Testing Current Generation Soil Erosion Models at Two-minute and Daily Scales Against Plot Scale Data from a Mid-hill Catchment of Nepal

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Abstract: It is rare that the performance of the current generation of soil-erosion models is evaluated over a full range of conditions. The mid-hills of Nepal have many types of terrace systems, with varied crop and land management practices, where empirical models are not transferable. This paper studies the applicability of erosion equations within three current generation of soil erosion models - WEPP, GUEST and EUROSEM - to the mid-hills of Nepal. USLE-type plot-scale daily data, from six locations, along with two-minute rainfalls (1997 – 1998) were obtained from a PARDYP/ICIMOD field study for Jhikhu khola catchment (111.41 km^2) in Nepal. The plots range from 61.8 to 103.5 m^2 in size, and are located on bare degraded land and upland cultivated terraces, with slopes ranging from 6.7^0 to 20.4^0. Two scale questions are addressed. 1) What is the effect of changing from process (nominally 2 minutes) to daily timescales on model performance. 2) Can we identify effective rainfall and runoff rates that improve model performance at daily timescales. A six-parameter process-based runoff model, incorporating both infiltration excess and saturation excess components, was developed after preliminary empirical analysis, to estimate runoff rates. The optimised values of some parameters, which were identified by using a downhill simplex optimisation algorithm, showed considerable temporal and spatial variation. At a two-minute scale, both runoff and erosion models predicted well and all three erosion models are equally competent, but at a daily scale, the WEPP model outperforms GUEST and EUROSEM models. Poor prediction by erosion models at a daily scale is due to the fact that daily averaged rainfall and runoff rates are considerably lower than instantaneous values, and the error associated with runoff simulation that is relatively higher at a daily scale than at a two-minute scale. A simple power function was fitted to daily data, to generate effective rates that correspond to accumulated short-period data. This worked well for runoff but not so well for erosion. Clearly, such fitted parameters need validation on other data sets and other temporal scaling approaches to enable use of daily data are also being investigated but are not discussed in this paper.

Keywords: Nepal; Current generation models; Erosion; Runoff; Scale issues

1. INTRODUCTION

A number of empirically- and physically-based soil erosion models have been developed already [eg. Beasley et al., 1980; Morgan et al., 1998; Yu and Rose, 1999] and some of the models have been tested to evaluate their performance [Ghidey and Alberts, 1996]. Model testing is critical in accepting a new model on steeper and terraced agriculture situations. However, it has not encompassed a wide range of situations.

In an effort to quantify soil erosion in the mid-hills of Nepal, Collins et al. [1998] evaluated the applicability of the Universal Soil Loss Equation (USLE) in Likhu Khola catchment and reported that the USLE technology is unsuitable in the mid-hill situations in Nepal. No attempt has been made to apply and validate the current generation of soil erosion models in the region. Therefore, we conduct a comparative study to test the applicability of the erosion equations of three current generation models: WEPP (Water Erosion Prediction Project), EUROSEM (European Soil Erosion Model) and GUEST (Griffith University Erosion System Template). The WEPP is an empirical model whereas EUROSEM and GUEST are physically based models. We examine the effect of changing timescale from two-minute (assumed to capture the fundamental process scale) to daily and attempt to identify effective rainfall and runoff rates that improve model performance at daily scales, at which data for this type of model is most commonly available. Two years of plot-scale data (1997 – 1998), from PARDYP field study in Jhikhu khola catchment (111.41 km^2) in Nepal are used.

Jhikhu Khola is situated within 27^{0}33'45" to 27^{0}42'30" North latitude and 85^{0}31'15" to 85^{0}42'30" East longitude, and located at 45 km east of Kathmandu valley (Figure 1). The plots are located on bare, degraded sloping lands and on rainfed upland terraces encompassing a range of slope angles (6.7^0 to 20.4^0) and two broad soil types. The erosion plots are not uniform in size (61.8 to 103.5 m^2). On cultivated terraces, terrace width, riser height and riser slope vary widely, details of which are given in Kandel [1998].

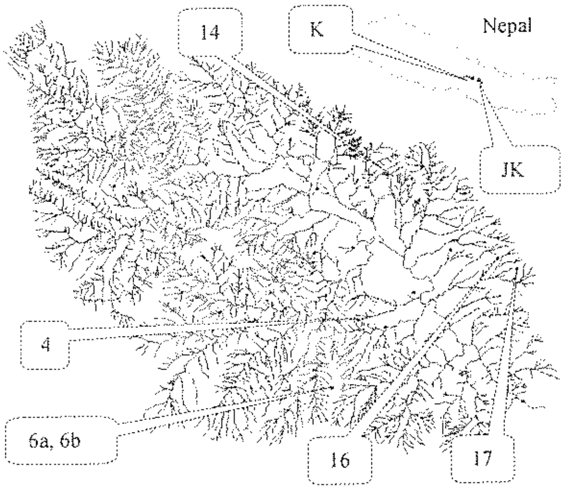

Figure 1. Research sites in Jhikhu Khola (JK) catchment in Nepal (K = Kathmandu).

2. METHODOLOGY

We use the following steps to assess model performance and to address the scale issues above. 1) Fit runoff and erosion models using 2-minute time-steps to daily data. 2) Optimise power functions relating daily rainfall and runoff to effective rates while retaining model parameters from 1 at daily time-steps. 3) Compare results between models to assess comparative model performance. 4) Compare results between time-steps to assess timescale effects.

2.1 Model Description

Rainfall and runoff rates are the most important hydrologic variables in process-based soil erosion modelling. In the mid-hills of Nepal, both rainfall excess and saturation excess processes are likely to generate runoff [Collins et al., 1998]. Therefore, a six-parameter runoff model has been developed to simulate both infiltration- and saturation-excess runoff. An exponential equation of spatially varying infiltration capacity is used to model infiltration [Yu et al., 1997].

$$I_i = I_c\left(1 - e^{-\frac{P_i}{I_c}}\right) \qquad (1)$$

where I_i is the infiltration rate (mm h^{-1}), P_i is the precipitation rate (mm h^{-1}), and I_c is the spatially averaged infiltration capacity (mm h^{-1}), when saturation occurs everywhere and the entire plot generates runoff. Saturation excess runoff is generated when the plot is saturated. Allowance is made for deep percolation but net lateral flow is assumed negligible. Manning's equation is selected to estimate overland flow velocity where required for erosion prediction.

In WEPP, sediment delivery from inter-rill areas is considered to be proportional to the product of rainfall intensity and runoff rate, with the constant of proportionality being the inter-rill erodibility parameter [Foster et al., 1995].

$$D_i = K_i.\ P_i.\ R_r.\ S_f.\ SDR \qquad (2)$$

where D_i is inter-rill detachment rate (kg m^{-2} s^{-1}), K_i is inter-rill erodibility (kg s m^{-4}), SDR is sediment delivery ratio, R_r is runoff rate (mm h^{-1}) and S_f is slope factor.

In EUROSEM, soil detachment by rainfall is related to the kinetic energy of the raindrop and leaf drip impacts and adjusted for non-erodible surfaces.

$$DR = (1 - PAVE) * K * KE * e^{(-bh)} \qquad (3)$$

$$DF = \beta * w * v_s * (TCc - C) \qquad (4)$$

where DR is soil detachment by raindrop impact (kg m^{-1}s^{-1}), PAVE is the proportion of non-erodible surface, h is surface water depth (mm), K is soil detachability (g J^{-1}), KE is rainfall energy (J m^{-2}), b is an exponent taken as 2.0 (0.9 – 3.1), DF is soil detachment by surface runoff (kg m^{-1}s^{-1}), v_s is particle settling velocity (m s^{-1}), w is width of flow (m), TCc is the transport capacity concentration (kg m^{-3}), C is the concentration in runoff (kg m^{-3}), and β is the detachment efficiency coefficient.

Soil detachment by flow is based on generalized erosion-deposition theory [Smith et al., 1995] as given in equation (4), which assumes that the transport capacity concentration of runoff reflects a balance between the two continuously counteracting processes of erosion and deposition [Morgan et al., 1998]). A summation of equations (3) and (4) gives the total detachment in an event.

$$TCr = a_2\, S\, Q^{b2} \qquad (5)$$

where TCr is the transport capacity rate (kg m^{-1} min^{-1}), a_2 and b_2 are calibration factors, S is slope steepness in Sine angle, and Q is discharge per unit width (m^2 min^{-1}).

Transport capacity for inter-rill flow, in EUROSEM, is expressed as a function of modified stream power based on the experimental work of Everaert [1991] on shallow inter-rill flow. However, preliminary analysis of the data under study indicated that the transport capacity equation of Everaert [1991] did not work well in this case. Therefore, a simple transport capacity equation, in the form of Beasly et al. [1980] given in equation (5) is used in this study as it works reasonably well in this context. TCr is converted to the concentration (TCc) when applied to equation (4). The minimum of total detachment and TCr is the soil erosion.

$$M = 0.01Q\left(\frac{aP}{3.6x10^6\phi} + \lambda\, k^\beta R_e^{0.4\beta} e^{-K_{sc}S_{cov}}\right) + \varepsilon \qquad (6)$$

$$R_e = \left(\frac{\sum R_i^{\,1.4}}{\sum R_i}\right)^{2.5} \qquad (7)$$

In GUEST, soil erosion during an event is related to both rainfall and flow-driven processes in the form as given in equation (6), where M is event soil loss (t ha^{-1}), Q is total runoff (mm), a is rainfall detachability (kg m^{-3}), P is the rainfall intensity (mm h^{-1}), ϕ is the depositability (m s^{-1}), and λ is a binary variable assuming 0 or 1 depending on whether runoff-driven processes are considered or not. The K is assumed to be constant in any given context of slope steepness, slope length and rill configuration. The β is an erodibility parameter with values generally $\leq$ unity, R_e is the effective runoff rate (mm h^{-1}) for an event, R_i is the instantaneous runoff rate (mm h^{-1}), S_{cov} is surface contact cover (%), and K_{sc} is a non-dimensional number, and ε is an error term. The effective runoff rate (R_e) is interpreted as the steady-state runoff rate effective in computing the flow-weighted, spatially averaged value of maximum possible sediment concentration during an erosion event [Rose and Yu, 1998].

2.2. Parameterisation

The summary of storms for the two-year period used in this analysis is presented in table (1). Rainfall at the two-minute scale was used for parameterisation of the model at each erosion plot. To account for seasonal variation in some parameter values (canopy interception, Ki*SDR [WEEP], a/ϕ, k & β [GUEST], n, a2, b2 [EUROSEM]), analysis was made by dividing annual data into three seasons, pre-monsoon (16th Feb to 15th Jun), monsoon (16th Jun to 15th Sept), and post monsoon (16th Sept to 15th Feb). All other parameters were temporally constant. The runoff, WEPP, GUEST and EUROSEM models have six, one, three and eight optimized parameters respectively. Runoff parameters were optimised first and then erosion parameters in each erosion model were optimised. All parameters in a model were optimised simultaneously by using a Downhill Simplex optimisation algorithm [Nelder and Mead, 1965] by minimizing the sum of squared errors. The simulated runoff and soil loss at the two-minute scale were integrated to daily scale to compare with observed daily data. The parameters identified at two-minute scale were then used at daily scale.

$$P_e = a_3\, P_i^{\;b3} \qquad (8)$$

$$R_e = c_3\, Rr^{\;d3} \qquad (9)$$

At daily scale, a two-parameter power function was fitted to approximate daily effective rates from the daily averaged rainfall and runoff rates as given in equations (8) and (9). The power function was selected in this study as it consistently performed better than other functions: exponential, linear and logarithmic. At daily scale, erosion was predicted using both simulated as well as measured runoff in order to observe the effects of runoff simulation error on soil loss prediction.

Table 1. A summary of storms in each site for two years (1997 – 1998) in Jhikhu Khola catchment.

Sites*	4	14	16	17	6a	6b
Storms count	116	112	98	98	149	149
Rainfall, mm	1857	1981	2030	2030	2203	2203
Runoff, mm	863	693	42	74	64	287
Soil loss, t/ha	35.04	73.45	2.56	4.38	27.91	38.43

* Sites 4 & 14 are degraded sloping lands and others are cultivated terraces.

$$COE = 1 - \frac{\sum_{i=1}^{n}\left(O - P\right)^2}{\sum_{i=1}^{n}\left(O - \overline{O}\right)^2} \qquad (10)$$

As a measure of the model's performance, a coefficient of efficiency (COE), expressed by Nash and Sutcliffe [1970] is used (equation 10) where O, P, $\overline{O}$ and n respectively represent observed data, predicted data, mean of the observed data, and number of observed data. The highest positive value of COE is unity and indicates the best performance of the model. Zero or negative values indicates poor performance of the model.

3. RESULTS AND DISCUSSION

There is a considerable temporal and spatial variation in calibrated parameter values. The canopy interception in the runoff model; soil erodibility and SDR in the WEPP model; detachability, k and β in the GUEST model; and Manning's n and transport capacity parameters in the EUROSEM model showed significant time trend. Therefore, they were optimised by seasons to account for their seasonal variations. To represent this space-time variation in parameter values, the empirical relation are being developed between the parameters and physically measurable variables such as soil properties and topographical attributes, wherever strong correlation is observed.

The coefficients of efficiency of each model at each time-step and site are presented in table (2). The performance of the runoff model is very good at a two-minute scale and good at a daily scale (Figure 2). When all 722-storm data over two years from all six sites are combined, an overall COE of 0.91 and 0.75 is obtained for runoff at two-minute and daily scales respectively. The model predicts that runoff is generated from both infiltration excess and saturation excess processes. The saturation excess is found to have occurred during monsoon seasons only and is observed at both two minute and daily time-steps.

Table 2. Nash's coefficient of efficiency (COE).

Sites >	4	14	16	17	6a	6b
Runoff						
- 2 min	0.89	0.92	0.85	0.58	0.58	0.87
- Daily	0.89	0.77	0.36	0.47	0.50	0.51
SE–2min						
Wepp	0.74	0.84	0.97	0.44	0.11	0.68
Guest	0.70	0.69	0.85	0.62	0.07	0.77
Eurosem	0.62	0.77	0.61	0.60	0.13	0.77
SE–Daily *						
Wepp	0.43	0.57	0.31	0.49	0.10	0.38
Guest	0.37	0.23	0.17	0.73	0.04	0.33
Eurosem	0.18	0.54	0.01	0.02	0.09	0.35
SE–Daily (O)						
Wepp	0.50	0.74	0.41	0.92	0.80	0.55
Guest	0.50	0.61	0.39	0.85	0.83	0.51
Eurosem	0.27	0.70	0.19	0.25	0.25	0.47

* SE-Daily – Daily erosion predicted from simulated runoff
SE-Daily (O) – Daily erosion predicted from observed runoff

The erosion results from all three models (WEPP, GUEST and EUROSEM) are comparable at two-minute time-steps (Figure 3) but the WEPP model outperformed GUEST and EUROSEM at daily time-step. Soil loss prediction from all these models is good at the two-minute scale except at site 6a. The overall COE of 722-storm data at two-minute scale for WEPP, GUEST and EUROSEM models are 0.77, 0.73 and 0.77 respectively. The erosion prediction from all three models at a daily time-step with simulated runoff is very poor (Figure 4) but when observed runoff is used instead of simulated runoff, all erosion models performed better (Figure 5). When the simulated runoff is replaced by observed runoff, the overall COE for WEPP model improved from 0.39 to 0.65, and that for GUEST and EUROSEM models improved from 0.33 to 0.59 and from 0.21 to 0.48 respectively.

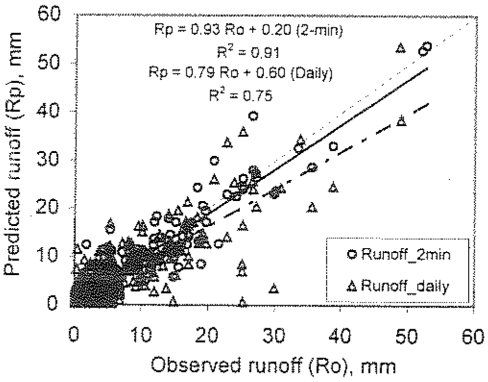

Figure 2. Runoff at two-min and daily time-step.

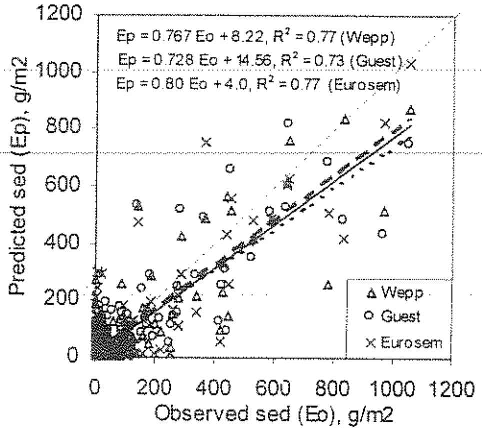

Figure 3. Sediment at two-minute time-step.

The positive intercept and the gradient less than one, of the best-fit line between observed and predicted values from all the models indicated that the lower values are over-predicted and the larger values are under-predicted at both temporal scales. This trend is stronger at daily scale. Other researchers have also observed similar trends in the WEPP model [Ghidey and Alberts, 1996]. The lower gradient of the regression line at daily scale compared to that at two-minute scale showed a greater degree of underestimation at higher values at the coarser timescale.

Besides a certain degree of inherent error in the data, other sources of errors in erosion prediction are likely to be from uncertainty in parameter values, runoff simulation, scale transfer and model structure. To quantify each of these errors, a detailed error analysis is required that is beyond the scope of this paper. However, when erosion prediction at two-minute and daily time-steps is compared, two types of errors are obviously visible: 1. Errors associated with runoff simulation and 2. Errors associated with time resolution effect on the rates of rainfall and runoff generation.

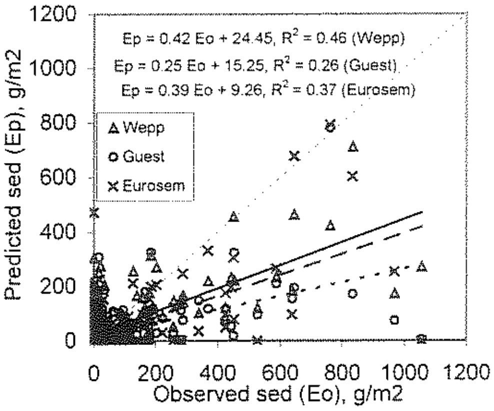

Figure 4. Sediment with simulated runoff (Daily).

The results show that poor erosion prediction at daily scales is due to both these errors. The first can be observed when figures (4) and (5) are compared. The poor prediction at site 6a at both time-steps is noticeable here. Poor erosion prediction at this site is mainly due to poor simulation of runoff, which is very low compared to the observed runoff on three major storms that caused more than 50 percent of total soil erosion. This type of error is also noticed at site 17. Comparing figures (3) and (5) provides insight into model errors due to time resolution. When time resolution is transformed from a finer to a coarser scale, this type of error occurs mainly due to the smoothing of instantaneous rainfall and runoff rates, which are the main agents responsible for soil detachment and transport. The erosion prediction errors at sites 16, 4 and 6b may be dominantly of this type. Yu et al. [1997] report that averaging over an interval of even 10 minutes causes a considerable loss of detail in temporal variation of rainfall and runoff rates. Therefore, averaging of these rates over a day is likely to contribute significantly to underestimation of soil erosion rates causing second type of error.

The results show that both the accuracy of simulated runoff volume as well as appropriate scaling between the process time-scale (minutes) and the model time-step are equally important for predicting erosion well at a daily time-step. In this analysis, it was attempted to achieve this temporal scaling by means of a power function relating daily average rainfall and runoff rates to daily effective rates. This worked well for runoff prediction but not so well for erosion. Alternatively, erosion prediction at daily scale could be improved by disaggregating daily rainfall to finer scale (which is currently being tested) or by integrating the processes to a daily time-scale using the statistical properties of the rainfall.

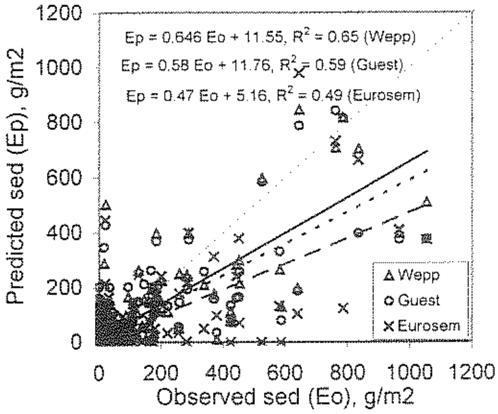

Figure 5. Sediment with observed runoff (Daily).

4. CONCLUSION

In this study, the applicability of new generation soil erosion models: WEPP, EUROSEM, and GUEST to Nepal mid-hill situations were tested at two-minute and daily scales using USLE-type plot-scale data. To estimate runoff rates for erosion prediction, a six-parameter surface runoff generation model was developed including both an infiltration-excess and a saturation-excess component. The runoff and erosion models were calibrated by season for each site to capture the seasonal and spatial variation of parameters. The runoff model predicted very well at the two-minute timescale and reasonably well at the daily timescale, despite some discrepancies between the measured and predicted runoff, especially on cultivated terraces. This may be due to surface sealing/crusting, cultivation practices and preferential flows through rat/root holes, which the model is not representing,

The results indicate that all three erosion models tested are equally competent and could be applied to predict erosion in Nepal mid-hill contexts at finer temporal scale. Soil loss prediction from all the models is good at two-minute scale but relatively poor at daily scale, where errors in small runoff crated large errors in erosion. Poor prediction at daily scale is due to the errors associated with both runoff simulation and the attenuation of instantaneous rates of rainfall and runoff when daily time-steps are used. In terms of parameter efficiency and overall performance on all six sites, the WEPP model outperformed GUEST and EUROSEM at both two-minute and daily time-steps. The EUROSEM model performed poorly at daily scale despite similar performance to WEPP model at the two-minute scale. Though the overall prediction is good at a finer time scale and reasonable at daily scale, the parameter values and their empirical relations need to be validated with a new set of data.

All models performed better at the 2-minute timescale than at the daily timescale. Specifically changing to daily timescales led to underestimated runoff and erosion and decreased performance in terms of both bias and scatter. This is due to resolution of the process time-scales in the two-minute simulations. It was not possible to estimate effective rainfall and runoff rates for application at daily timescales that fully compensated for lack of process resolution in time. Nevertheless improvements were gained at a daily scale using this approach, especially for runoff. Therefore other approaches to capturing temporal variation of instantaneous rates are being tested to improve erosion prediction at daily scale.

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