DISTRIBUTED EVALUATION OF THE CONTRIBUTION OF SOIL EROSION TO THE SEDIMENT YIELD FROM A WATERSHED

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ABSTRACT

The correct determination of the sediment yield from a basin is of paramount importance in several hydraulic and environmental applications, such as the evaluation of the storage reduction of artificial reservoirs. However, due to the highly episodic nature of sediment supply and transport in many environments and to the extreme complexity of the processes involved, the evaluation of the sediment load in a river is still highly uncertain. When the time scale of interest is sufficiently long, and when the primary sediment source comes from distributed erosion in the watershed, the problem can be tackled in an indirect fashion, by computing the contribution to the annual suspended sediment yield from soil erosion. In order to accomplish this task, we propose a distributed application of the widely used USLE formula. The formula is automatically applied along drainage networks derived from a digital elevation model and properly modified to take into account the presence of deposition zones in the watershed. © 1997 John Wiley & Sons, Ltd.

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INTRODUCTION

The assessment of the integral volume of sediment passing through a river cross-section over a given time interval is of great significance in the field of hydraulic engineering. This is evident if one considers siltation problems in reservoirs and channels, which may greatly reduce the storage capacity and increase the flood stages (e.g. Vanoni, 1975), or the instability in a river system induced by the alteration of the natural sediment yield from the drained basin. From the environmental point of view, sediment transport partly reflects the distributed erosion processes acting in the basin. Accordingly, it is also a measure of the slow process of topsoil erosion that causes the degradation and loss of one of the critical natural resources necessary in agriculture. Although the process is generally a very slow one, the volumes involved are huge. According to the 1992 *National Resources Inventory* of the United States of America, an average of more than $1{\cdot}3\,kg\,m^{-2}$ per year are lost on cultivated row-crop agriculture in the USA, due to water and wind erosion. These sediments are also an important source of pollution for waterways, in terms both of volume and of chemical contaminants bound to the grains.

The important implications of these and other considerations have spurred a steady research effort throughout the world, with different types of approaches. From the hydraulic point of view, the emphasis has generally been towards the assessment of the transport capacity of the stream, through the identification of sediment transport formulae by laboratory experiments, under unlimited supply sediment conditions, for stationary and quasi-uniform (in the sense of Yalin, 1977) two-dimensional flow fields (e.g. Graf, 1971; Yalin, 1977; Simons and Sentürk, 1992). As far as the suspended load is concerned, the distribution of the concentration of solids has been derived by linking such assumptions with further hypotheses on the nature of the stream turbulence and of sediment concentration at a reference height on the river bed (e.g. Rouse, 1937; Lane and Kalinske, 1941). However, one of the main criticisms of the hydraulically based approach is that the sediment transport is an intermittent process, strongly controlled by sediment availability. As stated by Bathurst

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in Thorne *et al*. (1987, p. 12): ‘sediment supply events tend to be episodic and non uniform in their spatial distribution with the result that the in-channel sediment transport is both unsteady and non uniform, even for steady water discharge’. If we agree with this consideration, we have to agree also on the point that, while it is traditional for hydraulic engineers to take a reach approach to evaluating sediment yield, the continuity of catchment processes suggests catchment-scale research projects. Moreover, in order to obtain the sediment yield on an annual scale from the transport formulae, temporal integration is required, which implies the knowledge of the time evolution of liquid discharge, $Q(t)$, at the cross-section.

We argue here that a more reliable assessment of sediment yield from a watershed would be possible if the hydraulic approach is supplemented by additional information on the mechanisms that feed sediments to the channelled flow.

In order to prevent land degradation, soil conservationists have focused their attention on the determination of the sediment supply capacity of the drained basin, by proposing several approaches for modelling soil erosion. These models do not usually consider the localized erosion processes that take place along the channel network whereas, particularly in steep areas, most of the contribution to the basin sediment yield happens during few intense events, due to the increased erosive power of the stream and to the localized collapse of stream banks along the channel network (e.g. Pitlick and Thorne, 1987). The amount of fine sediments mobilized in this way is often greater than the contribution coming from distributed erosion on the basin surface. However, in many other situations, when wash load from fine-grained soils dominates (such as a wind-deposited loess or an alluvial clay), these approaches are potentially very attractive in evaluating the supply of fine fractions to the channelled flow and, therefore, to the outlet of the basin.

Possibly the most widely known empirical approach for the estimation of the annual average soil loss by sheet and rill erosion is the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1962, 1965, 1978). The USLE has been derived from over 10 000 plot-years of runoff and soil loss data, collected on experimental plots of small extent. In spite of the lack of a physical basis, when the process is not transport limited, there is a general consensus that the USLE provides the best estimate of seasonal erosion (e.g. Owoputi and Stolte, 1995). This is a consequence of the capacity of the USLE to take into account the first-order factors that affect sheet and rill erosion and also of its extensive calibration. The formula was derived from data obtained on small plots of uniform steepness. Accordingly, its original scope of application was limited to these situations, therefore preventing the possibility of applying the formula to concave or convex, non-uniform slopes. More recently it has been modified to take into account variations of gradient and of soil erodibility along the slope (Foster and Wischmeier, 1974) and additional field data (USDA-ARS, 1991).

The problem with the application of the USLE arises because it must be applied at the plot scale, whilst the information that is often required is at the basin scale. Needless to say, as clearly shown by Stocking (1987), and, for Italian basins, by Raiteri (1995), estimates of regional erosion have little significance at the local level. Therefore there is a need for an approach to fill the gap between the two scales. Here we automatically integrate the USLE along an arbitrarily complex slope drainage network and hence demonstrate that the interest of the drainage structure derived from the digital elevation model (DEM) of a basin is not restricted to the geomorphological description of the basin and to its hydrologic characterization. These topologic structures are also important for integrating the traditional hydraulic approaches to the assessment of sediment yield and transport (Di Silvio, 1992).

EVALUATION OF SOIL EROSION ALONG A SLOPE

From a practical point of view the slope erosion process is the outcome of the interaction of extremely complex processes which are, at best, only conceptualized in even the physically based approach (e.g. WEPP; see Rawls *et al*., 1987; Nearing *et al*., 1989). The relationship that governs the soil erosion process is the continuity equation:

$$(1-\phi)\frac{\partial z}{\partial t}+\frac{\partial}{\partial x}(q_s)+\frac{\partial}{\partial t}\left(\frac{q_s}{U}\right)=0 \tag{1}$$

where z is the soil elevation (m), ϕ is the soil porosity (dimensionless), q_s is a solid discharge per unit width (m^2 s^{-1}), U is the vertically average velocity of the sheetflow (ms^{-1}) and x (m) is measured from the point of origin of overland flow. Assuming that the sequence of runoff events can be substituted by a single event, equivalent in terms of overall soil loss and steady in time, then the third term in Equation 1 can be neglected, obtaining:

$$(1-\phi)\frac{\partial z}{\partial t}+\frac{\partial}{\partial x}(q_s)=0 \tag{2}$$

Accordingly, the solid discharge per unit width $Q_s(x)$, can formally be obtained as a function of distance x from the point of the overland flow onset in the form:

$$Q_s(x)=\int_0^x \rho_s(1-\phi)\frac{\partial z}{\partial t}\partial x \tag{3}$$

where ρ_s is the sediment mass density (kg m^{-3}). The problem with Equation 3 lies in the determination of the erosion rate $\partial z/\partial t$. For a broad range of cases the rate is provided at a seasonal time scale by the USLE (Wischmeier and Smith, 1962, 1965, 1978). The USLE may be written as:

$$A=RK\left[\left(\frac{L}{22\cdot 13}\right)^m S\right]CP \tag{4}$$

where A is the average soil loss per unit area and unit time T (kg m^{-2} T^{-1}), R is the rainfall factor (J m^{-1} T^{-2}), K is a soil erodibility factor (kg T J^{-1} m^{-1}), L is the horizontal projection of overland flow length (m), S is the slope steepness factor, C is the cropping-management factor, P is the erosion-control practice factor and m is an exponent, dependent on the rill/inter-rill ratio (S, C, P and m are dimensionless).

Following Foster and Wischmeier (1974), A need not necessarily be on an annual basis; it is rather referred to time period T, implicit in the selected R value and, therefore, the USLE can be applied at a seasonal scale.

Although a thorough discussion of this formula is beyond the scope of this contribution, it is important to appreciate that the USLE was originally derived from data for essentially uniform slopes. Given the empirical nature of the formula, its correct application is limited to areas of necessarily small extents, because, as stated by Foster and Wischmeier (1974) for the case of irregular slopes: 'The effect of these irregularities on sediment load is not accurately reflected by the overall average steepness. Neither can successive segments of an irregular slope be treated as independent slopes when surface runoff flows from one segment to the next'. Another limitation of Equation 4 is that it was derived under supply-limited conditions: it does not incorporate a sediment delivery ratio that, in many situations, is considerably less than 1.

In order to overcome the first problem, Foster and Wischmeier (1974) have proposed a modification of the original formulation to take into account slope gradient irregularities as well as variations of the erodibility factor K along the slope. If we define x as the distance from the point of origin of the overland flow, they have provided a conceptualization of the erosion rate at the seasonal time scale, $\rho_s(1-\phi)\partial z/\partial T$, in the form:

$$\rho_s(1-\phi)\frac{\partial z}{\partial T}=D(x)=(m+1)RKSCP\left(\frac{x}{22\cdot 13}\right)^m \tag{5}$$

Then, the average sediment discharge $Q_s(x)$ in the time period T can be obtained by substituting Equation 5 into Equation 3 as:

$$\overline{Q}_s(x)=\int_0^x D(\xi)\mathrm{d}\xi=RKSCP\frac{x^{m+1}}{22\cdot 13^m} \tag{6}$$

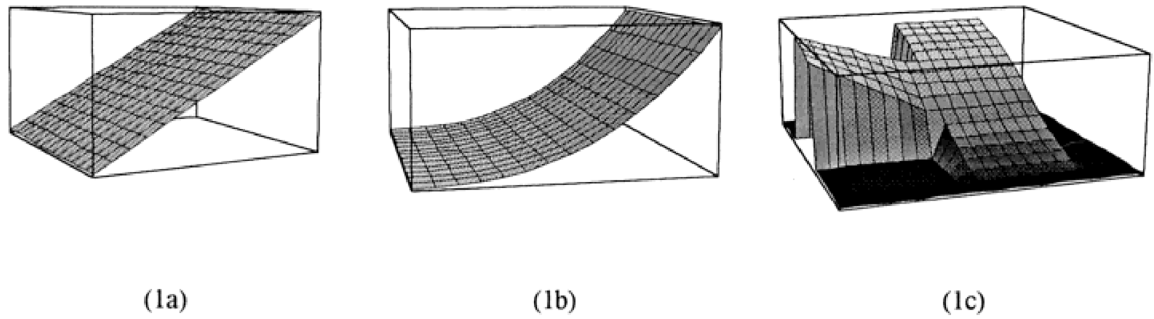

Figure 1. Uniform (a) and non-uniform (b) steepness slope. Composite, non-uniform slope (c). The slope drainage network (e.g. Figure 2d) can be seen as a composition of these elementary cases

Considering the case of non-uniform slopes subdivided in n uniform segments (see USDA-ARS, 1991), the sediment yield at the end of the slope, $Q_s(x_n)$, can be written as:

$$\overline{Q}(x_n) = \sum_{j=1}^{n} \Delta\overline{Q}_j = \frac{1}{(22\cdot 13)^m} \sum_{j=1}^{n} R_j K_j C_j P_j S_j \left[(x_j)^{m+1} - (x_{j-1})^{m+1} \right] \tag{7}$$

where x_{-1} and x_j are lengths from the point of inception of overland flow to the lower end of jth segment and ΔQ_j is the sediment yield from the jth segment. Therefore, while Equation 6 could be applied only to the case portrayed in Figure 1a, with spatially uniform gradient and parameters, Equation 7 is the extension that should be used in the case of Figure 1b, where these quantities are constant.

However, a real slope is something more complex than the simple slope of Figure 1a or 1b. For the example in Figure 1c which defines a *composite slope*, the segments located downstream of the junction between the two elementary slopes have two possible different values for x. The first is computed along the straight slope and the second going up to the left at the junction. Notwithstanding this ambiguity, we argue that x should reflect the role of cumulative overland flow discharge at a point, and that Equation 4 can be applied only for unlimited transport capacity of overland flow (i.e. the sediment load at a location is a function of the erosion characteristics of the upslope areas), and we compute the contribution from the jth segment as:

$$\Delta\overline{Q}_j = \frac{0\cdot 224}{(22\cdot 13)^m l^{m+1}} R_j K_j S_j C_j P_j \left[(a_j + 1)^{m+1} - (a_j)^{m+1} \right] \tag{8}$$

where a_j is the contributing area upstream of the jth cell and l is the characteristic linear dimension of the cell (m). This formula is equivalent to Equation 7 for segments located upstream of the junction, but differs from it for segments placed downstream. According to Equation 8, the sediment production for a segment located downstream of a junction is equivalent to that of a segment characterized by the same parameter set located along an elementary slope and draining the same cumulative area, as shown in Tables I and II. This approach was proposed and compared with field measurements in Pilotti *et al*. (1996b).

FROM THE SLOPE TO THE WATERSHED SCALE

Equation 8 can be applied to compute the sediment yield from a slope, when no deposition occurs. However, in many applications the results are required at a different scale, for example the sediment supply to the channel network from a whole watershed. The extension to the watershed scale of the procedure outlined above is conceptually straightforward, if one considers that a watershed can be regarded as being made up of slopes drained by a channel system. However, when the area of the watershed is not very small, the computational burden is heavy. Considering that water is the main driving mechanism for erosion and sediment transport, it seems reasonable to suppose that the mentioned processes take place along the idealized pathways followed by water flowing in the basin.

The water pathways for routing the sediment transport through the system can be derived by pre-processing the information contained inside a raster DEM of the watershed, provided that its resolution is sufficiently high

Table I. Local soil loss per unit time and per unit area from a composite T-shaped slope, with constant parameters. The flow is from left to right and the outlet cell is marked in bold. In this particular case, due to the local gradient, the flow from the two simple slopes converges into the cell marked in italics. Accordingly, from that point downwards the slope is a composite one. Note that the local soil loss from the junction cell downwards is the same one observed in the simple slope of Table II from the last two cells, that drain the same area. However, as could be expected, the cumulative production from the simple slope of Table II is higher because the average drained area per cell is higher

0	0	0	0·37	0	0
0	0	0	0·69	0	0
0	0	0	0·902	0	0
0·37	0·69	0·902	1·074	*1·595*	**1·702**

Table II. Local production for a simple slope, characterized by the same gradient and parameters of the composite slope of Table I. The flow is from left to right

0·37	0·69	0·902	1·074	1·224	1·358	1·481	1·595	**1·702**

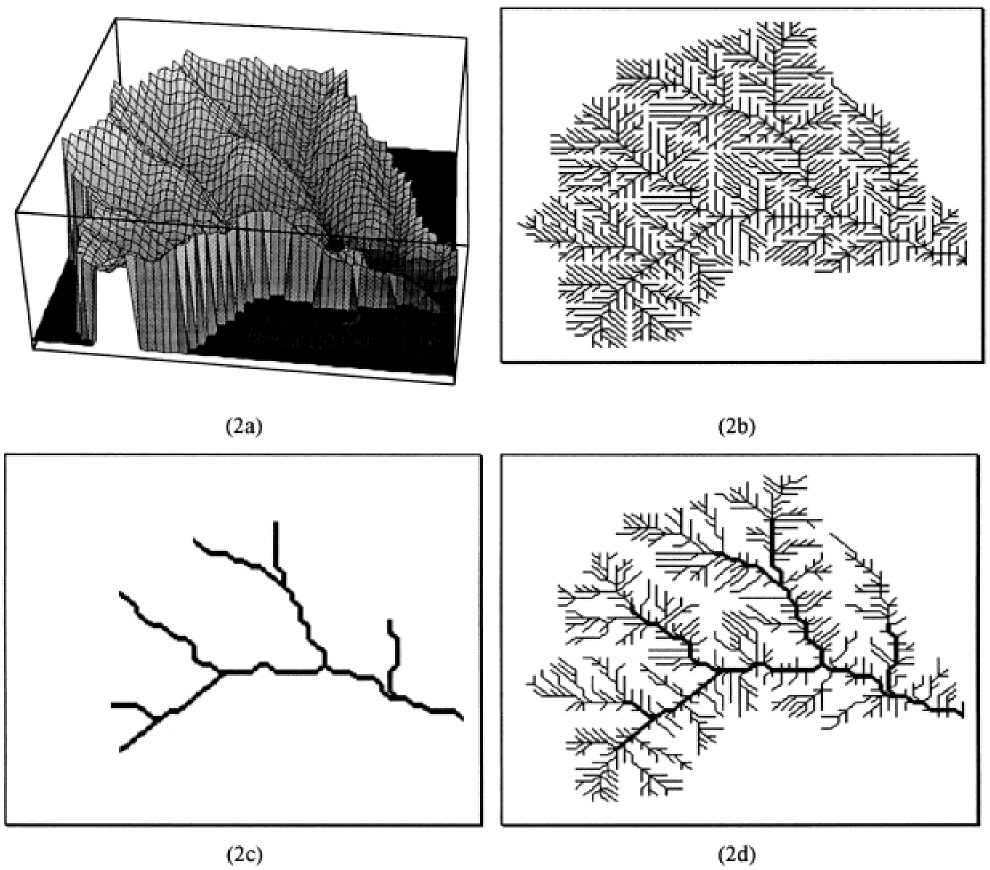

Figure 2. (a) The watershed *basin2.dtm* (area = 0·39 km^2, average slope 12 per cent) and its drainage networks: the space-filling drainage network (b) and the runoff concentration network (c). The wash load production coming from soil erosion is computed by exploring the drainage network (d), that has been derived from the slope drainage network, filtering out slopes shorter than 15 m, and zones of sediment deposition. The thick line in (d) is the runoff concentration network, along which the sediments, on an average yearly basis, are routed to the outlet.

for topographic homogeneity within each cell. The output is organized into two topologic structures. The first is the so-called *space-filling drainage network* (SFDN), that is a tree-like structure joining all the cells in the DEM along the direction of maximum gradient (see Figure 2b; refer to file *basin2.dtm* on diskette). The second structure represents the *channel network* (see Figure 2c), and is derived from the space-filling drainage network, by comparing the one derived using suitable algorithms (e.g. O'Callaghan and Mark, 1984;

Montgomery and Dietrich, 1988, 1989, 1994; Montgomery and Foufoula-Georgiou, 1993; Dietrich and Dunne 1993) with the other derived from field observations. Richards (1993) noted that the information content which is implicit in these structures can be used for a better comprehension of the dynamics of sediment in the basin. For the present purposes, the channel network is not restricted to the permanent channels present in the watershed but extended to include other areas of the watershed.

The difference between these two sets of drainage structures identifies a third drainage network, here called the *slope drainage network*, (SDN) that represents the integral of the slopes in the watershed, and we use the SDN for the automated, distributed application of the USLE formula, after correcting the SDN according to the specifications of the revised USLE (RUSLE) (USDA-ARS, 1991) for the computation of the topographic factors. This means that slopes with a length shorter than the surface runoff formation length are not included in the computation. While this constraint identifies the upper cutoff on the SDN, the lower cutoff is provided either by runoff concentration zones or by the presence of runoff interruption zones (see Figure 2d). The latter are identified and excluded by the SDN, where the topographic gradient is lower than a given threshold (e.g. Foster and Meyer, 1972) or where the presence of undisturbed soil intercepts the runoff. The distributed computation of Equation 8 is then accomplished by a recursive procedure (Pilotti and Rosso, 1990) and the model then delivers eroded soil from the runoff concentration zones to the channel as wash load.

In the present evaluation we therefore apply the USLE to the drainage network, at a scale that is comparable to the one used in the calibration. Each slope, draining to a point in the channel network, is regarded as a sub-basin, whose drainage network is considered as a connection of links. Each link is a segment in a slope, whose parameters are locally determined on the basis of the topographic information derived from the DEM and from the available raster data. Although the final procedure is totally automated, the modification of the original SDN by the user requires some 'expert' knowledge of the erosive processes in the basin.

AN AUTOMATED PROCEDURE FOR THE DISTRIBUTED ASSESSMENT OF SEDIMENT YIELD

In a previous paper (Pilotti *et al*., 1996a) the drainage network was derived by processing the information contained in a DEM. Here we present a program that extends the procedure and provides a tool to use the derived topologic description of the drainage structures for the assessment of the USLE formula in a distributed fashion at a watershed scale. Flacke *et al*. (1990) have proposed the implementation of a distributed application of the USLE using a triangular irregular network (TIN) based representation of the watershed surface. However, although the TIN provides a more efficient topographic representation than raster DEM, the use of raster data is generally preferred, because of the greater simplicity in its handling.

The program is contained on the *Technical and Software Bulletin* Disks and, after the source file has been read and the SFDN has been derived (passing through a possible depitting phase), the runoff concentration flow lines are extracted using either a fixed contributing area (e.g. O'Callaghan and Mark, 1984) or a variable contributing area criterion (e.g. Montgomery and Dietrich, 1988, 1989). The SDN that is consequently identified is not yet the drainage network that should be used for the computation, as shown by the guidelines provided in USDA-ARS (1991) for selecting slope lengths.

As a first consideration, the upper cutoff for the SDN is provided by the slope ridge. However, length x that appears in Equation 8 is the horizontal distance from the origin of overland flow, a point that may not necessarily correspond to the local slope ridge, e.g. for the presence of undisturbed soil along the ridge that does not yield surface runoff. On the other hand, the lower cutoff for the SDN is automatically provided by the convergence into the channel (or runoff) network; this is a situation that would perfectly correspond to one of the major hypotheses behind the USLE formula, i.e. that the process is not transport limited. However, in real cases not all of the eroded soil along a slope is delivered to the slope outlet.

Foster and Meyer (1972) found that the transport capacity of runoff from uniform slopes during moderate to intense rainstorms is usually sufficient to transport all available soil if the slope exceeds 2 or 3 per cent. In addition, sometimes the continuity of overland flow along a slope is disrupted by the presence of concentration points (a trivial case is the presence of a transversal road). In order to modify the SDN structure an option has been added in the *sdpp1.exe* program. This option allows the user to specify a fixed value for the runoff formation length in the basin and to automatically exclude all the cells from the SDN where the topographic gradient is lower than a given threshold. In addition, the user can manually select the cells that will cause the interruption of runoff and, consequently, of sediment transport. At the end of these operations, the user can save the topology of the modified SDN on a file, that will be read by the *usle.exe* program provided on the disk. The resulting SDN structure can be visualized on the screen by selecting the appropriate option within the menu.

The second program, *usle.exe*, reads the topologic outputs of *sdpp1.exe* and builds a tree-like structure which includes both the channel network and the SDN. The topographic and topologic information contained in this structure is completed by reading the raster files containing the data required for the local computation of Equation 8. These data comprise the raster matrix of the soil erodibility factor, K, of the rainfall factor, R, of the crop management factor, C, and of the erosion practice factor, P. Values for these factors can be obtained from published tables and charts. In particular, in Wischmeier and Smith (1978) a nomograph to compute the soil erodibility K factor has been presented. To use this nomograph, data on the granulometric composition of the soil, its organic matter content, its structure and permeability are required. If such detailed information is available, the user can provide the corresponding raster files to the program which, by approximating the original nomograph charts, automatically produces the raster soil erodibility file. The approximation has been found to be satisfactory in all our applications.

The tree-like structure is then visited and, at each cell of the channel network, a check is made to verify whether any slope enters the channel at that point. In such a case, the SDN corresponding to the input slope is visited, and Equation 8 is locally applied, segment by segment. In this way, both the local soil erosion (kg m^{-2} T^{-1} in SI units) and the cumulative soil loss (kg T^{-1}) along all the slopes present in the watershed are computed. The results are stored in two raster files (*.usl, *.usc).

In order to compute the topographic factors in Equation 8, the indications provided in USDA-ARS (1991) have been followed. In particular, slope length exponent m in Equation 8 is related to the ratio β of rill to inter-rill erosion by the equation:

$$m = \frac{c\beta}{(1 + c\beta)} \tag{9}$$

where c is a coefficient provided by the user that depends on rill/inter-rill erosion classes, and whose value ranges between 0·5 and 2, and β is a function of local gradient, θ, in the form:

$$\beta = \frac{\sin\vartheta}{0\cdot 0896(3\sin^{0\cdot 8}\vartheta + 0\cdot 56)} \tag{10}$$

The value of β is locally computed by the program. The slope steepness factor S in Equation 8 is computed as detailed by McCool *et al*. (1987). When the slope length is longer than 4·57 m (15 ft), the following formulae have been used:

$$S = 10\cdot 8\sin\vartheta + 0\cdot 03 \tag{11}$$

if the slope gradient is less than 9%, and

$$S = 16\cdot 8\sin\vartheta - 0\cdot 5 \tag{12}$$

otherwise. When the length of the slope is shorter than 4·57 m, Equations 11 and 12 are substituted by:

$$S = 3\sin^{0\cdot 8}\vartheta + 0\cdot 56 \tag{13}$$

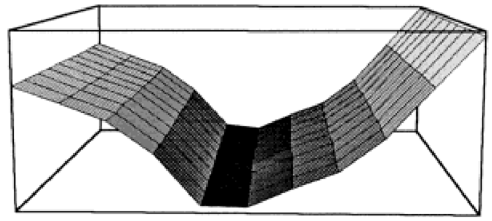

Figure 3. The watershed corresponding to *basin1.dtm*, that reproduces the concave and convex slopes of USDA–ARS 1991, tables 4–7, 4–8 and 4–9

ANALYSIS OF SOME TEST CASES

In order to illustrate the procedure we present the results of the computation performed using the files contained on the disk. As a first example, we present a test application with the file *basin1.dtm*. This file, shown in Figure 3, corresponds to a simple watershed made up of two slopes, drained by a runoff concentration zone. As can be seen, one of the slopes is convex and the other is concave and their topography corresponds to that described in USDA-ARS (1991, tables 4–7 and 4–8). In those tables the procedure that should be used for the computation of the topographic factor of the RUSLE formula is applied to the case of two irregular slopes, 121·92 m (400 ft long), where only the topographic gradient changes along the slope. The slope is then subdivided in a sequence of three segments of equal length. The topographic gradient, in the case of the convex slope, is 0·05 m/m for the first segment, 0·10 m/m for the second and 0·15 m/m for the third. The sequence is inverted for the concave slope (0·15, 0·10, 0·05).

As shown along the first line of *basin1.dtm*, the raster file is made up of 10×11 square cells, whose area is of 1652 m^2, corresponding to the area of a single segment of length 40·64 m (121·92/3). Here, for illustrative purposes, each of the slopes has been divided into five cells, or segments, and the portion described in USDA-ARS (1991) corresponds to the central part. The program *sdpp1.exe* has a pull-down menu structure, where the single options along the command bar are selected by pressing the left key of the mouse, and activated by pressing the right key. To activate the single options inside each menu, use the left key of the mouse.

After running *sdpp1.exe*, select *basin1.dtm* (In/Out – Select file – *.dtm) and read it (In/Out – Read file) The outlet is detected when the file has been shown on the screen (In/Out – Find outlet). Check to see that no pits or flat areas are present in the DEM (Global dp – Automatic depitting), and then compute the space-filling drainage network (Global dp – DEM topologic file) and then the channel network (Global dp – Drainage network models – Contributing area – 0·009), that we shall identify according to the fixed contributing area algorithm, with a threshold of 0·009 km^2. Next visualize the channel network (Screen – Show drainage network – 1) to check that it comprises only the draining axis of the watershed. In order to modify the SDN, we can select a runoff formation length of 30 m (USLE dpp – Runoff formation length – 30) inside the menu USLE dpp, and then visualize the resulting SDN (USLE dpp – Show erosion network). Next, specify a lower cutoff for the derived SDN, by supposing that, wherever the gradient is less than 0·03, deposition occurs (USLE dpp – Filter by slope – 0·03). This operation eliminates the contribution coming from the rightmost column of cells on the left slope. To end the pre-processing phase, eliminate the cells of the leftmost column on the right slope (USLE dpp – Overland flow breakpoints). Finally, write to file the topologic structure that is needed for the distributed computation of the USLE (USLE dpp – Write USLE input file) and then exit to DOS (In/Out – Exit to DOS).

Upon running *usle.exe* the program asks for the root name of the file used as a DEM at the beginning of the process. After selecting the units to be used for the output, the user has to specify if and which data among *R*, *K*, *C* and *P* will be provided in a raster format for the distributed computation of Equation 8. These data may be provided to the program in the same ASCII format of the *.*dtm* file (see examples on disk). However, if distributed information is not available or is deemed unnecessary (as could be the case for *R*), the user can specify a single value constant all over the watershed. Moreover, when data regarding soil texture are available in a raster format, the program can automatically create a raster file of soil erodibility *K* values, by using an approximation of the nomograph presented in Wischmeier and Smith (1978). Before using this option,

Table III. Local specific soil loss matrix resulting for the case of *basin1.dtm*. These results should be compared with those presented in the last column of tables 4–7, 4–8 in USDA–ARS (1991). The results in italics are related to the portion of the basin where *k* is not constant (see *basin1.k*), and should be compared with table 4–9 in USDA–ARS (1991). As a consequence of the definition of the slope drainage network made in *sdpp1.exe*, in this case the upper parts of the slopes do not contribute to the soil loss. In the same way, the lower part is an area of deposition, where Equation 8 is not applied. The drainage axis of the basin, being part of the channel network, is excluded by the distributed application of the USLE

0	*0·196*	*0·96*	*2·801*	0	0	0	1·465	2·987	2·832	0
0	*0·196*	*0·96*	*2·801*	0	0	0	1·465	2·987	2·832	0
0	*0·196*	*0·96*	*2·801*	0	0	0	1·465	2·987	2·832	0
0	*0·196*	*0·96*	*2·801*	0	0	0	1·465	2·987	2·832	0
0	*0·196*	*0·96*	*2·801*	0	0	0	1·465	2·987	2·832	0
0	0·726	2·999	7·57	0	0	0	1·465	2·987	2·832	0
0	0·726	2·999	7·57	0	0	0	1·465	2·987	2·832	0
0	0·726	2·999	7·57	0	0	0	1·465	2·987	2·832	0
0	0·726	2·999	7·57	0	0	0	1·465	2·987	2·832	0
0	0·726	2·999	7·57	0	0	0	1·465	2·987	2·832	0

Local production.
Area of each cell (acres): 0·4082181208
US units: ston/acre/year

Table IV. Cumulative sediment production along the space-filling drainage network of *basin1.dtm*. As can be seen, the presence of the deposition zones along the base of the slopes inhibits the propagation of sediment to the channel network of the watershed. Accordingly, in this test case, the delivery ratio to the outlet (cell marked in bold) in the considered time period, *T*, would be zero

0	*0·08*	*0·472*	*0·615*	0	0	0	2·973	2·375	1·156	0
0	*0·08*	*0·472*	*0·615*	0	0	0	2·973	2·375	1·156	0
0	*0·08*	*0·472*	*0·615*	0	0	0	2·973	2·375	1·156	0
0	*0·08*	*0·472*	*0·615*	0	0	0	2·973	2·375	1·156	0
0	*0·08*	*0·472*	*0·615*	0	0	0	2·973	2·375	1·156	0
0	0·296	1·52	4·611	0	0	0	2·973	2·375	1·156	0
0	0·296	1·52	4·611	0	0	0	2·973	2·375	1·156	0
0	0·296	1·52	4·611	0	0	0	2·973	2·375	1·156	0
0	0·296	1·52	4·611	0	0	0	2·973	2·375	1·156	0
0	0·296	1·52	4·611	0	**0**	0	2·973	2·375	1·156	0

Cumulative production along the drainage network
US units: ston/year
Cumulative production at the basin outlet: 0

however, the raster files containing information on the sand content (extension rootname.*snd*), silt+very fine sand content (rootname.*slt*), organic matter content (rootname.*org*), soil structure (rootname.*str*) and permeability class (rootname.*per*), that are needed for using the nomograph, must be placed in the used input directory so that the program can locate them. Finally, select US units, choose the default value (that is 1) for the *c* factor that appears in Equation 9 and answer negatively for the information regarding the soil texture. Actually, a *basin1.k* matrix is already present on the diskette and this matrix contains 1 but in the upper left part, where *K* assumes the values presented in USDA-ARS (1991, table 4–9). Answer positively when the program asks for distributed *K* values, and insert constant values for *R*, *P* and *C*, all set equal to 1, to reproduce the case of the above-mentioned tables.

As a result of the computation, two files (see Tables III and IV) are written to disk. The first, with name rootfile.*usl*, contains the local soil loss per unit area and unit time, in the selected output units: this file should be compared with the results presented in the USDA-ARS tables. The second, rootfile.*usc*, contains the cumulative production of sediment per unit time along the space-filling drainage network.

Tables I and II demonstrate the application of Equation 8 to a T-shaped composite slope, where, for the sake of simplicity, the topographic gradient and all the parameters are kept constant. The results are compared with a

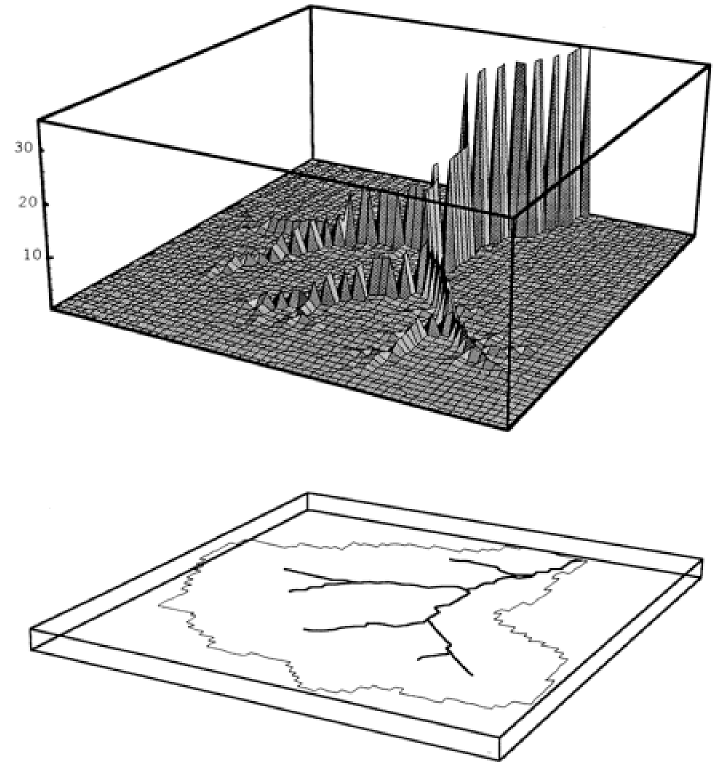

Figure 4. The average yearly cumulative wash load production (10^3 kg/year) along the runoff concentration network of *basin2.dtm*. The delivery ratio of the basin, defined as the ratio of yield to gross erosion, can be easily computed as the ratio of the sediment yield at the basin outlet to the integral of the local contribution contained in *basin2.usl*

straight, simple slope, characterized by the same parameters and gradients, and draining the same cumulative area in Tables I and II.

As a final example, let us show the advantages of the proposed approach by applying it to a realistic case, corresponding to the file *basin2.dtm*. The basin is shown in Figure 2a, while its space-filling drainage network, the channel network (derived assuming a fixed contributing area, $A = 0{\cdot}02\,\mathrm{km}^2$), and its SDN (derived imposing a runoff formation length of 15 m and sediment deposition where the gradient is lower than 0·02 m/m) are shown in Figures 2b, 2c and 2d. In this case, K will be computed by *usle.exe*, using the matrix provided on diskette (*basin2.slt, basin2.snd, basin2.org, basin2.str, basin2.per*). In conclusion, using $R = 1030$ US units, $P = 0{\cdot}3$ and $C = 0{\cdot}028$, constant over the watershed, the output files are easily obtained. The cumulative production along the channel network is shown in Figure 4.

While the *basin2.usl* file provides information on the location of the sources of sediments that can be of considerable interest to the soil conservationist the *basin2.usc* file is particularly informative to the hydraulic engineer, as it corresponds to the cumulative wash load transport throughout the watershed.

CONCLUSIONS

In this contribution, which extends the work in Pilotti *et al*. (1996a), we demonstrate that the interest of the drainage structures derived from the DEM of a basin is not limited to the geomorphological description of the basin and to its hydrologic characterization. The topologic structures can also be used for a distributed description of the erosive processes acting in the basin, as already shown by Di Silvio (1992), who has proposed a simplified model of bed-load transport that takes into account the space- and time-dependent processes in a watershed.

Visentini (1937) considered the silting problem in several Italian reservoirs, and observed that the contribution coming from soil erosion is sometimes predominant. For some of the Appenine watersheds, he observed that: '. . . the disgregation process is still going on, not as a consequence of real stream erosion as much as for the erosion of fine grained soils under the action of atmospheric factors. The transport of removed particles, which are soon reduced in small dimensions, mostly happens in suspension'. We have argued that, in these situations, it is important to complement the typical reach-oriented hydraulic approach with a watershed-scale approach. We conclude that the fine sediment fraction supply to the channel network can be computed at the watershed scale by using a modified version of the USLE formula.

In order to demonstrate this application, we have presented a program that uses the topologic information contained in the space-filling drainage network and allows the automated computation of the USLE throughout a given basin. This procedure is a proposal to fill the gap between the original slope scale, at which the USLE should be applied, and the basin scale, at which engineering evaluations are often required.

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APPENDIX

Program installation

The installation procedure for the two DOS executable programs, *sdpp1.exe* and *usle.exe*, is the same as that explained in Pilotti *et al*. (1996a). As far as *sdpp1.exe* is concerned, this is an upgraded version of *sdpp.exe*, containing a menu specifically devoted to data pre-processing for *usle.exe*. Given that the options available are basically the same as those present in *sdpp.exe* (although slightly reorganized), only the usage of these new options is presented in Table V.

Both *sdpp.exe* and *usle.exe* must stay in the same directory, along with the ASCII file *flslink* and the two files *dpmi16bi.ovl* and *rtm.exe*. A standard serial mouse driver must be loaded in memory. The *in* directory on diskette contains the files used as input by the program, while the *out* directory is used for outputs. The *bgi* is used for some drivers. While this subdivision is not mandatory, whatever the location of input, output and drivers, it must be correctly specified in *flslink*, that contains the paths of the directories relevant to the execution of the program. The use of the tutorial files is presented in the paper.

The program *sdpp1*, which reads only ASCII files whose format is evident from the examples provided on diskette, works in SI units. It must be used to produce the input for *usle.exe*, which uses the standard US units for

Table V. Items of the USLE data pre-processing pull-down menu

Item	Scope
Runoff formation length	By using this option, an upper cutoff on the slope drainage network can be chosen. The slope length factor is defined as the horizontal distance from the origin of overland flow; usually this distance does not coincide with the distance from the slope ridge. Accordingly the user can specify the minimum length (in metres) required for overland flow to develop. When not specified, this distance is assumed to be zero.
Show erosion network	Allows the visualization of the slope drainage network, possibly filtered, of the selected runoff formation length.
Overland flow breakpoints	The lower cutoff for the application of the USLE is provided either by runoff concentration zones (defined by carefully selecting the channel network), or by sediment interception zones. In order to specify the latter locations, the user can manually select the cells in the slope drainage network where sediments will be trapped. Use the left and right keys of the mouse, as shown on the screen.
Filter by slope	Another cause of sediment deposition is caused by an insufficient topographic gradient. By using this option, all the cells in the slope drainage network where the topographic gradient is smaller than a selected threshold are shown on the screen and marked into the SDN. The cluster of cells identified in this way provides another lower cutoff for the distributed application of the USLE. As explained in Pilotti *et al*. (1996a), the local slope is computed along the space-filling drainage network.
Remove all breakpoints	In case of wrong specification of lower cutoffs, this option removes all of the selected points. It acts both on points chosen by using *Overland flow breakpoints* and *Filter by slope*.
Write USLE input file	Writes on file the user's selections, as needed by *usle.exe*.

the dimensional *R* and *K* values. The output from *usle.exe* can be either in US units or in SI units, as preferred by the user.

The maximum dimension of the raster files that can be managed by the program is 65×65. When a basin requires a larger DEM, a possible solution is to subdivide it into sub-basins. The other limitation is on the structure of the derived channel network, which cannot contain a junction with more than three entering links. This is, however, a highly unlikely situation.

Note that some items may be inactive at the initial stages of the DEM processing: active items are highlighted in white, while the inactive ones are shaded grey. All output files produced by the program share the same name of the input DEM file (e.g. *sourcefile*) and suitable extensions are automatically assigned by the program (e.g. *dpt* for depitted files). A detailed list of the input and output files is provided in Pilotti *et al*. (1996a).