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Short note

Runoff mapping using WEPP erosion model and GIS tools

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Abstract

Soil erosion, associated with environmental impacts and crop productivity loss, is usually considered the most impacting of surface hydrology processes. Runoff plays a major role in the erosion process, but it is also important by itself as it directly influences several surface hydrologic processes. In this paper, a computer interface (Erosion Database Interface, EDI) is described that allows processing the surface hydrology output database of the Water Erosion Prediction Project (WEPP) erosion prediction model, resulting in a georeferenced estimation of runoff. WEPP output contains non-georeferenced daily information about estimated runoff at the lower end of each Overland Flow Element. EDI, when running with WEPP, allows extracting WEPP-calculated runoff values, transforming them into annual means and relocating them in a georeferenced database readable by Geographic Information Systems (GIS). EDI was applied to a 1990 ha watershed in southeast Brazil, with vegetation of mainly sugarcane, forest, and pasture. A 100-year climate simulation was used as input to WEPP, and erosion values were calculated at about six points per hectare and interpolated to a raster format. EDI was successful in preparing the database for automatic calculation of erosion and hydrologic parameters with WEPP and to restore georeferences to mean annual accumulated runoff data that were imported in the GIS as a vector database. Of all the resulting maps, the runoff map is the one that integrates all of the input parameters required for WEPP simulation, thus reflecting not only the physical environment but also crop growth and management and tillage operations. A very small correlation between runoff and erosion shows them to behave independently. Moreover, it is concluded that on analyzing runoff related to agricultural management, georeferenced runoff studies are especially important. In this context, EDI may be a useful tool to assess the effect of tillage and crop management on runoff production.

1. Introduction

Considering specific climate, slope and soil conditions, erosion rates vary mainly according to land use changes. Erosion 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). Soil erosion is thus considered to have the greatest impact among surface hydrologic processes. A computer program for georeferenced application of

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erosion models (Erosion Database Interface, EDI) was described in detail by Ranieri et al. (2002). EDI exchanges databases with Geographic Information Systems (GIS) and allows automatic erosion calculations using the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing, 1995) and/or the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978) models. The usefulness of EDI in comparing different erosion models and gauging their performance when applied to an area with similar input data was shown by Sparovek et al. (2000), and its application together with soil depth and crop productivity relationships to map erosion-induced crop yield losses at the watershed scale was described by Sparovek and Schnug (2001). Also, the definition of the optimal width of riparian forests integrating physical modeling with socio–economic variables was shown by Sparovek et al. (2002a).

Soil erosion predictions made by process-based models such as WEPP depend to a high degree on runoff estimates. Runoff is responsible for sediment transport (or deposition when transport capacity decreases) and detachment during the erosion processes, both extremely sensitive parameters in erosion prediction technology (Hergarten et al., 2000). Therefore, runoff plays a major role when analyzed under the perspective of the erosion process, and also has a significant importance by itself. Several surface hydrologic processes are directly influenced by runoff. River discharges and floods are impacted by runoff (Pielke, 1999; Sparovek et al., 2002b); pesticides and nutrients may be transported as dissolved particles in runoff water (Ghadiri and Rose, 1993; Burgoa and Wauchope, 1995) and the design of facilities and structures based on hydrologic engineering depends on accurate runoff estimation (Yanmaz and Coskun, 1995; McCuen and Okunola, 2002).

The WEPP model calculates several surface hydrologic parameters for predicting soil erosion (daily runoff, plant transpiration, soil evaporation, deep percolation, water stress for plant grow, and lateral subsurface flow) based on equations and procedures described by Stone et al. (1995). Erosion models are usually very sensitive to agricultural management (tillage, crop residues on soil surface, plant growth) and soil properties (clay content and type, soil structure, pore size distribution, water infiltration capacity) and combine all of these variables in space and time using complex calculation procedures.

The objective of this paper was to describe an extension of EDI that allows it to process the output database of WEPP that contains the surface hydrologic parameters, allowing a georeferenced estimation of runoff and the production of runoff maps. Pure hydrologic models simplify several parameters related to tillage, crop growth, residues, and other agricultural management practices. Process-based erosion models cannot deal with these simplifications because erosion is sensitive to them. Extracting the hydrologic part of erosion models may be useful for a better understanding of their influence on runoff. The application of the EDI extension was demonstrated here with a 1,990 ha watershed in Brazil.

2. Material and methods

2.1. EDI processing of WEPP runoff estimates

The required data and input parameters for EDI are described in detail by Ranieri et al. (2002); however, some of its most important aspects will be summarized here. EDI processes hillslopes, that are straight-line segments beginning at the top of a slope and ending down at runoff output (e.g., a river, channel or sediment fan), following the natural runoff direction. To apply EDI, the hillslopes have 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 metric coordinates and a corresponding hillslope, land use, and soil type number. From these data, EDI calculates slope gradients for each hillslope and stores these data together with the position (latitude and longitude in metric units) of each hillslope in order to be able to link WEPP output results to geographical positions later on.

Each hillslope is treated by WEPP as a composition of *overland flow elements* (OFE), defined as a section of a hillslope with uniform soil and management. EDI builds 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 into its respective OFEs. Another file that contains the desired output and calculation procedures (.inp) is built for each hillslope, and a batch file (.bat) is created to automatically run WEPP's executable file for the entire data set, using the DOS-version of WEPP.

WEPP's surface hydrology component (Stone et al., 1995) uses a sophisticated procedure to estimate runoff, based on climatic, agronomic, and pedologic features. Runoff is calculated as a result of rainfall, infiltration, and depression storage. Given a certain rainfall intensity and duration, cumulative infiltration is computed as a function of effective hydraulic conductivity, average capillary potential, soil moisture deficit, and rainfall rate, using the Green–Ampt Mein–Larson model (Chu, 1978). The rainfall excess is transformed into a runoff distribution in time after adjustment for soil saturated conditions and depressional storage. Maximum depressional storage and infiltration rates, determined by several soil and management factors, can impact runoff in a considerable way. This is why mechanistic erosion prediction models such as WEPP may be considered integrators of complex multidisciplinary knowledge, as far as runoff calculation is concerned.

WEPP runoff calculations operate initially assuming a unit area (1 m × 1 m). The runoff depth is the total depth of runoff under the excess rainfall curve minus depression storage. This depth is then assumed to be uniform over the entire contributing area. When a hillslope is composed of multiple OFEs, the runoff depth value reported in the output is the depth of runoff over the entire contributing area from the top of the hillslope to the bottom of the current OFE. That means that the effective length in the model runoff computations is the sum of the lengths of all OFEs down the hillslope over which runoff is occurring.

WEPP output results are contained in several files, among those the files with extension .wtr. These files are optionally created and contain detailed information about accumulated runoff estimates at the lower end of each OFE for each day (d) of each one of the n years (y) of the simulation ($Qac_{ofe,d,y}$, mm d^{-1} or 10^{-3} m^3 runoff water per m^2 of contributing area per day). The .wtr files are read by EDI, and daily runoff values are extracted and transformed into annual means for each OFE ($\bar{Q}ac_{ofe}$, mm y^{-1}).

$$\bar{Q}ac_{ofe} = \frac{\sum_{y=1}^{n}\sum_{d=1}^{365} Qac_{ofe,d,y}}{n}. \quad (1)$$

To estimate runoff values within each OFE, the accumulated runoff volume from the top of the hillslope to the bottom of each OFE (Vac_{ofe}, m^3 yr^{-1}) is computed as

$$Vac_{ofe} = \bar{Q}ac_{ofe} Lac_{ofe} W \times 10^{-3}, \quad (2)$$

where Lac_{ofe} (m) is the distance between the top of the hillslope and the bottom of the OFE and W (m) is the width of the OFEs. Assuming mass conservation, the volume of runoff produced by each OFE (V_{ofe}, m^3 y^{-1}) can be calculated as

$$V_{ofe} = Vac_{ofe} - Vac_{ofe-1} \quad (3)$$

and from V_{ofe} the average runoff for the OFE ($Qavg_{ofe}$, mm y^{-1}) can be computed as

$$Qavg_{ofe} = \frac{V_{ofe}}{L_{ofe} W} \times 10^3, \quad (4)$$

where L_{ofe} (m) is the length of the OFE. As an OFE is defined as a portion of a hillslope with equal soil and management, infiltration rate and runoff production may be assumed constant along one OFE. Therefore it may be assumed that

$$\begin{aligned} Qavg_{ofe} &= \frac{Qtop_{ofe} + Qbot_{ofe}}{2} \\ &= \frac{Qbot_{ofe-1} + Qbot_{ofe}}{2} \Rightarrow Qbot_{ofe} \\ &= 2Qavg_{ofe} - Qbot_{ofe-1}, \end{aligned} \quad (5)$$

where $Qtop_{ofe}$ (mm yr^{-1}) and $Qbot_{ofe}$ (mm yr^{-1}) are the runoff values at the top and the bottom of each OFE, respectively. If it is assumed that runoff at the top of each hillslope equals zero (i.e., $Qtop_1 = Qbot_0 = 0$), this approach allows estimation of $Qbot_{ofe}$ for each OFE by interpolating linearly between OFE bottom values. The runoff within each OFE can also be computed. After this, the coordinates not considered by WEPP processing are restored by EDI, and a file containing coordinates and runoff estimates in text format is created.

2.2. The case study

The Ceveiro watershed (1,990 ha) is located in the southeastern part of Brazil (Piracicaba) with central coordinates of S 22°38′54″ and W 47°45′40″. The climate according to Koeppen's classification is Cwa, i.e., humid subtropical with a dry winter and less than 30 mm of rain in the driest month. The temperature in the warmest month is higher than 22 °C and in the coldest below 18 °C. A summary of some meteorological data observed at a weather station about 10 km from the watershed is shown in Fig. 1. The landscape is usually composed of S-shaped profiles and the mean slope value is 13% (minimum slope 0.0%, maximum 59.0% and 90% of slope values are between 2.4% and 26.0%). The soil types in the area are usually sandy at the surface and mainly represented by Ultisol, Alfisols, and Entisols. In recent years significant land use changes were not observed in the area. For the calculation of soil erosion and runoff, data from 1995 were used. Land uses are sugarcane (66.3%), forests (17.4%), pastures (13.9%), corn (0.1%) and non-agricultural use (2.3%). Slope information was extracted from a topographic contour map at a scale of 1:10,000 with an original vertical resolution of 5 m, interpolated to 2 m vertical resolution using GIS triangulation tools. A total of 939 transects, with a mean length of 243 m distributed uniformly over the entire area were defined for soil erosion and runoff estimation. Local climatic data from daily 30-year 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 simulation of 100 years. Soil input files were calculated for each soil type using the equations suggested by Flanagan and Livingston (1995) based on soil analysis results of 223 sampling points. Management files for sugarcane, corn, pasture, and forest were computed

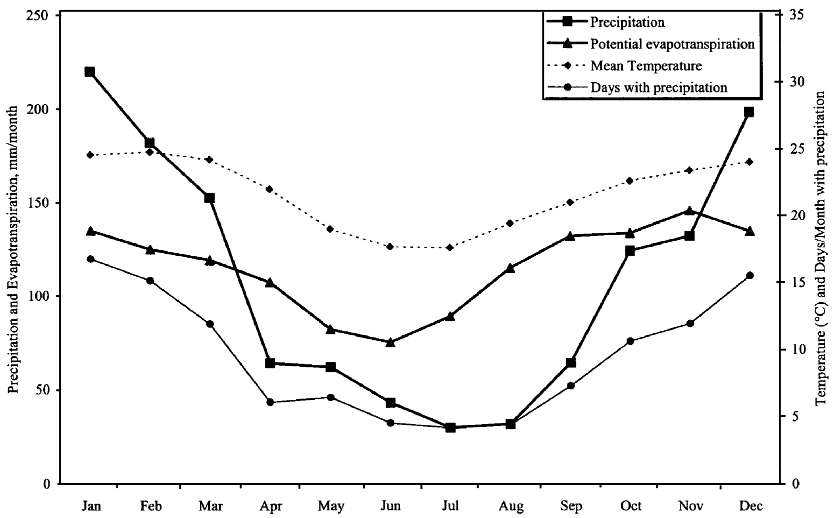

Fig. 1. Monthly means (1960–2001) of precipitation (mm), potential evapotranspiration (mm), mean temperature (°C) and number of days with precipitation, extracted from observations from a weather station near Ceveiro watershed.

Table 1
Description of variables used for simulations

Variable	Source/description	Reference
Model	WEPP applied to 11,238 points	Flanagan and Nearing (1995)
Soil map	Field survey	
Land use	Aerial photographs from 1995 supplemented with field survey	
Topography	Digital contour map at scale 1:10,000	
Climate	Recent 30 years of local daily records converted to WEPP input files using CLIGEN version. 4.3.	Nicks et al. (1995)
WEPP soil input files	Based on samples from 223 profiles analytical data (very fine sand, sand, clay, organic matter, cation exchange capacity, rocks and soil depth)	Flanagan and Livingston (1995)
WEPP management input files	Based on local crop data	Flanagan and Livingston (1995)

following the methods described by Flanagan and Livingston (1995). The input parameters were adjusted to represent local crops and pasture management and the forest parameters.

The GIS procedures were carried out by means of *TNTmips* (Micro Images®) version 6.6. Erosion and runoff values were calculated for each intersection point of the transects with the contour line map (a total of 11,238 points or about six points per hectare) and interpolated to a raster format (pixel of $10 \times 10\,\mathrm{m}$) by kriging using a spherical variogram calculated within the GIS. The range of the erosion semivariogram was 320 m and the sill value was $3.0\,\mathrm{Mg\,ha^{-1}\,yr^{-1}}$. For runoff, the range of the semivariogram was 335 m and the sill value was 298 mm. The variables used for simulations, their description, and sources are shown in Table 1.

3. Results and discussion

The extended version of EDI was successful in preparing the database for automatic calculation of erosion and hydrologic parameters with WEPP. The mean annual accumulated runoff data were georeferenced based on the coordinates of the initially defined transects and imported in the GIS as a vector database. The result of the interpolation to a raster element covering the entire watershed area is shown in Fig. 2A, together with the erosion map of the same area calculated by Sparovek and Schnug (2001) (Fig. 2B), the geology of the area 1 (Fig. 2C) and the land use (Fig. 2D). Of these, the runoff map integrated all input parameters required for WEPP simulation, thus reflecting not only the physical environment (soil type, slope length, and inclination) but also crop growth

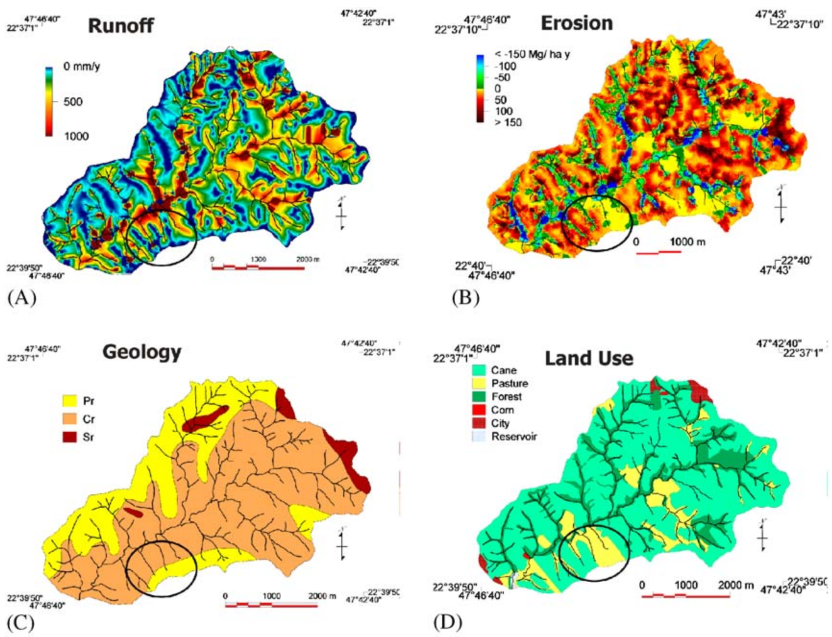

Fig. 2. WEPP 100-year average annual runoff estimates (A) and soil erosion estimates (B) produced using EDI interface, and maps of geology (C) and land use (D) in Ceveiro watershed.

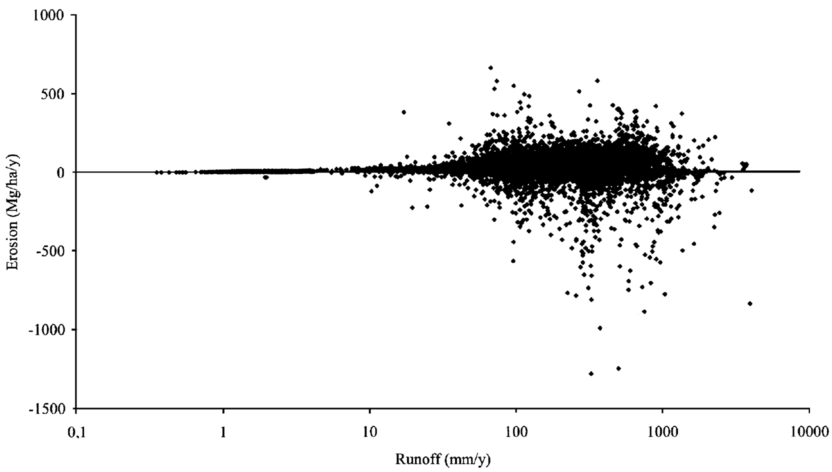

Fig. 3. WEPP 100-year simulation mean soil erosion estimates plotted against runoff estimates for Ceveiro watershed (negative erosion values indicate deposition in WEPP).

and management and tillage operations. WEPP is an erosion prediction model known to be very sensitive to management and crop performance (Nearing et al., 1990), making this approach especially useful when the evaluation of agronomic aspects is one of the objectives of a hydrologic study. Also, the runoff data treated by EDI in a georeferenced way allow spatial analysis.

The higher parts of the watershed, especially the northwestern region, are mostly represented by the Pirambóia geologic formation (Pr, Fig. 2C), which consists of coarse sediments and is associated with more sandy soils. Most other parts developed in the Corumbataí formation (Cr) of fine sediments that usually weather to soils having high clay contents in the subsurface horizons. When observing the geographic distribution of erosion (Fig. 2B), these differences in geology are masked by the effect of land use (Fig. 2D). On the other hand, runoff (Fig. 2A) shows a different trend in the northwestern region, making this a good example of how runoff estimates result from the overall integration of physical and management variables and in some cases do not follow the erosion pattern. The area highlighted by the ellipse in Fig. 2 is showing WEPP's distinct sensitivity for runoff and erosion. The change from Pirambóia geologic formation (Pr, sandy) at the top of the hill to Cr (clayey) increases runoff from the midslope to the floodplain. The same trend did not occur for soil erosion, as clearly indicated by the colors of the map. In this case, the dominant land use type (pasture) reduced erosion amounts to very low rates independent of the geologic formation. The runoff parameter in WEPP is probably more sensitive to changes in the physical environment than the erosion parameter, but in both cases management and soil attributes are integrated in the estimates. Another important feature of EDI is related to the geographical location of runoff. Spatial analysis, especially the identification of hot spots (areas related to very high runoff production) can only be addressed using geographic tools.

As might be expected from the previous discussion, runoff and erosion as estimated by WEPP showed no correlation. In Fig. 3, erosion estimates of the 11,238 points calculated by WEPP were plotted against runoff estimates. Despite some indication that very low runoff values are somewhat related to very low erosion rates (values concentrating at the origin of the graph), these variables are not correlated. The scattered pattern of the points plotted on the graph and a correlation coefficient of 0.07 clearly indicate that an increase of runoff is not necessarily associated with an increase of soil erosion. Therefore, when runoff depth estimation by itself is the aim of the study, erosion values should not be used as a proxy, and runoff should be specifically calculated separately.

4. Conclusions

1. The software tools described in this paper allow use of the WEPP erosion prediction model for georeferenced mapping of runoff estimates.
2. Predicted runoff was not correlated with predicted soil erosion.
3. Georeferenced runoff studies are especially important when the objective is to analyze runoff related issues under prospective agricultural management systems.
4. EDI may be a useful tool to assess the effect of tillage and crop management on runoff production.

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