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Testing the hillslope erosion model for application in India, New Zealand and Australia

A.L. Cogle [a,*], L.J. Lane [b], L. Basher [c]

[a] Department of Natural Resources and Mines, P.O. Box 1054, Mareeba 4880, Queensland, Australia
[b] United States Department of Agriculture, Agricultural Research Service, Tucson, AZ, USA
[c] Landcare Research, P.O. Box 69, Lincoln, New Zealand

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Abstract

The hillslope erosion model (HEM) was developed to describe erosion and sediment yield on rangelands and is based on mathematical relationships among sediment yield, runoff, hillslope characteristics, and a relative soil erodibility value. It is available on the web site, http://www.eisnr.tucson.ars.ag.gov/HillslopeErosionModel. Currently, HEM has had limited application outside the USA. Our aim was to test the utility of the model with data from (a) a sandy loam at Hyderabad, India; (b) a clay loam at Pukekohe, New Zealand; and (c) a heavy red clay soil in northern Australia. Calibration showed that derived relative soil erodibility values for Indian and Australian locations differed from those determined for the USA datasets, however the default value appeared to be applicable for the New Zealand data with some variability. Our testing suggests that further calibration and analysis 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.
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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 among 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://www.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 three 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,b; 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 emphasises 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

* Corresponding author. Tel.: +61-7-40484715; fax: +61-7-40923593.

E-mail addresses: lex.cogle@nrm.qld.gov.au (A.L. Cogle); ljlane@tucson.ars.ag.gov (L.J. Lane); Basherl@landcare.cri.nz (L. Basher).

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

where Q_s is total sediment yield per unit width of the plane (kg/m), Q the total storm runoff volume per unit width (m^3/m), C_b the mean sediment concentration over the entire hydrograph (kg/m^3), x the 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, per cent vegetative canopy cover, and per cent surface ground cover.

The soil erosion and sediment yield model developed for hillslopes is called the HEM hereafter. The HEM and its technical documentation are available on the Internet (http://www.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. As an example, Fig. 1(a) shows how K_i and K_r vary with vegetative canopy cover, and Fig. 1(b) illustrates the variation of K_i, K_r, B, and K with surface ground cover. As is apparent in these figures ground cover has a greater impact on soil erodibility in the HEM than does canopy cover. 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 depends on 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 (e.g. weeds).

Soil loss (kg) was plotted against runoff (m^3) to esti-

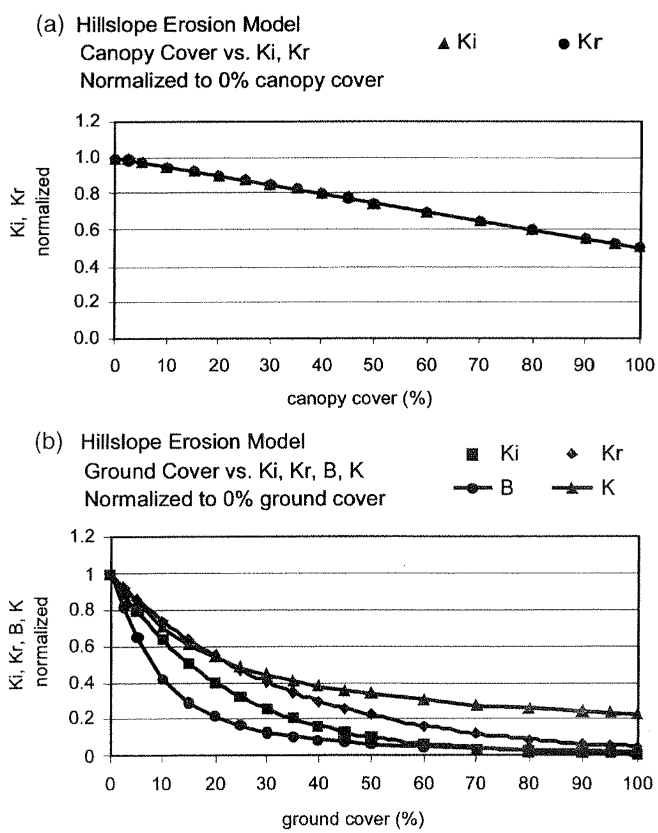

Fig. 1. Relationships between model parameters and hillslope characteristics for the HEM: (a) canopy cover vs. K_i and K_r, normalised to 0% canopy cover, (b) ground cover vs. K_i, K_r, B and K, normalised to 0% ground cover (after Lane et al., 2001).

mate a mean sediment concentration for each dataset and this was compared to the predicted sediment concentration from the HEM using the default erodibility value. An example is shown for the Indian bare soil dataset (Fig. 2). The mean sediment concentration of the dataset is 0.362%. Running the HEM with the default erodibility of 2.31 resulted in a sediment concentration of 4.0%. Subsequent iteration produced sediment concentrations of 0.290% (erodibility, 0.2) and 0.382% (0.16). An erodibility of 0.15 produced the closest estimated sediment concentration (0.359%) to the observed mean sediment concentration (0.362%). The HEM was subsequently run with the identified erodibility value (0.15) to provide soil erosion values for predicted and observed data and the relationships were further analysed using regression.

Following the identification of the optimal erodibility value for bare soil datasets the HEM was run with data containing cover effects of either crop, pasture or ground residues. Details of the sites where data were collected are listed in the following subsections.

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).

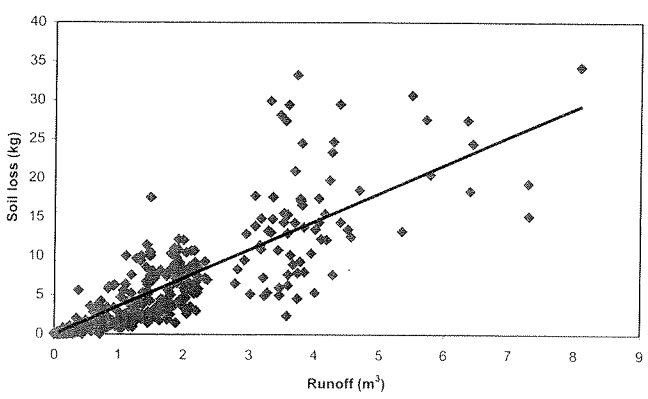

Fig. 2. Soil loss (kg) vs. runoff (m^3) for the optimised Indian bare soil dataset. The equation through the axis is $y = 3.62x$ with an R^2 of 0.72.

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 and 2.0%. There were three replications. Fifteen treatments were imposed and included:

1. A tillage by amendment factorial for annual crops, which comprised nine treatments and compared three different tillage depths at 0 cm (T_0), 10 cm (T_{10}) and 20 cm (T_{20}) and three mulches: no mulch (N_m), 15 t/ha farmyard-manure (F_m), and 5 t/ha rice straw (R_m), which were applied annually.
2. Perennial species, which were rotated to annual crops after 4 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 to 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 were collected in drums during each storm. Runoff volume and suspended sediment concentration were 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 1113 mm (Walkamin) and 1387 mm (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 5 m × 20 m with a sediment trough and tipping bucket for measuring runoff rate and soil loss. There were 12 fully logged and functioning

Table 2
Summary of validation results for the HEM for New Zealand (Pukekohe) data using the default erodibility value of 1.38

Dataset	N	Observed data (t/ha)		Predicted data (t/ha)		Regression $y = a+bx$		
		Mean	SD	Mean	SD	a	b	R^2
Plots 1 and 4 bare	59	2.26	3.74	2.39	3.86	0.490	0.84	0.81
Plots 2 and 3 bare	27	2.20	3.83	2.69	4.70	0.229	1.03	0.84
Plots 2 and 3 pasture	30	0.017	0.050	0.006	0.011	0.0034	0.13	0.56

Table 3
Summary of validation results for the HEM for Australian data (Atherton Tablelands)

Dataset	N	Observed data (t/ha)		Predicted data (t/ha)		Regression $y = a+bx$		
		Mean	SD	Mean	SD	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[a] (optimised 0.23)	35	1.51	1.22	1.12	1.66	−0.219	0.89	0.43

[a] Crop data from conventional and reduced tillage plots.

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 (Fig. 3(b)).

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.

4. Discussion

The HEM was applied to three different soil types, in a bare condition, and environments across the world. The default erodibility value provided good estimates of erosion in New Zealand on a clay loam, however the variability of the estimate was high, as indicated by the percentage difference between predicted and observed means and standard deviations. Optimisation of the erodibility value for an Indian sandy loam and Australian clay was necessary before erosion estimates were acceptable for bare soils, but there was also substantial variability on the estimate. This variability is an issue, however, as we were trying to evaluate the model for a broader application from its current rangeland basis, we believe our approach has illustrated the value of HEM, and that it would be useful for non-rangeland land use.

We recognise that the approach used to optimise the erodibility value for this study lumped a range of soil and site characteristics, but this is also implicit in the simple approach of the HEM methodology. Certainly individual sites had characteristics and properties different to those used for calibration in the USA, not least since the USA sites were on rangelands. For example 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 also 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. These soil properties alone help in interpreting the response of the default erodibility value, and the need to change it from the default. In addition, climatic characteristics at these locations, such as the strong seasonal rainfall patterns in India and northern Australia, may impact on the optimisation of erodibility, as the parameter could change during the course of the wet season. However, it is possible to quickly evaluate this potential change in soil properties due to the ease of use of HEM.

The model was applied to data from soils with pasture and crop cover for all sites using the respective optimised erodibility value (India, Australia) or default value (New Zealand). 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 were 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 were considered too small to be used in model assessment. Extra work with datasets for soils with cover, either crop or ground, is hence desirable to further validate HEM in agricultural locations.

Throughout the world access to the Internet is growing enormously and this provides access to many people and community groups who have no 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 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 latter step is necessary to achieve understanding for a sustainable resource management future.

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