Testing the Hillslope Erosion Model for Application in India, New Zealand and Australia

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Abstract : The Hillslope Erosion Model (HEM) was developed by scientists at the USDA-ARS Southwest Research Watershed Centre to describe erosion and sediment yield on rangelands. It is based on mathematical relationships between sediment yield, runoff, hillslope characteristics, and a relative soil erodibility value. A large dataset was available to calibrate the model, in the USA, where it has also had substantial application. It was made available on a web site, to enable ready use by interested parties (http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel). Currently however, the HEM has had limited application in other countries. Our aim was to test the utility of the model with data from 3 international sites. The first was a dataset from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Hyderabad, India. Runoff and erosion data were collected from a replicated plot experiment comparing the impact of mulching, tillage and perennial rotations on soil structure over 10 years. The surface soil texture was sandy loam and the slope was 2%. In New Zealand, experimental plots at Pukekohe, North Island, comparing the impact of pasture vs. bare soil on soil loss and runoff, were operated over a 3 year period on a slope of 15.6 % and a clay loam soil of volcanic origin. In northern Australia, a project funded by the Australian Centre for International Agricultural Research is obtaining runoff and erosion data from heavy red clay soils managed as bare, reduced or conventional tillage and grass pasture on a 6% slope. All sites were subject to natural rain. Calibration showed that derived relative soil erodibility values for Indian and Australian locations differed from those determined from the USA datasets, however the default value was applicable to the New Zealand data. These analyses suggest that further calibration and analyses are necessary before default values can be identified for all sites. We also suggest however, that cautious use with derived soil erodibilities is possible at these locations, as further model testing occurs.

Keywords: Erosion, Hillslopes

1. INTRODUCTION

The Hillslope Erosion Model (HEM) was developed by scientists at the USDA-ARS Southwest Research Watershed Centre to describe erosion and sediment yield on rangelands [Lane et al. 2001]. It is based on mathematical relationships between sediment yield, runoff, hillslope characteristics, and a relative soil erodibility value. A large dataset was available to calibrate the model, in the USA, where it has also had substantial application. It was made available on a web site, to enable ready use by interested parties (http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel).

Currently however, the HEM has had limited application in other countries, but the potential is large given that internet usage is increasing dramatically. Our aim was to evaluate the utility of the model with data from other international sites and agricultural systems. We had ready access to data from 3 sites. Two of these were in the tropics (India and northern Australia), while the third was from a temperate climate (New Zealand).

1.1 The Hillslope Model

To estimate erosion and sediment yield from runoff at the hillslope scale, a simple, robust sediment yield model was selected [Lane et al., 1988, Lane et al., 1995a, 1995b, Lane, et al., 2001]. This model is a time-averaged solution of the coupled kinematic wave equations for overland flow and the sediment continuity equation. Thus, the solution emphasizes spatially distributed soil erosion and sediment yield processes averaged over a specified time period.

The solution to the sediment continuity equation for the case of constant rainfall excess was integrated through time [Shirley and Lane, 1978] and produced a sediment-yield equation for individual runoff events as:

$$Q_s(x)=QC_b \\ =Q\{B/K+(K_i-B/K)[1-\exp(-K_r x)]/K_r x\} \quad (1)$$

where Q_s is total sediment yield per unit width of the plane (kg/m), Q is the total storm runoff volume per unit width (m^3/m), C_b is mean sediment concentration over the entire hydrograph (kg/m^3), x is distance in the direction of flow (m), and the model parameters are as are described in the technical documentation. Briefly, B is a sediment transport coefficient (kg/s/$m^{2.5}$), the depth-discharge coefficient is $K = CS^{1/2}$, with C as the Chezy hydraulic resistance coefficient for turbulent flow ($m^{1/2}$/s), and S is the dimensionless slope (slope steepness) of the land surface. The interrill erosion coefficient is K_i (kg/m^3) and the rill erosion coefficient is K_r (1/m)

The above sediment-yield equation for a single plane was extended to irregular slopes [Lane et al., 1995a]. This extension was accomplished mathematically by transforming the coupled partial differential equations to a single ordinary differential equation (integration through time). As an ordinary differential equation, the solution on a plane could easily be solved for sequential segments of the entire plane. Finally, the extension was accomplished practically by approximating irregular hillslope profiles by a cascade of plane segments. With the extension of the model (Eq. 1) to irregular slopes, inputs for the entire hillslope model are runoff volume per unit area and a dimensionless, relative soil-erodibility parameter. Input data for each of the individual segments are the slope length and steepness, percent vegetative canopy cover, and percent surface ground cover.

The soil erosion and sediment yield model developed for hillslopes is called the Hillslope Erosion Model (HEM) hereafter. The HEM and its technical documentation are available on the Internet (http://eisnr.tucson.ars.ag.gov/HillslopeErosionModel).

The HEM is used to simulate erosion and sediment yield as a function of position on a hillslope and to simulate the influence of spatial variability in hillslope properties (topography, vegetative canopy cover and surface ground cover) on sediment yield and mean sediment concentration. While the simple model may be less powerful than more complex models, the single-event model used has an analytic solution, simplified input, relatively few parameters, and an internal database to relate slope steepness, soil erodibility, vegetative canopy cover, and surface ground cover to the model parameters.

An important component of the HEM is the database it contains. Model calibration results, corresponding relationships from the literature, and expert judgment were used to build a database relating soil properties, slope length and steepness, vegetative canopy cover and ground surface cover with the model parameters. The database was incorporated as a subroutine within the computer program to simulate erosion and sediment yield. Default values of the relative soil erodibility parameter used in the HEM were derived, and then grouped by soil textural class, using experimental plot data for over 2000 events in the USA [Lane et al., 2001]. Application of the HEM beyond the USA databases where it was calibrated and validated is dependent upon extending the databases and parameter estimation algorithms to additional locations and conditions.

2. METHODS

Datasets from three locations (India, New Zealand and Australia) were identified. Initial requirements were for homogeneous datasets, which could be used to look just at the soil response, that is data from plots prior to the imposition of treatments, but which had little or no cover (eg. weeds).

Soil loss (kg) was plotted against runoff (m^3) to estimate a mean sediment concentration for each dataset and this was compared to the predicted sediment concentration from HEM using the default erodibility value (data not shown).

The HEM was run with the default erodibility value using mean runoff to produce a mean soil erosion value. The erodibility value was varied until erosion values matched for predicted and observed data.

Subsequently the optimal erodibility values were used with data containing cover effects of either crop, pasture or ground residues.

Details of the sites where data was collected are:

2.1 India

The project was established in July 1988 at the International Crops Research Institute for the Semi Arid Tropics (ICRISAT), Patancheru (18°N, 78°E), 26 km north west of Hyderabad, Andhra Pradesh, India [Smith et al., 1992].

The soil belongs to the Patancheru series, a member of the family of Udic Rhodustalfs [Murthy and Swindale, 1993], locally regarded as a crusting, hardsetting soil. The surface texture is a sandy loam merging to a sandy clay loam or light clay at 10-15 cm and then to gravelly sandy loam overlying murrum (a layer of decomposing parent material. ICRISAT has an average rainfall of 784 mm, with over 80% falling between the months of June and October. Agronomic details and harvest information are provided by Cogle et al., [1997]. Rainfall at the experimental site was measured with a tipping bucket pluviometer.

Each plot was 28 m long (down slope) and 5 m wide with a land slope between 1.5-2.0%. There were 3 replications. Fifteen treatments were imposed and included:

a) A tillage by amendment factorial for annual crops, which comprised nine treatments and compared 3 different tillage depths at 0 cm (T_0), 10 cm (T_{10}) and 20 cm (T_{20}) and 3 mulches, (no mulch (N_m), 15 t ha^{-1} farmyard-manure (F_m), and 5 t ha^{-1} rice straw (R_m), which were applied annually.

b) Perennial species, which were rotated to annual crops after four years comprised six treatments: sole perennial pigeon pea (P) (*Cajanus cajan* L), sole buffel grass (C) (*Cenchrus ciliaris* L)., sole Verano (St) (*Stylosanthes hamata* L.), and mixtures of these species viz. PSt, PCSt and CSt.

2.2 New Zealand

Four experimental plots near Auckland at Pukekohe, North Island, New Zealand (37.18°S, 174.98°E) were operated from 1971 through 1973 [Basher et al., 1997]. All plots were 13.1 m long by 3.1 m wide at a nominal slope steepness of 15.6 %. Runoff and soil loss transported across the sill at the base of the plots was collected in drums during each storm. Runoff volume and suspended sediment concentration was measured after each event. Rainfall at the site was measured with a Dines recording pluviometer. The soil was a clay loam of volcanic origin belonging to the Patumahoe series, a Andic Palehumult. Plots were subject to natural rainfall. Plots 1 and 4 were kept bare for the entire 3 year period and data from 59 runoff events were available for analysis. Plots 2 and 3 were kept bare during 1971 and through mid-March 1972 and data from 27 runoff events were available for analysis. After March 1972, Plots 2 and 3 were in pasture grass with nearly complete grass cover.

2.3 Australia

A project to study conservation tillage practices was set up at Kairi, Atherton Tablelands (17.12°S, 145.34°E) in 1990/1991. Soils of the main cropping area are Red Ferrosols [Malcolm et al., 1999]. The long term mean rainfall for the cropping area of the Atherton Tablelands ranges between 1113mm (Walkamin) and 1387mm (Atherton) and the climate is defined as semi arid. The trial included a runoff study with 12 plots comparing a set of the tillage and rotation treatments (bare, conventional tillage, reduced tillage and grass pasture).

The runoff plots were 5m x 20m with a sediment trough and tipping bucket for measuring runoff rate and soil loss. There were 12 fully logged and functioning runoff plots. Two dataloggers recorded runoff rate from each plot, and also from 2 pluviometers for rainfall rate. The 12 plots were operational late in the 1996/97 wet season.

3. RESULTS

3.1 India

Erosion at the ICRISAT site was over predicted by the default erodibility value in HEM (Table 1). Indeed the optimised erodibility value (0.15) for this site was below the range of erodibilities (0.33 – 4.29) for this surface soil texture available on the HEM web page. The relationship (R^2 = 0.74) found for the optimised erodibility showed that the model could provide good estimates of soil erosion from bare sandy loam soil surfaces, once an erodibility value was known.

The optimised erodibility value was used to estimate erosion from plots, which had been planted to annual crops of either sorghum or maize, after a dry season fallow. The results showed that reasonable estimates could be achieved. It should be noted however that cover measurements were only of projected canopy cover and that accurate measurements of ground cover were not used.

Table 1. Summary of validation results for the Hillslope Erosion Model for Indian data - ICRISAT.

		Observed data (t/ha)		Predicted data (t/ha)		Regression y = a + bx		
Data set	N	Mean	Std Dev	Mean	Std Dev	a	b	R^2
Bare (Default 2.31)	69	0.593	0.585	5.911	3.922	2.201	6.40	0.57
Bare (Optimised 0.15)	69	0.593	0.585	0.548	0.387	0.146	0.71	0.74
Crop (Optimised 0.15)	39	0.263	0.194	0.384	0.232	0.151	0.89	0.56

3.2 New Zealand

The New Zealand results are summarized in Table 2. The ratio of mean predicted to measured mean sediment yield was 2.39/2.36 = 1.01 for bare Plots 1 and 4, and 2.69/2.39 = 1.13 for Bare Plots 2 and 3. The corresponding R^2 values between predicted and observed sediment yield were 0.81 and 0.84 for Plots 1 and 4 and 2 and 3, respectively. The ratio of mean predicted to mean measured sediment yield for the pasture Plots 2 and 3 was 0.006/0.017 = 0.35 with an R^2 value of 0.56.

The model over predicted mean sediment yield on the bare plots by about 1 to 13% while explaining about 80 % of the variance in observed sediment yield. On the pasture plots, the model under predicted mean sediment yield by about 65 % while explaining about 60% of the variance in the observed sediment yield data. It should be noted that on the pasture plots the observed and predicted sediment yields were very low and that in both cases the standard deviations were much larger than the means (i.e. 0.050/0.017 =2.9 for the observed data and 0.011/0.006 = 1.8 for the predicted data).

Table 2. Summary of validation results for the Hillslope Erosion Model for New Zealand (Pukekohe) data using the default erodibility value of 1.38.

		Observed data (t/ha)		Predicted data (t/ha)		Regression y = a + bx		
Data set	N	Mean	Std Dev	Mean	Std Dev	a	b	R^2
Plots 1 & 4 Bare	59	2.26	3.74	2.39	3.86	0.490	0.84	0.81
Plots 2 & 3 Bare	27	2.20	3.83	2.69	4.70	0.229	1.03	0.84
Plots 2 & 3 Pasture	30	0.017	0.050	0.006	0.011	0.0034	0.13	0.56

3.3 Australia

Erosion at the Atherton Tablelands site was over predicted by the default erodibility value in HEM (Table 3). The optimised erodibility value (0.23) for this site was at the lowest end of the range of erodibilities (0.23 – 2.59) for this surface soil texture available on the HEM web page. The relationship (R^2 = 0.87) found for the optimised erodibility showed that the model could provide good estimates of soil erosion from bare clay soil surfaces, once the erodibility was known.

The optimised erodibility value was used to estimate erosion from plots, which had been planted to maize or peanuts. The results showed that a reasonable estimate could be achieved. It should be noted however that cover measurements were only of projected canopy cover and that accurate measurements of ground cover were not used.

Table 3. Summary of validation results for the Hillslope Erosion Model for Australian data (Atherton Tablelands).

Data set	N	Observed data (t/ha)		Predicted data (t/ha)		Regression y = a + bx		
		Mean	Std Dev	Mean	Std Dev	a	b	R^2
Bare (Default 1.41)	51	3.11	2.75	21.71	33.50	-2.889	7.91	0.87
Bare (Optimised 0.23)	51	3.11	2.75	2.87	4.43	-0.382	1.01	0.87
Crop * (Optimised 0.23)	35	1.51	1.22	1.12	1.66	-0.219	0.89	0.43

* Crop data from conventional and reduced tillage plots.

4. DISCUSSION

The HEM was applied to three different soil types and environments across the world. The default erodibility value provided good estimates of erosion in New Zealand on a clay loam, however optimisation of the erodibility value for an Indian sandy loam and Australian clay was necessary before erosion estimates were acceptable for bare soils. The Indian sandy loam had been cropped for many years prior to the experiment and was in a very degraded situation, which may explain the optimised erodibility being outside the HEM range. Indeed, the Indian soil crusts readily, which could provide some erosion protection. The Australian clay was a well-structured Red Ferrosol and its erodibility value was at the lower end of the available HEM range.

The model was applied to data from soils with pasture and crop cover for all sites using the respective optimised erodibility value or default value for the New Zealand soil. The results showed a reasonable relationship with observed data. There are two possible causes of fair estimates in our evaluation. In the Indian and Australian examples accurate ground cover values were not collected and the ground cover was determined as a proportion of the canopy cover. The second reason is that where ground cover was known at each of the sites, the runoff and soil loss was generally very low. These data were used in New Zealand evaluation and as can be seen in Table 2 only very low quantities of sediment were recorded or estimated. In India and Australia, the erosion and runoff was considered too small to be used in model assessment.

Throughout the world access to the internet is growing enormously and this provides access to many people and community groups who haven't ready access to erosion prediction technology. The value of HEM is that it introduces the concept, educates potential users and provides a tool for erosion calculations for a diverse group of people. The danger, however, is that inappropriate values can be calculated based on incorrect inputs, or these tools may be applied in inappropriate scenarios. Resource management scientists need to balance these two issues as they promote tools for sustainable management to the broader scientific and general community.

5. SUMMARY

Our evaluation of HEM has shown that while the model is already a valuable tool ready for use in the USA, application of the model in the India, New Zealand and Australia will require calibration with observed data. However, the model's aim of being easily accessible, via the internet, has already promoted the understanding of soil erosion processes to the broader scientific and general community. This later step is necessary to achieve understanding for a sustainable resource management future.

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