Catena 145 (2016) 39–46

Contents lists available at ScienceDirect

Catena

journal homepage: www.elsevier.com/locate/catena

Comparison between the USLE, the USLE-M and replicate plots to model rainfall erosion on bare fallow areas

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ARTICLE INFO

Article history:
Received 13 January 2016
Received in revised form 11 May 2016
Accepted 20 May 2016
Available online 28 May 2016

Keywords:
USLE database
Soil loss prediction
USLE/RUSLE
USLE-M
Runoff

ABSTRACT

It has been proposed that the best physical model of erosion from a plot is provided by a replicate plot (Nearing, 1998). Event data from paired bare fallow plots in the USLE database were used to examine the abilities of replicate plots, the USLE and the USLE-M to model event erosion on bare fallow plots. The Nash-Sutcliffe efficiency factor as applied to logarithmic transforms of the data was used to evaluate the overall performance of models at a number of locations. The value of this efficiency factor is influenced by both systematic and stochastic differences between the pairs. Systematic differences are the result of systematic differences in event runoff or event sediment concentration or both, and the degree of the impact of them varies as the regression coefficient for the relationship between the soil losses from the pairs varies from the value of 1.0. In most cases the replicate model performed better than the USLE-M that modelled event soil loss as a product of observed event runoff and event sediment concentration directly related to the EI_{30} index. Generally, failure of replicates to match runoff was compensated by the ability of the replicated to determine sediment concentrations better than the USLE-M.

1. Introduction

The Universal Soil Loss Equation (USLE; Wischmeier and Smith, 1965, 1978) and subsequent revisions (eg RUSLE; Renard et al., 1997) and refinements, have provided a model for predicting soil erosion loss that has been used rightly and wrongly throughout the world. The USLE operates mathematically in two steps. The first step is the prediction of long term (~20 years) average annual soil loss from the unit plot (A_1), a bare fallow area 22.1 m long on a 9% slope gradient, in terms of a rainfall runoff factor (R) and a soil dependent factor (K).

$$A_1 = RK \tag{1}$$

where A_1 has units of mass per unit area, R is the long term product of storm kinetic energy (E) and the maximum 30-minute intensity (EI_{30}), and K is the loss of soil per unit of R. In order to predict soil losses from areas which differ from the unit plot, A_1 is multiplied in the second step by factors that account for slope length (L), slope gradient (S), crop and crop management (C) and soil conservation practice (P).

$$A = A_1 LSCP \tag{2}$$

where $L = S = C = P = 1.0$ for the unit plot. Eq. (1) provides the means of taking account of spatial variations in climate and soil. Consequently, the unit plot is the primary physical model on which the USLE modelling approach is based. However, it has been proposed that the best physical model of erosion from a plot is provided by a replicate plot (Nearing, 1998). The USLE data base contains data from replicated bare fallow plots installed at a number of locations. The objective of work reported here is to examine the concept that "the best physical model of erosion from a plot is provided by a replicate plot" by analyzing event data from individual pairs of replicated bare fallow plots contained in the USLE data base and compare the result with the ability of the USLE/RUSLE and the USLE-M (Kinnell and Risse, 1998) to model event soil losses on bare fallow areas.

1.1. Measures of model effectiveness

Replicated plots show "random" (stochastic) variations in soil losses between them (Wendt et al., 1986) at the event scale that tend to be normally distributed (Nearing, 1998). The primary issue that concerned Nearing was the observation that the coefficients of variation were higher for small soil losses than high soil losses so that he perceived that the observation that models like the USLE and WEPP (Flanagan and Nearing, 1995) tended to over predict small soil losses and under predict large soil losses (Tiwari et al., 2000) was a mathematical phenomenon rather than a function of any bias inherent in the models themselves. Subsequently, Nearing et al. (1999) examined data from

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http://dx.doi.org/10.1016/j.catena.2016.05.017
0341-8162/

replicated plot using a relative difference term described by.

$$R_{diff} = (M_2 – M_1)/(M_2 + M_1) \tag{3}$$

where M_1 and M_2 are the paired losses from two replicate plots. The properties of R_{diff} are that its value may vary between −1 and +1 and when $M_1 = M_2$ have a value of zero (Nearing et al., 1999). In their analysis, Nearing et al. computed two values of R_{diff}. For each pair of plots, A and B, the first R_{diff} value was calculated using the soil loss from plot A as M_1 and the soil loss from plot B as M_2. The second value was calculated using the soil loss from plot B as M_1 and the soil loss from plot A as M_2. The values were then plotted against the respective values of M_1. Consequently, for every paired loss, there are two values of R_{diff} of equal absolute value but one is positive and the other is negative, and the negative value is always plotted against the lower of the two soil losses and the positive value always plotted against the higher of the two soil losses. Nearing (2000) proposed that

$$R_{diff.lower} = 0.236 \log10(M) – 0.641 \tag{4a}$$

$$R_{diff.upper} = -0.179 \log10(M) + 0.416 \tag{4b}$$

provided the lower and upper boundaries for the 95% occurrence interval for R_{diff} for the soil losses on both bare fallow and vegetated plots in USDA repository.

Eqs. (4a) and (4b) result from the analysis of event soil losses from a large number of replicate plots that included not just bare fallow but also cropped plots. Fig. 1A shows the values of R_{diff} obtained for bare fallow plots 1-8 and 1-18 at Presque Isle, ME for the 85 events when both plots produced soil loss. 6% of the R_{diff} fell beyond the limits set by Eqs. (4a) and (4b). In contrast, for bare fallow plots 1-8 and 1-3 at the same location, 27% of the R_{diff} values for 82 erosion events that produced soil loss on both plots fell beyond the limits set by Eqs. (4a) and (4b) (Fig. 1B). Although, this comparison obtained using the Nearing's approach indicates that plots 1-8 and 1-18 were better at modelling the soil losses from each other than plots1-8 and 1-3, that approach does not reflect the fact that the average absolute difference from the observed values when plots 1-8 and 1-18 were considered (0.324 t ha^{-1}) was more than half that when plots 1-8 and 1-3 were considered (0.687 t h^{-1}). Also, the method does not facilitate comparisons to be made when all the R_{diff} values fall within the upper and lower limits. Consequently, the approach proposed by Nearing (2000) does not provide a usable index for evaluating the capacity an individual plot to act as a model of a replicate.

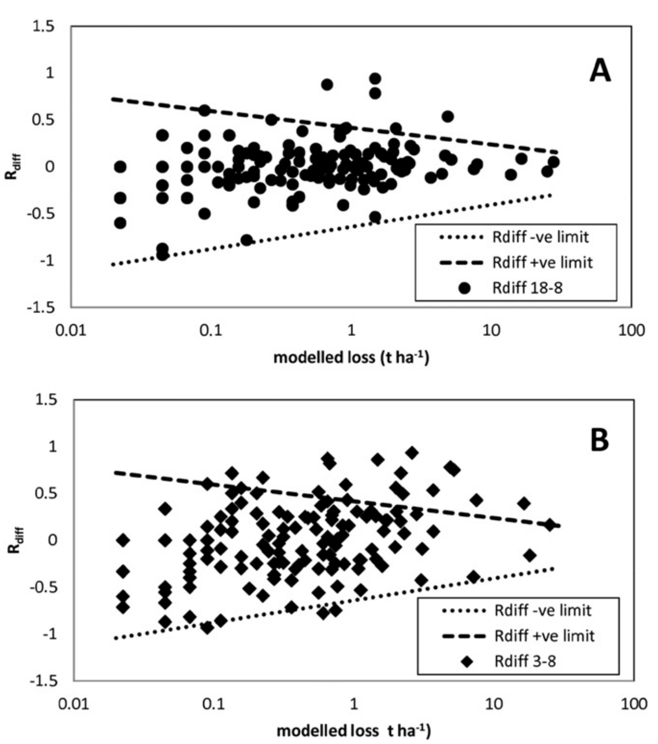

Fig. 1. R_{diff} values for (A) replicate bare fallow plots 18 and 8, and (B) for replicate bare fallow plots 3 and 8, at Presque Isle calculated using Eq. (3) together with the upper and lower limits determined by Eqs. (4a) and (4b).

Recently, Bagarello et al. (2015) suggested that the relationship between the absolute differences between observed or measured (M) and modelled or predicted (P) values as expressed by.

$$|P – M| = aM^{b1} \tag{5}$$

where a and b_1 are empirical coefficients, is sufficient to establish the accuracy level of the predictions. However, Eq. (5) cannot be evaluated if any of the absolute differences in the data set equal zero. Consequently, because there are a number of events where event soil loss from the replicate bare fallow in the USLE database were the same, Eq. (5) is not suitable for evaluating the capacity of a bare fallow plot to act as model of a replicate in the USLE database.

It follows from above that the methodologies adopted by Nearing (2000) and Bagarello et al. (2015) are not suited to evaluating the capacity of replicates to model soil loss from individual bare fallow plots in the USLE database. Often, the Nash-Sutcliffe model efficiency index ((Nash and Sutcliffe, 1970) is applied to determine how effective a model is in predicting observed values. The index,

$$NSE = 1 - \frac{\sum_{n=1}^{N} (Y_o - Y_m)^2}{\sum_{n=1}^{N} (Y_o - M_o)^2} \tag{6}$$

where Y_o is the observed value, Y_m is the modelled value, and M_o is the mean of Y_o, provides a comparison between the ability of the model and using the mean of the observed values to predict the observed values. Positive values indicate that using the model is better using the mean whereas negative values indicate that using the model is worse using the mean. A value of 1.0 is produced by the perfect model. Consequently, as demonstrated here in this paper, the fundamental approach underlying the Nash-Sutcliffe model efficiency index provides a method that is well suited to evaluating the capacity of replicates, the USLE and the USLE-M to model soil loss from individual plots.

2. Data source and analysis

Kinnell and Risse (1998) used bare fallow plot data held in an archive of data originally used by Wischmeier and Smith in developing the USLE to provide metric values of K at 14 locations in the USA. The majority of the plots had slope lengths of 22.1 m and slope gradients varied from 3 to 19% (Kinnell, 1998). 11 locations had replicated bare fallow plots. Data from the same archive is used here. The USLE database currently available online (http://topsoil.nserl.purdue.edu/usle/) provides more extensive runoff and soil loss data at some locations but lacks data at others (e.g. Morris (MN), LaCrosse (WI), Madison (WI), Guthrie (OK), Castana (IA)). Also, the current data base lacks information about the treatments applied to the plots.

The data for the pairs of replicated plots were sorted to remove a small number of events where data were recorded for one plot but not for the other. The model efficiency was then calculated using the Nash-Sutcliffe index (Nash and Sutcliffe, 1970) applied to log