Reconstructing the Patterns of Sediment Transport and Related Hydrological Processes Using the WEPP Model

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Abstract This paper presents simulation results and discusses some issues related to parameterisation of the WEPP model (Water Erosion Prediction Project) to predict sediment transport and runoff from bare soil on experimental hillslopes (13.1 x 3.1 m) at Pukehohe, in south Auckland, New Zealand. Soil loss and runoff data collected from 1971 to 1973 were compared with the simulation results. While WEPP's modelling capacity is being widely explored, our analysis reveals that some procedures for determining the input parameters are unsuitable for New Zealand soils, including those for calculating "baseline effective hydraulic conductivity", which results in greater estimated runoff values than measured ones. This problem is due partly to the high clay content and strongly structured soils at the site, and indicates that the procedures recommended in the current version of WEPP's user summary perform poorly. By using a rating curve for measured sediment and runoff at the experimental plot outlets, sediment hydrographs can be generated for any particular location on the hillslopes, which overcomes the limitation of the steady-state nature of WEPP's sediment routing procedure. Further analysis shows that on a planar hillslope there is a location where soil detachment reaches its maximum rate.

1. INTRODUCTION

Soil erosion is one of the major concerns in Pukehohe, south Auckland, New Zealand, a peri-urban area that has been used for growing vegetables since the early 1900s [Basher et al., 1997a]. Due to high rainfall (mean annual rainfall 1,287 mm) and intensive vegetable production, annual soil loss can be as high as 6,000 t.km^{-2} [Basher et al., 1997b]. In order to quantify soil losses, field experiments were carried out from 1971 to 1973 using plots of bare soil to measure runoff and soil loss. In this paper, we report some results using a physically based erosion model WEPP (Water Erosion Prediction Project) developed by the US National Soil Erosion Research Laboratory [NSERL, 1995], and compare the results with those from the runoff plots.

2. THE MODEL

The WEPP model can be run in two modes: hillslope and watershed. In both modes the model is subdivided into nine conceptual components [NSERL, 1995, p. 4]:

[1] Weather generation – climate data used in WEPP's simulations are generated by a program CLIGEN, which creates climate-input-data files including daily values for rainfall depth, duration, maximum intensity, time to maximum intensity, maximum and minimum temperatures, solar radiation, wind speed, and wind direction, and dew point temperature.

[2] Winter process – simulates soil freezing and thawing, snowfall, and snow melting.

[3] Irrigation – simulates both stationary sprinkler and furrow irrigation systems.

[4] Hydrology – computes infiltration, runoff, soil evaporation, plant transpiration, soil water percolation, plant and residue interception of rainfall, depression storage, and soil profile drainage by subsurface tiles.

[5] Soils – soil physico-chemical properties and impacts of management practices are computed in the soil component.

[6] Plant growth – calculates above- and below-ground biomass productions for both annual and perennial cropland simulations, and for rangeland plant communities in rangeland simulations.

[7] Residue decomposition – for cropland, this is based on a "decomposition decay" approach to track the type and amount of residue from three previous harvests, and takes into account several types of residue management such as residual removal, shredding, burning, and contact pesticide application.

[8] Hydraulics of overland flow – computes the impacts of soil roughness, residue cover, living plant cover on runoff, flow shear stress, and flow sediment transport capacity.

[9] Erosion – uses a steady-state sediment continuity equation to estimate the change in sediment load in the flow with distance downslope. Soil detachment in inter-rill areas is modelled as a function of rainfall intensity and runoff rate, while delivery of inter-rill sediment to rills is a function of slope and surface roughness. Detachment of soil in the rills is predicted to occur if the hydraulic

shear stress of the flow exceeds a critical value, and the sediment already in the flow is less than the flow's transport capacity. Deposition in rills occurs when the sediment load in the flow is greater than the capacity of flow to transport it.

The details of the parameters required for each file are discussed in WEPP User Summary [NSERL, 1995], and also in a number of reports [Tiscareno-Lopez et al., 1993, 1994].

3. THE INPUT PARAMETERS

The nine components of the WEPP are organised in five input files:

3.1. Soil Data File

There are extensive requirements for soil physical, chemical, and hydraulic parameters, which include inter-rill erodibility (K_i), rill erodibility (K_r), hydraulic sheer stress (τ), Green-Ampt infiltration parameter (hydraulic conductivity, K), the number of soil layers, cation exchange capacity (CEC), and initial saturation.

3.2. Climate File

In this analysis, both hourly data and 10-minute rainfall data were used. The 10-minute data obtained by digitising charts from a recording rain gauge. With non-breakpoint simulations, a number of hourly rainfall events were analysed to get rainfall shape parameters.

3.3. Management Data File

As the field plots in Pukehohe were bare soil surfaces, the number of inputs to the management file were significantly reduced. Two roughness coefficients important in this file are random roughness (rro) and initial roughness (rrinit) which are adjusted to minimise the difference between the simulated and observed soil losses. It has been found that soil loss and runoff for each rainfall event are very sensitive to these two parameters.

3.4. Slope Data File

Data for the Pukehohe experimental plot were obtained and a slope gradient of 0.1428 used.

An irrigation file is optional, and is not used here.

4. RESULTS

4.1. Simulated Rainfall and Runoff

Simulations using the breakpoint method for rainfall generated the results shown in Figure 1.

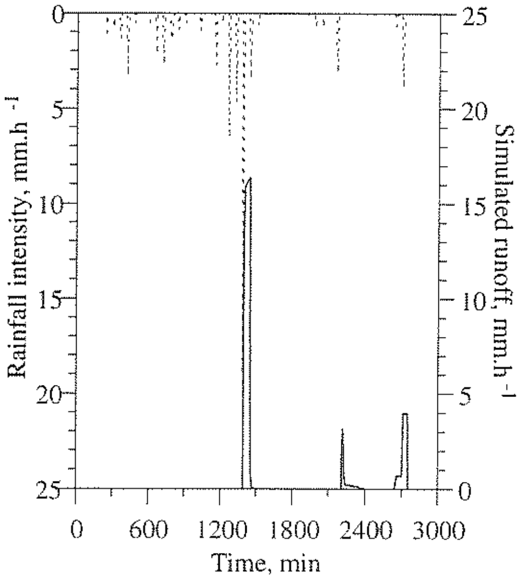

Fig. 1. Simulated rainfall and runoff, 16 May 1972

Higher values of simulated runoff are consistent across many simulations. The observed and simulated results. are listed in Table 1.

Table 1. Summary of a simulation 16 May 1972

Items	Observed	Simulated	Relative error
Runoff coefficient	0.22	0.32	45.5%
Soil loss [kg.m^{-2}]	1.242	1.206	2.9%

The simulated soil loss is very close to that observed, but runoff was not able to be easily optimised.

We further present simulation results using different parameters:

[1]. Rainfall with a total depth greater than 10 mm was used only, because the sites used for data collection were a few km apart, and the distance produced large errors for small rainfall events.

[2]. An average value for the two roughness coefficients obtained from optimisation was used, and the results compared with observed ones using rainfall depth data for the same site.

With 10-minute interval rainfall data collected a site a few kilometres from the experimental plots, and using the breakpoint method for rainfall input, the simulated soil losses versus the observed ones are graphed in Figure 2.

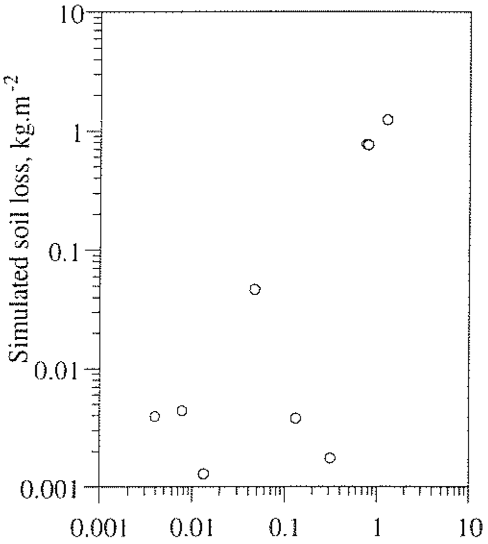

Fig. 2. Comparison of simulated results

In Figure 2, data for plots 1 and 4 at Pukehohe collected in 1972 and 1973 were used. The simulated figures are in good agreement with measured ones for large rainfall events, but not small events.

Because detailed data for the site are not available, extrapolation of the parameters was made to cases where detailed information on rainfall and other parameters are available at other sites. Several extrapolation methods have been attempted to derive rainfall parameters, namely i_p and t_p, for rainfall events on the site in 1972 and 1973.

[1]. An average value for roughness coefficients [random and initial roughness are both equal to 0.023695] was used for the different simulations, given in Figure 2.

[2]. Correlating rainfall parameters: the duration and depth of rainfall data for 1987 to 1989 was used to derive the duration, i_p and t_p for 1972 and 1973, based on the data on rainfall depth for the experimental sites. Analysis of 184 events gives a mean i_p of 2.3915, and mean t_p of 0.3946 for the events from 1987 to 1989

With these extrapolated parameters, and other parameters identical to those in the soil, slope and management files used to generate results in Fig. 2, the rainfall depth data for the same site where soil loss data were collected were used to run the simulations, and the results are graphed in Figure 3.

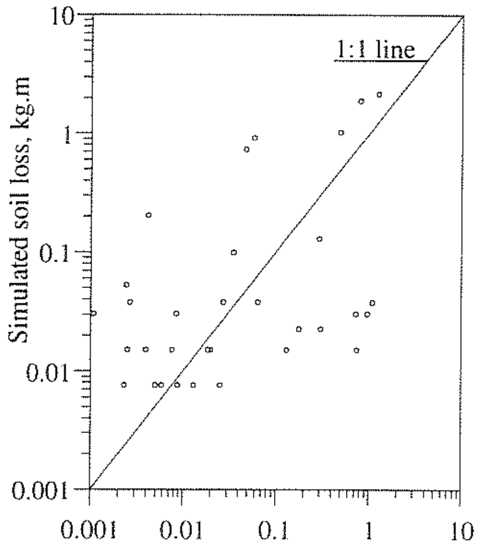

Fig. 3. Simulated versus observed soil loss

It can be seen from Figure 3 that with the extrapolated parameters, the simulated soil losses are in good agreement with the observed ones. This also indicates that the WEPP model should perform better if more accurate data are used.

4.2. Soil Loss along a Slope

Also, WEPP simulates the spatial variation of erosion–deposition along a hillslope. For one of the four experimental plots [plot No. 1, area: 13.1 x 3.1 m^2] in Pukehohe, the simulated detachment (soil loss) is shown in Figure 4.

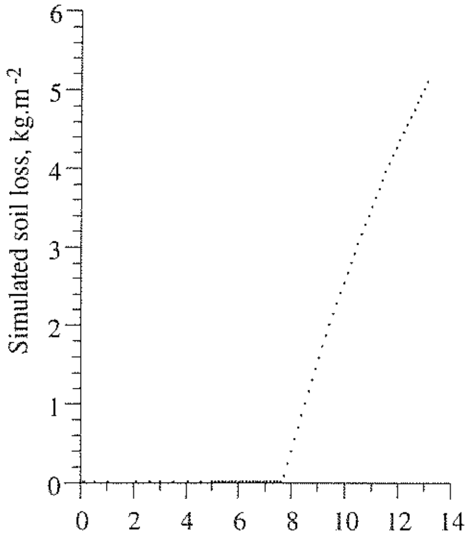

Fig. 4. Changes in detachment along a hillslope

Figure 4 shows that the inter-rill contribution to the soil loss is very small, while the rill contribution does not increase until 7.7 m, and thereafter starts to increase rapidly. Further analysis shows that there are changes in the rate of detachment, measured as the rate of change in detachment along the slope. The data indicate that there is a point where the detachment reaches a maximum value, implying variable hydraulic effects of concentrated runoff on slope erosion and its morphology. Analysis also shows that this point changes subject to different parameters.

5. DISCUSSION

The WEPP model is a physically-based model, and a sophisticated research and management tool for a number of soil physical and hydrological issues. Our analysis presented in this paper shows that the WEPP model is a powerful tool for hydrological analysis. Because of its powerful capabilities, application of the model should be pursued further, which could include running scenarios to assess various soil physical and hydrological effects of land use and other management practices.

The WEPP model has been evaluated and calibrated by many, including its developers [Risse at al., 1994; Savabi, 1994; Soto and Díaz-Fierros, 1995; Fogarty, 1998; more reports on its webpage. In this paper, we only report some simulation results using WEPP's hillslope module. Our preliminary exercises show that while WEPP's modelling capacity is being widely explored, procedures for determining some input parameters are unsuitable for some New Zealand soils, including those for calculating "baseline effective hydraulic conductivity", and possibly other erodibility parameters, which results in an overestimate of runoff compared to measured values. This problem is due partly to the high clay content and the strong structure of soils at the site, and the procedures recommended in the current version of WEPP's user summary are not applicable. In order to apply WEPP to New Zealand conditions, different parameterisation approaches have been attempted.

Numerous runs of the WEPP model show that the procedures described in the user manual underestimate several parameters including K_b, as clay in NZ soils is much higher than in any US soils (max 40% in US soils used in WEPP User Summary while generally over 66% in Pukehohe soils].

Because the hydraulic conductivity is underestimated, simulated runoff is higher than that measured. It is reasoned that other underestimated parameters may include rill erodibility K_r, inter-rill erodibility K_i and shear stress τ, which are all estimated using empirical relationships based on clay, sand, and organic matter content.

There is a need for further sensitivity analysis because published reports [Tiscareno-Lopez et al., 1993, 1994] did not analyse some key parameters including the surface initial roughness coefficient and random roughness coefficient.

Parameterisation of soil and climate files is a challenge, particularly those that cannot be easily measured, such as K_b, rro, and many other parameters appeared in the "management file".

Simulations show that spatial variability of detachment-deposition on a planar hillslope has a uniform then a rapid increase along the slope, and further analysis of the data shows that there is a location where the detachment reaches its maximum value. This phenomenon indicates that there is a most unstable location on a hillslope in terms of soil loss and slope stability, subject to hydraulic, physical, and other hydrological parameters. Further analysis is in progress to examine the implication of these phenomena and their practical implications, such as the changes in this "sensitive point" due to variation of topography, climate (rainfall etc), and hydraulic and other parameters subject to development and surface disturbances, such as farming practices.

As far as WEPP's capability is concerned, the model is limited, on the one hand, by the steady-state erosion model that is central to the whole package, and on the other by its inability to incorporate natural topography into the slope file. Registration of an undulating topography in the model is essential to modelling the natural processes, which cannot be satisfactorily achieved by coupling WEPP to other methods [Savabi et al., 1995]. Inclusion of the refined basic model [Lei et al., 1998] and registration of 3-D topographical information would be major tasks to make WEPP more powerful.

6. ACKNOWLEDGEMENTS:

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