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EROS: A GRID-BASED PROGRAM FOR ESTIMATING SPATIALLY-DISTRIBUTED EROSION INDICES

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Abstract—EROS is a grid-based terrain analysis program for estimating the spatial distribution of soil loss and erosion-and-deposition potential in a catchment. The sediment transport index is similar to the length-slope factor in the Revised Universal Soil Loss Equation, but is applicable to three-dimensional terrain. It characterizes the effects of topography and catchment hydrology on soil loss, and helps to identify areas in a catchment that are highly susceptible to erosion by flowing water. The method is based on characterizing the sediment transport capacity of overland flow using a stream-power approach. The terrain attributes generated by TAPES-G provide the basic terrain attributes used by EROS. Stream networks, subcatchments and the spatial distribution of individual attributes can be plotted interactively or copied to the ARC/INFO geographic information system (GIS) for further analysis and display. Copyright © 1996 Elsevier Science Ltd.

Key Words: Digital Elevation Model, Terrain analysis, Erosion, Deposition.

INTRODUCTION

EROS is one of a suite of terrain analysis programs (TAPES—Terrain Analysis Programs for the Environmental Sciences) developed by Professor Ian D. Moore prior to his death in September 1993. The program follows the approach taken in the other TAPES programs—that effective GIS-compatible tools can be constructed for examining spatially variable environmental processes which include the key factors determining system behavior, but are based on simplified representations of the underlying physics. Some physical sophistication is sacrificed to allow improved estimates of spatial patterns in the landscape. These models provide a means of relating pattern to process and can operate with minimal data sets (Moore and others, 1993).

EROS calculates a simple erosion index that accounts for the major hydrological and terrain factors affecting erosion. The index is a dimensionless sediment transport capacity that is a non-linear function of specific discharge and slope. It is derived from the transport-capacity-limiting sediment flux in the Hairsine–Rose (Hairsine and Rose, 1991, 1992a, 1992b), WEPP (Laflen, Lane and Foster, 1991; Laflen and others, 1991) and catchment evolution (Willgoose, Bras, and Rodriguez-Iturbe, 1991) erosion theories (Moore, Wilson, and Ciesiolka, 1992). The index is equivalent to the length-slope factor in the Revised Universal Soil Loss Equation (Renard and others, 1991) for a two-dimensional hillslope, but it is simpler to use and conceptually easier to understand (Moore and Wilson, 1992). A major advantage of the index is that it can be extended easily to three-dimensional terrain (Moore and Wilson, 1994). It also accounts for different runoff-producing mechanisms and soil properties using a spatially variable weighting function and can be implemented within a GIS.

The TAPES suite of programs are written in FORTRAN 77 and C for UNIX systems, and graphical display tools are based on the X-Windows system. Source code and further documentation is available from the Centre for Resource and Environmental Studies at The Australian National University.

EROS INPUTS

EROS requires a TAPES-G output file containing X, Y, Z (elevation), slope, flow direction and drainage area (Gallant and Wilson, 1996). It looks for metadata on the input file to determine the grid cell size, missing value and field numbers, and assumes standard TAPES-G format if there are no metadata. EROS recognizes an elevation value of 0 as a missing value, and also recognizes TAPES-G's missing value of −999.0. It uses the same missing value in its output file. EROS assumes that the coordinates and elevation values are in metres, but there is no problem using other units as long as the elevation units are the same as the units of the X and Y coordinates.

EROS can also use a soil boundaries file which contains polygons specifying boundaries of soil types

and a weighting factor for each polygon. The file is formatted as follows: (1) an integer specifying the number of soils for each model run, (2) the number of vertices in the polygon, the soil number and the weight for the polygon, and (3) the x, y coordinates of the polygon (one record per x, y coordinate pair). The second and third items are repeated for the second and all subsequent soil polygons. Soil numbers must be integers starting from 1.

EROS OUTPUTS

EROS produces an output file in either binary or ASCII. Each DEM grid point with all its attributes is written as a single record—either one line in an ASCII file or one unformatted record in a binary file. X, Y, Z, erosion index, weighting factor and drainage area fields are written to this output file. The X, Y, and Z fields are copied from the input file, and the weighting factor is determined from the soil polygons or the EROS program itself. The erosion index is also calculated by the program. The drainage area field is similar to the drainage area calculated by TAPES-G, but in some instances it is modified by the soil weighting factors. Metadata are also written to the beginning of the file describing the contents of the file and the options and parameters used by EROS to produce the file. Another program (TAPESOUT) works with one topographic attribute at a time and can read ASCII as well as binary output files. The ASCIIGRID command is used to convert ASCII files to grids in ARC/INFO. The topographic attributes can be manipulated further using ARC/INFO's map algebra and display tools.

ESTIMATION METHODS

The user must select one of two erosion indices each time they run EROS. One index calculates the spatial distribution of soil loss potential with a simple dimensionless transport capacity index, T_c, that can be written as

$$T_{cj}^{*} = \left(\frac{\sum_{i \in C_j} (\mu_i a_i)/b_i}{22.13} \right)^m \left(\frac{\sin \beta_j}{0.0896} \right)^n, \qquad (1)$$

where μ_i is a weighting coefficient ($0 \leqslant \mu_i \leqslant 1$) that is dependent on the runoff generation mechanism and soil properties (i.e. infiltration rates), a_i is the area of the ith cell, b_i is the width of each cell, β_j is the slope in degrees, m and n are constants (0.6 and 1.3, respectively), and C_j is the set of i element indices which are hydrologically connected to cell j. When $\mu = 0$ no rainfall excess is generated; when $\mu = 1$ 100% rainfall excess is generated. The other index represents the change in sediment transport capacity across a grid-cell, ΔT_c, and provides a possible measure of the erosion or deposition potential in each cell (Moore and Burch, 1986a). The change in sediment transport capacity can be written as

$$\Delta T_{cj} = \varphi \left[\left(\sum_{i \in C_j^-} (\mu_i a_i)/b_{j-} \right)^m (\sin \beta_{j-})^n - \left(\sum_{i \in C_j} (\mu_i a_i)/b_i \right)^m (\sin \beta_j)^n \right], \qquad (2)$$

where φ is a constant, subscript j signifies the outlet of cell j and $j-$ signifies the inlet to cell j, and C_j^- is the set of i element indices which are hydrologically connected to cell j minus the current cell (Moore, Wilson, and Ciesiolka, 1992). A positive value of ΔT_{cj} indicates net deposition and a negative value indicates net erosion.

The source of the input values used in Equations (1) and (2)(and the fate of the TAPES-G attributes needed by EROS) depends on the method used in EROS to estimate weighting coefficients. Three choices are provided: (1) $\mu_i = \mu = 1$, which assumes that rainfall excess is generated uniformly over the entire catchment; (2) Hortonian overland flow in which μ_i is spatially variable and a function of the infiltration characteristics of the soil; and (3) saturation overland flow in which overland flow only occurs in zones of saturation in the landscapes.

The uniform rainfall excess method uses the slope and drainage area terms provided by TAPES-G with simplified versions of Equations (1) and (2) in which

$$T_c^{*} = \left(\frac{A_s}{22.13} \right)^m \left(\frac{\sin \beta}{0.0896} \right)^n \qquad (3)$$

$$\Delta T_{cj} = \varphi [A_{sj-}^m (\sin \beta_{j-})^n - A_{sj}^m (\sin \beta_j)^n]. \qquad (4)$$

where β is the slope (in degrees) and A_s is the specific catchment area or drainage area per unit width orthogonal to a flowline ($m^2 m^{-1}$). Equation (3) is equivalent to the length-slope factor in the Revised Universal Soil Loss Equation (Renard and others, 1991) for hillslopes with no convergence or divergence (Moore and Burch, 1986a, 1986b; Moore and Wilson, 1992).

TAPES-G is a grid-based terrain analysis program that calculates a variety of primary topographic attributes by applying a second-order, finite-difference scheme centered on the interior node of a moving 3×3 square-grid network (Gallant and Wilson, 1996). Slope, β, is computed as

$$\beta = \arctan \left\{ \left[\left(\frac{\partial z}{\partial x} \right)^2 + \left(\frac{\partial z}{\partial y} \right)^2 \right]^{1/2} \right\}, \qquad (5)$$

where

$$\frac{\partial z}{\partial x} = (Z_6 - Z_4)/2\lambda \quad \text{and} \quad \frac{\partial z}{\partial y} = (Z_2 - Z_8)/2\lambda, \qquad (6)$$

the Zs are the elevations of the nine nodes and λ is the grid-spacing. Specific catchment area is computed with one of four drainage area methods available in TAPES-G. A depressionless DEM can be created first with the method of Jenson and Domingue (1988) if desired.

The D8 (deterministic-eight node) algorithm developed by O'Callaghan and Mark (1984) allows flow from a node to only one of eight nearest neighbors based on the direction of steepest descent. This algorithm tends to produce flow in parallel lines along preferred directions, which will only agree with the aspect when aspect is a multiple of 45°, and it cannot model flow dispersion. D8 remains the most widely used method for determining drainage areas in spite of these limitations. The Rho8 (random-eight node) algorithm developed by Fairfield and Leymarie (1991) is a stochastic version of the D8 algorithm in which the expected value of the direction is equal to the aspect. Like the D8 algorithm, the Rho8 algorithm cannot model flow dispersion, but it does simulate more realistic flow networks. With this algorithm, long parallel flow paths are broken up at the cost of many more cells without upslope connection, distorting the distribution of contributing area.

The FD8 and FRho8 algorithms (option 3) are modifications of D8 and Rho8 that allow flow dispersion or catchment spreading to be represented (Moore and others, 1993). This pair of algorithms allows flow to be distributed to multiple nearest-neighbor nodes in upland areas above defined channels and uses the Rho8 or D8 algorithms below points of channel initiation. The proportion of flow or upslope contributing area assigned to multiple downslope nearest neighbors above channels is determined on a slope-weighted basis using methods similar to those proposed by Freeman (1991) and Quinn and others (1991). This third option gives much more realistic distributions of contributing area and also eliminates D8's parallel flow paths. Because stream lines are usually quite well defined, the flow dispersion algorithm usually is best disabled in areas of high contributing area, and TAPES-G provides a threshold termed the "maximum cross grading area" above which the simple D8 or Rho8 method is applied.

The fourth method provides a completely different approach for modeling flow accumulation and dispersion. Flow is generated at each pixel (source pixel) and is followed down a stream tube until the edge of the DEM or a pit is encountered using a modified version of the DEMON algorithm of Costa-Cabral and Burges (1994). These stream tubes expand and contract in response to the DEM surface, and thus naturally model both convergence and divergence. DEMON shows the differences between convergent and divergent areas more accurately than FD8/FRho8, and takes a similar amount of processing time.

The Hortonian overland flow method should be selected if runoff is to be determined by infiltration excess, and for a file with two or more soil polygons with weighting factors. EROS will ask for the name of this file and then perform a series of point-in-polygon overlays to assign weighting factors to individual DEM grid points. The drainage areas are recalculated using these weights, the flow directions copied from TAPES-G, and one or other of the D8, Rho8 and FD8/FRho8 methods discussed earlier. The slope values copied from TAPES-G and these new drainage areas are used to calculate T_c^* in Equation (1).

The saturation overland flow method should be selected if runoff is to be determined by surface saturation, controlled by a user-specified critical wetness index. For this situation, $\mu_i = 0$ when $\ln(A_s/\tan\beta) < W_c$ and $\mu_i = 1.0$ when $\ln(A_s/\tan\beta) \geq W_c$, where $\ln(A_s/\tan\beta)$ is a wetness index (Moore, Burch, and MacKenzie, 1988) and W_c is a user-specified critical wetness index that identifies the location of zones of surface saturation in the landscape. Moore, Wilson, and Ciesiolka (1992), for example, used a critical wetness index of 6.0 and found that $T_c^* > 2.5$ showed good agreement with areas of degradation observed in a 9.6 ha catchment in Queensland, Australia during 1979–1980 when vegetation was sparse. The wetness index values are calculated for each grid point and compared with the user-specified critical wetness index value to determine the weightings used in Equation (1).

SPATIAL EXTENSIONS OF SOIL EROSION MODELING

The two erosion indices computed by EROS can help with regional-scale erosion assessments in North America where large digital databases are readily available and erosion models are relatively abundant as well as in other parts of the world where models and data may be more difficult to acquire and use for erosion assessments.

Most of the erosion assessments performed in North America during the past two decades have used the Universal Soil Loss Equation (USLE) (e.g. Hession and Shanholtz, 1988; Ventura and others, 1988; Wilson, 1989). This model was empirically derived from about 10,000 plot-years of data (Wischmeier and Smith, 1978) and has recently been revised (Renard and others, 1991). The USLE and the Revised Universal Soil Loss Equation (RUSLE) can be written as

$$A = RKLSCP, \tag{7}$$

where A is the soil loss, R is the rainfall-runoff erosivity factor, K is a soil erodibility factor, L is a slope length factor, S is a slope steepness factor, C is a cover-management factor, and P is a supporting practices factor. Landuse and management are represented by CP and can, with some difficulty, be inferred by remote sensing combined with ground-truthing.

Climate erosivity is represented by R and can be computed directly from a knowledge of rainfall intensities and amounts. R varies on a regional scale. Soil erodibility is represented by K, and in the United States values of K have been interpolated or measured for all mapped soil series as part of the

SOILS-5 database that is derived from county soil surveys. Soil series are mapped at scales of 1:15,000 to 1:20,000 in these surveys. The effects of topography and hydrology on soil loss are characterized by the combined *LS* factor. Soil loss predictions are more sensitive to slope steepness than slope length. Estimation of the *LS* factor poses more problems than any of the other factors in the USLE (Renard and others, 1991) and is a particular problem in applying it to real landscapes as part of a GIS. Table 1 presents expressions for the *L* and *S* factors in both the USLE and RUSLE.

There are a number of implicit assumptions concerned with runoff generation and sediment transport imbedded in the equation, including: (1) runoff is generated uniformly over a catchment; (2) runoff occurs via the infiltration excess mechanism (i.e. Hortonian overland flow) and ignores saturation overland flow; and (3) sediment deposition is not represented. These assumptions help to explain why the application of this model to landscapes is more difficult than its application to soil loss plots (i.e. uniform slope profiles). The third assumption, in particular, represents a major practical problem because the model does not distinguish those parts of hillslope profiles experiencing net erosion and those areas experiencing net deposition (i.e. the lower ends of concave slopes). The model should be applied only to those parts of the landscape experiencing net erosion (Wilson, 1986). Griffin and others (1988) have rewritten the original USLE to calculate erosion at any point in a landscape experiencing net erosion. Their equation is easier to implement for large areas, although the user must still distinguish those areas experiencing net erosion and deposition at the outset. Their approach can also be combined with the irregular slope adjustment proposed by Foster and Wischmeier (1974) and used to determine average soil loss along hillslope profiles. Both of these versions retain the one-dimensional structure of the original equation and as a result, they cannot (like the original model) directly handle converging and diverging terrain (i.e. real three-dimensional landscapes).

Most of the attempts to use a GIS in conjunction with the USLE to model spatially varying soil loss have proceeded without addressing the problems that are incurred in scaling up USLE applications from slope profiles to large areas (i.e. catchments, counties, etc.). Descriptions of GIS/USLE applications by Ventura and others (1988) and Hession and Shanholtz (1988), for example, fail to mention the need to distinguish areas experiencing net erosion and net deposition before applying this equation (as discussed earlier). It is not clear how they respond to this challenge (if at all) and the discussion about scale (i.e. the size of the raster cells and/or vector polygons used to compute soil loss) and the consequences of using source data compiled at different scales is also vague. Hence, the definition of slope gradient and length used by Ventura and others (1988) is unclear and the definitions used in both applications are probably different from those specified in the original USLE. The appropriate data could have been compiled, interpreted, and used in conjunction with the USLE in ways that avoided these problems using manual (see Griffin and others, 1988) or automated techniques such as those proposed in EROS.

The two erosion indices that we have implemented in EROS not only avoid many of the problems and limitations of using a one-dimensional model such as the USLE in North America, but they also offer new opportunities for evaluating erosion hazard in other parts of the world with fewer data resources.

Topographic maps are available in most countries and can be used to calculate topographic attributes and plan additional data collection networks (i.e. hydrological monitoring, soil surveys, biological surveys). As additional environmental data become available, they can be used to provide improved estimates of the terrain-based indices. For example, the susceptibility of the landscape to sheet and rill erosion can initially be estimated using only topographic data. As hydrological and soils information becomes available, this information can be integrated into the predictions and finally, as information on vegetation and cover is developed, the full RUSLE or

Table 1. *LS* factors in Universal Soil Loss Equation (USLE) and Revised Universal Soil Loss Equation (λ = slope length in metres; β = slope angle in degrees)

	S		$L = (\lambda/22.13)^m$	
USLE (Wischmeier and Smith, 1978)	$65.4 \sin^2\beta + 4.56 \sin\beta + 0.0654$		$m = 0.5$	$\tan\beta > 0.05$
			$m = 0.4$	$0.03 < \tan\beta \leq 0.05$
			$m = 0.3$	$0.01 < \tan\beta \leq 0.03$
			$m = 0.2$	$\tan\beta \leq 0.01$
RUSLE (McCool and others, 1987a, 1987b)	$10.8 \sin\beta + 0.03$	$\tan\beta < 0.09$	$m = F/(1+F)$	
	$16.8 \sin\beta - 0.50$	$\tan\beta \geq 0.09$	$F = (\sin\beta/0.0896)/(3\sin^{0.8}\beta + 0.56)$[a]	
	$3\sin^{0.8}\beta + 0.56$	$\lambda \leq 4$ m	$F = 0$	deposition
	$(\sin\beta/0.0896)^{0.6}$	thawing soils with $\tan\beta \geq 0.09$	$\lambda = 4$ m	$\lambda \leq 4$ m
Moore and Burch[b] (1986a, 1986b)	$LS = (A_s/22.13)^m(\sin\beta/0.0896)^n$ where $m = 0.4$, $n = 1.3$, and A_s = specific catchment area			

[a]Assumes rill and interrill erosion are equal.
[b]Derived from unit stream power theory.

a complete physically based erosion model, such as the WEPP or Hairsine–Rose models referred to earlier, can be used. Hence, we see different layers of data being developed over time with elevation data and the related topographic attributes constituting a minimum data set. Topographic attributes can be estimated easily from a digital elevation model using any one of a number of terrain analysis methods. Most GIS are based on a pixel or cellular structure so that grid-based methods of terrain analysis can provide the primary geographic data for them and can be integrated easily within their analysis subsystems.

PROGRAM AVAILABILITY

To obtain copies of TAPES-G, EROS and TAPESOUT, contact Kate Ord at the Centre for Resource and Environmental Studies, Australian National University, Canberra, ACT 0200, Australia; telephone, +61 6 249 3381; fax, +61 6 249 0757; and e-mail, kateo@cres.anu.edu.au.

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