Scale effects in predicting soil erosion

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ABSTRACT Soil erosion losses from upland areas over small drainage basins ($A < 10$ km^2) can be estimated by subdividing the drainage area in small homogeneous units covering a few hectares. This procedure, however, becomes rapidly tedious and time consuming when applied to large watersheds ($A > 100$ km^2). The information required to describe the geometry, rainfall, soil properties and vegetation involves prohibitive sampling and data analysis. A simplified methodology for estimating soil erosion losses from large watersheds was developed from extensive investigations on the Chaudière watershed ($A = 5830$ km^2). Various grid sizes ranging from 0.03 to 4 km^2 were applied on the watershed to compute rainfall erosion. As a result, a correction factor function of the drainage area is introduced and soil erosion over large areas can be estimated from the average characteristics in terms of mean slope, representative vegetation and mean erodibility factor. The mean value and confidence intervals of the correction factor are shown in Figure 5.

INTRODUCTION

Reliable estimates of upland soil erosion losses for small drainage basins ($A < 10$ km^2) are usually obtained by subdividing the total area in small homogeneous units smaller than a few hectares. Soil erosion is computed on each unit and erosion maps are plotted with the aid of computers.

Predicting soil erosion losses from large watersheds ($A > 100$ km^2) using this procedure, however, rapidly becomes tedious and time consuming. The information required to describe the geometry, rainfall, soil properties and vegetation involves extensive sampling and prohibitive data analysis.

This paper discusses a simplified method to reduce the labor intensive data requirements while keeping reasonable accuracy, for predicting soil losses from large watersheds. The applicability of upland erosion equations such as the USLE to larger basin areas is examined through an extensive grid size analysis.

UPLAND EROSION

Rainfall induced overland flow has the ability to detach and transport large amounts of sediments from upland areas. The sediment transport capacity of overland flow depends mainly on slope and discharge whereas the soil characteristics, vegetation and conservation practices reduce the transport capacity (Julien, 1982; Julien & Frenette, 1985). A general approach to soil erosion modeling (Julien & Simons, 1985) shows similarities between several sediment transport relationships found in the literature including the Universal Soil Loss Equation (USLE).

The Chaudière drainage basin in the province of Québec, Canada, has been selected for the grid size investigation. This large Appalachian basin covers 5830 km^2 at the gaging station. All the parameters of the USLE could be evaluated and extensive data analysis on this basin shows that the slope and the crop-management factor were the most significant factors in annual soil losses relationships; the runoff length, rainfall and soil variability and practice factor being comparatively less sensitive (Frenette & Julien, 1986):

$$e' = 48.13\ (0.0076 + 0.0053\ s' + 0.00076\ s'^2)\ c' \tag{1}$$

The annual soil erosion loss per unit area e' in kt/km^2 is function of the slope s' in percentage and the average crop-management factor c' of the USLE.

GRID SIZE ANALYSIS

A very small square grid can be superposed to the drainage basin such that the slope s' and the factor c' are uniform for each unit. The uniform slope s' in percentage is evaluated from the maximum elevation h_2 and minimum elevation h_1 located on opposite corners, the side length of the square ℓ and the angle θ shown in Fig. 1:

$$s' = \frac{100(h_2 - h_1)}{\ell(\cos\theta + \sin\theta)} \tag{2}$$

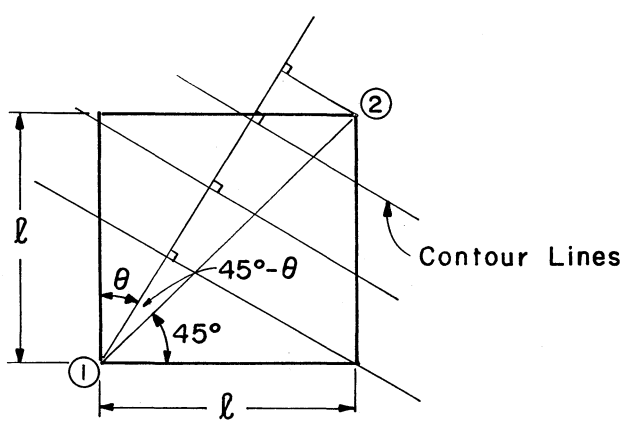

Fig. 1 Infinitesimal grid on a uniform slope.

As the grid size increases, however, the slope varies within each unit and the extreme elevations are not found in opposite corners. The following slope estimator s is defined as a function of the maximum elevation E_{max}, the minimum elevation E_{min} and the drainage area A:

$$s = \frac{100(E_{max} - E_{min})}{\sqrt{A}} \tag{3}$$

Similarly, on large areas, the mean value of the crop management factor c is defined. When s and c are used in place of s' and c', Equation (1) yields the soil loss estimator e. A correction factor Q_e is defined as the ratio $Q_e = e/e'$. As the grid size gradually decreases, uniform slope and vegetation are expected and calculations based on either Equation (2) or (3) are identical ($Q_e = 1$) when $\theta = 0$. As θ is randomly varied, both theoretical and field data analysis of small uniform and homogeneous slopes indicate that Equation (3) overpredicts soil losses by only 13 percent ($Q_e = 1.13$).

For larger drainage areas the following grid size analysis has been devised (Julien, 1979). Square areas covering 4 km^2 have been randomly selected on the basin and subdivided into 144 sub-units (12x12 matrix). In a first step, the subunits were grouped as shown in Figure 2. The equation was applied to each sub-unit of the group and to the whole group to calculate the soil erosion loss on each unit and sub-unit. The coefficient Q_e' denotes the ratio of the soil erosion of the group over the sum of individual losses. The process was repeated for a group of nine (3x3 matrix) sub-units, sixteen (4x4 matrix) sub-units and so forth. A similar procedure was repeated for smaller unit areas (0.25 km^2 and 2.8 ha) and also combining sub-units of 4 km^2 on the watershed up to total unit areas in excess of 2000 km^2.

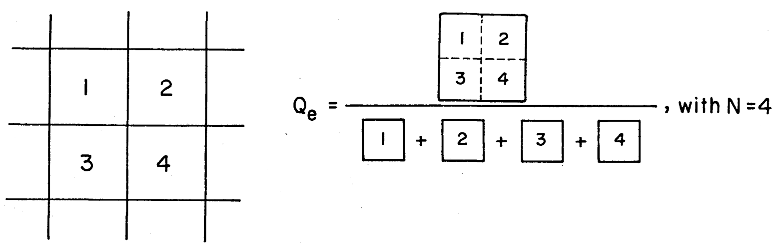

Fig. 2 Definition sketch for the correction factor Q_e'.

Several thousand values of the correction factor were computed and analysis of the first three moments indicate that after log transformation the reduced variables are nearly log normal since the skewness approaches zero. Regression analysis shows that the mean value $\bar{Q}_e'$ of the coefficient Q_e remains basically constant as $A < 0.125$ km^2 (hence $\bar{Q}_e' = \bar{Q}_e = 1.13$). When $A > 0.125$, the coefficient $\bar{Q}_e$ gradually decreases with drainage area. The agreement with observed data shown in Figure 3 is excellent considering that $R^2 = 0.97$:

$$\bar{Q}_e = 1.13 \qquad ; A < 0.125 \text{ km}^2 \tag{4}$$

$$\bar{Q}_e = 0.85\ A^{-0.137} \qquad ; A > 0.125 \text{ km}^2 \tag{5}$$

The standard deviation was also scrutinized by regression analysis and the following relationship for the confidence intervals at 95 percent is recommended for large basins:

$$Q_{e_{95}} = \bar{Q}_e \times 10^{\pm 1.96(0.148 - 0.0226 \log_{10} A)} \tag{6}$$

The confidence intervals at 66 percent and 95 percent are shown in Figure 4 with the data from one of the data sets used for this investigation.

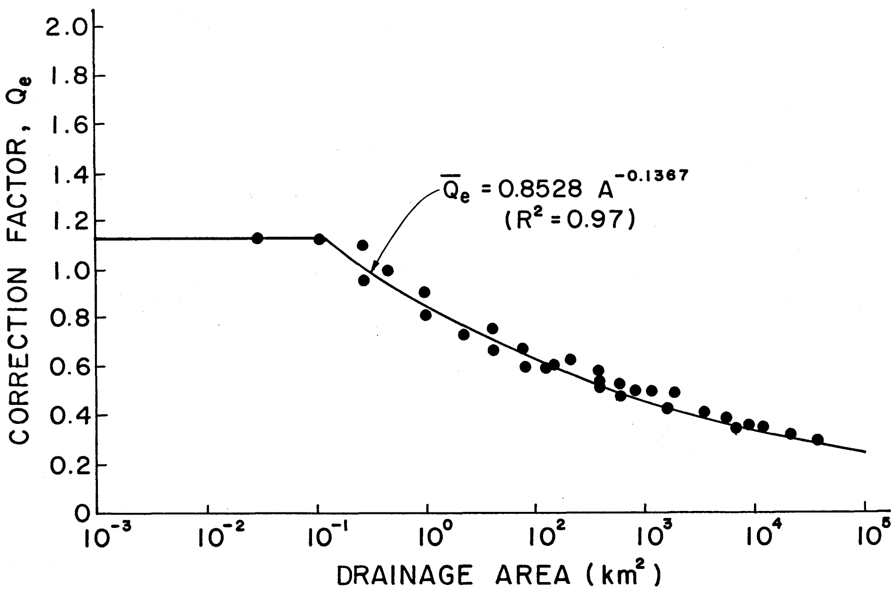

Fig. 3 Mean values of the correction factor $\bar{Q}_e$.

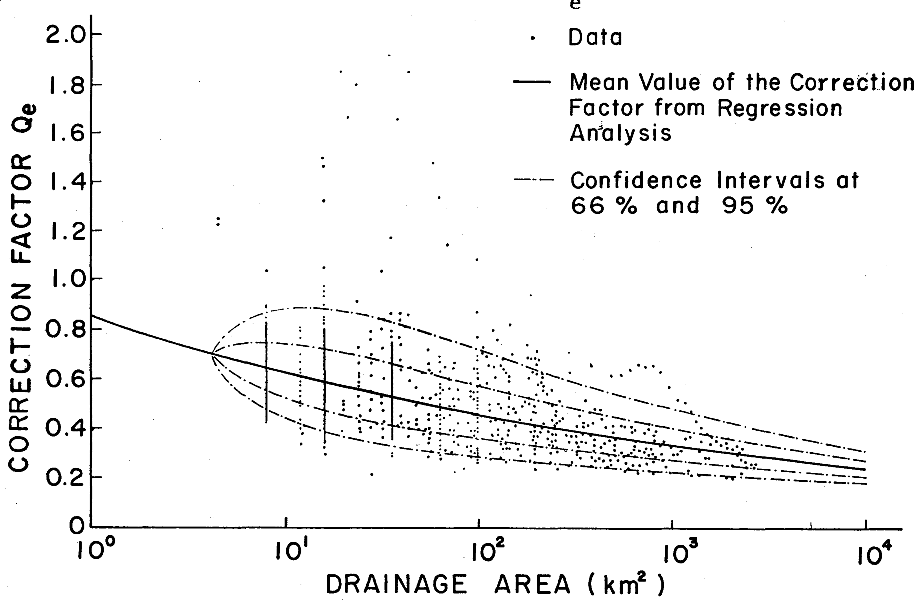

Fig. 4 Correction factor vs drainage area.

The most significant conclusion is drawn from the gradual decrease of the standard deviation with the drainage area. This enables reasonably accurate predictions of the total soil loss for the whole drainage area. Obviously, better accuracy is obtained when the sum of erosion on small units is considered. The proposed method, however, showed to be sufficient as a first approximation when applied to several drainage basins in Canada. An example is given below to estimate upland erosion losses (sheet and rill erosion) from large watersheds.

EXAMPLE

To predict annual rainfall erosion losses from upland areas, an equation relevant to the study area is selected (e.g., Eq. 1). The average slope of the watershed s is calculated from Equation 3 and the average crop management factor c of the watershed is estimated. The expected value of soil loss is then obtained after using c and s in Equation (1) then dividing by the mean value of the correction factor function of the drainage area (Fig. 5 or Eq. 5). The confidence limits at 95 percent are also estimated from Equation (6) (or Fig. 5).

Basin characteristics: $A = 1000\ \text{km}^2$

$E_{max} = 300$ m

$E_{min} = 10$ m

$c = 0.35$

1) From Equation (3); $s = \dfrac{100\ (0.3 - 0.01)\ \text{km}}{\sqrt{1000}\ \text{km}} = 0.92\%$

2) Assuming that Equation (1) is applicable; $e = 48.13(0.0076 + 0.0053 \times 0.92 + 0.00076 \times 0.92^2)\ 0.35 = 0.22\ \text{kt km}^{-2}$

3) From Equation (5) (or Fig. 3); $A = 1000\ \text{km}^2$, $\bar{Q}_e = 0.33$.

$$\bar{E} = \frac{A\ e_i}{\bar{Q}_e} = \frac{1000\ \text{km}^2 \times 0.22}{0.33}\ \frac{\text{kT}}{\text{km}^2} = 668\ \text{kT}$$

4) From Equation (6) (or Fig. 5); $A = 1000\ \text{km}^2$, $Q_{e_{95}} = 0.23$ and 0.48

$$E_{0.025} = \frac{220\ \text{kT}}{0.48} = 458\ \text{kT}$$

$$E_{0.975} = \frac{220\ \text{kT}}{0.23} = 956\ \text{kT}$$

Hence the total annual rainfall erosion is likely to range between 458 kT and 956 kT with an expected value of 668 kT.

DISCUSSION

Although the USLE is used herein, a modified version of the Kilinc and Richardson's equation was shown to give identical results. Sensitivity analysis of the field data was also conducted to verify the decrease in the correction factor Q_e as given from Equation (5).

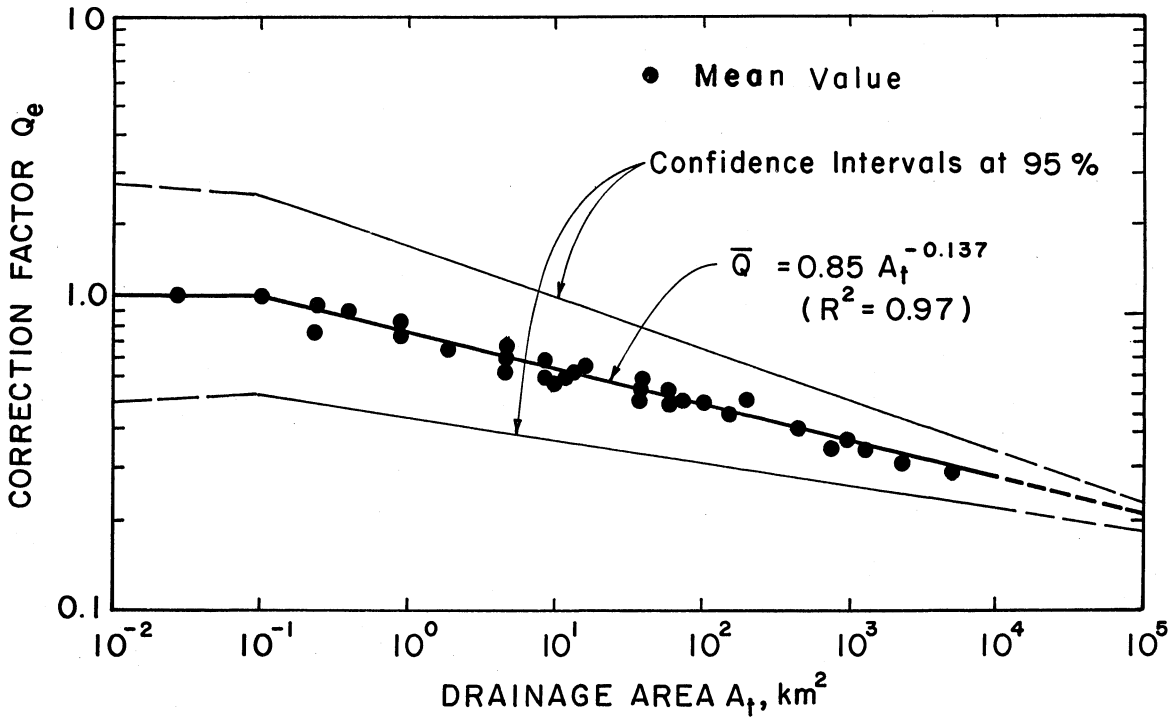

Fig. 5 Mean value and confidence limits at 95 percent of the correction factor Q_e vs drainage area.

The correction factor diagram (Fig. 5) might not be universally applicable although it can be used as a first approximation. The method should be preferably applied on morphologically homogeneous areas since the same soil loss equation is applied to the entire basin. The analysis presented, however, is expected to yield results similar to Equation (5) for regions morphologically different. This method has been applied with considerable success to several large basins in Canada (Julien, 1979; Frenette & Julien, 1980). First approximations of soil losses from large watersheds can be rapidly obtained with this method prior to initiating elaborate calculations.

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