EVALUATING SPATIAL DISTRIBUTION OF SOIL EROSION USING WEPP EROSION MODEL AND GIS TOOLS: A REVIEW

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Abstract. Soil water erosion is a major global environmental problem. In order to develop a comprehensive soil and water conservation plan, it is essential to estimate runoff and soil loss. Simulation models are important available tools for soil erosion assessment without costly and time consuming field tests. In this paper, the capability of the WEPP (Water Erosion Prediction Project) watershed model for simulating runoff and soil lossisreviewed. Monthly and event-by-event runoff and sediment yieldcan be simulated by the WEPP model.The geo-spatial interface of the WEPP model (GeoWEPP) is used in preparing the database with WEPP. The breakpoint climate data generator (BPCDG) and climate component of the WEPP model (CLIGEN) can be used to generate the climate file. The overall results of the model calibration may show over-predictions or under-predictions.The model may predict sediment yield for selected events with a low E_{NS} but the model performance may be poor for continuous simulating and vice versa. The sensitivity analysis and calibration process can show that the sediment yield and runoff are sensitive in some parameters such as inter-rill erosion and effective hydraulic conductivity. The review indicates that the WEPP model can be used for developing soil and water conservation management plan.

Keywords: Erosion modeling, GeoWEPP model, runoff, soil loss, WEPP

INTRODUCTION

Degradation of soil and waterresources will affect the quality of theenvironment. Controlling water erosion to conserve soil quality and to increase agricultural productivity is the most important environmental issues.Soil water erosion is known as a main threat for environment (Clark et al., 1985) and crop productivity (Lal, 1995) which makes the knowledge of the erosion process essential to environmentprotection (Matson et al., 1997). Soil degradationis responsible for making 0.3–0.8% of the world's arable landunsuitable for agricultural production every year (Lafond et al., 2006). Therefore, soil and water resourcesmust be safeguarded against degradation and deterioration factorsfor sustainable agricultural production and environment protection.In Iran, soil erosion rate from cultivated landsis high. The exact managementof the problem in Iran is a subject of debate, and there isa need to study soil erosion and monitor to assess the problem. It is essential to estimate runoff and soil loss to develop a management plan for soil and water conservation.

Appropriate simulation models can be used to soil erosion assessment, without costly and time consuming field experiments (Pieri et al., 2007). Among the available tools to assess soil erosion, models are important because reliable models can be used to evaluate a variety of management scenarios without costly and time consuming field experiments. The Universal Soil Loss Equation (USLE) has been used as a soil erosion model on the field scale. Considering the limitations of the empirically based USLE, process-based soil erosion models have been developed such as the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989). This model represents the state-of-the-art in modeling the effects of changes in surface characteristics on soil erosion that computes spatial and temporal distributions of soil loss and sediment from overland flow on hillslopes (WEPP Hillslope model), soil loss and sediment yield from concentrated flow in small channels (WEPP Watershed model), and sediment deposition in impoundments (Flanagan and Nearing, 1995). The WEPP is able to represent complex slope geometries, nonuniform soils, and cropping and management practices on a hillside which this ability is a major improvement over the USLE in WEPP. Erosion Prediction Project (WEPP) model is one of the most utilized tools for simulating water erosionand sediment yield. Soil erosion prediction models need to be properly calibrated and validated using measured data of the watershed before model application. The WEPP erosion model is a new prediction model, which can be adapted to the case of the various study areas.WEPP has been calibrated and applied in various locations in United States (Huang et al., 1996; Laflen et al., 2004) and other countries (Rosewell, 2001; Brazier et al., 2000). However, application of WEPP in the Iranian environment and many areas is lacking in the literature. There isa study using WEPP for modeling erosion in the hilly areaof Sicily (Spadaro et al., 2004). WEPPis used successfullyworldwide (Pieri et al., 2007; Baigorria and Romero, 2007; Shenet al., 2009; Shen et al., 2010; Pandey et al.,2008) for estimating runoff and soil loss from different land use types.Furthermore, several studies have been conducted to test the sensitivity of model parameters and evaluated the performance of the WEPP under the US conditions, on the hillslope scale (Nearing et al., 1990, Flanagan, 1991, Zhang et al., 1996) and reported generally acceptable indices of model efficiency. However, a few studies have been made in other countries, due to the need of large input data sets.Zeleke (2010)applied the WEPP model to the traditional cropping systems of theEthiopian highlands.They found that the model over-estimates runoff. In addition, the model slightly under-estimates soil loss that is contrary to the findings of similar studies in the US. The model predicted soil loss, with model efficiencies of 0.74, 0.58, and 0.72 respectively. Xinxiao et al. (2009) calibrated and validated the runoff and sediment yield simulated by GeoWEPP model of the WEPP model using the runoff and sediment yield data from two watersheds, in the Loess Plateau of China.

The simulation results showed the model could be used to simulate the runoff and sediment yield in these small watersheds.Dun et al. (2009) assessed the performance of the WEPP modified model by applying it to a research forest watershed in the Pacific Northwest, USA. Simulated annual watershed discharge was negligible using WEPP v2004.7, and was 262 mm using WEPP v2008.9, in agreement with field-observed 275 mm. Yüksel et al. (2008) estimated the sediment yield and runoff from Orcan Creek watershed in Kahramanmaras region using GeoWEPP model. The index of agreement was 0.98 and 0.99 for sediment yield and runoff, respectively, which showed satisfactory performance. Pandey et al. (2008) calibratedand validated the WEPP model for a small hilly watershed (Karso) of India. Their results showed that the sediment yield is highly sensitive to inter-rill erodibility and effective hydraulic conductivity, whereas, runoff is sensitive to effective hydraulic conductivity only. High value of coefficient of determination (R^2) (0.81–0.95), Nash–Sutcliffe simulation model efficiency (0.78–0.92) and percent deviation values (4.43–19.30) for sediment yield indicates that the WEPP model can be successfully used in the studied area.Pieri et al (2007) tested the WEPP model in the Apennines Mountain Range, northern Italy. Results showed that WEPP could apply for the water balance for the modeled experimental plot. Gronsten and Lundekvam (2006) conducted a study for simulating surface runoff (yearly and daily) and soil loss by the WEPP Hillslope model v. 2002.7 in southeastern Norway. In general, their results showed that the WEPP Hillslope model simulated fewer runoff events than observed for all management systems during 1990–1998.

Overall, the studies have proved good applicability and performance of WEPP for simulating soil erosion and runoff. Clearing of forests for cultivated land on steeper slopes accelerates soil erosion over a long period of time, which leads to soil loss in these areas. Monitoring of soil erosion processes on such areas requires various gauging stations installation that is often expensive. Suitable simulation models can be used to soil erosion assessment, without costly and time consuming field experiments in such area. Accurate and precise calibration of the WEPP model is important in the watershed conditions for accurate simulation results. The main objective of this paperis to reviewWEPP model and available findings on the application method and suitability ofthe WEPP model in the watersheds to perform calibration, validation and sensitivity analysis for simulating the runoff and sediment yield.

WEPP MODEL DESCRIPTION

WEPP was developed to estimate sediment yield and runoff based on some erosion factors including soil type, climate conditions, plant cover, and topographic condition. WEPP is a process-based distributed parameters model for simulating runoff and soil loss within a watershed (Flanagan and Nearing, 1995) or along a hillslope (Laflen et al., 1991). The hillslope version of the model has nine components including weather generation, winter processes, irrigation, surface hydrology, subsurface hydrology, soil, plant growth, residue decomposition, overland-flow hydraulics, and erosion. The channel hydrology and hydraulics, channel erosion, and impoundments components were added in the watershed version. The WEPP works in continuous as well as single-storm simulation mode. This model is considered to possess the state-of-the-art knowledge of the erosion science, and has become an important tool for runoff and sediment estimation (Lane et al., 1997). WEPP can divide a hillslope into multiple overland flow elements (OFE), which is defined as an area having uniform soil properties, slope and management. The model predicts the spatial and temporal distribution of soil erosion or sediment deposition in a watershed. The distributed input parameters for the model include rainfall amount and intensity, soil texture, plant growth parameters, residue decomposition parameters, effects of tillage operations on soil properties and residue amount, slope shape, steepness and orientation, and soil erodibility.

Although a detailed description of WEPP components is presented in the model documentation (Flanagan and Nearing, 1995), a brief description of the major components is included below. Daily or single-storm climate can be generated for the WEPP model with CLIGEN (Nicks et al., 1995). Infiltration is computed by a Green-Ampt Mein-Larson equation (Mein and Larson, 1973). Overland flow is routed using either an analytical solution to the kinematic wave equations or regression equations. Peak runoff rate at the channel or watershed outlet is calculated by the methods used in the CREAMS model (Knisel, 1980) and a modified rational equation used in the EPIC model (Sharpley and Williams, 1990).

The model considers inter-rill and rill erosion process in hillslopes as well as in channels. The movement of suspended sediment in rill, inter-rill, 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.Actual evapotranspiration (ET) is evaluated using the Penman–Monteith model (Allen et al., 1998). The overland-flow hydraulics component performs overland flow routing based primarily on the approximate solutions to the kinematic wave equations. In addition, this component estimates hydraulic properties as affected by surface soil and vegetation cover conditions.

GeoWEPP Model

GeoWEPP is the geo-spatial interface of the WEPP model developed as a project conducted by the Purdue University, Agriculture Research Service, and the USDA National Soil Erosion Research Laboratory.GeoWEPP can generate manually necessary input data and allows to process Digital Elevation Model (DEM), soil surveys, land use maps, and farming data. This modelintegrates WEPP model and TOPAZ (topography PArameteriZation) to estimate soil erosion and runoff in the watershed. In order to estimate soil erosion using the GeoWEPP, required input files including land cover, land use, slope, climate, soil, and management are generated. After defining the channel network, TOPAZ generates the sub-watersheds (Fig.1).

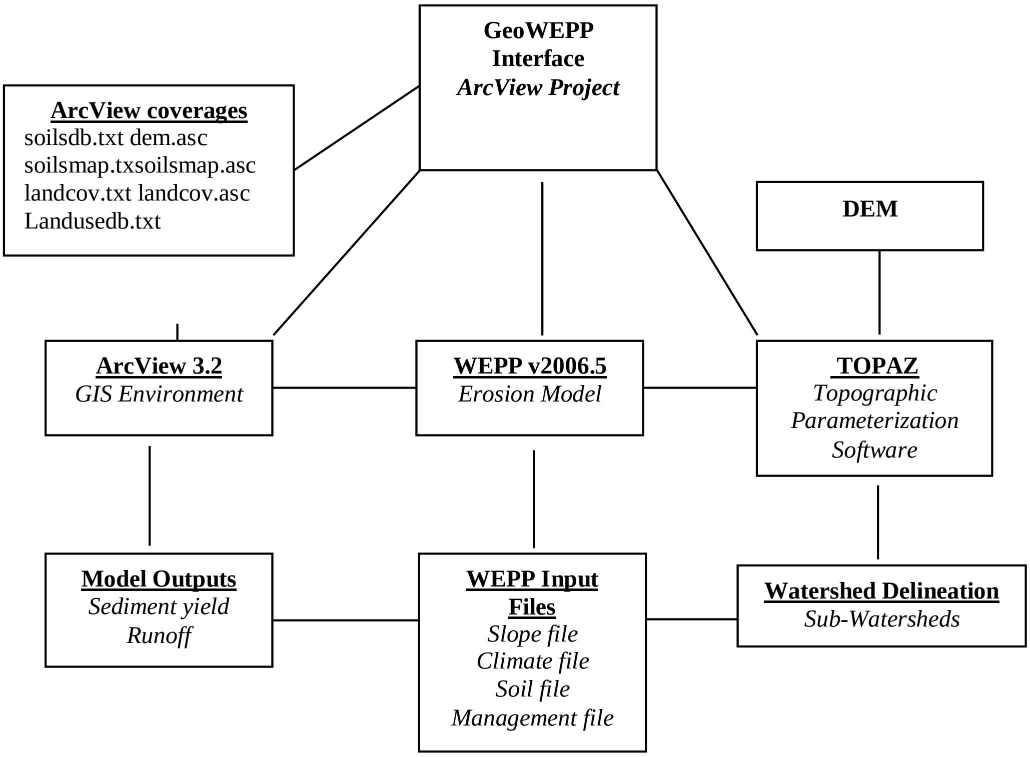


Fig.1. A flowchart of the GeoWEPP (Yuksel et al., 2008)

WEPP Model Application

The WEPP watershed model can be used for continuous simulating monthly sediment yield and runoff andestimating runoff and erosionrelated to storm eventsin studied watershed.The WEPP model requires four input files including climate, topography, soil, and management which were generated. Then, spatial erosion and sediment yield distribution is determined. After this, the critical sub-watersheds effective in sediment yield and erosion are determined using the response unit method.The linear regression coefficients and Nash and Sutcliffe (1970) model coefficientsare used during calibration, sensitivity analysis, and validation processes to determine goodness of fit of the measured and estimated values.In addition, the model is calibrated for soil erodibility parameters and effective hydraulic conductivity.

MODEL INPUT REQUIREMENTS

As mentioned above, WEPP model requires four input files including slope, climate, soil, and management. In the following, the input data in WEPP are briefly described:

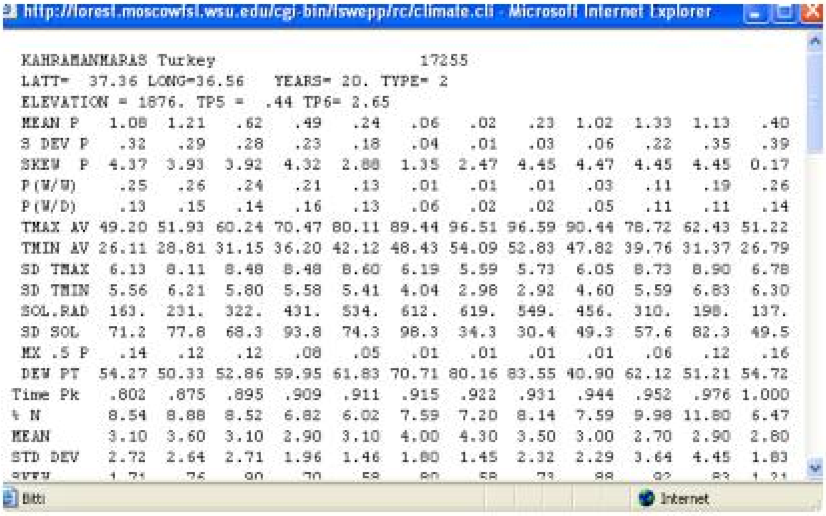
Slope input file. The slope file is generated based on parameters such as slope length, orientation, and steepness whichare provided for each overland flow element (OFE). OFE is a region of homogeneous soil, crop, and management within the hillslope. Slope parameters for OFEs are derived from the DEM. The hillslopes and channels aredelineated. To produce sub-watershed profiles, GeoWEPP applies TOPAZ based on DEM data.The channels may be derived from DEMs, generated by using TOPAZ based on the 1:250000 scale topographic maps.

Climate input file .Climate data for the considered period are used for continuous simulating. Meteorological data such as maximum and minimum temperature, relative humidity, solar radiation, and wind velocity are collected from nearest station to the study region. WEPP accepts two different types of climate input files including the CLIGEN (climate component of the WEPP model) format (Nicks *et al*., 1995) and BPCDG (breakpoint climate data generator). The BPCDG and CLIGEN are used to generate the climate file. Climate data required by the WEPP model including observed precipitation, daily temperature (maximum, minimum, and dew point temperature), wind speed and direction,solar radiation are used for BPCDG program (Zeleke et al., 1999) to generate climate file(Fig.2)running a simulation of studied years.BPCDG and CLIGEN programs (Flangang, 1995)generate climate data in the format accepted by the model using observed meteorological database. CLIGEN is used for continuous simulating and BPCDG for storm events.

Soil input file. Physical and chemical properties of soil in the watershed are obtained from a detailed soil survey. In WEPP, required parameters in the soil file are soil texture (% sand, silt, and clay), Albedo, initial saturation level, hydraulic conductivity, rill erodibility and inter-rill erodibility, and critical shear. The values of the other properties including initial saturation level (%), albedo, hydraulic conductivity, rill andinter-rill erodibility, and critical shear are calculated using equations described in the WEPP technical documentation (Flanagan and Nearing, 1995). All the calculated parameters except albedo may calibrate before application of the model for simulating. Soil parameters used for simulations by the model may includes soil texture (% sand, silt, and clay), organic Matter (%), CEC (meq/100 g), and rock fragments (%).The Green-Ampt effective hydraulic conductivity equation may be used to estimate hydraulic conductivity. The inter-rill- (Ki) and rill- (Kr) erodibility, critical shear stress (tc), and the effective hydraulic conductivity (Kb) are computed usingequations in WEPP User Summary (1995).

Management input file. The required management file data (e.g. the amount of vegetation, residue management, initial conditions) are obtained by field-measurements and default management parameter values and then entered into the WEPP. The initial condition existed at the beginning of the simulation, is important for continuous simulation. The initial conditions are provided based on the records and measurements in the studiedwatershed.

The management file is generated for different land use types (agriculture, rangeland, residential regions, forest, and …). Vegetation cover management practices parameters, all other relevant data, and irrigation and drainagedata are gathered from soil survey study conducted in the region. Default physiological crop parameter values for studied area are extracted from the WEPP database (Flanagan and Livingston, 1995).



http://forest.moscowfsl.wsu.edu/cgi-bin/fswepp/rc/climate.cli - Microsoft Internet Explorer

KAHRAMANMARAS Turkey 17255
LATT= 37.36 LONG=36.56 YEARS= 20. TYPE= 2
ELEVATION = 1876. TP5 = .44 TP6= 2.65

MEAN P	1.08	1.21	.62	.49	.24	.06	.02	.23	1.02	1.33	1.13	.40
S DEV P	.32	.29	.28	.23	.18	.04	.01	.03	.06	.22	.35	.39
SKEW P	4.37	3.93	3.92	4.32	2.88	1.35	2.47	4.45	4.47	4.45	4.45	0.17
P(W/W)	.25	.26	.24	.21	.13	.01	.01	.01	.03	.11	.19	.26
P(W/D)	.13	.15	.14	.16	.13	.06	.02	.02	.05	.11	.11	.14
TMAX AV	49.20	51.93	60.24	70.47	80.11	89.44	96.51	96.59	90.44	78.72	62.43	51.22
TMIN AV	26.11	28.81	31.15	36.20	42.12	48.43	54.09	52.83	47.82	39.76	31.37	26.79
SD TMAX	6.13	8.11	8.48	8.48	8.60	6.19	5.59	5.73	6.05	8.73	8.90	6.78
SD TMIN	5.56	6.21	5.80	5.58	5.41	4.04	2.98	2.92	4.60	5.59	6.83	6.30
SOL.RAD	163.	231.	322.	431.	534.	612.	619.	549.	456.	310.	198.	137.
SD SOL	71.2	77.8	68.3	93.8	74.3	98.3	34.3	30.4	49.3	57.6	82.3	49.5
MX .5 P	.14	.12	.12	.08	.05	.01	.01	.01	.01	.06	.12	.16
DEW PT	54.27	50.33	52.86	59.95	61.83	70.71	80.16	83.55	40.90	62.12	51.21	54.72
Time Pk	.802	.875	.895	.909	.911	.915	.922	.931	.944	.952	.976	1.000
% N	8.54	8.88	8.52	6.82	6.02	7.59	7.20	8.14	7.59	9.98	11.80	6.47
MEAN	3.10	3.60	3.10	2.90	3.10	4.00	4.30	3.50	3.00	2.70	2.90	2.80
STD DEV	2.72	2.64	2.71	1.96	1.46	1.80	1.45	2.32	2.29	3.64	4.45	1.83

Bitti Internet

Fig. 2. Generated climate file (Yuksel et al., 2008)

WEPP SIMULATION AND MODEL PERFORMANCE

Simulation methodology. The runoff and sediment yield data from the studied watersheds, are used to calibrate and validate the monthly runoff and sediment yield,and runoff and sediment yield from rainfall events are simulated by GeoWEPP model of the WEPP Model. Therainfall events identified during studied years, are chosen for single-event simulations. The calibrationmay be donemanually based on trial-and-error procedure (Sorooshian and Gupta, 1995). Accurate simulation depends upon quality and large quantum of input data. To do sensitivity analysis to know of the parameters which affect the output of the model to a larger extent with a low change in their values is important to enhance the model performance. Sensitivity analysis of the model is performed to assess the model output variations with change in soil input parameters. The model's sensitivity to an input parameter is determined by change in the values of input parameters, while no change in other parameters and then comparing the estimated runoff and sediment yield. Sensitive parameters, which are estimated using the proposed equations (Flanagan and Livingston, 1995), areused for calibration. Nearing et al. (1990) and Pandey et al. (2008)demonstrated that the WEPP model is very sensitive to soil input parameters for runoff and erosion simulation. The soil input parameters considered for sensitivity analysis including effective hydraulic conductivity, interrill and rill erodibility, and critical hydraulic shear may be considered for calibration. The values of soil parameters areset within the prescribed range (Flanagan and Livingston, 1995). Simulations are performed optimizing the parameters values until a minimum percent deviation value be obtained. The values of these parameters may be increased and decreased by ±10, ±20, ±25, and ±50% from their calibrated values during the analysis and sensitivity ratiosare determined. After calibration, precise validation is carried out for model verifying before it be applied and used for the runoff and sediment yield simulations of the studied watersheds. The performance of the calibrated model isassessedduring validation. The measured surface runoff and sediment yield values are compared with the model-simulated values.

Model performance. To assess the model performance, goodness-of-fit between measured and predicted values can be determined using the percent deviation (Dv) (Martinec and Rango, 1989) and Nash and Sutcliffe (1970) simulation coefficient (E_{NS}) for the observed and estimated runoff and the coefficient of determination (r^2) determined from linear regression during calibration, sensitivity analysis and validation process.

$$R^2 = \left[\frac{\sum_{I=1}^{n}(Q_i-\bar{Q})(P_i-\bar{P})}{\sqrt{\sum_{i=1}^{n}(Q_i-\overline{Q})\sum_{i=1}^{n}(P_i-\overline{P})}}\right]^2 \quad (1)$$

$$R_e = \frac{P_i - Q_i}{Q_i} \times 100\% \quad (2)$$

$$E_{ns} = 1 - \frac{\sum_{i=1}^{n}(Q_i - P_i)^2}{\sum_{i=1}^{n}(Q_i - \overline{Q})^2} \quad (3)$$

Where Q_i and P_i are the observed and estimated values, respectively. E_{ns} compares estimated values to the 1:1 line between measured and estimated values. E_{ns} ranges from -1 to 1. The results areassessed and required decisions are made to calibrate some soil parameters.

Runoff and sediment yieldsfrom continuous and event by event simulations. In this step, the sediment yield map is generated which indicates the critical areas in the study region.The performance of the model can be also statistically evaluated on an annual and event basis for selected events. The model may performdifferent in predicting event valuesand annual values and the model performance for continuous and single-event simulations of the WEPP model maybe different. Probable reasons for this are discussed in the following. In general, the validation results may indicate that the model has an acceptable performance to runoff and sediment yield prediction from rainfall events but a low or medium performance in monthly sediment yield estimation.The trend of the simulated values may correspond to the trend of the observed values for calibration and validation periods. The observed peak runoff values may correspond to the estimated values for validation. In an investigation, Kırnak (2002) reported the WEPP-estimated sediment yield and runoff against observed data revealed r^2 of 0.94 and 0.91, respectively. Thus, it can be concluded that the WEPP model can be used to generate acceptable predictions of sediment yield and runoff in a watershed. The model may tend to over- and under-predict smaller and larger events. This may be resulted that soil loss process is a complex phenomena affecting by rainfall, runoff, soil particle distribution, land use, land slope and management and interaction between them. Thus, randomness in sediment yield values may be considerable.The under-estimation of larger values of runoff may be attributed to the role of surface sealing that may be not well reflected in the model.Soil surface sealing effect on runoff producing and sediment yieldis obvious, during the larger rainfall events with high initial soil water content.During high rainfall events, the runoff generation process may be different in various parts of the watershed with high runoff generation depending on slope gradient.Thismay make some error in runoff estimation during same calculation process of runoff for total hillslope. Imprecise calibration of subsurface parameters in the study may lead to generate some errorin the model output.Pandey et al. (2008) and Croke and Nethery (2006)showed that the larger observed values were under-estimatedthat may becaused by representing the random components of the observed data (Nearing, 1998). Thus, the over- and under-estimating may not be due to the model prediction capability. Kramer and Alberts (1995) and Zhang et al.(1996) applied the WEPP andstated that smaller values were over-estimated and larger values were under-estimated for average annual and event runoff. The random component related to the larger values may be high resulted fromagricultural activities and high rainfall. Moreover, the sediment yield under-estimation by WEPP may be due to the imprecise of calibration of the soil-related parameters. Therefore, some of the observed variations can be attributed to errors in the database.

SENSITIVITY ANALYSIS

Sensitivity analysis is done to identify effective parameters and quantify the influence of these parameters on model outputs. Sensitivity analysis determines the accuracy level required in determination of parameters for the model application. The results of sensitivity analysis mayshow that the variation of e.g. effective hydraulic conductivity affects the runoff and/or sediment yield is sensitive to e.g. rill erodibility, inter-rill erodibility, and critical shear stress of soil. Considered parameters for the sensitivity analysis are soil-related parameters. The values of these parameters are increased and decreased by ±10, ±20, ±25, and ±50% from their calibrated values during the analysis and sensitivity ratios are determined. In erosion process, rill, inter-rill and critical shear stress are considereddominant. Effective hydraulic conductivity may be more effective in runoff generation compared to other soil-related parameters, which can be revealed from the values of sensitivity ratio in runoff simulation. Hantush and Kalin (2005) found that the model-estimated sediment yieldis very sensitive to soil-related parameters. Thus, it is essential to estimate the soil parameters precisely for accurate simulation.

Some of the errors in soil loss estimation may be attributed to the runoff estimations. Existing errors in runoff may correspond to errors in soil loss, indicating the importance of good runoff simulation to accurate estimation of soil loss processes. The sediment yield map can indicate the sediment yield and erosion rate in different part of the watersheds.Very high land slope in theconsidered region may be one of the most important factors in erosion process. In addition, a high erosion rate may be observed in agricultural area and river side regions which may be due to the shear stress of the river flow (Singh et al., 2011).The areas under agriculture, which may have loose surface soil as a result of land cultivation, may be responsible for high sediment yield.

EVALUATING THE EFFECTIVENESS OF SUB-WATERSHEDS IN RUNOFF AND SEDIMENT YIELD

In this step, the watershed is delineated to several sub-watersheds and then the effectiveness of each of the sub-watersheds in runoff and sediment yield process (for the studied year) can be assessed using hydrologic response units (HRUs) method. HRUs technique allows the partitioning of a watershed into a number of sub-watersheds with unique land use, soil properties, andmanagement. Then, critical sub-watersheds in terms of runoff and sediment generationareidentified. Sediment yield map in the effective sub-watersheds in runoff and sediment yieldcan present spatial sediment yield distribution in sub-watersheds which are most important ones to generate runoff and sediment producing. The sub-watersheds having a high rate of sediment yield may be under agricultural activities which face threat of soil degradation. This may prove the conservation measures necessity considering the high economically value of the lands in these regions.

CONCLUSION

In the present paper, the application of WEPP and its capability to model runoff and erosion in the watershed was reviewed and discussed. The review result indicates that WEPP may adequately simulate the runoff and sediment yield. Comparison between WEPP-predicted and observed runoff and sediment yield may indicate that WEPP tends to under- or over-predict sediment yield. Moreover, during WEPP application, precise calibration of the soil-related parameters can be done in order to improve predictions and accurate model calibration for the study sites. It may befound that the model-estimated sediment yield is sensitive to soil-related parameters. Thus, it is essential to estimate the soil parameters precisely for accurate simulation. WEPP may bea useful tool for assessing the spatial soil erosion distribution in the study areas.It can be suggested that database improvement helps to accurate calibration and WEPP model applicationas useful tool for predicting soil loss inthe study regions.However, the modelperformance must be evaluated for predictingsediment yield for selectedevents and continuous simulating in the study sites.

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