Application of Water Erosion Prediction Project (WEPP) to estimate soil erosion from single storm rainfall events from construction sites

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Abstract

Soil erosion is a major form of land degradation and has been recognised as a severe environmental problem since late 18th century. Mathematical modelling of soil erosion has been proven to be a cost effective technology to predict soil erosion from different land use practices. The Water Erosion Prediction Project (WEPP) is regarded as one of a new generation of soil erosion models as it is process based and predicts soil erosion at spatial and temporal scales. In addition, WEPP is applicable for hillslopes as well as small watersheds and estimates soil erosion in hourly, monthly or annual timestamps from single storm or multiple storm rainfall events from variety of land use practices.

This paper discusses the application of WEPP to estimate soil erosion from the single storm rainfall event with different soil conditions. Soil erosion is measured from the erosion plot experiments carried out at the University of Western Sydney using large-scale rainfall simulators. Experiments were carried out in dispersive clayey soil and permeable sandy soil with three common land use practices to represent the construction sites in New South Wales. Soil, land use and climate data obtained from the experiment and collected from secondary sources were used as input to the model. Predicted soil loss values were compared with corresponding measured ones. Results obtained from 22 different runs show that WEPP can efficiently estimate soil erosion due to single storm rainfall event from construction sites.

Key Words

Soil erosion, WEPP, modelling, rainfall simulation, construction site

Introduction

The USDA Water Erosion Prediction Project (WEPP) model represents a new generation of erosion prediction technology based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics and erosion mechanics (Flanagan *et al.* 1995). WEPP uses steady state sediment continuity equation to estimate soil erosion and deposition in the hill slope and the watershed in hourly, daily, monthly or annual basis from single storm or multiple storm rainfall events from variety of land use practices.

Soil erosion in hillslope is represented as two components in the WEPP model: soil particle detached by raindrop and transported by thin sheet flow, known as interrill erosion component and soil particle detached by shear stress and transported by concentrated flow, known as rill erosion components. The steady state sediment continuity equation used to estimate net detachment in the hillslope is expressed as (Foster *et al.* 1995):

$$\frac{dG}{dx} = D_f + D_i \quad (1)$$

where: G=Sediment load (kg/m^2/s) at distance x from the origin of hillslope, x=Distance down slope (m), D_i=Interrill sediment delivery rate to rill (kg/m^2/s) and D_f =Rill detachment rate (kg/m^2/s). Interrill erosion function of above equation (D_i) is given as (Foster *et al.* 1995):

$$D_i = K_{iadj}\, I_e \sigma_{ir}\, SDR_{RR}\, F_{nozzle} \left(\frac{R_s}{w}\right) \quad (2)$$

where: K_{iadj} =Adjusted interrill erodibility (kg s/m^4), I_e=Effective rainfall intensity (mm/h), σ_{ir} =Interrill runoff rate (mm/h), SDR_{RR}=Interrill sediment delivery ratio, F_{nozzle}=Adjustment factor for sprinkler irrigation nozzle impact energy variation, R_s=Rill spacing (m), w=Width of rill (m) and rill erosion function (D_f) is given as (Foster *et al.* 1995):

$$D_f = K_{radj}\left(\tau_f - \tau_{cadj}\right)\left(1 - \frac{G}{T_c}\right) \quad (3)$$

where: K_{radj} = Adjusted soil erodibility parameter (s/m), τ_f =Flow shear stress (kg/m/s^2), τ_{cadj}=Adjusted critical shear stress of the rill surface (kg/m/s^2) and T_c=Sediment transport capacity of the rill flow (kg/m/s) is given by the relation (Foster *et al.* 1995;Huang and Bradford 1993)

$$T_c = K_{tr} q_w s \quad (4)$$

where: K_{tr} = constant parameter, q_w= flow discharge per unit width (m^2/s)and s = slope (%)

The deposition equation is given as (Foster and Meyer 1972; Foster *et al.* 1995):

$$\frac{dG}{dx} = \frac{\beta_r V_f}{q_w}\left(T_c - G\right) + D_i \quad (5)$$

where: V_f = Effective fall velocity of the sediment (m/s) and β_r = Raindrop induced turbulence coefficient (0-1).

Parameters in equations 1 and 5 are normalized with corresponding parameter values of uniform hillslope condition. The equations are then solved to find soil erosion and deposition at particular point of interest at distance x from the top of the hillslope at desired time interval.

Model interface

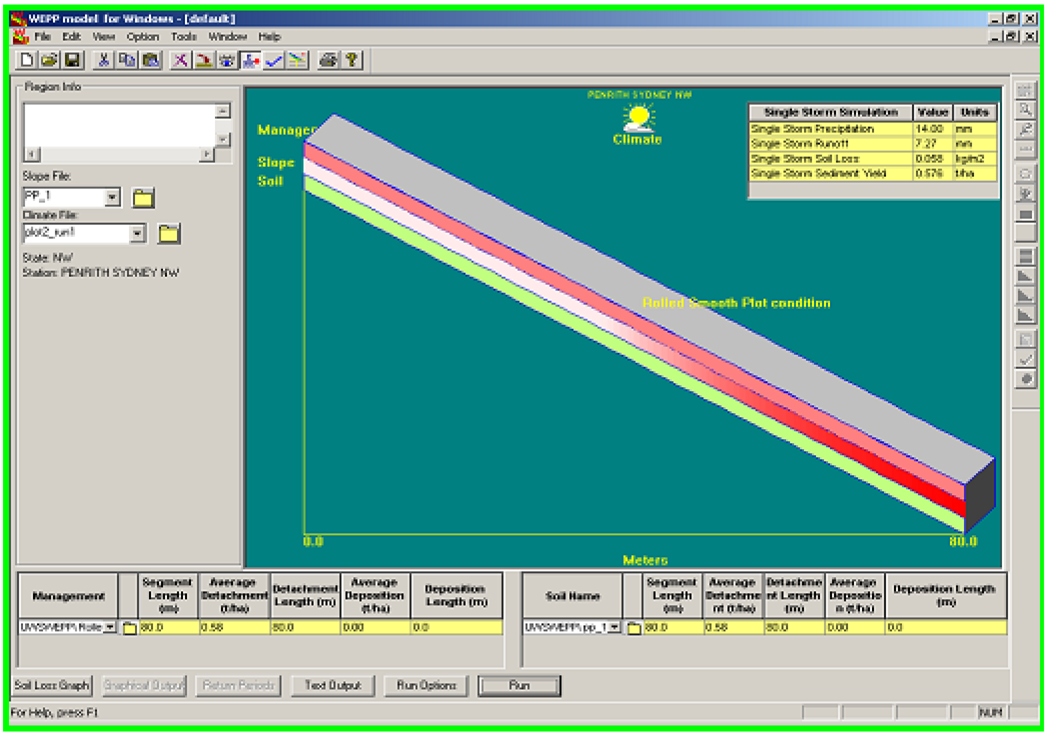

Figure 1. WEPP Windows Interface.

WEPP software consists of an erosion prediction model (WEPP) written in the FORTRAN programming language, a climate generator program (CLIGEN) also written in the FORTRAN programming language, and a Windows interface (WEPPWIN) written in the Visual C++ programming language (Flanagan and Frankenberger 2002). The interface accesses databases, organizes WEPP and CLIGEN simulations, creates all necessary input files for WEPP and CLIGEN, and executes the FORTRAN models when necessary (Flanagan and Frankenberger 2002). The interface also accesses and processes output information from the FORTRAN models for display and access by the user.

The main Windows interface screen shows a graphical depiction of a hillslope profile, with various areas providing access to input databases and output display (Figure 1). The profile shape is drawn based upon the model slope inputs, which can be accessed through the middle layer on the graphic. Soil information can be accessed through the bottom layer on the graphic, and the cropping/management information through the top profile layer. Climate inputs can be selected or generated through the icon at the top centre of the screen. The horizontal profile length dimensions are provided at the bottom of the screen in either English or metric units.

Construction sites are significant source of sediment and other non point source pollution. Soil erosion from construction sites, without proper soil erosion and sediment control practices can average between 20-200 tones/acre/year, which is 10 to 20 times greater than typical losses from the agricultural land (NRCS 1999). Soil erosion from construction sites thus is more severe in terms of intensity than from agricultural land and degrades land more rapidly.

Different erosion models have been developed in the past to estimate the rate of soil erosion from different landuse practices. USLE, RUSLE, SOILOSS, EPIC, CREAMS and WEPP are few examples. WEPP was developed to overcome spatial and temporal limitation many previous models like USLE and EPIC. However, soil erosion is a natural process influenced by local natural variables, it is essential to evaluate soil erosion prediction models before their application. This study was aimed to evaluate efficiency of WEPP in predicting soil erosion from single storm rainfall events from construction sites in New South Wales so that the model could be use as an alternative tool over existing models.

Methods
Evaluation of WEPP was carried out using the data from the erosion plot experiments carried out at Penrith campus of the university and at Gosford, NSW. The rainfall intensities used in this experiment were chosen to be representative of the low (one year average recurrence interval (ARI)) to medium (five to 10 year ARI) with 30-minute rainfall duration. The intensities were obtained using IFD curves of selected sites published by Engineers Australia (IEAust 1987). Erosion plots of 80m length and 5m width with slope varying between 7% or 8% were used with three land use treatments: Rotary hoed, rolled smooth and topsoil restored. These land use conditions are considered as representative of general construction site conditions in New South Wales, Australia (Pudasaini *et al.* 2004). Sediment collection troughs and standard RBC flumes (Figure 2) Bos (1991) were installed to collect sediment deposited and to measure runoff from each of the plots.

Figure 2. RBC Flumes.

Large-scale pressure sprays rainfall simulators (Figure 3) calibrated by Farre (2001) were used for the rainfall simulation. Rainfall intensity was measured by placing rain gauges in pre-specified grid across each erosion plot. Discharge was measured in 30 second or one minute interval, manually by reading the water height in the stilling well. Soil samples were collected from three different locations of each plot before and after experimental runs and analysed. Model parameters such as organic matter content, percentage clay, percentage silt, percentage sand, soil albedo and percentage rock fragment were also obtained from the detailed soil analysis data. Sediment concentration in runoff water was estimated from volumetric analysis of runoff water sampled during the experimental run. Sedigraphs and hydrographs were used to estimate total suspended soil from each run. Total soil loss from each run is estimated as sum of suspended soil and sediment deposited in the collection trough.

Climate input file required to run WEPP model was prepared by running stochastic climate generator model CLIGEN included in WEPP model. Date of rainfall, nearest climate station, rainfall duration, measured peak intensity and duration of rainfall were used as input to create climate input file from CLIGEN. Soil input file and slope file were also prepared in same manner using graphical user interface included in the model. Due to the lack of much information about the land use data required to prepare the management file, a suitable management file from the WEPP database that matched the adopted land use condition (rotary hoed, rolled smooth and topsoil restored) was used to run the model. Model outputs were compared with corresponding measured soil loss value obtained from the erosion plot experiment.

Figure 3. Rainfall simulation & erosion plot.

Model Efficiency
A new approach of error estimation (Pudasaini *et al.* 2004) is introduced to evaluate the efficiency of the model against the measured soil erosion. A perpendicular distance *(p)* dropped from plotted point of measured versus predicted soil loss *(x, y)* to a line passing through the origin with slope angle of 45^o (OP, Figure 4.) is regarded as error of prediction. This definition is justified because for perfect prediction this distance should be zero. The perpendicular distance *(p)* thus obtained is normalized with corresponding perpendicular distance from the origin *(r).* The standard error of prediction *(SE)* is defined as square root of average of sum of the square of the ratio *(p)* to *(r)*. Equation 6 gives standard error for *(n)* data. Value of *(SE)* ranges from 0 to 1, with the lesser the value the better the prediction.

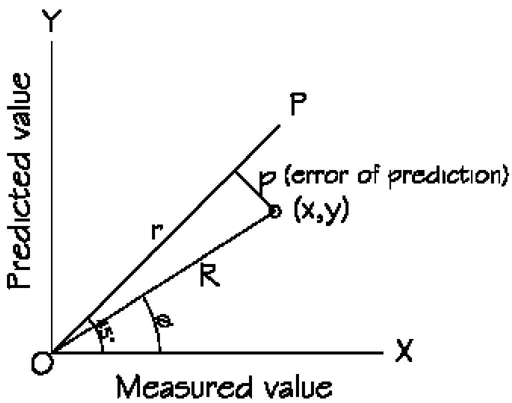

Figure 4. Geometry of error of prediction

$$SE = \sqrt{\frac{\sum \left(\frac{p}{r} \right)_i^2}{n}} \qquad (6)$$

and model efficiency (η) is given by the equation:

$$\eta = 1 - SE \qquad (7)$$

which gives the applicability of the model to predict soil erosion.

Results

Model predictions were reasonable for all land use conditions with percentage difference ranging from 49 to –55 for Penrith plots experiments. More difference were observed from Somersby plot experiments and predicted values of soil erosion. This should be because of the lack of detail land management data and use of default values from WEPP database. Table 1 provides the summary of the model output. It shows measured versus predicted soil loss for the particular land use and rainfall condition of each site.

Table 1. Summary of model output and efficiency of the model.

Site Location	Land use condition	Precipitation (mm)	Runoff (mm)	Predicted soil loss (kg/m2)	Measured soil loss (kg/m2)	Normalised error of prediction	Standard error	Model Efficiency
Penrith	Rotary Hoed	31.0	24.02	0.384	0.345	0.002862	0.28	0.72
		28.0	21.03	0.336	0.268	0.012674		
		32.0	25.02	0.401	0.363	0.002474		
		36.0	29.02	0.465	0.467	4.61E-06		
	Rolled Smooth	14.0	5.50	0.062	0.123	0.108723		
		33.5	26.65	0.398	0.256	0.047143		
		26.0	19.16	0.276	0.272	5.33E-05		
		33.5	26.65	0.398	0.359	0.002654		
	Top Soil restored	23.6	16.77	0.237	0.315	0.019967		
		23.1	16.27	0.229	0.309	0.022112		
		28.4	21.56	0.315	0.520	0.060276		
		41.0	34.15	0.520	1.083	0.123354		
Somersby	Rotary Hoed	25.0	17.08	0.361	0.125	0.235802		
		25.4	17.48	0.369	0.131	0.226574		
		38.2	30.26	0.606	0.314	0.100736		
		37.1	29.16	0.586	0.230	0.190334		
	Rolled Smooth	38.7	31.22	0.711	0.295	0.170996		
		43.5	36.02	0.809	0.619	0.017703		
	Top Soil restored	21.4	13.95	0.341	0.089	0.343448		
		22.2	14.74	0.359	0.291	0.010944		
		35.1	27.62	0.637	0.796	0.012312		
		35.9	28.42	0.653	0.835	0.014961		

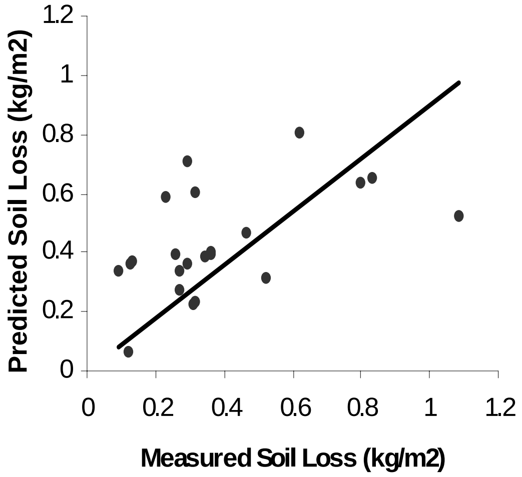

Figure 5. Measured vs predicted soil loss

Standard error of prediction using Equation 6 was estimated to be 0.28 giving model efficiency of 72%. Figure 5. also shows a plot of measured versus predicted soil loss. This scatter plot also shows the relative concentration of plotted points near the line of 45^o, showing the reliability of model prediction. As model efficiency of 72% should be regarded as good value, model can be used to predict soil erosion from single storm rainfall events and result can be used in natural resourses conservation and planning. Use of grassed surface as alternative management practice reduced soil erosion from the bare soil by more than 90%.

Conclusion

This study shows a good potential of using WEPP to predict soil erosion from different land use management practices adopted in construction sites from single storm rainfall event. Proper calibration of model parameters is essential to get good prediction result and to reduce standard error of prediction or the model efficiency.

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