic and igneous rocks. Soils of the study area are formed predominantly from the weathering of sedimentary and metamorphic rocks, quartzite, conglomerate, phyllite and sand stone. Topography of the watershed is rolling hills with steep slopes and interspersed with valleys. The slope in the study area varies from 0 to more than 35%. The landforms are susceptible to moderate and severe erosion, and formation of gullies.

The climate of the watershed is humid subtropical. The annual rainfalls were 2508.8 and 2842.5 mm in 2003 and 2004, respectively. Nearly 87% of total rainfall was received during May–Octo-

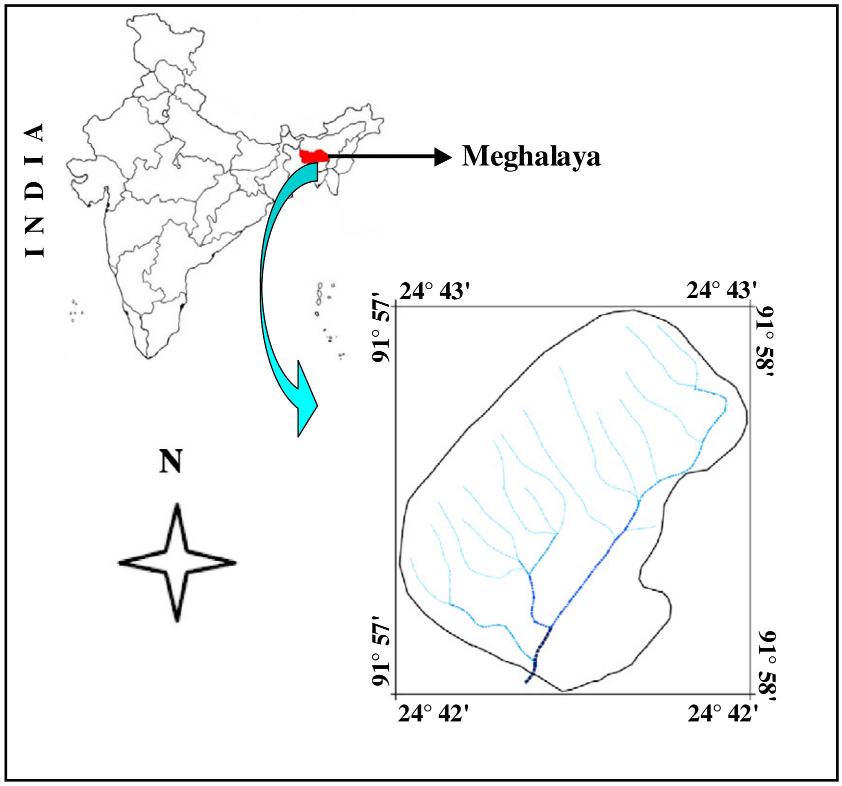

Fig. 1. Location the Umroi watershed.

ber. The mean monthly maximum temperature varied from 18.2 °C in January to 32.5 °C in August and the mean monthly minimum temperature varied from 3.9 °C in January to 17.8 °C in July. The relative humidity remained between 51% and 96%. Bright sunshine hours varied from 9 to 11 during the dry months and remained in the range of 2 to 8 during the monsoon months. Monthly mean of wind speed was the highest in April with an average value of 5.62 km h^{-1} and the lowest in October with an average value of 2.49 km h^{-1}. The evaporation rate during March–April remained in the range of 7.1 to 9.0 mm day^{-1}. The average value of evaporation rate during the rest of the period of the year was between 4.1 and 6.6 mm day^{-1}.

The crop production system in the watershed can be broadly classified into two distinct types, viz., settled agriculture in the plains, valleys, foothills and terraced slopes, and shifting agriculture (*bun* agriculture) in hillslopes. Rainfed agriculture is practiced in kharif season from June to October. The main crops of the watershed are paddy (*Oryza sativa L.*), ginger (*Zingiber officinale*), turmeric (*Curcuma longa*), soybean (*Glycine max Merr.*), maize (*Zea mays L.*), sweet potato (*Ipomoea batatas*) and french bean (Phaseolus vulgaris).

2.1. Bun agriculture

Bun agriculture is the practice of growing crops on raised beds (locally known as *buns*) made along the slope particularly in upland (Fig. 2). Generally tuber crops like ginger, turmeric and sweet potato are grown in *buns* (Fig. 3) followed by upland paddy in the subsequent year. The *bun* field is subsequently left abandoned for 2–3 years for regeneration of vegetation and natural soil fertility build-up. The *bun* agriculture differs from typical slash-and-burn agriculture in mode of burning of vegetation and extent of soil manipulation. Firstly, in *bun* agriculture closed and slow burning of vegetation is practiced whereas in typical slash-and-burn agriculture open and fast burning is done. Secondly, the quantum of soil manipulation is much higher in *bun* agriculture than in slash-and-burn agriculture under which dibbling system is followed for sowing of seeds. Therefore, the *bun* agriculture is more hazardous than the typical slash-and-burn agriculture from soil conservation point of view. In the study watershed farmers grow crops in *bun* field for two years in succession.

Fig. 2. Freshly made *buns*.

During personal interaction with farmers of the watershed two main reasons were expressed for adopting *bun* agriculture. The first reason is safety of crops in high and intense rainfall conditions, and the second reason is that farmers feel more comfortable in performing agricultural operations along the slope. The watershed receives high rainfall in long wet spells during the monsoon season, which may wash away the *buns* if made across the slope. For making *buns*, vegetations in the selected fields are cut during

Fig. 3. *Buns* with ginger crop.

the months of December and January, and arranged in rows at an interval of approximately 1–1.5 m along the slope. The cut vegetations are left in the field for 15 to 30 days to dry. The dried vegetations are covered with soil and burnt. Most of ash containing nutrients remains in *buns* due to closed burning. The width of the *buns* in the watershed ranged between 0.80 to 1.20 m and length between 8 to 21 m. The length varied with slope steepness and uniform slope length on a hillslopes. However, farmer's preference was for longer one. The height varied from 0.30 to 0.45 m from base of the channel between the two *buns* formed after excavation of soil for covering vegetation. It was estimated that only 40–45% area of field is effectively used for crop cultivation in *bun* agriculture.

3. WEPP watershed model overview

The Water Erosion Prediction Project (WEPP) watershed model (Flanagan and Nearing, 1995) is an extension of the WEPP hillslope model (Laflen et al., 1991). The WEPP is a physically based distributed parameters model. It estimates runoff and soil loss from a watershed using fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics. It describes the physical processes of soil particle detachment, transport, and deposition due to hydrologic and mechanical forces acting on hillslope and channel. This model is considered to possess the state-of-the-art knowledge of the erosion science, and has become an important analytical tool for runoff and sediment estimation (Lane et al., 1997). The model was initially developed for soil and water conservation planning, and environmental assessment. It has advantage over other existing erosion prediction models as it provides estimate of spatial and temporal distribution of soil loss or deposition in a watershed over a broad range of conditions. The distributed input parameters for the model include rainfall amount and intensity, soil texture, plant growth parameters, residue decomposition parameters, effects of tillage implements on soil properties and residue amount, slope shape, steepness and orientation, and soil erodibiliy. The WEPP works in continuous as well as single-storm simulation mode.

The hillslope version of the model had nine components: climate generation, winter processes, irrigation, hydrology, soil, plant growth, residue decomposition, hydraulics of overland flow, and erosion. Three components: channel hydrology and hydraulics, channel erosion, and impoundments were added in the watershed version. Although the detailed description about all these components can be found in the model documentation (Flanagan and Nearing, 1995), a brief description is provided here for ready reference. Infiltration is computed using the Green-Ampt Mein-Larson equation. Overland flow is routed using either an analytical solution to the kinematic wave equations or regression equations derived from the kinematic approximation. Peak runoff rate at the channel or watershed outlet is calculated by two methods: (1) the method used in the CREAMS model (Knisel, 1980); and (2) a modified rational equation used in the EPIC model (Sharpley and Williams, 1990). The user has to select the method for the simulations. The model considers interrill and rill erosion process in hillslopes as well as in channels. The movement of suspended sediment in rill, interrill, and channel flow areas is calculated using steady state continuity equation at peak runoff rate. Watershed sediment yield is calculated considering soil detachment from hillslopes and channels, transportation, and deposition of sediment in hillslopes and channels. Sediment deposition and sediment discharge from impoundments is modeled using conservation of mass and overflow rate concepts.

4. Methodology

4.1. Meteorological data

The Umroi watershed was adopted by the Indian Council of Agricultural Research (ICAR) in 2001. ICAR installed a weather observatory in the watershed and a hydrologic gauging station comprising of a rectangular weir and a stage level recorder at the outlet of the watershed to monitor the flow. Rainfall data were measured by the automatic as well as non-recording type rain gauges installed in the watershed. Continuous measurement of rainfall amount, intensity and time was made for the years 2003 and 2004. Other meteorological data such as maximum and minimum air temperature, relative humidity, solar radiation, and wind velocity were collected from a meteorological observatory of ICAR Barapani office located 8 km away from outlet of the watershed. The daily rainfall chart recorded during the year 2003 and 2004 at the watershed were analyzed for rainfall amount, intensity, duration and time to peak intensity to generate brake point data sets for each interval in the day.

4.2. Hydrological data

Daily runoff volumes from the watershed were measured using water stage level recorder and rectangular weir installed at the outlet. The flow velocities were measured manually using current meter for all the rainfall events during 2003 and 2004 at the outlet. The recorded runoff hydrographs for each storm were analyzed for computation of runoff rate and runoff volume from the watershed. The measured daily runoff volume was converted to daily runoff depth using the area of the watershed. Straight-line method suggested by Subramanium (1996) was used for base flow separation.

Sediment flow data at the outlet of the watershed resulting from each storm were measured manually using USDH-48 bottle type silt sampler. The runoff sample was filtered through the filter paper of pore size 1.2 μm. The sediment retained on the filter paper was dried in the oven at 105 °C for 24 h and its weight was determined taking into account the weight of the filter paper. The measured sediment yield in gram per litre ($g\,L^{-1}$) was converted to $Mg\,ha^{-1}$ using the watershed area and runoff volume. Though the sediment measurement was instantaneous but it was assumed that the concentration was uniform through out the runoff period. The measured surface runoff and sediment yield values were compared with the model-simulated values.

4.3. Field measurement of soil properties

Soil properties are important factors affecting runoff and soil erosion. Physical and chemical properties of soil for three layers at three well-distributed locations in the watershed were determined using standard laboratory methods. Cation exchange capacity (CEC) was measured using the method of Sumner and Miller (1996). Organic carbon was determined using Walkley–Black wet oxidation method (Jackson, 1973). Albedo, effective hydraulic conductivity, interrill erodibility, rill erodibility and critical shear were calculated using equations suggested in the WEPP model's User Summary (Flanagan and Livingston, 1995). All the calculated parameters except albedo were calibrated before application of the model for simulating various management scenarios. Soil parameters used for simulations by the model are presented in Table 1.

4.4. Digital elevation model for watershed characterization

The digital elevation model (DEM) is quite efficient in extracting the hydrological data by analyzing different topographical attributes like elevation, slope, aspect, relief, curvatures etc. for modeling purpose. Topographic sheet No. 78/O 14 of the study area of 1:50,000 scale having contours at 20 m interval and drainage lines were obtained from the Survey of India office, Shillong. The contours and drainage lines were digitized using ARC/INFO software (ESRI, 1997). The digitized contours were assigned identity numbers (ID) representing contour elevations. The lattice, that is the surface interpretation of a grid, represented by equally spaced sample points referenced to a common origin and a constant sampling distance in the *X* and *Y* directions was initially developed with the help of digitized contours. Each mesh point contains the *z* value of that location, and is referenced to a common base *z* value, such as mean sea level. Surface *z* values of locations between lattice mesh points were approximated by interpolation between adjacent mesh points. Finally, the lattice was converted into DEM (cell size $23\ \text{m} \times 23\ \text{m}$) of the watershed using interpolation (Fig. 4). The WEPP model does not extract data from DEM automatically. The values for topographical attributes from the DEM for the delineated hillslopes were entered manually in the input files of the model.

4.5. Satellite data

The cloud free digital satellite data of the study watershed were obtained from the National Remote Sensing Agency (NRSA), Hyderabad. Indian Remote Sensing Satellite (IRS-1D LISS-III) data (Path: 110 and Row: 053) of 23rd February 2002 were used to prepare LU/LC map of the watershed after several ground truth verifications. Major land uses of the watershed are dense forest (59.55 ha), open forest (33.54 ha), Upland paddy (33.21 ha), lowland paddy (59.20 ha), *bun* agriculture (21.85 ha), degraded land (29.15 ha) and settlement (2.94 ha).

Table 1
Soil properties used for simulations.

Soil properties	Soil depth (cm)		
	0–30	30–100	100–180
Sand (%)	46.68	36.14	26.46
Clay (%)	24.44	34.41	44.52
Rock fragments (%)	7.92	5.71	5.17
CEC (meq/100 g)	12.59	16.42	19.42
Organic matter (%)	2.27	1.48	0.64
Albedo	25	na	na
Effective hydraulic conductivity (mm h^{-1})	11.6	na	na
Interrill erodibility (10^6 kg s m^{-4})	7.0	na	na
Rill erodibility (s m^{-1})	0.015	na	na
Critical shear stress (N m^{-2})	2.9	na	na
Initial saturation level (%)	70	na	na

na: not applicable.

4.6. The WEPP model application

The WEPP watershed model (Ver. 2002) was used for simulating runoff and erosion, and evaluation of management scenarios. On the basis of simulation results management practices were developed to control sediment yield. The observed data of 2003 and 2004 consisting of runoff, soil loss, weather, soil properties, and cultural practices were used as input to the model.

4.6.1. Model inputs

Inputs to the model were given through 6 files: (1) climate, (2) slope, (3) soil, (4) plant/management, (5) channel, and (6) impoundment. Climate input files were prepared by running Break Point Climatic Data Generator (BPCDG) programme (Zeleke et al., 1999) which generated breakpoint climate data in the format accepted by the model using observed standard weather data sets. Raclot and Albergel (2006) reported that break point data generated using BPCDG programme improved the results of WEPP application in a Mediterranean cultivated catchment. Date, amount, intensity and duration of rainfall, minimum and maximum temperatures, wind velocity and direction at 8 and 18 h of the day, daily values of radiation and dew point temperatures for the period of 2003–2004 were used as input to BPCDG to create climate input file.

Slope orientation, slope length and slope steepness were provided for each overland flow element (OFE) on a hillslope. Hillslopes are defined as a set of grid cells in the DEM that drain to the left, right, or top of each individual channel and OFE is a region of homogeneous soil, crop, and management within the hillslope. Hillslopes in the watershed were identified using DEM and drainage map. Seventy-five hillslopes with an average area of 3.19 ha and 49 channels were delineated (Fig. 5). Slope orientation, length and steepness for OFEs and channels were derived from the DEM.

Input soil parameters' values are given in Table 1. For friction slope of the channel, the model has two options: (1) friction slope equal to topographic slope of the channel and (2) calculated by the model to take into account backwater effects. As the general slope of the watershed is high, there is very little or no effect of backwater. Therefore, friction slope of the channel was set equal to the topographic slope of the channel. Manning's '*n*' value of 0.04 was selected from Chow (1959) according to vegetation conditions of the channels. Channels were not maintained, weeds and brush were uncut with clean bottom and brush on sides. Soil and slope files were prepared in WEPP – window interface file builder.

The plant/management input file contains all the information related to plant parameters, tillage sequences and tillage implement parameters, plant and residue management, initial conditions, contouring, subsurface drainage, and crop rotations. The plant/management file was built by editing the existing model database file in interface file builder and saved with a different name. While editing, all the crop and tillage related parameters were changed as per the watershed conditions. Tillage and crop management information which included type of tillage equipment and date of use, planting date, type of crop, harvest date, residue management etc. were entered into the plant/management files according to watershed records and personal communications with farmers and scientists working in the watershed. Most of the plant specific parameters used were WEPP default values at

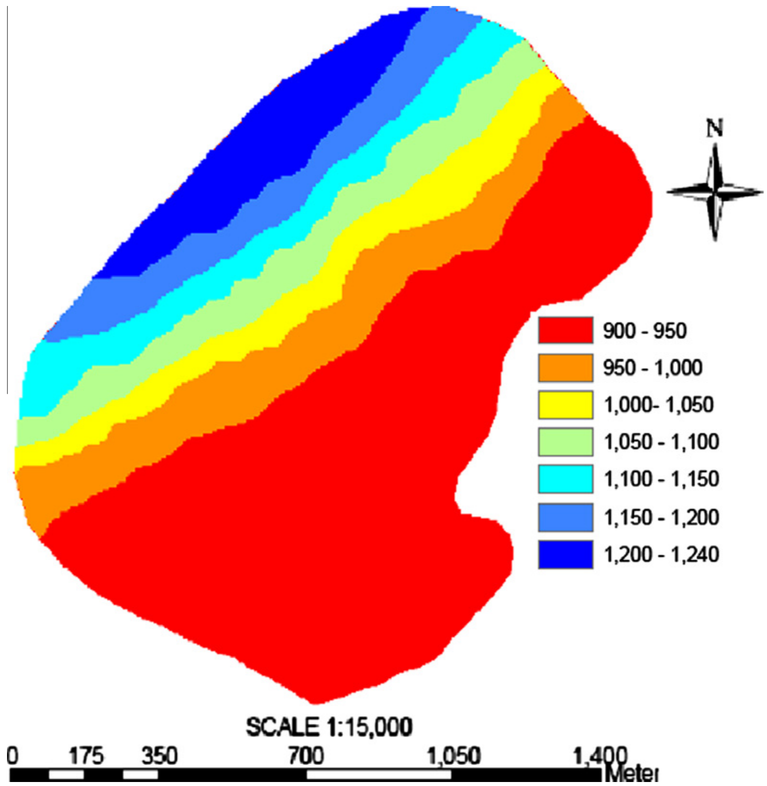

Fig. 4. Digital elevation model of the Umroi watershed.

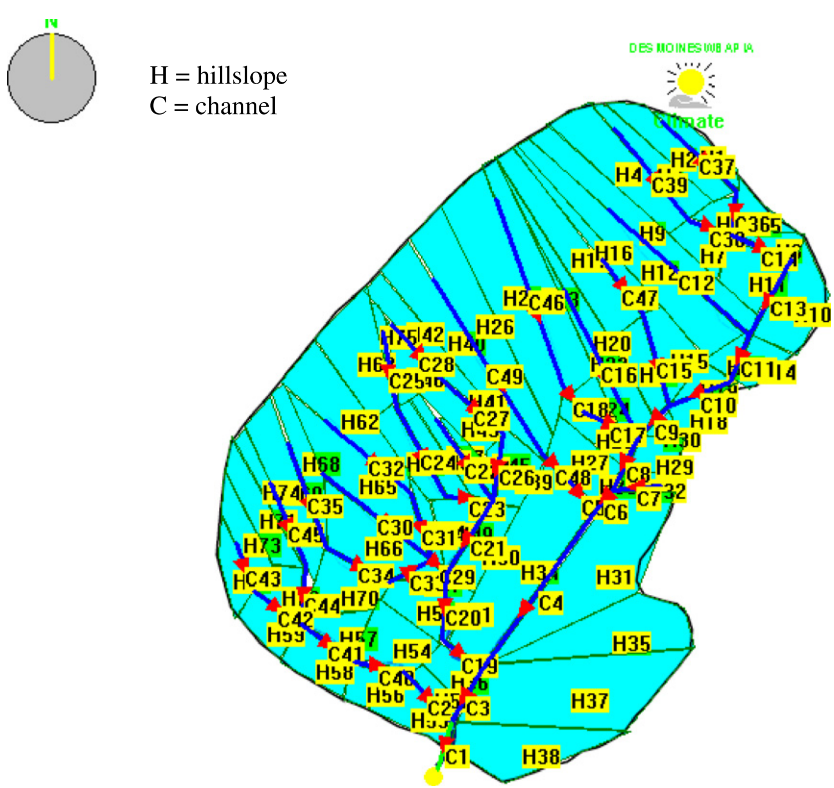

Fig. 5. Delineated hillslope and channels in the Umroi watershed.

medium yield level. The model contains default data for maize, soybean, peanut (*Arachis hypogaea*), forest and grassland, which were used in the present study. However, crop data related to paddy were gathered from Crop Parameter Intelligent Database System (CPIDS) (Ascough et al., 1998) and from available literature (Chatterjee and Maiti, 1981).

Specifying the initial conditions is most important for continuous simulation. The initial conditions are the conditions, which existed at the beginning of the simulation. In the model, initial conditions on January 1st are considered. In the present study, initial conditions were provided based on field-measured data and the watershed records. For agricultural land, fallow was taken as initial conditions as only one crop during monsoon was grown in the watershed.

4.7. Model performance evaluation

Precise calibration of the WEPP model is essential in the study conditions for accurate simulation results (Pieri et al., 2007). Split sample calibration approach was adopted for model's performance evaluation. Two-years' data set pertaining to 2003 and 2004 was split into two parts. The data of 2003 were used for model calibration and that of 2004 for model validation. The manual calibration based on trial-and-error procedure (Sorooshian and Gupta, 1995) was used in the study. Sensitive parameters, which were estimated using the recommended equations (Flanagan and Livingston, 1995), were considered for calibration. Previous studies on the WEPP model (Nearing et al., 1990; Bhuyan et al., 2002; Pandey et al., 2008) indicated that the model is very sensitive to soil input parameters for runoff and soil loss simulation. Soil parameters such as: effective hydraulic conductivity, interrill and rill erodibility, and critical hydraulic shear were considered for calibration in the present study. The values of parameters were chosen within the prescribed range (Flanagan and Livingston, 1995). Several simulations were performed adjusting the parameters' values until a minimum value for root mean square error (RMSE) was obtained (Xevi et al., 1997).

Sensitivity analysis help identify those parameters which affect the model response to a great extent. Hantush and Kalin (2005) described the sensitivity analysis as measure of how a relative perturbation of the parameter is propagated into the relative perturbation of the prediction. Sensitivity analysis provides a quantifiable response of a model output over a range of an input parameter. To quantify the impact of change in the values of input parameters on the outputs, the relative sensitivity equation (McCuen, 1973) was used. The same equation was used for WEPP model by Nearing et al. (1990) and Brunner et al. (2004). The hydrological models are more sensitive to weather and soil parameters (Nearing et al., 1990; Baffaut et al., 1997). As weather parameters are generally recorded by precisely calibrated automatic weather station hence there is no chance of manual error in their measurement. Therefore, sensitivity analysis of weather parameters was omitted. Thus, sensitivity analysis of the model was carried out to assess the variations in the model output with change in soil input parameters only. The model's sensitivity to an input parameter was determined by varying the parameter, while keeping other parameters constant, and comparing the corresponding simulated runoff and sediment yield. The soil input parameters considered for sensitivity analysis were effective hydraulic conductivity, interrill erodibility, rill erodibility and critical shear stress. The values of these parameters were increased by 50% and decreased by 50% from their calibrated values during the analysis and sensitivity ratios were determined.

After calibration proper validation is equally essential for model testing before it could be used for developing management practices. During validation, the performance of the calibrated model was judged without any changes in the input files except the climate and plant/management files. The model was validated for daily runoff and sediment yield using 2004 data set.

4.8. Evaluation criteria for the model

A number of test statistics and techniques were used to test the goodness-of-fit of the model to simulate reality. American Society of Civil Engineers (ASCE) Task Committee on criteria for evaluation of watershed management models (1993) recommended that both visual and statistical comparisons between model-computed and measured quantities be made whenever data are presented. Root mean square error (RMSE) (Thomann, 1982), percent deviation (D_V) (Martinec and Rango, 1989), Nash and Sutcliffe (1970) simulation coefficient (E_{NS}) were determined. Also the Student's *t*-test at 95% significance level (Gupta and Kapoor, 2002) was performed to compare means of simulated and measured values of daily runoff and sediment yield.

5. Results and discussion

5.1. Simulation of runoff

The daily measured runoff hydrographs for the calibration (May–October 2003) and the validation (May–October 2004) periods are shown in Figs. 6 and 7, respectively. It is observed from Figs. 6 and 7 that the trend of the simulated values closely match the trend of the measured values for both calibration and validation periods. However, the measured daily runoff of higher magnitude is under-predicted by the model during simulations for calibration and validation periods. Scattergram plots for the daily measured as well as simulated runoff for the calibration (Fig. 8a) and the validation period (Fig. 8b) show that the majority of data points are evenly distributed about the 1:1 line. Few runoff events of high magnitude are below the 1:1 line indicating under-prediction of larger values. Such data points were resulted from the daily rainfalls of 91.6 mm on 14th July 2003, 176.7 mm on 10th October 2003, 190.7 mm on 7th October 2004 and 214.6 mm on 8th October 2004. The storms of such magnitude may be considered as exceptions.

Goodness-of-fit statistics for calibration and validation are presented in Table 2. Student's *t*-tests showed that the means of measured and simulated runoff are not significantly different at 95% confidence level as *t*-calculated < *t*-critical for both periods. The RMSE of 1.42 and 1.77 mm, D_V of −1.71 and −3.01, and E_{NS} of 0.94 and 0.87, respectively for the calibration and the validation period indicate reasonably accurate simulation of surface runoff by the model (Table 2).

The under-prediction of larger values of runoff may be explained as follows. During the larger rainfall events occurring at a time of high antecedent soil water content, splash erosion process become dominant and might affect the infiltrability 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. Such phenomena may not have been well represented in the model and caused under-prediction of runoff of high magnitudes. In hilly watershed with high slope, the time of concentration is reduced during high rainfall events resulting in high runoff generation. Land slope is a dominant factor for distribution of soil moisture within the soil mass and runoff response on a hillslope. Moisture translocation from higher elevation to lower elevation desaturates upper part of a slope and replenishes lower sloped areas. Therefore runoff generation process will be different in different parts of the watershed depending upon land gradient. Uniform calculation of runoff for all parts of hillslope may lead to some error in runoff prediction. The watershed received 206 and 242 mm rainfall in May month of 2003 and 2004, respectively. Soil was saturated before onset of monsoon in June. As the number of rainy days was high (86 during the calibration and 98 during the validation period) soil water content was high resulting in high runoff production from the storms. Base flow contribution in the flow at the outlet is more in hilly watershed having large area under forest. The watershed has 59.55 ha area under dense forest

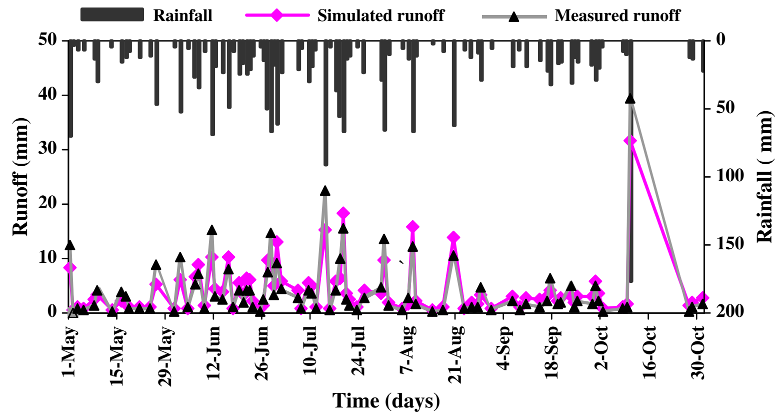

Fig. 6. Measured and simulated daily runoff hydrograph for model calibration.

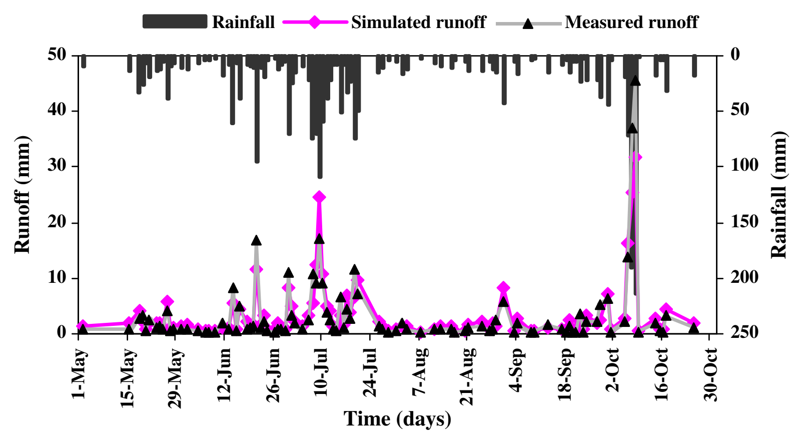

Fig. 7. Measured and simulated daily runoff hydrograph for model validation.

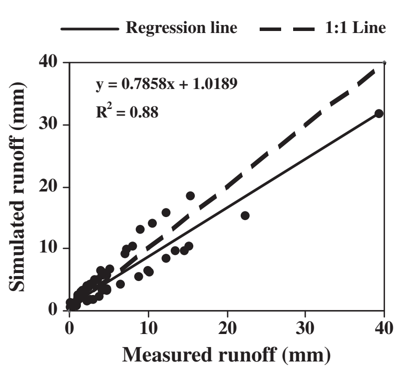

Fig. 8a. Comparison between measured and simulated daily runoff for model calibration.

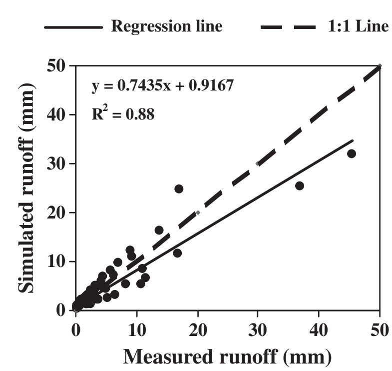

Fig. 8b. Comparison between measured and simulated daily runoff for model validation.

cover accounting for 24.87% of the total watershed area, which contributed subsurface flow at the outlet. Base flow separation is considered to be somewhat arbitrary and no available methods for separation of base flow from surface runoff are perfect (Bedient and Huber, 1992). For the present study, the straight-line method of base flow separation technique was used to obtain direct runoff hydrograph (Subramanium, 1996). So any error in base flow separation may also result in high surface runoff. Therefore, it is reasonable to assume that these facts were responsible for under-prediction of runoff by the model. However, accurate calibration of subsurface parameters which was not conducted in the present may improve the model output particularly in the forested watershed.

The watershed received 2508 mm rainfall in 2003 and 2842 mm in 2004. Recent studies on application of WEPP model on watershed scale were for rainfall less than 1300 mm (Pandey et al., 2008; Raclot and Albergel, 2006; Croke and Nethery, 2006). In these studies also model was reported to under-predict the larger values. Under-prediction for larger measured values and over-prediction for smaller measured values by the model is due to limitations in representing the random components of the measured data (Nearing, 1998). In earlier applications of the WEPP

Table 2
Goodness-of-fit statistics of measured and simulated daily runoff.

Statistical parameter	Runoff (mm)					
	Calibration period			Validation period		
	Measured		Simulated	Measured		Simulated
Mean	4.17		4.30	3.75		3.41
Std. Dev.	5.78		4.84	6.54		5.17
Maximum	39.4		31.7	45.5		31.8
Total	358.7		369.5	367.6		334.0
No. of events	86		86	98		98
RMSE (mm)		1.42			1.77	
D_V		−1.71			−3.01	
E_{NS}		0.94			0.87	
t-calculated		−0.15			−0.07	
t-critical (two tailed)		1.974			1.974	

RMSE: root mean square error, D_V: percent deviation, E_{NS}: Nash–Sutcliffe simulation coefficient, *t*-calculated: Student's *t*-test calculated for equal means at 95% confidence level.

Table 3
Sensitivity ratio of different parameters.

Parameter	Calibrated value as base value	Range of test value		Sensitivity ratio	
		−50%	+50%	Runoff	Sediment yield
K_e (mm h^{-1})	11.6	5.8	17.4	−0.364	−0.277
K_i (10^6 kg s m^{-4})	7.0	3.5	10.5	0	0.315
K_r (s m^{-1})	0.015	0.0075	0.0225	0	0.801
τ_c (N m^{-2})	2.9	1.45	4.35	0	−0.182

K_e: Effective hydraulic conductivity, K_i: interrill erodibility, K_r: rill erodibility, τ_c: critical shear stress.

(Ghidey and Alberts, 1996; Kramer and Alberts, 1995; Zhang et al., 1996), it was reported that smaller values were tended to be over-predicted and larger values were under-predicted for event-by-event, annual totals, and average annual runoff. Similar trend in prediction was also reported in case of USLE (Risse et al., 1993) and RUSLE (Rapp et al., 2001) applications.

5.2. Sensitivity analysis

The WEPP model requires large quantum of data as input for simulation. Accuracy in simulation depends upon quality of data. The user should know the parameters, which should be calibrated precisely to improve the performance of model. Thus, it is pertinent to do sensitivity analysis to know about the parameters, which affect the output of the model to a larger extent with slight variations in their values. Sensitivity analysis not only helps identify influencing parameters but also quantify their influence on model outputs. Moreover, for the purpose of the model application, sensitivity analysis also determines the level of accuracy or precaution needed in determination of parameters. For example if modeling is performed for water resource development, hydraulic conductivity is to be determined more precisely and while considering non-point source of pollution, erodibility of the soil is to be determined more precisely. The results of sensitivity analysis are presented in Table 3.

The results of sensitivity analysis (Table 3) revealed that among the parameters considered, the change in effective hydraulic conductivity only affected the simulated runoff with a sensitivity ratio of −0.364 and sediment yield is sensitive to rill erodibility, followed by interrill erodibility, effective hydraulic conductivity and critical shear stress of soil in that order. All the parameters considered for the sensitivity analysis were soil-related parameters, which showed their effects on the model output. Sensitivity of the model to rill erodibility is greatest for sediment simulation. This shows that the rilling process is dominant in high slope and high rainfall condition. 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 slope generates large volume of runoff with higher velocity. In such situation sediment carrying capacity of flow is not limiting even if interrill erosion contributes fair amount of sediment load to flow. Average slope length of hillslopes in the watershed was more than 100 m. In case of higher slope length, rill erosion will be dominant as compared to interrill erosion. This may also be one reason for higher sensitivity ratio of rill erodibility. Critical shear stress of soil has also influence on the model response for sediment yield as indicated by its sensitivity ratio (Table 3). 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. Interrill, rill and critical stress are considered in the model to calculate erosion that is, these parameters are dominant in erosion process. Hydraulic conductivity is more dominant in runoff generation process as compared to other parameters, which is evident from the values of sensitivity ratio in runoff simulation (Table 3). Runoff occurs when rainfall exceeds the infiltration rate of the soil. On steep slope and in high rainfall conditions, this may not be true all the time particularly during intense rain. These may be the possible reasons of greater influence of hydraulic conductivity on runoff as indicated by higher sensitivity ratio than that of sediment yield. The model's overall response to soil parameters is due to their use in calculation of soil properties such as hydraulic conductivity, bulk density, erodibility by the model. The results obtained are in agreement with the reported results of previous studies (Nearing et al., 1990; Baffaut et al., 1997; Bhuyan et al., 2002; Brunner et al., 2004; Pandey et al., 2008). Hantush and Kalin (2005) also found using KINROS2 model (Smith et al., 1995) that the model-predicted total flow and sediment yield was very sensitive to soil related parameters such as antecedent relative effective soil saturation, saturated hydraulic conductivity, plane roughness coefficient, median particle diameter. Therefore, it can be inferred that more precise estimation of soil parameters is essential for accurate evaluation of management scenarios.

5.3. Simulation of sediment yield

The measured and simulated daily sediment yield along with their seasonal / cumulative values and scattergrams for calibration and validation periods are shown in Figs. 9–11b, respectively. The visual inspection of Figs. 9–11b indicates similarity in trend of measured and simulated values. The measured and simulated seasonal sediment yield were 21.91 Mg ha^{-1} and 23.05 Mg ha^{-1}, respectively during calibration period while the corresponding values were 21.94 Mg ha^{-1} and 21.27 Mg ha^{-1} during validation period. The scattergram plots of simulated and measured sediment yield for the calibration (Fig. 11a) and the validation (Fig. 11b) periods show that the data points are scattered around 1:1 line. Though, the majority of daily values of large magnitude are under-predicted the seasonal sediment yield values are simulated well (Figs. 9–11b). This may be explained by the fact that soil erosion process is highly complex phenomena and affected by interaction among rainfall, runoff, soil texture and structure, land use, land slope and conservation measures. Therefore, magnitude of randomness in daily values of sediment yield may be large. So, a hydrologic model is most likely to simulate annual values better than the daily values of sediment yield.

Goodness-of-fit statistics for simulation of sediment yield (Table 4) revealed that the means of daily measured and simulated sediment yield for the calibration and the validation periods are not significantly different at 95% confidence level as *t*-calculated < *t*-critical for both periods. Maximum peaks of 1.82 Mg ha^{-1} for calibration period and 2.18 Mg ha^{-1} for validation period were under-predicted by the model. Low RMSE values of 0.08 and 0.09 Mg ha^{-1}, low D_V values of 3.05 and −5.23, and high E_{NS} value of 0.95 and 0.90, respectively for calibration and validation periods indicate model's capability for simulating daily sediment yield with acceptable accuracy.

Similar to the runoff simulation, the WEPP model showed the tendency of under-predicting the larger values of sediment yield also. High sediment yield from the watershed indicate the dominance of rill erosion in the area. The watershed has 44.80 ha under *bun* agriculture and land degradation. Under intense rainfall and high land slope conditions interrill and rill erosion processes become prominent resulting in significant soil erosion. Due to higher slope of the watershed, the eroded soils are carried to the outlet and there is little chance of deposition. Few critical areas of the watershed may contribute significant amount of sediment at the outlet. Scouring action of concentrated flow in *bun* made along the slope, degraded areas, and in channels during heavy rainfall might have accelerated the soil erosion process. Area under *bun* agriculture, which had loose soil on surface as a result of earthing up of soil, interculture operations and after harvest of tuber crops, were responsible for high sediment at the outlet. Also soil loss is most critical during pre-monsoon season due to minimal vegetation covers and presence of loose soil on surface. The watershed received 849 and 615 mm rainfall during May–June in 2003 and 2004, respectively. These factors seem to be responsible for higher sediment yield from the watershed. Probably such randomness associated with the measured values was not picked up by the model during simulations resulting in under-prediction. Nearing (1998) studied the concept of over and under-prediction by deterministic model using a synthetic example and 6014 measured soil loss data, and reported that phenomena of under-prediction of larger values and over-prediction of smaller values by a model is not necessarily associated with bias in model prediction rather with limitations in representing the random component associated with the measured data. In the present study, the random component associated with the larger values may be quite high due to *bun* agriculture and high rainfall causing the overall trend of under-prediction by the WEPP model. The nature of prediction in the present study is in agreement with the findings of Nearing (1998).

5.4. Evaluation of vegetative and structure based management scenarios

The WEPP model was recommended for evaluating erosion-related crop management practices for Indian conditions (Pandey et al., 2008). As the sediment yield from the Umroi watershed was high, crop, tillage, and impoundment were considered for evaluation to develop erosion control management practices. Maize, peanut and soybean at three fertilization levels such as: low, medium and high were considered. Rice being the staple food for the people of the watershed, it is the main cereal crop of the watershed in low land and upland situations. Maize is the second popular crop of the watershed as it also serves as feed for animal. Soybean and peanut crops are grown by some farmers for home consumption. Also soybean and peanut is the cash crop and maintains soil health by nitrogen fixation in the soil (Narayana, 1993). Four tillage treatments namely, field cultivator, drill-no-tillage, drill single disk opener and mould board plough were considered for evaluation of sediment yield reduction. To evaluate the struc-

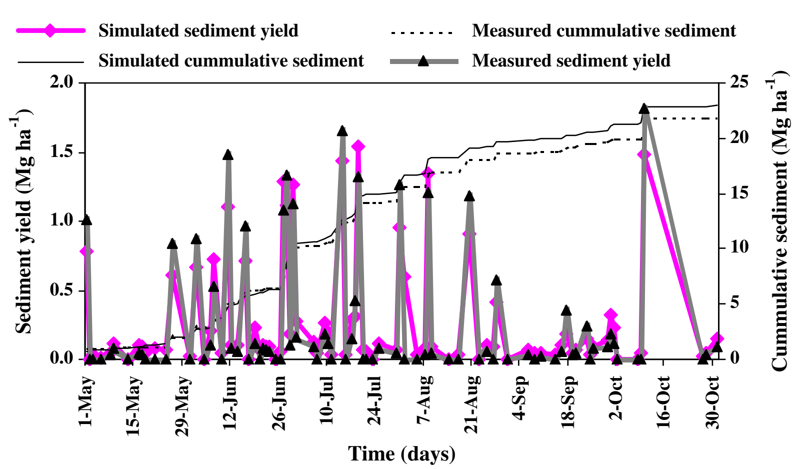

Fig. 9. Measured and simulated daily as well as cumulative sediment yield for model calibration.

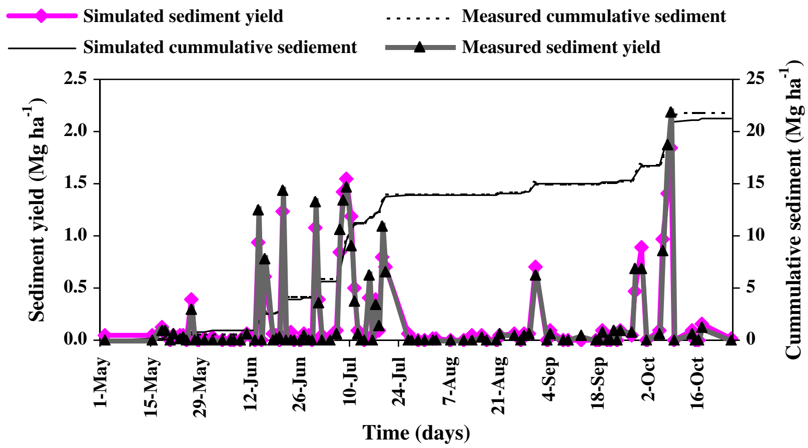

Fig. 10. Measured and simulated daily as well as cumulative sediment yield for model validation.

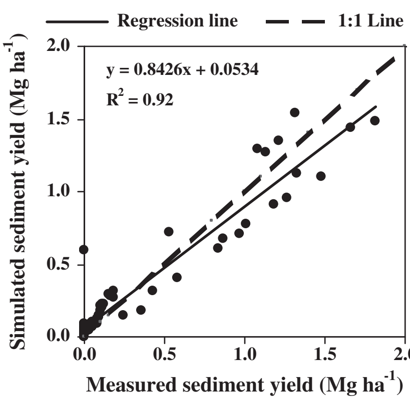

Fig. 11a. Comparison between measured and simulated daily sediment yield for model calibration.

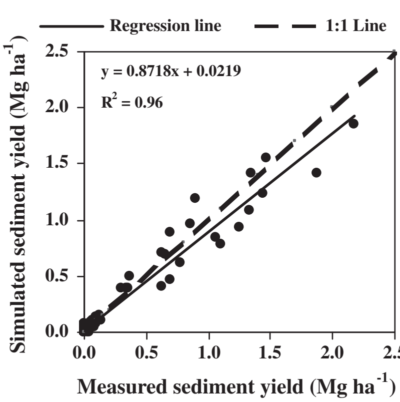

Fig. 11b. Comparison between measured and simulated daily sediment yield for model validation.

ture based management scenarios, two scenarios were hypothesized: with impoundment existence (WIMS) and without impoundment existence (WoIMS), and simulated using the model. Considering the cost of the structure, availability of the local materials and economic conditions of farmers, porous rock-fill check dam and trash barrier were selected as structural measures because both can be constructed easily and cheaply with locally available materials (Flanagan and Livingston, 1995). For evaluating the management scenarios, the measured rainfall, temperature, humidity and solar radiation data for the years 2003 and 2004 were used. In order to evolve appropriate management strategies for control of sediment yield from the watershed, several simulations were performed. The simulated sediment yield was compared with the measured sediment yield from the watershed with existing cropping and tillage practices.

5.4.1. Effective watershed management

As sediment yield of the watershed is quite high (>21 Mg ha^{-1}) it falls under very high soil erosion class (Singh et al., 1992) exceeding the permissible limit of 11 Mg ha^{-1} (Hall et al., 1985). Effective watershed management is therefore, essential to control sediment yield. It is hypothesized that adoption of cropping management practices alone cannot bring down the sediment yield within the safe erosion limit. Structure management measures are also needed to control sediment yield. Crop and tillage management will help reduce load on structures, which need to handle high flow particularly in high rainfall conditions. Therefore, in addition to the structural measures crop and tillage management practices were necessary to conserve rainfall and soil *in situ* and to reduce the number of structures thereby cutting down the cost of treatments. The WEPP model has functionality and capability to model crop as well as land management practices.

5.4.2. Evaluation of alternate cropping practices

Efforts were made to evaluate the effectiveness of different management strategies in reducing sediment yield by simulating the effect of crops viz., maize, soybean and peanut at three fertilization levels in upland situation. The crops were selected on the basis of their demand in local market and preference of the farmers of the watershed. Several simulations were made with the calibrated and validated WEPP model using the measured climatic data of 2003 and 2004. The effects of treatments were analyzed and evaluated on the basis of sediment yield. Simulated sediment yield of different cropping practices were compared with measured sediment yield of the watershed with existing cultivation practices of *bun* agriculture for 2003 and 2004. The results of the simulations are presented in Table 5.

It is evident from Table 5 that reduction in sediment yield occurred in all the treatments. Both crop as well as fertilization level affected sediment yield. The reduction was the maximum with 35.69% in case of soybean with high fertilization level followed by peanut with high fertilization level with 35.19%. For a crop the maximum reduction occurred with high fertilization level. This may be due to development of larger canopy and root density of the crops due to high fertilization. Nitrogen use efficiency for most soil–plant system is between 50% and 70% and the remainder is

Table 4
Goodness-of-fit statistics of measured and simulated daily sediment yield.

Statistical parameter	Sediment yield (Mg ha^{-1})			
	Calibration period		Validation period	
	Measured	Simulated	Measured	Simulated
Mean	0.25	0.27	0.22	0.21
Std. Dev.	0.46	0.40	0.45	0.41
Maximum	1.82	1.54	2.18	1.85
Total	21.91	23.05	21.94	21.27
No. of events	86	86	98	98
RMSE (Mg ha^{-1})	0.08		0.09	
D_V	3.05		−5.23	
E_{NS}	0.95		0.90	
t-calculated	−0.20		0.111	
t-critical (two tailed)	1.974		1.972	

Table 5
Effect of crop and fertilization level on sediment yield.

Treatment	Year			
	2003		2004	
	Sediment yield (Mg ha^{-1})	% Change	Sediment yield (Mg ha^{-1})	% Change
Maize + LFL	18.81	(−) 14.15	17.53	(−) 20.10
Maize + MFL	18.44	(−) 15.84	18.54	(−) 15.50
Maize + HFL	16.58	(−) 24.33	17.07	(−) 22.20
Soybean + LFL	17.52	(−) 20.04	16.54	(−) 24.61
Soybean + MFL	15.45	(−) 29.48	14.60	(−) 33.45
Soybean + HFL	14.37	(−) 34.32	14.11	(−) 35.69
Peanut + LFL	17.20	(−) 21.50	16.85	(−) 23.20
Peanut + MFL	15.62	(−) 28.71	16.21	(−) 26.12
Peanut + HFL	15.01	(−) 31.49	14.22	(−) 35.19

(−): Decrease.
LFL: low fertilization level, MFL: medium fertilization level, HFL: high fertilization level.

transported in sediment and runoff, and leached through the root zone (Stanford, 1973). Interaction of rainfall and land slope can have a major effect on fertilizer use efficiency. Therefore, fertilizer use efficiency may be low in the study watershed. Due to these facts low and medium fertilization level had less effect on sediment control.

From the simulation results (Table 5) it could be inferred that growing of soybean and peanut in upland situations in place of traditional *bun* agriculture and upland rice can reduce the sediment yield of the watershed. Peak period of rain in the watershed is July, August and September. Sowing time of soybean and peanut was considered in last week of June. These crops act as cover crop during the peak period of rain resulting in reduced sediment yield. From farmers viewpoint also these two crops can be suitable alternatives to the paddy crop since these crops are cash crop in the area. But on the basis of personal interaction with the farmers of the watershed it was apparent that it would be difficult for the farmers to adopt any other crop in place of rice since rice is the staple food in the area. However, it is suggested that efforts should be made to replace rice by soybean or peanut in upland areas in a phased manner to reduce sediment yield and also being the cash crop, can improve economic condition of local farmers.

5.4.3. Tillage treatment

Tillage is an important agricultural operation having impact on soil erosion. In high rainfall areas, tillage may facilitate the formation of rills and may result in increased erosion rate. It was thought that paddy crop is not to be replaced by any other crop in low land areas, as rice is the staple food for the local people. Effect of tillage in paddy cultivation on sediment yield was evaluated using the calibrated and validated model. Paddy is grown in lowland and mild sloped areas of the watershed. Four tillage treatments viz., field cultivator, drill-no-tillage system, drill single disk opener and mould board plough were considered for evaluation. Simulated sediment yield resulting from tillage treatments were compared with sediment yield in case of the conventional tillage practices in the watershed. The results of tillage treatment simulations are presented in Table 6.

It is noticed from Table 6 that reduction in sediment yield occurred in case of filed cultivator, drill-no-tillage and drill single disk opener with varying magnitude. The reduction in sediment yield was the maximum (21.88%) in case of drill-no-tillage followed by drill single disk opener (15.77%) and field cultivator (13.14%) as compared to the farmers' practice of tillage with country plough and spading. Use of mould board plough for field preparation of paddy increased the sediment yield of the watershed by 21.15% as compared to the farmers' practice of land preparation. Based on the simulation results of the tillage treatments it can be inferred that sediment reduction can be obtained by adopting drill-no-tillage system, drill single disk opener or field cultivator. Due to sloping topography and high drainage density in the watershed, drill-no-tillage and field cultivator seems to be feasible options.

5.4.4. Structural management

The WEPP watershed model routes the sediment either from hillslope to channel to impoundment to another channel to watershed outlet or hillslope to impoundment to channel to watershed outlet. An impoundment can be fed either by only one hillslope or by maximum three channels. The model simulated the sediment yield from the hillslopes and channels after account-

Table 6
Effect of tillage treatment on sediment yield.

Treatment	Year			
	2003		2004	
	Sediment yield (Mg ha^{-1})	% Change	Sediment yield (Mg ha^{-1})	% Change
T1	19.03	(–) 13.14	19.73	(–) 10.07
T2	18.07	(–) 17.03	17.14	(–) 21.88
T3	20.27	(–) 7.49	18.48	(–) 15.77
T4	25.32	(+) 15.56	26.58	(+) 21.15

+: Increase, – : decrease.
T1: Field cultivator, T2: Drill no tillage, T3: Drill single disk opener, T4: mould board plough.

Table 7
Simulated sediment yield budget for 2003 and 2004.

Year	Soil eroded from hillslopes (Mg)	Soil deposited in hillslopes (Mg)	Soil eroded from channels (Mg)	Soil deposited in channels (Mg)	Sediment yield at the outlet (Mg)
2003	5535.73	511.08	494.44	0	5519.09
2004	5145.83	683.55	630.61	0	5092.89

ing for deposition in hillslopes, channels and impoundment. The annual sediment budget of the watershed is presented in Table 7.

Eroded soil from the hillslopes made their way out of the watershed through channels. As the average slope of the channel in the watershed is high (2.06%) and also the rainfall, there is very little chance of sediment deposition in channel (Table 7). Sediment yield budget of the watershed (Table 7) revealed that 8.96 and 12.38% of the total sediment yield in 2003 and 2004, respectively were contributed by channel erosion. Therefore, structural or engineering measures will help reduce sediment yield not only by controlling channel erosion but also by deposition of eroded soil from hillslopes.

The model supports six types of impoundment structures namely; (1) drop spillway, (2) perforated riser used to slowly empty the terrace system into a subsurface conduit, (3) culvert, (4) emergency spillway, (5) rock-fill check dam, and (6) filter fence or trash barrier (Flanagan and Livingston, 1995). Considering the cost and availability of local materials for the construction, rock-fill check dam and trash barrier were considered for simulation of sediment yield from the watershed. Trash barrier and porous rock-fill check dam will not block the flow completely, thus there is minimal chance of their failure. Database related to these two impoundment structures in the model were modified according to the dimensions of the channels where these structures were considered in the simulations. Dimensions of the channels were measured at the considered locations.

Two scenarios were hypothesized (WIMS: with impoundment structures and WoIMS: without impoundment structures) to evaluate the structure-based management of the watershed. Hypothesized scenarios were simulated to assess their effects on sediment yield from the watershed. The measured and model-simulated sediment yield for WIMS and WoIMS scenarios were compared for the year 2003 and 2004 (Fig. 12 and Table 8). Comparison of simulated sediment yield for WIMS and WoIMS scenarios revealed that 8 rock-fill check dams and 18 trash barriers resulted in reduction of sediment yield by 55.40 and 53.88% in 2003 and 2004, respectively (Table 8). The numbers of structures (Fig. 13) were arrived at during the simulations to reduce the sediment yield within the maximum permissible soil loss limit of 11 Mg ha^{-1} (Hall et al., 1985).

5.4.5. Effect of combinations of best management practices and conservation structures

So far, in this paper individual scenarios of crop, tillage and conservation structures have been simulated to evaluate their effects

Fig. 12. Comparison of simulated sediment yield for structural measures scenarios with the measured sediment yield.

on sediment yield behavior of the watershed. It will be pertinent to quantify sediment yield response of the watershed due to adoption of combinations of crop and tillage management practices and installation of conservation structures. Twelve combinations of scenario consisting of three crops: maize, soybean and peanut each with high fertilization level, two tillage systems: field cultivator and drill-no-tillage systems and two scenarios for conservation structures: without and with structures were considered for further simulations. Only high fertilization level for crops was considered as it resulted in maximum reduction in sediment yield (Table 5). Similarly two most effective tillage systems in reducing sediment yield were considered (Table 6) for simulations. The results of sediment loss reductions due to adoption of combinations of management practices as compared to the measured values are listed in Table 9. The results revealed that sediment yield was substantially reduced with the maximum of 78.40% in case of soybean – drill-no-tillage – with structural controls combination and the minimum of 67.32% in case of maize – field cultivator – with structural controls combination. Field cultivator tillage system when adopted with soybean and peanut with structural controls in the drainage line was predicted to reduce sediment yield by 75.66 and 72.47%, respectively (Table 9). Therefore, on low and medium slope field cultivator may be used for sowing soybean and peanut for better land preparation which may result in higher productivity. On the other hand, maize should be grown only with drill-no-tillage system as maize with field cultivator was predicted

Table 8
Effect of check dams and trash barriers on sediment yield.

Year	Soil eroded from the watershed (Mg)	Sediment transported out of the watershed (Mg)		Sediment controlled by the check dams (Mg)	Control in sediment loss (%)
		WoIMS	WIMS		
2003	6030.17	5519.09	2461.44	3057.65	55.40
2004	5776.44	5092.89	2348.91	2743.98	53.88

WoIMS: without impoundment structures, WIMS: with impoundment structures.

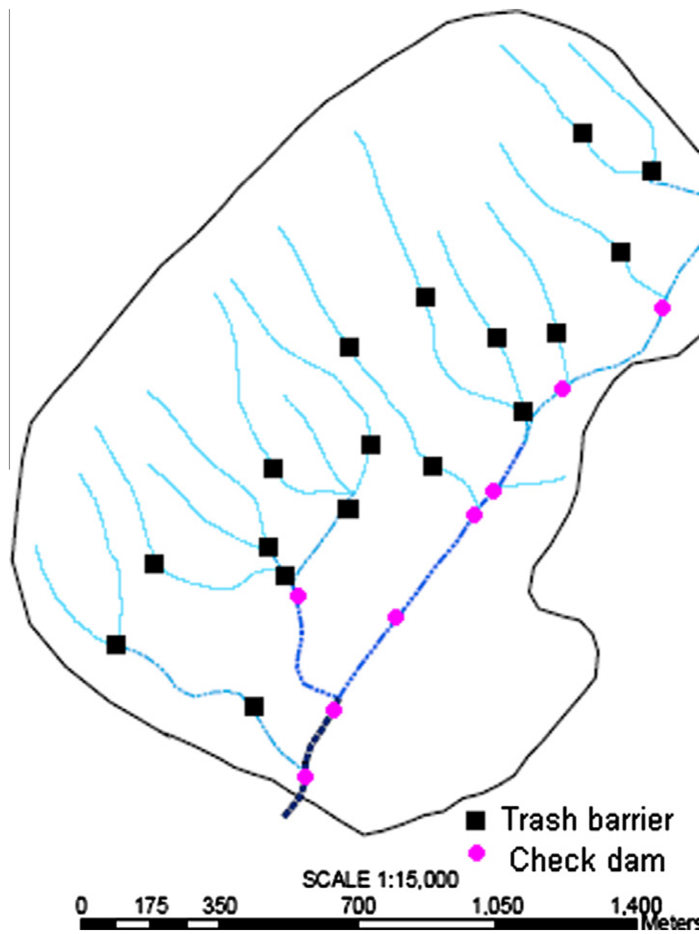

Fig. 13. Location of proposed structural measures in the Umroi watershed.

to result in relatively higher sediment yield. However, on steep slopes only drill-no-tillage should be adopted for growing crops. As maize is the main crop after paddy in the watershed, one situation of maize intercropped with soybean was also visualized. Maize may be sown during last week of March to first week of April and soybean during last week of June. This cropping system has the potential to reduce sediment yield as soybean develops full canopy during peak rainy season of August and September and will act as cover crop. Moreover, after harvest of maize cobs, stem and leaf residue will remain in the field to protect soil. In this way, maize and soybean could be grown to fulfill the food and nutritional requirements of farmers of the watershed with minimum hazard to soil.

Simulation results for different scenarios revealed that effective watershed management planning should be done by integrating vegetative and structural measures. Vegetative measures control erosion thereby reducing the chance of occurrence of variability in soil fertility while structural measures control sediment transport. Also, vegetative measures reduce the load on structures, thus increasing the life and efficacy of the structures. In the simulation studies, location of structures was decided based on critical hillslopes. The location of structure was considered at the downstream side of the critical hillslopes, which were contributing higher sediment yield. At the upstream where runoff flow was low, the structure was considered at the junction of two channels but in the downstream the structure was considered in individual channels. Simulation results indicated that installation of 26 structures could result in average reduction of sediment yield from 22.16 to 10.04 Mg ha^{-1} which is within the safe limit of soil loss. However, even this rate of sediment yield is quite high and should be further reduced to enhance sustainability of agricultural production. Combination of Soybean – drill-no-tillage – structural control has potential to control sediment yield to 4.74 Mg ha^{-1}. Installation of more such structures will result in further sediment yield reduction. These structures reduce the runoff flow velocity in the channel resulting in increased infiltration and sediment deposition. Trash barriers and rock-fill check dams are the low cost structures. Construction materials such as wood and boulders are available in the watershed. These structures can be made by the local people under the supervision of conservation professional from the State

Table 9
Estimated reductions in sediment yield due to adoption of combinations of management practices as compared to the measured values for 2004.

Management combination			Sediment yield (Mg ha^{-1})	Reduction (%)
Maize	Field cultivator	WoIMS	16.13	26.48
		WIMS	7.17	67.32
	Drill-no-tillage	WoIMS	13.22	39.74
		WIMS	6.42	70.74
Soybean	Field cultivator	WoIMS	13.10	40.29
		WIMS	5.34	75.66
	Drill-no-tillage	WoIMS	10.75	51.00
		WIMS	4.74	78.40
Peanut	Field cultivator	WoIMS	12.56	42.75
		WIMS	6.04	72.47
	Drill-no-tillage	WoIMS	11.03	49.73
		WIMS	5.16	76.48

WoIMS: without impoundment structures, WIMS: with impoundment structures.

Government. Few people of the watershed can be trained for construction and maintenance of the structures. Regular inspection and repairing of structures are essential particularly in the first two monsoon season. Afterwards the structures will be stabilized. Installation of check dams and trash barriers will contribute in developing water resource by improving the discharge of perennial and seasonal streams. People of the watershed depend mainly upon stream for cultivation of *rabi* crop. Thus, prolonging and increasing the discharge of streams by installing structures in drainage line will result in increasing the *rabi* crop area which will improve the farmers' livelihood.

6. Conclusions

In the present study, we tested the WEPP model for its efficacy to predict runoff and sediment yield in high rainfall and steep slope conditions of eastern Himalaya. The model was used to develop vegetative and structural control measures to enhance agricultural sustainability in the Umroi watershed representing the typical agro-climatic conditions of eastern Himalaya. Based on results of the study the following conclusions were drawn:

1. The WEPP model simulates runoff and sediment yield satisfactorily in high rainfall and high slope conditions of eastern Himalaya with Nash–Sutcliffe coefficients > 0.87 and percent deviations < ± 5.23. Comparison between WEPP–simulated and measured values of runoff and sediment yield revealed that the model tends to under-predict the values of higher magnitude. Future studies on subsurface components of the model parameters may be useful to enhance model predictability particularly in case high subsurface flow.
2. Simulation results indicate that soybean and peanut crops have the potential to replace paddy crop in upland for reducing sediment yield by 29.60 and 27.70%, respectively.
3. Simulation results indicated that replacing existing tillage practice of spading with drill-no-tillage system and field cultivator may reduce the sediment yield by 21.88 and 13.14%, respectively.
4. Simulation results shows that installation of 26 porous rock-fill check dams and trash barriers in the Umroi watershed can reduce the sediment yield by 54.67%.
5. The results clearly indicated that crop and tillage management practices and structural controls individually are not capable of reducing sediment yield to less than 5 Mg ha^{-1}. Simulation of combinations of crop, tillage and structural control scenarios revealed soybean – drill-no-tillage – with structural controls combination has potential to reduce sediment yield by 78.40% i.e. to 4.74 Mg ha^{-1}. Maize intercropped with soybean may be adopted in place of upland paddy to reduce soil loss and to meet food and nutritional requirement.
6. The calibrated, validated WEPP model can be successfully used to develop crop and structural management strategies in high rainfall and high slope conditions of eastern Himalaya.

Acknowledgements

The authors are grateful to the Director, ICAR Research Complex for NEH Region, Umiam, Meghalaya, India for providing the necessary data, facilities and support for this work. The authors are also thankful to Indian Council of Agricultural Research, New Delhi for funding the project "Hydrological Behavior of Small Watersheds and Sustainability of Production Systems" under which the present study was conducted. We also thank the Editor and anonymous reviewers for their valuable technical comments and suggestions to improve the paper.

References

Amore, E., Modica, C., Nearing, M.A., Santoro, V.C., 2004. Scale effect in USLE and WEPP application for soil erosion computation from three Sicilian basins. J. Hydrol. 293 (1–4), 100–114.
Arnold, G.J., Srinivasan, R., Muttiah, R.S., Williams, J.R., 1998. Large area hydrologic modeling and assessment Part I: Model development. J. Am. Water Resour. Assoc. 34 (1), 73–89.
Arnold, J.G., Williams, J.R., Nicks, A.D., Sammons, N.B., 1990. SWRRB: A Basin Scale Simulation Model for Soil and Water Resources Management. User's Manual, A&M University Press, College Station, Texas, USA, 125p.
ASCE Task Committee, 1993. Criteria for evaluation of watershed models. J. Irrig. Drain. Eng. 119 (3), 429–442.
Ascough II., J.C., Deer-Ascough, L.A., Weesies, G.A., 1998. CPIDS: A plant parameter selection programme for erosion prediction modeling. Comput. Electron. Agric. 20, 263–276.
Baffaut, C., Nearing, M.A., Ascough II., J.C., Liu, B.Y., 1997. The WEPP watershed model: II. Sensitivity analysis and discretization on small watersheds. Trans. ASAE 40 (4), 935–943.
Baigorria, G.A., Romero, C.C., 2007. Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes. Environ. Model. Softw. 22, 1175–1183.
Beasley, D.B., Huggins, L.F., Monke, E.J., 1982. Modeling sediment yield from agricultural watersheds. J. Soil Water Conserv. 37 (2), 113–117.
Bedient, P.B., Huber, W.C., 1992. Hydrology and Floodplain Analysis. second ed., Addison–Wesley Publishing Company, New York, USA.
Bhuyan, S.J., Kalita, P.K., Janssenc, K.A., Barnesa, P.L., 2002. Soil loss predictions with three erosion simulation models. Environ. Model. Softw. 17 (2), 135–144.
Bingner, R.L., 1990. Comparison of the components used in several sediment yield models. Trans. ASAE 33 (4), 1229–1238.
Bingner, R.L., Murphee, C.E., Mutchler, C.K., 1992. Predictive capabilities of erosion models for different storm sizes. Trans. ASAE 35 (2), 505–513.
Brunner, A.C., Park, S.J., Ruecker, G.R., Dikau, R., Vlek, P.L.G., 2004. Catenary soil development influencing erosion susceptibility along a hillslope in Uganda. Catena 58, 1–22.

Chatterjee, B.N., Maiti, S., 1981. Principles and Practices of Rice Growing. Oxford and IBH Pub. Co., New Delhi, India (variously paged).

Chow, V.T., 1959. Open-Channel Hydraulics. McGraw-Hill Book Co., NY, USA, p. 680.

Croke, J., Nethery, M., 2006. Modelling runoff and soil erosion in logged forests: scope and application of some existing models. Catena 67, 35–49.

den Biggelaar, C., Lal, R., Wiebe, K., Breneman, V., Reich, P., 2004. The global impact of soil erosion on productivity II: effects on crop yields and production over time. Adv. Agron. 81, 49–95.

ESRI, 1997. ERDAS Reference Manual, Version 8.4, ESRI, Inc. Atlanta, Georgia, USA.

Flanagan, D.C., Livingston, S.J., 1995. USDA-Water Erosion Prediction Project-WEPP User Summary. NSREL Report No.11. USDA-ARS National Soil Erosion Res. Lab., West Lafayette, IN, USA.

Flanagan, D.C., Nearing, M.A, 1995. USDA-Water Erosion Prediction Project: Hillslope Profile and Watershed Model Documentation. NSERL Report No. 10. USDA-ARS National Soil Erosion Res. Lab., West Lafayette, IN, USA.

Ghidey, F., Alberts, E.E., 1996. Comparison of measured and predicted runoff and soil loss for Midwest claypan soil. Trans. ASAE 39 (4), 1395–1402.

Gupta, S.C., Kapoor, V.K., 2002. Exact sampling distributions. In: Fundamentals of Mathematical Statistics, Sultan Chand & Sons, Darya Ganj, New Delhi, India, pp. 14.1–14.74.

Hall, G.F., Logan, T.J., Young, K.K., 1985. Criteria for determining tolerable soil erosion rates. In: Follet, R.F., Stewart, B.A. (Eds.), Soil Erosion and Crop Productivity. Am. Soc. Agron., Madison Wisconsin, USA.

Hantush, M.M., Kalin, L., 2005. Uncertainty and sensitivity analysis of runoff and sediment yield in a small agricultural watershed with KINROS2. Hydrol. Sci. J. 50 (6), 1151–1171.

Huang, C.H., Bradford, J.M., Laflen, J.M., 1996. Evaluation of the detachment transport coupling concept in the WEPP rill erosion equation. Soil Sci. Soc. Am. J. 60, 734–739.

Jackson, M.L., 1973. Soil Chemical Analysis. Indian Reprint, Prentice Hall of India Pvt. Ltd., New Delhi, India (variously paged).

Knisel, W.G., 1980. CREAMS: A Field Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems. Conservation Research Report No 26, USDA, Washington DC, USA, p. 643.

Kramer, L.A., Alberts, E.E., 1995. In: Validation of WEPP 95.1 Daily Erosion Simulation. ASAE Paper No. 95-2384, ASAE, St. Joseph, MI, USA.

Laflen, J.M., Lane, L.J., Foster, G.R., 1991. WEPP – a next generation of erosion prediction technology. J. Soil Water Conserv. 46, 34–38.

Lafond, G.P., May, W.E., Stevenson, F.C., Derksen, D.A., 2006. Effects of tillage systems and rotations on crop production for a thin Black Chernozem in the Canadian Prairies. Soil Tillage Res. 89, 232–245.

Lane, L.J., Renard, K.G., Foster, G.R., Laflen, J.M., 1997. Development and application of modern soil erosion prediction technology: the USDA experience. Euras. Soil Sci. 30 (5), 531–540.

Martinec, J., Rango, A., 1989. Merits of statistical criteria for the performance of hydrologic models. Water Resour. Bull. AWRA 25 (20), 421–432.

McCuen, R.H., 1973. The role of sensitivity analysis in hydrologic modeling. J. Hydrol. 18, 37–53.

Narayana, V.V.D., 1993. Soil and Water Conservation Research in India. Indian Council of Agricultural Research, Pusa, New Delhi, India, pp. 146–151.

Nash, J.E., Sutcliffe, J.V., 1970. River flow forecasting through conceptual models, Part-1: A discussion of principles. J. Hydrol. 10 (3), 282–290.

Nearing, M.A., 1998. Why soil erosion models over-predict small soil losses and under-predict large soil losses. Catena 32, 15–22.

Nearing, M.A., Deer-Ascough, L., Laflen, J.M., 1990. Sensitivity analysis of the WEPP hillslope profile erosion model. Trans. ASAE 33 (3), 839–849.

Pandey, A., Chowdary, V.M., Mal, B.C., Billib, M., 2008. Runoff and sediment yield modelling from a small agricultural watershed in India using the WEPP model. J. Hydrol. 348, 305–319.

Pieri, L., Bittelli, M., Wu, J.Q., Dun, S., Flanagan, D.C., Pisa, P.R., Ventura, F., Salvatorelli, F., 2007. Using the water erosion prediction project (WEPP) model to simulate field-observed runoff and erosion in the Apennines mountain range, Italy. J. Hydrol. 336, 84–97.

Raclot, D., Albergel, J., 2006. Runoff and water erosion modelling using WEPP on a mediterranean cultivated catchment. Phys. Chem. Earth 31, 1038–1047.

Rapp, J.F., Lopes, V.L., Renard, K.G., 2001. Comparing soil erosion estimates from RUSLE and USLE on natural plots. In: Ascough II, J.C., Flanagan, D.C. (Eds.), Soil Erosion Research for 21st Century. Proc. Int. Symp. (3–5 January 2001). Am. Soc. Agril. and Biological Engineers, St. Joseph, Michigan, USA.

Risse, L.M., Nearing, M.A., Nicks, A.D., Laflen, J.M., 1993. Assessment of error in the universal soil loss equation. Soil Sci. Soc. Am. J. 57, 533–825.

Satapathy, K.K., 1996. Shifting cultivation in North Eastern Region: an overview. J. Soil Water Conserv. 34 (2–4), 171–179.

Schröder, A., 2000. WEPP, EUROSEM, E-2D results of application at the plot scale. In: Schmidt, J. (Ed.), Soil Erosion: Application of Physically Based Models. Springer-Verlag, Berlin, pp. 99–247.

Sehgal, J.L., Abrol, I.P., 1994. Soil Degradation in India: Status and Impact. Oxford and IBH Publishing Company Pvt. Ltd., New Delhi, India, p. 80.

Sharpley, A.N., Williams, J.R., 1990. EPIC-Erosion/Productivity Impact Calculator: Model Documentation. USDA Technical Bull. No. 1768, p. 235.

Shen, Z., Gong, Y., Li, Y., Liu, R., 2010. Analysis and modeling of soil conservation measures in the Three Gorges Reservoir Area in China. Catena 81 (2), 104–112.

Shen, Z.Y., Gong, Y.W., Li, Y.H., Hong, Q., Xu, L., Liu, R.M., 2009. A comparison of WEPP and SWAT for modeling soil erosion of the Zhangjiachong Watershed in the Three Gorges Reservoir Area. Agril. Water Manage. 96 (10), 1435–1442.

Singh, G., Babu, R., Narain, P., Bhushan, L.S., Abrol, I.P., 1992. Soil erosion rate in India. J. Soil Water Conserv. 47 (1), 97–99.

Smith, R.E., Goodrich, D.C., Woolhiser, D.A., Unkrich, C.L., 1995. A kinematic runoff and erosion model. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, Colorado, USA, pp. 697–732.

Sorooshian, S., Gupta, V.K., 1995. Model calibration. In: Singh, V.P. (Ed.), Computer Models of Watershed Hydrology. Water Resources Publication, Highlands Ranch, Colorado, USA, pp. 23–68.

Stanford, G., 1973. Rational for optimum nitrogen fertilization for corn production. J. Environ. Qual. 2, 159–166.

Subramanium, K., 1996. Engineering Hydrology. Tata McDraw-Hill Publishing Company Limited, New Delhi, India, pp. 180–190.

Sumner, M.E., Miller, W.P., 1996. Cation exchange capacity and exchange coefficients. In: Sparks, A.L. (Ed.), Methods of Soil Analysis. Part 3. Chemical Methods. Am. Soc. Agron., Madison, WI, pp. 1201–1230.

Thomann, R.V., 1982. Verification of water quality models. J. Environ. Eng. 108 (5), 923–940.

Wischmeier, W.H., Smith, D.D., 1978. Predicting Rainfall Erosion Losses. USDA – Agricultural Research Services, Handbook 537. Washington, DC, USA, 57p.

Xevi, E., Christiaens, K., Espinao, A., Sewnandan, W., Mallants, D., Sorensen, H., Feyen, J., 1997. Calibration, validation and sensitivity analysis of the MIKE-SHE model using the Neuenkirchen catchment as a case study. Water Resour. Manage. 11, 219–242.

Young, R.A., Onstad, C.A., Bosch, D.D., Anderson, W.P., 1989. AGNPS: a non-point source pollution model for evaluating agricultural watersheds. J. Soil Water Conserv. 44 (2), 68–73.

Yu, B., Rosewell, C.J., 2001. Evaluation of WEPP for runoff and soil loss prediction at Gunnedah, NSW, Australia. Aust. J. Soil Res. 39, 1131–1145.

Zeleke, G., Winter, T., Flanagan, D.C., 1999. BPCDG: Breakpoint Climate Data Generator for WEPP Using Observed Standard Weather Data Sets. <http://topsoil.nserl.purdue.edu/nserlweb/weppmain/BPCDG.html>.

Zhang, X.C., Nearing, M.A., Risse, L.M., McGregor, K.C., 1996. Evaluation of WEPP runoff and soil loss predictions using natural runoff plot data. Trans. ASAE 39, 855–863.