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Slope length and sediment yield from hilly cropland

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ABSTRACT In the Universal Soil Loss Equation (USLE), the geomorphological elements affecting erosion are slope length and gradient of the plot. In humid climates under natural conditions, a hilly landscape evidences slope length and gradient in dynamic equilibrium with environment, so that erosion is low enough to allow vegetation growth. Erosion and drainage density strongly increase, and average slope length (L°) consequently decreases, as the landscape reacts to new conditions (bare soils and fixed time tillage) tending to a new equilibrium, which is never reached because further practices prevent drainage network increase. This trend results in greater erosion and soil loss. In order to reduce erosion, slopes are subdivided into strips of short length (L) by drainage ditches, banks, etc. Erosion on cropped slopes depends on L. The authors suggest the most suitable value of L as $L^* = L^\circ/n$, where n is empirically determined for that landscape and valid for any value of L°. This paper describes a methodology for automatic computation and mapping of L°. Some examples are reported concerning small instrumented basins where sediment yield has been measured.

INTRODUCTION

In a landscape under natural conditions, erosion intensity on slopes depends on many factors including climate, lithology, geomorphology, and vegetation which are themselves interdependent. On a geological time scale, a landscape undergoes significant changes, but on a short time scale, the system can be considered as invariant in its main characteristics. The morphological characters of a landscape result from many factors such as weathering, climate, tectonic movements, rock response, etc. which combine to express their different features and variations. The analysis of geomorphological elements is therefore useful in studying and evaluating different controls such as tectonics, lithology, pedology, and partially, climate.

Erosion and sedimentation is the main active process which models a landscape. The drainage basin is the natural morphological unit on which water erosion acts in its various forms. Depending on scale and goals, erosion can be thought of at the level of the whole basin or of the drainage network in detail. The stream network is not only the route for downstream transport but also the entrainment source of bed, suspended and dissolved, load. Erosion can also be viewed at the level of the slope system of a basin, which is the main source of sediment. Finally, it can also be considered within a single slope.

Using parametric models, erosion may be related to specific morphological elements which can be numerically expressed. Thus erosion has been related to the surface area (Strand, 1972; Livesey, 1972), shape and hypsometry (Renfro, 1972; Schumm, 1956) of a basin; to channel geometry and geomorphological parameters of a drainage network (Gregory, 1977; Ciccacci *et al.*, 1977; Ciccacci *et al.*, 1979); to relief energy and drainage density (Pellegrini, 1979; Horton, 1945; Canuti & Tacconi, 1971; Canuti & Tacconi, 1975); and finally, to slope (S) and length (L) on a single slope.

S and L factors are considered parameters which synthesize the effects of morphology on erosion rates. In nature, these two parameters are strictly interdependent. In a given landscape, any increase in S can be observed to correspond to a decrease in L; in other words, low values of S are most likely to be found associated with high values of L and vice versa.

On landscape slopes under natural conditions, where vegetation cover is almost continuous, erosion intensity is low enough to allow soil to form and be preserved, so that vegetation may develop. If an important factor in the system varies rapidly, morphology will no longer be in equilibrium with the new conditions, and the S and L parameters will tend to change in order to reach a new equilibrium. When natural vegetation is eliminated and soil is mechanically tilled for cropping, a sudden change in an important component of the system, namely, vegetation and soil, results, causing the system to react by changing its morphological parameters.

When ploughed or bare, soil is more erodible and sheet and chiefly rill erosion increase. Rills can be considered as an embryonic form of extending drainage streams. If erosion proceeds long enough, drainage density increases and slope length therefore decreases, down to such a low value that new rills will not form, and a new equilibrium will then be ensured. In practice, cropped slopes are tilled at least once a year and rills are eliminated.

The most obvious result of increased erosion is soil impoverishment and loss, i.e. a reduction of its productive capability. Since ancient times, farmers have been well aware of these effects, and have managed hillslopes with terraces, banks, ditches, etc., to ensure soil stability and conservation. These practices correspond to an artificial reduction of both slope gradient and length.

In old cropping systems, chiefly based on manual labour, terraces or similar management practices did not hamper tillage, but considerably reduced erosion. In modern systems of extensive agriculture, the limits of manoeuvrability of farming machines and the need to minimize cropping costs lead to enlarged cropped areas either horizontally or along the maximum slope gradient. However, temporary or permanent conservation practices are needed also for modern cropping systems, in order to reduce erosion of fertile soil.

Agricultural use of slopes is therefore conditioned by this question: what should be the maximum distance along the maximum slope gradient between two conservation structures in order to produce an acceptably low soil loss? The problem has been considered by many authors (Erodi *et al.*, 1964; Hudson, 1971; Morgan, 1979; Holy, 1980; Kirkby & Morgan, 1980). This paper proposes a different approach to the problem starting from an analysis of landscape morphological parameters.

MEAN SLOPE LENGTH

Slope length is the distance measured along the line of maximum gradient between the summit of the divide and the corresponding point in the stream. In a landscape produced by water erosion, this distance is at a maximum at the farthest point from the confluence of two streams and decreases to zero at the confluence. In practice it is very difficult to measure this parameter. Instead, mean slope length ($L°$) can be considered, defined as "the mean length of the projections parallel to the maximum gradient, on a horizontal plane, of every possible transect between the divide and the corresponding stream". $L°$ is a function of drainage density (D) (Billi *et al.*, 1979). In reality, there is no linearity between $L°$ and D, as $L° \cong 1/2D$. Drainage density should be measured by considering the whole network, including the shortest streams of first order, by using aerial photographs ranging from 1:33 000 to 1:8 000 in scale, according to the type of landscape.

As a morphological parameter, $L°$ can be easily surveyed and numerically evaluated for large regions, once the whole drainage network is available. $L°$ is in equilibrium with the other elements of a natural landscape. If the vegetation cover is eliminated and soil is periodically tilled with farm machines, $L°$ can be thought as being no longer in equilibrium and soil loss too high to ensure soil conservation. In order to reduce soil loss, erosion control practices are then needed, resulting in an artificial alteration of S and L. Modern agricultural systems tend to act on L rather than S, for many reasons including the need to avoid soil erosion and storage, not to alter slope stability, and to contain costs (Hudson, 1971; IAHS, 1974; Soil Conservation Service NSW, 1971).

The problem remains of knowing what is the maximum value of L required for cropping activity. All over the world research committees have dealt with the problem, and a great number of laboratory and field experimental stations have been set up to solve it. These studies have suggested models such as the USLE, which determines soil loss from variables representing climate (R), soil erodibility (K), plot geometry (S and L), cropping management (C), and erosion control practice (P). Once the tolerated soil loss is fixed and the other factors are known, this model or other similar ones allow determination of L for a given cropping activity.

As already stated, in a natural landscape L is in equilibrium with the other parameters. If it is assumed that, for different landscapes with a continuous vegetation cover, vegetation removal and soil tillage will lead to similar land reactions resulting in an increase in D and a decrease in L until a new equilibrium is reached, then the final L will be different for different landscapes, and proportional to the original L. In other words, final L will be 1/n of the initial L. $L°$ being the average value of L, final $L°$ will therefore be 1/n of starting L°.

In the case of cropped slopes, final L° is in equilibrium with the new conditions due to tillage, while initial L° refers to the previous natural conditions, and can be calculated and mapped from the drainage network. Then

$$L^* = L^\circ/n \tag{1}$$

where L* depends on the L° value and is valid at least for a region with homogeneous physical characters. n can be calculated either empirically or by correlating data collected from past or existing experimental plots against the L° value of the landscape where the plots are located. This should be a focus of future research.

SURVEY AND COMPUTATION OF L°

L° can be evaluated using different methods with different accuracies. However, a detailed survey of the drainage network is required to comply with the standards mentioned above. Carlston (1973) demonstrated that, for parallel streams and divides, the average distance between streams and divides is

$$L^\circ = 1/2D \tag{2}$$

where D is drainage density. Sguazzoni & Tacconi (1974) demonstrated that the equation $L^\circ = 1/2D$ is also valid for converging streams and is, in general, independent of stream pattern. The equation is correct if first order streams are assumed to extend to the divide. In practice, when surveying the drainage network, streams are found to cease at a certain distance from the divide, because erosion there is too low for a stream to develop, and a streamless strip results where, as on lateral slopes, only overland flows acts (Horton, 1945). L° is therefore overestimated. L° can be mapped by subdividing the basin into segments of suitable shape and size. L° of every segment is then the prevailing L° inside the segment. To avoid overestimating L°, Billi *et al.* (1979) suggested surveying the whole divide network as well as the stream network. The divide network is generally denser than the stream network. L° can be calculated as:

$$L^\circ = 1/D + 1/D^\circ \tag{3}$$

where D° (km^{-1}) is the divide density. The difference between L° evaluated by equation (2) and equation (3) depends on the stream network hierarchy. L° can be mapped as the prevailing value in a mesh of suitable shape and size by this method as in the case of the previous one. The two methods described above are used in practice for mapping L°, but they do not guarantee computation precision and spatial accuracy of information.

METHODOLOGY FOR AUTOMATIC COMPUTATION AND MAPPING OF L°

A procedure has been established to produce thematic maps representing the morphological elements of slopes and drainage networks. These maps do not employ meshes of simple geometric shape; they consist of polygons representing the shape of every slope (Morandi Cecchi & Montani, 1979; Morandi Cecchi & Montani, 1980).

This procedure was later extended to map drainage density (D) and mean slope length (L°), and it also allowed an analysis of L variations within each slope. The input consists of contour lines, and network of streams and divides. These three groups of data are digitized in discrete form (the apparatus used is TEKTRONIK GRAPHIC SYSTEM 4051 supporting TEKTRONIK GRAPHIC TABLET 4956). The discretizing process involves transforming the curved line under examination into a polygonal line approximating the curve without missing relevant information.

The mean slope length (L°) map is derived from the slope aspect map, which is automatically computed by considering the aspect of every single slope unit to be uniform. Then, if the stream network is detailed enough, the planimetric outline of a slope is automatically isolated, and an elevation is assigned to every point of the polygonal outline, by automatic overlaying of the streams and divides onto contour lines and linear interpolation between these. Then, the equation of the interpolating plane (i.e. the best plane approximating to real slope) can be determined. The angle formed for every slope by the northward direction and the planimetric projection normal to the interpolating plane, is its northwise aspect.

As a slope is represented by its interpolating plane, the direction of the projection normal to the interpolating plane on the horizontal plane corresponds to the direction of the maximum gradient, and therefore to slope length (L) direction. The latter are computed, starting from every discretized point on the divide, parallel to that direction. Since many slope lengths are calculated, their statistical parameters and distribution are known (Tacconi *et al.*, in preparation). At a stream confluence, L equals zero. For first order streams, slope length is computed parallel to the slope normal direction and toward the uppermost stream point, where the distances of the streamless area surrounding the divide converge. This L° computation procedure has been applied to the instrumented experimental basins of Virginio and Pesciola creeks. They both have an area of 62 km^2, and are developed in Pliocene marine sediments (consisting of gravel, sand, silt and clay) typical of the Chianti hills (Aminti *et al.*, 1975). In these basins, L° ranges from 10 m, where clay outcrops, to 50 m where sub-basins have been instrumented since 1978 to measure sediment yield (Becchi *et al.*, 1979). Moreover, erosion intensity and features are observed to empirically define n and L* in equation (1). Data from two sub-basins, where bed load and suspended load concentration have also been measured since 1978, are reported as an example. Basin A (Fig.1) is wooded, whilst basin B is cropped. Suspended sediment concentrations range from 0.03 to 1.0 $g\ l^{-1}$ for basin A, and from 0.1 to 10 $g\ l^{-1}$ for basin B. During the 30 months of measurement, bed load transport totalled 37.6 kg for basin A and 900 kg for basin B (Billi & Tacconi,

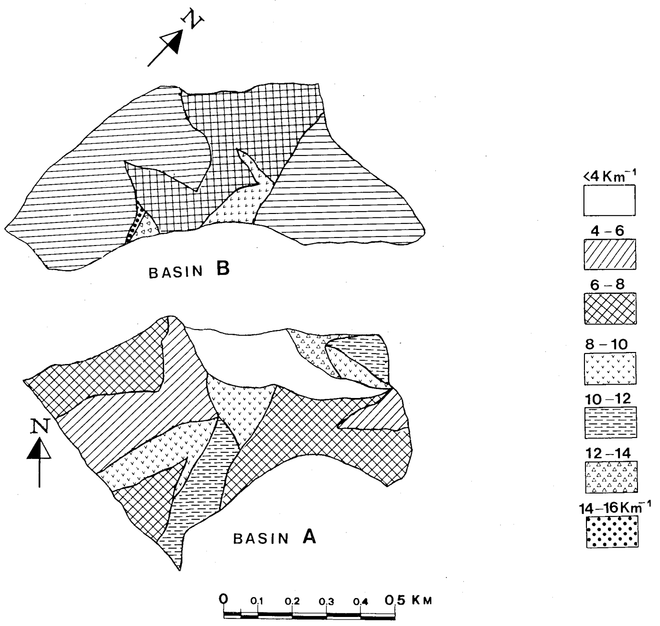

FIG.1 Drainage density maps of basins A and B.

1981) (see Table 1). Basin A is under natural conditions, so S and L are in equilibrium (Fig.2). On the contrary, in basin B, once under similar natural conditions to basin A (being located next to it and having similar soils), the forest has been cleared and soil tilled; therefore S and L are no longer in equilibrium and erosion

TABLE 1 Bed load yields (dry weight) from the two experimental basins

Year	*1978*								
Date	*12-14*								
Basin A (kg)									
Basin B (kg)	*10.1*								
Year	*1979*								
Date	*1-17*	*2-5*	*2-27*	*4-24*	*5-25*	*9-26*	*10-22*	*11-13*	*11-27*
Basin A (kg)		*4.9*	*2.2*	*3.4*		*6.5*			*2.5*
Basin B (kg)	*64.2*	*78.6*	*54.0*	*100*	*81.1*	*100*	*20.1*	*8.7*	*100*
Year	*1980*								
Date	*1-4*	*4-8*	*6-16*	*10-13*	*11-17*	*12-12*			
Basin A (kg)		*8.7*	*2.5*			*2.0*			
Basin B (kg)	*100*	*100*		*7.2*	*19.3*	*8.6*			
Year	*1981*								
Date	*4-21*								
Basin A (kg)									
Basin B (kg)	*8.0*								

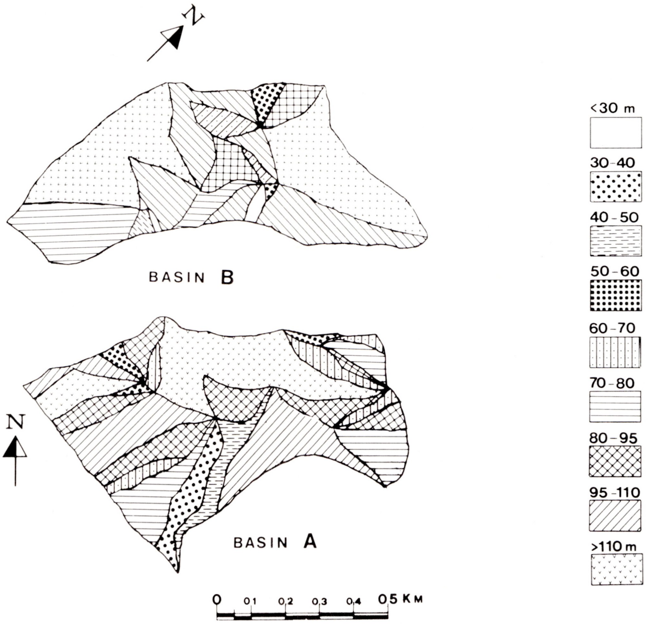

FIG.2 Mean slope length maps of basins A and B.

intensity has strongly increased (Fig.2). In basin B, many rills have developed which remove fine soil particles as well as transporting gravel toward the stream.

CONCLUSION

It is hard to calculate L* by parametric models such as the USLE, because data on climate and soil character are needed and are not easily obtained. L* is an important parameter in evaluating land for agriculture and mechanization.

L* is proportional to L° by an empirically definable constant. L° is a morphological parameter reflecting the stream network and it can be surveyed at low cost in large regions by photo interpretation.

This first approach to estimating L* is presented as a suggestion for improving research in this field through re-examination of data obtained from experimental plots and small instrumented basins in different physical situations. These data could be related to the natural condition of the landscape where they have been surveyed.

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