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Erosion database interface (EDI): a computer program for georeferenced application of erosion prediction models

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Abstract

The multidisciplinary approach of soil erosion research often requires erosion to be treated as spatial georeferenced information. This condition is essential so as to be compatible with information analyzed via Geographic Information Systems (GIS). The original versions of important soil erosion prediction models such as the Universal Soil Loss Equation (USLE) and Water Erosion Prediction Project (WEPP) do not operate on a georeferenced basis. The Erosion Database Interface (EDI) is a computer program for georeferenced application of USLE and WEPP. EDI uses, as input, a text format database with points defined by coordinates (x, y and z) representing hillslopes, each point associated to soil type and land use. Such input data can be provided by different methods. Exclusive field work with ordinary topographic equipment and GIS procedures are examples of methods that can be used for this purpose. Flexibility in the methods adopted for providing input data is an important prerequisite for erosion prediction in tropical and developing regions, where soil erosion is a major concern and the availability of digital data is usually restricted. Hillslopes for EDI were defined as straight line segments beginning at the upper slope and ending down at runoff output. This restricts EDI as a complete erosion-prediction method for areas where runoff deflecting features predominate or where channel or gully erosion is to be considered. As output, EDI provides georeferenced soil erosion values in another text format database. This database can be used directly for statistical or geostatistical analysis or imported into a GIS for further processing. A practical example representative of a sugarcane-growing area located at the southeastern part of Brazil is used to illustrate EDI's performance. In this example, soil erosion maps were produced from GIS data using EDI as interface for erosion calculations for WEPP and USLE.

Keywords: Soil erosion; Modeling; GIS; Watershed

1. Introduction

Soil erosion, resulting mainly from agricultural land use, is associated with environmental impacts (Clark et al., 1985) and crop productivity loss (Lal, 1995; Pimentel et al., 1995) which makes the understanding of the erosion process important to guarantee food security (Daily et al., 1998) and environmental safety (Matson et al., 1997). Due to methodological restrictions, erosion rates can be precisely measured only in small-scale experiments. For large scales, only estimates can be made. Following a recent trend of other branches of science (Cipra, 2000), erosion prediction is currently based on models, mostly developed during the last 20 years (Renard and Mausbah, 1990). The Universal Soil

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Loss Equation—USLE (Wischmeier and Smith, 1978), requiring a small number of input parameters and for which an extensive experimental database is available (Lane et al., 1992), is one of the most widely used erosion-prediction equations. More recently, mechanistic soil erosion-prediction models have been developed. These models use several equations divided in modules (e.g. hydrology, plant grow, soil water balance), each one related to a specific part of the erosion process. Among these, the Water Erosion Prediction Project—WEPP (Flanagan and Nearing, 1995) is one of the most important.

In order to include erosion as a variable in a decision-making process or land-use planning action, it is important to relate erosion rates to other geographic information (e.g. land use, crop management, soil type, farm size and socio-economic indicators). Geographic information is usually treated in Geographic Information Systems (GIS). WEPP and USLE are originally not associated to geographic coordinates, i.e. calculated soil loss or deposition rates are not georeferenced using the primary USLE formula or the WEPP software.

In this paper, we describe a computer program named Erosion Database Interface (EDI) that allows a georeferenced application of USLE and WEPP. An example for EDI's use with a database representative of sugarcane production in southeast Brazil generated with GIS is also presented.

2. Material and methods

2.1. EDI's general assumptions and procedures

Independent of which erosion model is used, WEPP or USLE, EDI processes only hillslopes. The definition used for hillslope is a straight-line segment beginning at the upper slope and ending down at runoff output (e.g. a river, channel or sediment fan). A hillslope should also follow the natural runoff direction. This excludes this first version of EDI as a useful interface for erosion/sedimentation estimation associated to features such as channels, impoundments or gullies. This hillslope approach also restricts EDI's exclusive adoption in areas where linear runoff intercepting or deflecting features such as terraces, small contour vegetated strips or roads want to be represented. Additionally, conditions where landscape structure and tillage plays a major role or are the main objectives of the research (Van Oost et al., 2000) are not indicated for exclusive application of EDI. In these cases, EDI may be used for the part of the area or for the erosion-prediction process for which the adopted hillslope definition is valid, but complementation with other methods will be necessary.

The hillslopes location has to be made before using EDI. The selection of an automatic procedure or manual definition may influence the results of erosion estimations (Desmet and Govers, 1996) but will not affect how EDI will operate, thus, will not be further discussed in this paper. To apply EDI, the hillslope has to be converted to a database format composed of points distributed along the line segment that represents each hillslope. In this text format database (.csv), each point has its x, y, z coordinates (expressed in metric units) and the corresponding hillslope, land use and soil type number. The distance between points (equally distributed or not) used to represent the hillslopes will also not influence the operation of EDI but may be important for the precision of erosion estimations. The distance between points should be a function of the kind of process the erosion values will have (statistic or geographic), and special attention on spatial representatives should be paid if raster interpolations are planned. An example of the input data file used in the example representing hillslopes 1 and 2 (from a total of 84 hillslopes for the entire watershed) is shown in Table 1.

For the slope length, EDI calculates linear regressions using the coordinates x and y of all points that represent each hillslope. The slope gradient is calculated based on the ratio between the altitude values linearly interpolated between the points from the input file and the distance between these points, calculated based on algorithms applied to the regression equations, form the x and y coordinates. These regression equations are also important because they are used to interpret WEPP output files (.sum) adding the coordinates lost during WEPP operation for calculations of erosion values.

The adoption of a database format as input information for EDI makes its adoption flexible. The input database may be defined in different ways, some examples are described:

(a) Direct measurement in field using topographic equipment (theodolites, total station) of x, y local coordinates and relative z altitudes complemented by local soil and land-use surveys.
(b) Direct measurement in field using Geographic Position Systems (GPS) technology for x, y geographic coordinates (metric projection) and z altitudes (BSL) complemented by local soil and land-use surveys. To increase precision, post-processing of field records with data from a base station may be indicated in this case.
(c) Interpretation of thematic maps (paper printed), extracting coordinates (local or geographic) for x, y and z from contour lines complemented by other maps or remote-sensed sources (aerial photographs or satellite images) or field surveys for soil and land-use data.

Table 1
Example of input text format database file used for erosion calculations by EDI for WEPP and USLE in Ceveiro watershed for hillslopes 1 and 2 from a total of 84 hillslopes

X[a]	Y[b]	Z[c]	Soil[d]	Land use[e]	Hillslope[f]
215972.14	7492357.91	500	5	1	1
215990.84	7492351.37	498	5	1	1
216012.30	7492343.87	496	5	1	1
216036.98	7492335.24	494	5	1	1
216064.13	7492325.75	492	5	1	1
216093.04	7492315.65	490	5	1	1
216109.58	7492309.86	488	5	1	1
216125.73	7492304.22	486	5	1	1
216145.52	7492297.30	484	3	1	1
216168.09	7492289.41	482	3	1	1
216188.68	7492282.21	480	3	1	1
216196.28	7492279.56	478	3	1	1
216204.46	7492276.70	476	3	1	1
216218.54	7492271.77	474	3	1	1
216236.58	7492265.47	472	3	1	1
216253.16	7492259.67	470	3	1	1
216263.90	7492255.92	468	3	1	1
216274.53	7492252.20	466	3	1	1
216288.76	7492247.23	464	23	1	1
215972.28	7492367.25	500	5	1	2
215992.31	7492362.44	498	5	1	2
216010.06	7492358.18	496	5	1	2
216033.34	7492352.59	494	5	1	2
216061.82	7492345.76	492	5	1	2
216091.39	7492338.66	490	5	1	2
216108.31	7492334.60	488	5	1	2
216123.42	7492330.97	486	5	1	2
216143.98	7492326.04	484	5	1	2
216169.89	7492319.82	482	3	1	2
216191.85	7492314.55	480	3	1	2
216204.36	7492311.55	478	3	1	2
216215.97	7492308.76	476	3	1	2
216229.35	7492305.55	474	3	1	2
216249.48	7492300.72	472	3	1	2
216268.06	7492296.26	470	3	1	2
216279.50	7492293.51	468	3	1	2
216291.42	7492290.65	466	3	1	2

[a] Easting in Universal Transverse Mercator (UTM) coordinates (zone 23S, ellipsoid IUGG 1967, datum South American 1969 Brazil).
[b] Northing in UTM coordinates.
[c] Altitude (BSL) in metric units extracted from the digital contour line map from the Ceveiro watershed.
[d] Soil type, where 3—Arenic Paleudult; 5—Typic Dystrochrept and 23—Typic Udorthent.
[e] Land use, where 1—sugarcane.
[f] Hillslope number.

(d) Extraction of x, y and z geographic coordinates from digital maps using GIS tools. The altitude values may by extracted from a raster Digital Elevation Model (DEM) or directly from contour lines. The procedures for extracting the altitude data directly from contour lines were used in the example. This option was included because soil erosion models are very sensitive to slope gradient and length (Nearing et al., 1990; Risse et al., 1993). The use of contour lines for altitude may be useful, in some cases, to avoid precision degradation caused by the calculation algorithm used to create the DEM (Srinivasan and Engel, 1991; Jones, 1998). The flexibility for using DEM and/or contour data for the topographic parameters may be an advantage for EDI when compared to other approaches for erosion estimation via GIS based exclusively on DEM (Hamlett et al., 1992; Mellerowicz et al., 1994; Sabavi et al., 1995).

EDI was designed to have greater flexibility in relation to the procedures adopted for building the input data to help its adoption in developing regions, where usually the availability of digital data is limited and erosion is a major concern (the developing regions are mostly located in tropical latitudes). The construction of a geocoded database for erosion estimation based exclusively on fieldwork with ordinary topographic equipment up to sophisticated GIS procedures covers the total range of expected conditions that will be experienced when working in developing regions. The text database format also allows connecting EDI more easily to GIS or statistical programs considering that most of these systems can import and export text format. The georeferenced soil loss output data can be used for geostatistical analysis or for the calculation of classical parameters such as mean value and variance. Another option is to import EDI's output data into a GIS for further operations (e.g. interpolation, transfer of data to other georeferenced information such as polygons or regions, visualization in the form of map or graphical representation of erosion along the hillslopes).

EDI was designed to operate with user directions as little as possible. With the system set up to fit the available input database and to get the desired output, no further user assistance is needed. Independent of the size of the database, EDI will process data automatically. This makes EDI adaptable to different scales without spending time for repeating routines that could be processed automatically.

2.2. EDI procedures for use with USLE

USLE is represented by the following equation (Wischmeier and Smith, 1978)

$$A = R \times K \times L \times S \times C \times P \tag{1}$$

where: A is the mean annual soil loss ($\mathrm{Mg\,ha^{-1}\,y^{-1}}$); R is the rainfall and runoff factor ($\mathrm{MJ\,ha^{-1}\,mm\,h^{-1}}$); K is the soil erodibility factor ($\mathrm{Mg\,ha^{-1}\,(MJ\,ha^{-1}\,mm\,h^{-1})^{-1})\,y^{-1}}$; LS is the topographic factor related to slope length (L) and gradient (S); C is the cover and management factor; and P is the support practice factor.

For EDI, each soil type has its own K-value and each land use has its own $C \times P$-value. These values are stored in a soil-type text format file and in a land-use type file. The R factor is constant for each program run and user defined in EDI's internal setup.

Based on the x, y and z coordinates, EDI will calculate the L and S factors dividing the whole hillslope into n 1-m segments. The combined LS value for each of these segments is estimated according to the methods suggested by Foster and Wischmeier (1974) and Wischmeier and Smith (1978). First, the slope length factor (L) is calculated for segment i (L_i, $i \leqslant n$):

$$L_i = \left(\frac{i}{22.13}\right)^{0.5}. \tag{2}$$

Then, the slope steepness factor (S) from the first segment up to segment i, S_j ($1 \leqslant j \leqslant i$), based on the slope steepness from the segment (σ_j, $\mathrm{m\,m^{-1}}$), is calculated using the x, y, z coordinates from the neighboring points:

$$S_j = 65.41\frac{\sigma_j^2}{1+\sigma_j^2} + 4.56\frac{\sigma_j}{\sqrt{1+\sigma_j^2}} + 0.065. \tag{3}$$

The LS factor at the end of segment i (LS_i) is then calculated by

$$LS_i = L_i \sum_{j=1}^{i} P_j S_j \tag{4}$$

with P_j as the weighting factor:

$$P_j = \frac{j^{m+1} - (j-1)^{m+1}}{i^{m+1}} \tag{5}$$

where $m = 0.5$ for a slope steepness $\geqslant 0.05\,\mathrm{m\,m^{-1}}$, or equal to 0.3 for a slope steepness $\leq 0.03\,\mathrm{m\,m^{-1}}$ and, for a slope steepness between 0.03 and $0.05\,\mathrm{m\,m^{-1}}$, it is calculated by

$$m = 10\sigma. \tag{6}$$

Then, the soil loss rate A is calculated following the USLE general equation (Eq. (1)) for the whole database using the K, LS, and CP factors corresponding to each point and the R factor defined for the specific run.

EDI will generate output files with longitude (x) and latitude (y) in meters and soil loss in $\mathrm{kg\,m^{-2}\,y^{-1}}$ or $\mathrm{Mg\,ha^{-1}\,y^{-1}}$. This output file may contain the same geographic points as the input file, user-defined equidistant length intervals or 100 points per Overland Flow Element (OFE, represented by uniform land use and soil numbers).

2.3. EDI procedures for use with WEPP

The WEPP management and soil input files (.man and .sol, respectively) considering a single OFE, corresponding to the soil and land-use numbers in EDI's input file, have to be available in a format appropriate for the desired WEPP version. EDI will build a soil data input file (.sol), a management input data file (.man) and a slope input data file (.slp) for each hillslope after dividing it in the respective OFEs. The slope files are calculated based on the x, y and z coordinates directly from the input file (e.g. Table 1). Another file containing the desired output and calculation procedures (.inp) is built for each hillslope, and a batch file (.bat) to automatically run WEPP's executable file (WEPP. EXE) for the entire data set. Following this procedure, WEPP calculations are done automatically only with the WEPP. EXE file and all hillslopes are processed without further assistance. As its output, WEPP creates summary files (.sum) containing the erosion prediction data. In the WEPP output files, the coordinates get lost because WEPP processes do not include geographic information. These files are interpreted and georeferenced by EDI and the same output options for soil loss data as described for USLE are available for WEPP. The coordinates lost during WEPP calculations of erosion data are restored using the regression equations based on the x and y coordinates calculated for the hillslopes by EDI.

2.4. An example of the application of EDI

To illustrate EDI's performance, a practical example was prepared representing a Brazilian sugarcane production area. The input database construction used a digital contour map for definition of the x, y, and z geographic coordinates, and digital maps for soil types and land use. The output results for USLE and WEPP were imported in the GIS and converted to raster format to allow the visualization of the results. The example was based on a 77 ha watershed (Ceveiro watershed) located in the southeastern part of Brazil (Piracicaba) with central coordinates of 22°38′54″S and 47°45′49″W. Climate, according to Koeppen's classification is Cwa (Humid subtropical with a dry winter and <30 mm rain in the driest month, the temperature in the hottest month is beyond 22 C and in the coldest, below 18 C). The landscape is composed of S-shaped profiles and the mean slope value is 18%. The soils, according to Soil Taxonomy (Soil Survey Staff, 1990) were classified as Arenic Paleudult (83%), Typic Dystrochrept (10%) and Typic Udorthent (7%). Current land use, determined in filed surveys, is composed of sugarcane (70%), riparian forest following drainage lines (22%), and some pastures (8%). Sugarcane is also the main crop in the region, occupying 80% of the arable land. Management files for WEPP were computed based on the methods described in Flanagan and Nearing (1995). The input parameters were adjusted to represent local crops and pasture management as well as the forest parameters. The C and P values for USLE were defined based on bibliographic data, selecting the values that could better represent local management. Soil input files for WEPP were based on equations suggested by Flanagan and Nearing (1995) and calculated for each soil type based on soil analysis results. Soil erodibility or USLE's K factors were calculated based on soil analysis data following the general procedure described by Wischmeier et al. (1971) adapted to Brazilian conditions by Denardin (1990). Local climatic data from daily 30 years records were used to calculate climate inputs. The climate input file for WEPP was generated using CLIGEN ver. 4.3 (Nicks et al. 1995) running a 98 years simulation. The USLE R factor was estimated, based on the same climatic data, as 6235 MJ ha^{-1} mm h^{-1} using the procedures described by Lombardi Neto and Moldenhauer (1992). Altitude information was extracted from a topographic contour map at scale 1:10,000 with an original vertical resolution of 5 m, interpolated to 2 m vertical resolution using GIS triangulation tools. Soil erosion estimations were made for WEPP and USLE using the same transects (84 transects with mean length of 243 m) defined manually following straight paths of surface runoff (Fig. 1a). A small distance between the transects (≈ 20 m) was selected to allow a better raster interpolation of EDI's output soil erosion data. For these interpolations, a spherical variogram was calculated and a 10 m × 10 m pixel raster calculated by kriging. The GIS procedures were carried out by means of *TNTmips* (Micro Images®) version 6.2. All data were georeferenced based on the metric Universal Transverse Mercator coordinate system (zone 23S, ellipsoid IUGG 1967, datum South American 1969 Brazil).

3. Results and discussion

EDI was effective as a GIS interface for erosion rates calculation on a georeferenced basis for both models, USLE and WEPP. The cartographic result of erosion estimations by EDI after GIS raster interpolation is shown for USLE in Fig. 1b and for WEPP in Fig. 1c.

The soil erosion maps produced with EDI's output data reflect the model's theoretical assumptions. USLE does not estimate sediment depositions. Thus, the usual sediment-trapping landforms (i.e. toe slope with lower steepness, floodplains and riparian forests) identified with WEPP simulation (Fig. 1c) are not present on the map of USLE (Fig. 1b). In these positions, USLE estimated a reduction in erosion rates due to a decrease of C, P and S factors but soil loss is indicated as the only process. For both models, erosion estimations were sensitive for topographic and land-use changes. On the pasture, USLE showed lower erosion rates as compared to the same topographic position with sugarcane. WEPP also estimated low erosion or deposition rates at the pastures. For both models, erosion rates increased from the flatter upper slopes to the steeper mid- or end-slopes, showing high sensitivity to slope steepness and length. However, this increase was more significant for USLE, showing that this model is more sensitive to topography-related variables. Higher soil loss estimations for the Revised Universal Soil Loss Equation or RUSLE (Renard et al., 1997) as compared to WEPP were attributed to a lower sensitivity to crop-related para-

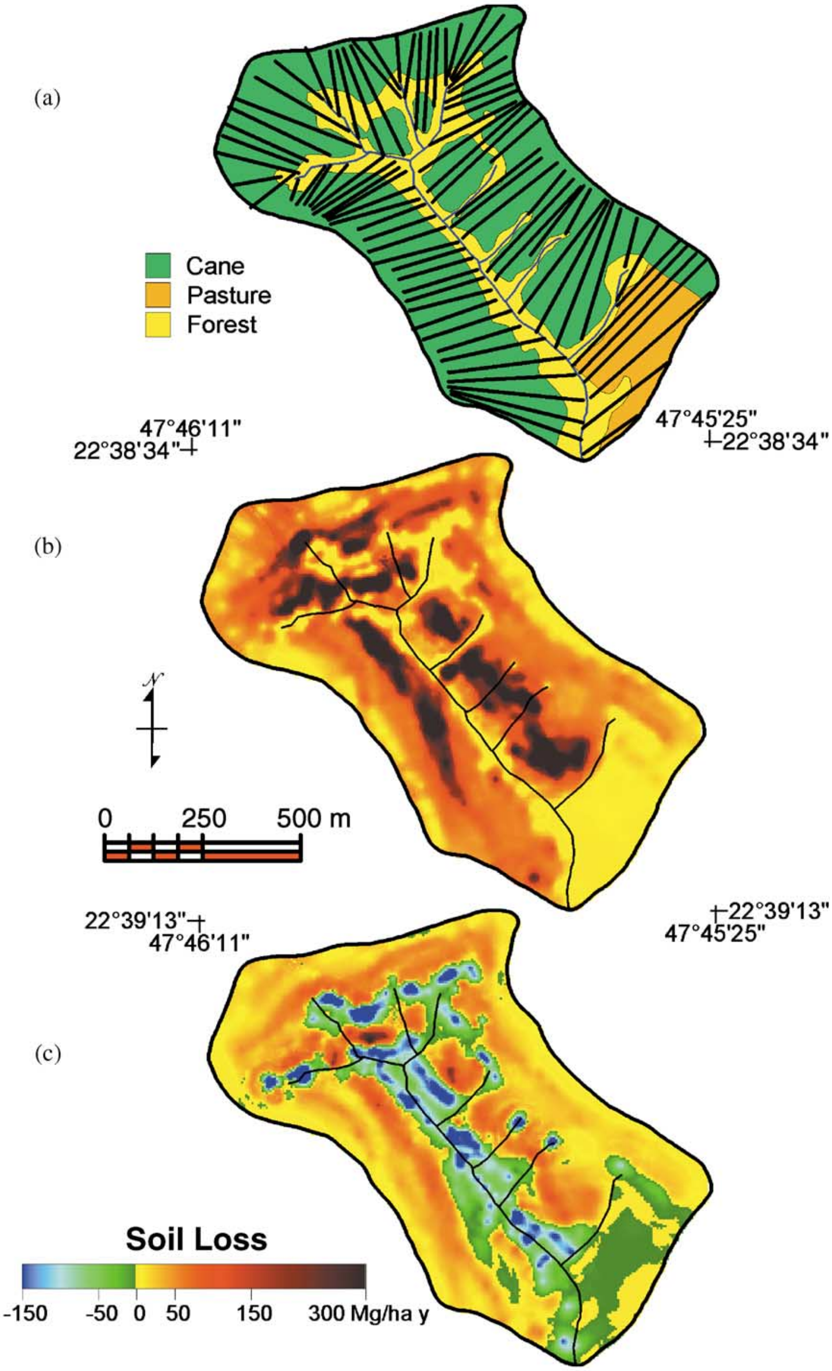

Fig. 1. (a) Land use, soil erosion estimation transects (black straight lines) and drainage lines (blue curve lines) of Ceveiro watershed; (b) soil erosion estimation for Ceveiro watershed by EDI for the USLE *; (c) soil erosion estimation for Ceveiro watershed by EDI for the WEPP *, negative values indicate sediment deposition. * Results were derived by kriging.

meters and higher sensitivity to topographic factors in RUSLE (Nearing et al., 1990).

The greater spatial variability of erosion rates, observed for both models, makes it clear that it is important to consider erosion as a spatial variable. The mean soil-loss rates, based on the interpolated values, estimated by USLE of $86\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$ and WEPP of $35\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$ (excluding the depositional areas) indicate that the models estimated erosion differently (USLE $\approx$2.5 times more than WEPP) and that the erosion rates are greater than the usually accepted values of soil loss tolerance of $12\,\mathrm{Mg\,ha^{-1}\,y^{-1}}$ or less (Grossman and Berdanier, 1982). This information is important and may indicate that the model's input parameters still need calibration in relation to determined erosion rates to make its performance more comparable or precise. The selected transects may also have exceeded length limits for USLE resulting in overestimation.

The cartographic representation of erosion rates, possible by GIS processing of EDI's output data, gives another dimension and value to this kind of information. Technically, the advantages are related to the possibility of comparing these data to other spatially variable information or including erosion rates as georeferenced data in more complex models. Another important aspect of a cartographic representation, especially considering land-use planning actions, is to represent erosion rates in an understandable format. A farmer not familiar with soil erosion research, may find it difficult to understand the meaning of a specific soil erosion rate that was estimated to occur in a part of the farm, but probably, may promptly react on seeing that part of the area flagged with a red color on a soil erosion map.

To give some indication on EDI's performance, the time needed for preparing and processing the WEPP simulation (more time-consuming than for USLE's application) for the example presented in this paper was measured. On an office PC (Pentium® III, 866 Mhz processor) the 84 hillslopes were successfully processed in 20 min including: (a) the creation of EDI's input files via GIS, (b) initial file processing in EDI, (c) automatic WEPP calculations, (d) georeferencing of WEPP output files via EDI, and (e) importing soil erosion results back in GIS.

4. Conclusions

The Erosion Vector Interface (EDI) is an efficient program for georeferenced erosion prediction based on the Universal Soil Loss Equation (USLE) and Water Erosion Prediction Project (WEPP) model.

A greater flexibility for creating the input database may be an important factor towards its adoption in developing regions where extensive digital databases are usually not available.

The text formats for input and output databases make it easy to adapt to EDI to GIS or statistical programs considering that most of these systems can import and export text formats.

EDI is a non-commercial software protected by copyright in the name of the authors and of the project sponsoring agency (FAPESP). Those interested in using EDI for research purposes should contact the corresponding author via electronic mail for further instructions on how to get a copy from software installation files, manual and tutorials.

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