Available online at www.sciencedirect.com
ScienceDirect
Environmental Modelling & Software 22 (2007) 1175–1183
Environmental Modelling & Software
www.elsevier.com/locate/envsoft

# Assessment of erosion hotspots in a watershed: Integrating the WEPP model and GIS in a case study in the Peruvian Andes

Guillermo A. Baigorria [a,*], Consuelo C. Romero [b]

[a] Agricultural and Biological Engineering Department, University of Florida, Gainesville, FL 32611, USA
[b] Departamento de Suelos, Universidad Nacional Agraria La Molina, Lima 12, Peru

Received 8 April 2005; received in revised form 3 January 2006; accepted 9 June 2006
Available online 22 August 2006

**Abstract**

This paper presents a case study in assessment of erosion hotspots in an Andean watershed. To do this, we made use of an interface called Geospatial Modelling of Soil Erosion (GEMSE): a tool that integrates Geographical Information Systems (GIS) with the Water Erosion Prediction Project (WEPP) model. Its advantages are: (i) it is independent of any special GIS software used to create maps and to visualize the results; (ii) the results can be used to produce response surfaces relating outputs (e.g. soil loss, runoff) with simple inputs (e.g. climate, soils, topography); (iii) the scale, resolution and area covered by the different layers can be different among them, which facilitates the use of different sources of information. The objective of this paper is to show GEMSE's performance in a specific case study of soil erosion in La Encañada watershed (Peru) where the hillslope version of WEPP has been previously validated. Resulting runoff and soil loss maps show the spatial distribution of these processes. Though these maps do not give the total runoff and soil loss at the watershed level, they can be used to identify hotspots that will aid decision makers to make recommendations and plan actions for soil and water conservation.


*Keywords:* Geospatial modeling; WEPP; GIS; Soil loss; Runoff; Andes

## Software availability

Name of software: Geospatial Modelling of Soil Erosion (GEMSE)
Developer and contact address: G.A. Baigorria, Frazier Rogers Hall, University of Florida, Gainesville, FL 32611, USA
Coding language: Delphi 7
Software requirements: Any GIS software only for visualization purposes
Hardware requirements: PCs with Windows 98, Windows 2000 or Windows XP.
Program size: 1.1 Mb
Available since: 2004

## 1. Introduction

Modeling has formed the core of a great deal of research focusing on inherently geographic aspects of our environment, and has led to the understanding of distributions and spatial relationships in everything from astronomy to microbiology and chemistry (Parks, 1993). In the case of soil erosion, simulation models have become important tools for the analysis of hillslope and watershed processes and their interactions, and for the development and assessment of watershed management scenarios (Santhi et al., 2006; Miller et al., 2007; Lu et al., 2005; Metternicht and Gonzales, 2005; He, 2003). Since erosion can adversely affect ecosystems on-site as well as off-site, the estimation of runoff and soil loss in catchments is becoming more important as concerns about surface water quality increase (Cochrane and Flanagan, 1999). For this, the "hotspots" (source areas of sediments) within a watershed need to be identified. However, many of the predictive models do not examine the problem in a geographic context (Pullar and Springer, 2000).

* Corresponding author: Fax: +352 392 4092.
*E-mail address:* gbaigorr@ifas.ufl.edu (G.A. Baigorria).

1364-8152/$ - see front matter © 2006 Elsevier Ltd. All rights reserved.
doi:10.1016/j.envsoft.2006.06.012

Under these circumstances, a Geographical Information System (GIS) becomes a valuable tool. A GIS is a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world (Burrough, 1986). GIS has made a tremendous impact in many fields of application, because it allows the manipulation and analysis of individual ''layers'' of spatial data, and it provides tools for analyzing and modeling the interrelationships between layers (Bonham-Carter, 1996). Coupled to an environmental model, a GIS can interpret simulation outputs in a spatial context (Pullar and Springer, 2000). It is presumed that better integration of GIS and environmental modeling is possible by exploiting the opportunity to combine ever-increasing computational power, more plentiful digital data, and more advanced models. GIS/modeling tools necessarily encourage the best implementation of new and better ''hybrid'' tools. According to Parks (1993), there are three primary reasons for integration: ''(1) spatial representation is critical to environmental problem solving, but GIS currently lack the predictive and related analytic capabilities necessary to examine complex problems; (2) modelling tools typically lack sufficiently flexible GIS-like spatial analytic components and are often inaccessible to potential users less expert than their makers; and (3) modeling and GIS technology can both be made more robust by their linkage and co-evolution.'' Both GIS and simulation models have been developed with their own conventions, procedures and limitations. However, linking them at a technical level does not guarantee improved understanding or useful prediction (Burrough, 1986). More quantitative quality indicators, together with spatial statistics and error analysis, are needed to improve the value of GIS/modeling interfaces (Hartkamp et al., 1999).

A comprehensive description of some of the most popular models of watershed hydrology in the world can be found in Singh (1995). As an example, we can mention some of them. The TOPMODEL (Beven et al., 1984) was developed as a distributed hydrologic model that uses digital elevation data and spatial information on soil, vegetation and precipitation to estimate the soil moisture distribution at catchment level, thereby taking account of the spatial heterogeneity of both topography and soils. One of the most promising of the physically based models currently used to model erosion is the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995). But it was not developed with a flexible graphical user interface for spatial and temporal scales applications (Renschler, 2003). The first application of WEPP with a raster-based GIS was by Savabi et al. (1995). Another effort to integrate WEPP and GIS was by Cochrane and Flanagan (1999) for watershed erosion modeling, using an interface between Arc View and WEPP. In both cases, the integration of WEPP with a GIS was done to facilitate and improve the application of the model. Another computer interface called Erosion Database Interface (EDI) processes the surface hydrology output of the WEPP model resulting in a georeferenced estimation of erosion and runoff. The results were erosion (Ranieri et al., 2002) and runoff (de Jong van Lier et al., 2005) of a sugarcane growing area at southeastern Brazil. The Geo-Spatial Interface for WEPP (GeoWEPP) (Renschler, 2003) is another example of a tool that combines GIS and WEPP. It utilizes readily available digital geo-referenced information from accessible Internet sources like topographic maps, digital elevation models, land use and soil maps (Renschler et al., 2002), with the aim of evaluating various land-use scenarios to assist with soil and water conservation planning. For those users of WEPP with no experience with commercial GIS packages there is a new web-based WEPP-GIS system that only requires a user to have a network connection and web browser (Flanagan et al., 2004). The digital elevation data are processed on the server side to delineate watershed, channels and hillslopes that, once located, WEPP simulations are conducted. Results in graphical format are sent as images to the client computer. These two last examples' applicability, however, can fail where the availability of digital data is restricted, which often occurs in developing countries.

This paper presents a new tool capable of integrating process-based models with Geographic Information Systems (GIS) for improving the analysis of point-estimated results on larger scales. This interface, called Geospatial Modelling of Soil Erosion (GEMSE), makes use of the Water Erosion Prediction Project (WEPP) model, producing different maps in GIS format as a result of this integration. Analysis of these maps gives insights useful for the evaluation of land resources and agricultural sustainability and for estimating risks in a specific area.

## 2. Materials and methods

### 2.1. The study area

Field data for running the model were obtained in the northern Andean Highlands of Peru, in La Encañada watershed. The study area is approximately 6000 ha and it is located at 7°4′ S latitude and 78°16′ W longitude, ranging between 2950 and 4000 m above sea level (a.s.l.) (Fig. 1a).

Two main climate regimes can be identified during the year in this area: the rainy season and the dry season. Three automatic weather stations were set up in the study area to record the climate data on a daily basis. A summary of climate conditions is shown in Table 1. A detailed description about rainfall characteristics in the study area is given in Romero (2005) and Romero et al. (in press).

According to the Soil Taxonomy classification (USDA and NRCS, 1998) the main soil orders in the watershed are Entisols, Inceptisols and Mollisols (INRENA, 1998). The spatial distribution of the main soil groups is shown in Fig. 1b. In the highest part of the watershed there are deep soils with a high content of organic matter. Shallow soils are also found; their low organic matter content is mainly because the topsoil has been removed by erosion. Approximately 65% of the area has a slope gradient less than 15%. Very steep slopes (up to 65%) are also present, increasing the risk of erosion in this mountainous area. As steep slopes often occur adjacent to the river, water erosion will contribute directly to the river sediment load.

The land use in La Encañada watershed is divided into croplands (55%), cultivated pasture (13%), natural pasture (20%) and scrub (12%) (INRENA, 1998). Deep soils with the largest amount of organic matter are used as croplands, with cereals, potato, maize and legumes the most important crops. However, crop yields are variable, depending on soil fertility and also on climatic conditions. Poorly fertile shallow soils that show soil erosion characteristics are also cropped, even though most of these areas are only appropriate for natural pasture (Proyecto PIDAE, 1995). The planting date for the main crop varies temporally and spatially. For instance, a survey of the planting dates

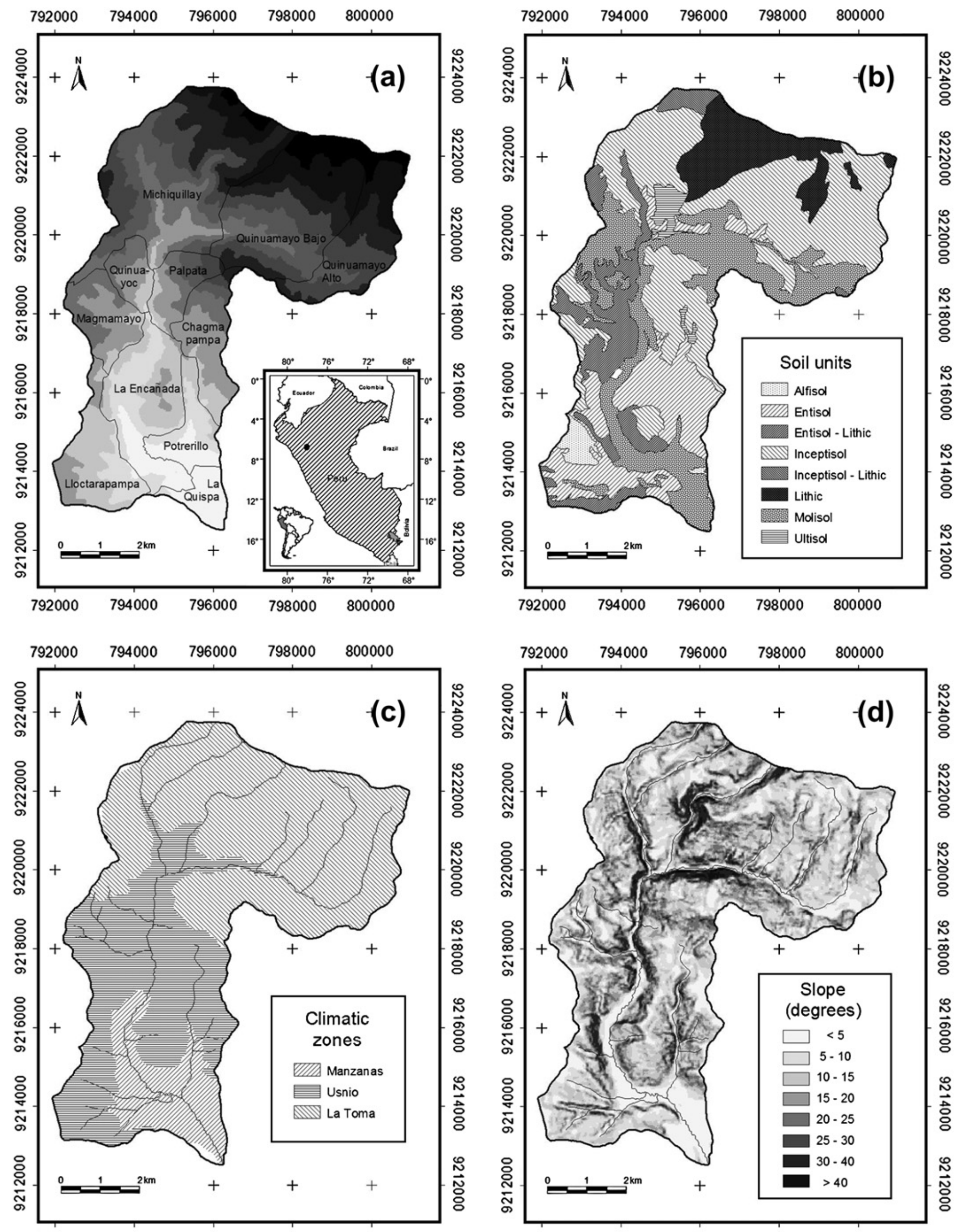


Fig. 1. Spatial information of La Encañada watershed, northern Peru. (a) Location, (b) soil map modified from Jimenez (1996), (c) climatic zones, and (d) slope map.

for potato and barley at La Encañada (Baigorria et al., submitted for publication) showed that most farmers preferred to plant potato in June and to sow cereals in December. However, these two crops can also be planted at different dates, as an insurance against crop failure due to highly variable climatic conditions.

### 2.2. The Water Erosion Prediction Project (WEPP)

The Water Erosion Prediction Project (WEPP)[1] model (Flanagan and Nearing, 1995) is based on modern hydrological and erosion science and calculates runoff and erosion on a daily basis. It is a widely used erosion prediction model (Merrit et al., 2003) that has predicted average runoff and soil loss under different conditions (Bhuyan et al., 2002; Tiwari et al., 2000; Ghidey et al., 1995; Kramer and Alberts, 1995). Based on the fundamentals of infiltration, surface runoff, plant growth, residue decomposition, hydraulics, tillage, management, soil consolidation and erosion mechanics, it provides several major advantages over empirically based erosion prediction models, including the estimation of spatial and temporal distributions of net soil loss (Nearing et al., 1989). WEPP uses mainly physically based equations to describe hydrologic and sediment generation and transport processes at the hillslope and in-stream scales. The model operates on a continuous daily time-step.

The model's main disadvantage is the data requirement that may limit its applicability in areas with limited data. In addition, the watershed version of WEPP may be of limited applicability to large-scale catchments, as simulation involves individual hillslope scale models being "summed-up"

[1] Available from http://topsoil.nserl.purdue.edu/nserlweb/weppmain/.

Table 1
Summary of climate conditions at the three weather stations (average from 4 years)

| Weather station (altitude m a.s.l.) | Solar radiation (MJ $m^{-2}$) | Maximum temperature (°C) | Minimum temperature (°C) | Total rainfall (mm) |
|---|---|---|---|---|
| Las Manzanas (3020) | 18.3 | 16.2 | 5.9 | 782.1 |
| Usnio (3260) | 19.2 | 14.2 | 6.1 | 717.3 |
| La Toma (3590) | 19.9 | 10.8 | 2.8 | 801.0 |

to the catchment scale, increasing data requirements and error (Merrit et al., 2003).

WEPP has been tested for the Peruvian Andean conditions. The first application was made by Bowen et al. (1998) in the central Andes of Peru, although this study was not considered as a validation. In a second approach, we validated the hillslope version of the model for this watershed using three different sized runoff plots, at four different locations under natural rainfall events. Runoff and soil erosion were evaluated after each rainfall event during 2001. All climatic characteristics, soil physical parameters (like soil texture, organic matter content, erodibility values, hydraulic conductivity), topographical and management characteristics were determined in the field and laboratory. Since the erodibility of soils and the erosivity of rainfall were considered low, the measured and predicted runoff and erosion from the agricultural fields were low too (<1 mm runoff and <0.5 Mg $ha^{-1}$ soil loss per event) (Romero, 2005; Romero et al., submitted for publication).

### 2.3. The Geospatial Modeling for Soil Erosion (GEMSE) interface

GEMSE is a Windows-based software interface (Fig. 2) designed to integrate the database structure and visualization advantages of GIS and the accuracy of process-based models. The basic databases required for GEMSE include climate, soil, topography and land use information, while the basic maps required are climatic zones, soil units and digital elevation model (DEM). The DEM is used to derive the slope angle and slope shape (convexity or concavity) used by WEPP. The slope angle was calculated by using the algorithm developed by Monmonier (1982).

The slope shape is ascertained pixel by pixel, analyzing the altitude from the 3 × 3 pixel neighborhood to determine the flow direction vector. This determines two pixels on opposite sides of the central-evaluated pixel (Fig. 3a). Applying the definition of profile curvature (Pellegrini, 1995; Burrough and McDonnell, 1998), the magnitude of the rate of change of the slope is described as a quadratic equation. Then using the slope of the three pixels determining the flow direction through the central-evaluated pixel in the 3 × 3 pixel neighborhood, the quadratic equation is fitted (Fig. 3b). The points extracted at different distances from the center of the central-evaluated pixel are used to define the concavity or convexity of the slope in WEPP (Fig. 3c). The distances between each consecutive pair of extracted points are assigned as a unique overland flow element (OFE). Finally, the total slope length (50 m) is built by five 10-m length slopes.

Using the hillslope version of the WEPP model, the main output maps are soil loss (kg $ha^{-1}$) and runoff (mm). The output resolution depends on the input resolution. In the present study, the cell size was 50 × 50 m, to enable hotspots to be easily detected.

To use GEMSE the user does not need to have a deep knowledge of modeling. For the development of databases and maps, basic knowledge of GIS is required. One of the advantages of the interface is that it is independent of any

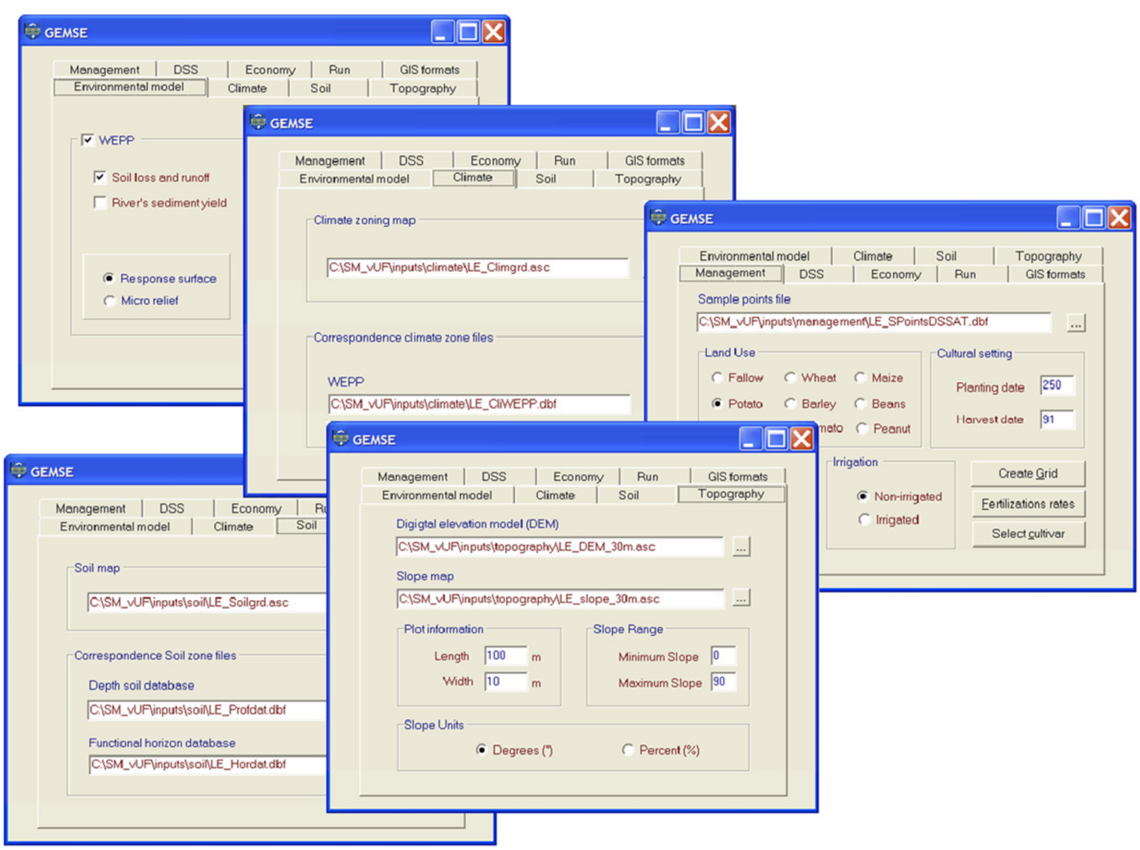


Fig. 2. Main views of GEMSE interface.

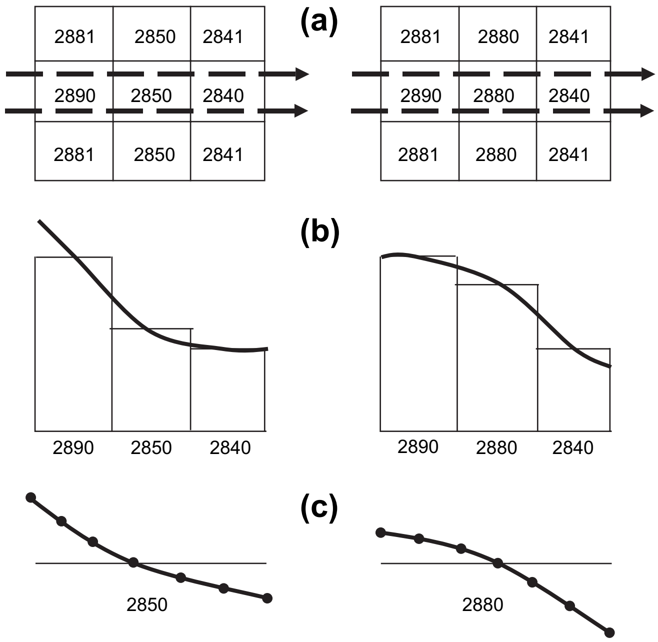


Fig. 3. Determination of the slope shape (profile curvature). (a) Flow direction by using DEM. (b) Profile view of the three pixels forming the flow direction and graphical fitting of the quadratic function using slopes. (c) Slope shape of the central-evaluated pixel. Concave and convex slope shapes at left and right, respectively.

special GIS software that is basically used only to build maps and to visualize the results. The results can also be used to produce response surfaces relating the outputs (soil loss, runoff, etc.) to inputs (climate, soil, topography and land use management). Another advantage is that the scale, resolution and the area covered by the layers (of course, totally covering the study area) can be different, making it easier to use different sources of information. Large areas can be simulated according to the current land use but also under different hypothetical or forecast scenarios (Baigorria et al., submitted for publication). It is important to keep in mind that the accuracy of the results depends on the quality and resolution of the inputs and on the quality of the previously calibrated models.

## 2.4. Interface inputs

GEMSE uses the input maps in ASCII formats exported by ArcView, whereas the databases that relate climate, soil and topography data with the maps are in Dbase IV format. The scales and resolution of the spatial inputs can vary according to the variable. In the present case study, all inputs maps were projected in UTM 18 zone based on WGS84 for the southern hemisphere. The attributes used for the climatic and the soil maps were the climatic zone and the soil unit respectively. The attributes used for DEM and slope maps were altitude (meters) and slope (degrees) respectively.

### 2.4.1. Climate

Climate in this area is classified as Tropical Summer Rain High Mountain Climate (Haw) according to Koppen's reformed classification (Rudloff, 1981). The interface makes use of a digital climate map in which different polygons identify the different climatic zones. This map is related to a database containing the observed climatic data assigned to each climatic zone, from 1995 to 1999. The meteorological variables used by WEPP are rainfall amount, rainfall duration, ratio of time to rainfall peak/rainfall duration (Tp), ratio of maximum rainfall intensity/average rainfall intensity (Ip), maximum and minimum temperatures, dew temperature, incident solar radiation, and wind direction and velocity (Flanagan and Livingston, 1995). Another option for Tp and Ip, if recording rain gauge data are available, would be break-point precipitation, which is usually better input for validation studies (Romero, 2005). In the present study, three climatic zones (Fig. 1c) proposed by Proyecto PIDAE (1995) were used. Three weather stations representing each climatic zone were used to build their respective multi-year climate files in WEPP format (P1.cli). No more years were simulated since there was no available data for the three weather stations before 1995 and after 1999.

### 2.4.2. Soils

The interface makes use of a digital soil map in which different polygons identify the different soil units (Fig. 1b). This map is related to two databases describing the physical and chemical characteristics of the different horizons in the soil profile. For the present case study, a digital 1:25,000 soil map made by Overmars (1999) was used; it classifies the soil by functional horizons according to the evaluated soil profiles. The advantage of using this high-resolution map is its applicability for modeling. Overmars mapped the soil according to the relationship between topography and soil variation, with the aim of being able to predict a typical soil profile at different locations in the study area.

### 2.4.3. Topography

The topography variables used are altitude and slope. In the present application, the digital elevation model (DEM) was provided by De la Cruz et al. (1999) and the slope map (Fig. 1d) was generated from this DEM.

### 2.4.4. Management

Land use management is set in the software as two different land uses: crop and fallow. To illustrate GEMSE's performance, a practical example was prepared representing fallow conditions on a 6000 ha watershed (La Encañada) located in northern Peru. The fallow initial condition from WEPP was taken and the rill and interrill cover adjusted at 0%. In the case of crops (potato and barley), we took the initial conditions database from WEPP. The planting date was established manually and no irrigation was specified.

### 2.4.5. Pixel points

A Dbase file containing all the point coordinates covering the study area at a defined cell size is used. This file is generated using the "Grid Generator" option incorporated into the software. The geographic coordinates of the corners of the study area as well as the distance between cells are required as inputs. The output is a square or rectangular grid of points covering the entire area defined by the specified corners and resolution. A Boolean mask can be used optionally in order to define the exact areas to be simulated.

## 2.5. Interface execution

Following the flow chart in Fig. 4, the interface reads the first pair of coordinates generated by the Grid Generator option. Coordinates are used to find the climatic zone and the soil unit in the respective maps. With this information, the interface creates internally the climate (P1.cli) and soil (P1.sol) files in the formats required by WEPP. The slope file of WEPP (P1.slp) is defined by the slope angle, slope shape and the slope length. The slope angle is read directly from the map, and the pixel size is assigned as the slope length (50 m). Slope shape, as described in Section 2.3, is calculated according to the profile curve definition. The management file (P1.man) is created only once for each run for all the pixels. When all the files required by WEPP have been generated, the model is run automatically. The output files are kept internally by the interface and stored in a geo-referenced Dbase file. After this process has finished, the next pair of coordinates are read and processed in the same way. When all the coordinates have been read, the process is over, and the results are ready to be imported to different GIS formats for visualization. For the import process, it is important to realize that the output file containing all the soil erosion and runoff results also contain in the first two columns the geographic coordinates where each realization was performed. Then the simulated values can be assigned to geographical coordinates, and all together form the final output maps. Depending on the number of sample points, the total area studied and the resolution of the input maps, the time taken to run the model varies from minutes to hours.

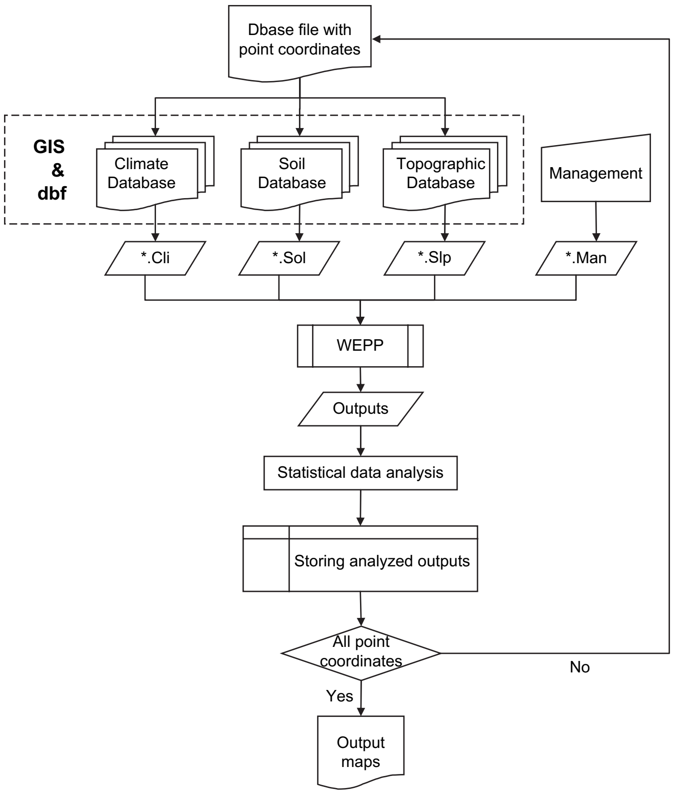


Fig. 4. Flowchart of GEMSE.

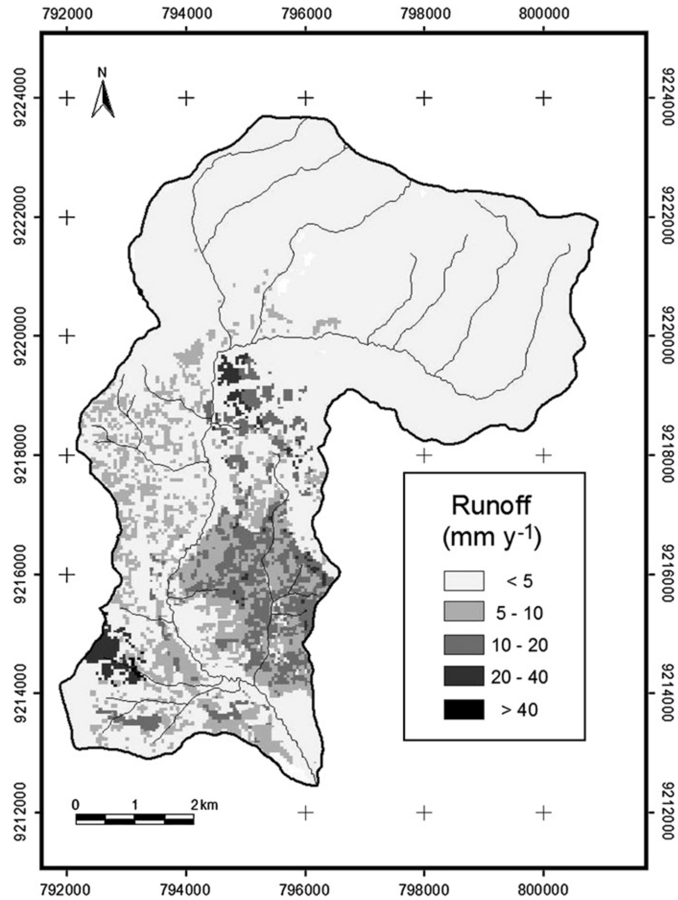


Fig. 5. Runoff map of La Encañada using the GEMSE interface and the WEPP model.

### 2.6. Scenario simulation

In the present case study in La Encañada watershed, potato, barley and fallow land uses were simulated in different areas according to the land use map of the study area (INRENA, 1998). In the case of crops, planting dates were determined according to the field survey performed by Baigorria et al., (submitted for publication). These planting dates were established as the ones used most frequently by the farmers in the study area.

### 2.7. Output generation

After the simulations, runoff and soil loss maps under different land uses were aggregated. Note that the term soil loss represents the sediment yield output from WEPP.

## 3. Results and discussion

### 3.1. Runoff

The runoff map for La Encañada watershed is shown in Fig. 5. The estimated runoff values are the annual average of a 4-year continuous simulation on simulated hillslopes of 50 × 50 m (pixel size), expressed as mm year$^{-1}$. We can observe the runoff distribution on the map at pixel level or in apparently homogeneous areas presenting the same value. The estimated runoff values ranged from <5 mm year$^{-1}$ to 40 mm year$^{-1}$. Only a few pixels showed values over 40 mm year$^{-1}$. Two important areas are clearly visible on the map: the northern area, presenting low values of runoff, and the central/southern area with the highest estimate of runoff. The northern part corresponds to the highest part of the watershed, where deep soils are present and La Toma climate prevailed. The 4-year rainfall analysis in this watershed reported that around 90% of rainfall events had an intensity value <7.5 mm h$^{-1}$ (Romero, 2005; Romero et al., in press). A higher number of rainfall events with intensity values >7.5 mm h$^{-1}$ were observed in Manzanas (16 events, with a maximum intensity of 147 mm h$^{-1}$) than La Toma (7 events, with a maximum intensity of 130 mm h$^{-1}$), which indicated that the former area could be prone to suffer more runoff or erosion effects.

The combined effect of the low erosive events plus the deep soils found in the La Toma area promoted the infiltration of water and resulted in a low runoff production, shown on the map as the white area. Eighty percent of the surface area had estimated values of runoff <5 mm, as we can see in the histogram (Fig. 6a). Therefore, this area can be considered a stable zone or the buffer zone protecting the bottom of the watershed. The main land use of this zone is natural pasture, which acts as a protective cover for the soil.

The central and southern part of the watershed, where Manzanas is located, is the area where most crops are cultivated and had more number of rainfall events with >7.5 mm h$^{-1}$ intensities. This area is also prone to get flooded easily due to the bad drainage characteristics of its soils. Greater amounts of estimated runoff can be identified on the map: almost

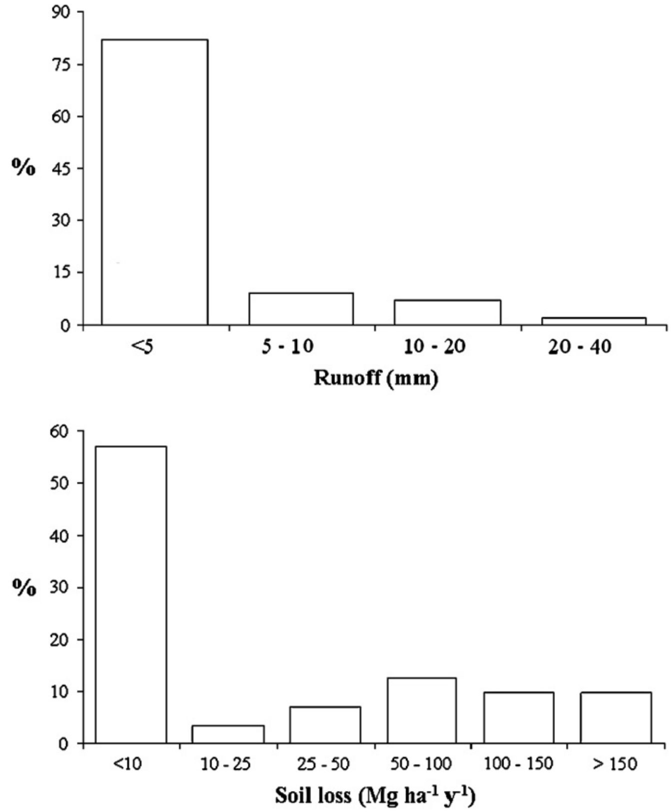


Fig. 6. Histograms showing the percentage of the area under different estimated values of runoff (a) and soil loss (b).

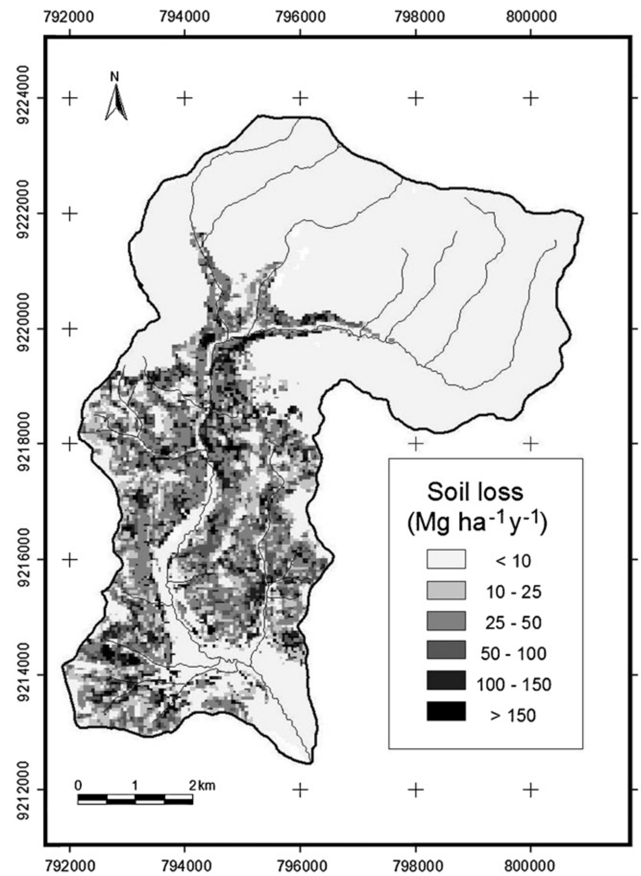


Fig. 7. Soil erosion map of La Encañada watershed using the GEMSE interface and the WEPP model.

15% of the area of the map has estimated values from 5 to 20 mm, and 5% has estimates exceeding 20 mm (Fig. 6a). The variability of climate, soils, slope and management is well represented by the model.

### 3.2. Soil loss

The estimated soil loss map of La Encañada is shown in Fig. 7. The results of running the model for 4-year continuous simulation on each pixel of the DEM (representing hillslopes of 50 by 50 m) are expressed in Mg ha$^{-1}$ year$^{-1}$. Each pixel represents a single slope profile where the WEPP model was applied. GEMSE does not consider flow from cell to cell in the DEM. The map shows areas susceptible to erosion. As in the runoff map, we can observe two regions within the watershed. The northern area, with low soil loss rates ($<$10 Mg ha$^{-1}$ year$^{-1}$) corresponds to the area with the lowest estimated runoff in Fig. 5. This area is usually under natural pasture, also preferred by farmers for growing cereals, which has the characteristic to protect the soil surface against the erosivity of rainfall. In the simulation, we established barley since it is the crop that most resembles the natural pasture that normally grows in this area. In addition, farmers do not disturb the soil when sowing barley. This is why most of the area does not show a great amount of soil loss. However, there are some plots where higher values of soil loss can be observed that would correspond to those unprotected areas that normally are located on the steepest slopes facing the river.

The central part of the watershed, where most of the farming occurs, has pixels with different estimated soil loss values, representing the variability of soils, land use (crop or fallow), slope and climate. The lowest part of the watershed presents low values of soil loss, since this area corresponds to the flattest part of the watershed (valley); due to the availability of water it is cropped year-round with improved pastures. For these two areas, the estimated soil loss values ranged from $<$10 Mg ha$^{-1}$ year$^{-1}$ to $>$150 Mg ha$^{-1}$ year$^{-1}$.

Although it seems that the model predicts high rates of soil loss in the area, a different picture emerges when a histogram of the quantification of pixels is made: on almost 58% of the total area the estimates of soil loss are low ($<$10 Mg ha$^{-1}$ year$^{-1}$), nearly 10% of the area has estimates 25–50 Mg ha$^{-1}$ year$^{-1}$, 12% has estimates from 50–100 Mg ha$^{-1}$ year$^{-1}$, 10% has estimates from 100 to 150 Mg ha$^{-1}$ year$^{-1}$ and only 10% has estimates $>$150 Mg ha$^{-1}$ year$^{-1}$ (hotspots) (Fig. 6b). The model estimates high values of soil loss ($>$100 Mg ha$^{-1}$ year$^{-1}$) specifically in those areas where slope angle exceeds 40° (78% gradient).

It seems unlikely that, for example, 30 mm year$^{-1}$ of runoff is able to carry 125 Mg ha$^{-1}$ year$^{-1}$ in this watershed. This would mean 417 g of sediment per liter of runoff. However, a maximum value of 395 g of sediment per liter of runoff was recorded at a runoff plot at the bottom of the watershed in a sandy clay loam soil at 10% slope inclination, during the previous validation study of the hillslope version of the WEPP model (Romero et al., submitted for publication). Note that the climate map shown in Fig. 1c had much influence on the resulting runoff and soil loss maps, giving two well-defined areas in the maps concerned. This would be improved if the interface could use high-resolution climate maps. After the study was completed a better climate map for this specific area became available (Baigorria et al., 2004; Baigorria, 2005); it is intended to test the interface with this new input.

## 4. Conclusions

GEMSE is operational software that integrates GIS properties with the Water Erosion Prediction Project (WEPP) model in order to analyze the spatial variation of runoff and soil loss. In the present study, the objective was to test the performance of GEMSE in generating soil loss and runoff maps from the WEPP model outputs in La Encañada watershed (northern Peru). The generation of these maps made easier the visualization of the erosion process at spatial and temporal scales according to the actual land use of the watershed.

Areas at risk of runoff and soil loss were identified from the maps. For runoff, the risk areas were associated with the flattest part of the watershed. For soil loss, the susceptible areas were related to the steepest slopes within the watershed. Although the map does not give the total soil loss at the watershed level, it can be used to identify the most susceptible areas to be eroded in the area (what we called ‘‘hotspots’’), thus helping not only farmers but decision makers to formulate recommendations for soil and water conservation strategies. GEMSE can be used in either small or large watersheds. This demonstrates that GEMSE is an option that can be used for strategic applications of the WEPP model.

## Acknowledgements

The International Foundation for Science (IFS), Stockholm, Sweden, supported this research through a grant to C.C. Romero and USAID & Soil Management – CRSP project funded grant No. 291488. Joy Burrough advised on the English. The author conducted part of this research while in association with the Department of Production Systems and Natural Resources Management of the International Potato Center. Thanks are due to Prof. L. Stroosnijder for his useful comments in the manuscript. The authors wish to thank three anonymous reviewers for their observations and advice which helped us significantly improve the present paper.

## References

Baigorria, G.A., 2005. Climate interpolation for land resource and land use studies in mountainous regions. Dissertation thesis, Wageningen University and Research Centre, Wageningen, The Netherlands.

Baigorria, G.A., Stoorvogel, J.J., Romero, C.C., Quiroz, R., Weather and seasonal-climate forecast to support agricultural decision-making at different spatial and temporal scales. Computer and Electronics in Agriculture, submitted for publication.

Baigorria, G.A., Villegas, E.B., Trebejo, I., Carlos, J.F., Quiroz, R., 2004. Atmospheric transmissivity: distribution and empirical estimation around the central Andes. International Journal of Climatology 24, 1121–1136.

Beven, K.J., Kirby, M.J., Schoffield, N., Tagg, A., 1984. Testing a physically-based flood forecasting model TOPMODEL for three UK catchments. Journal of Hydrology 69, 119–143.

Bhuyan, S.J., Kalita, P.K., Janssen, K.A., Barnes, P.L., 2002. Soil loss predictions with three erosion simulation models. Environmental Modelling & Software 17, 137–146.

Bonham-Carter, G.F., 1996. Geographic information systems for geoscientists: modelling with GIS. In: Computer Methods in the Geosciences, vol. 13. Pergamon, Ontario, Canada, 398 pp.

Bowen, W., Baigorria, G. Barrera, V., Cordova, J., Muck, P., Pastor, R., 1998. A process-based model (WEPP) for simulating soil erosion in the Andes. Natural Resource Management in the Andes. CIP Program Report, pp. 403–408.

Burrough, P.A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Oxford University Press.

Burrough, P.A., McDonnell, R.A., 1998. Principles of Geographic Information Systems: Spatial Information Systems and Geostatistics. Oxford University Press.

Cochrane, T.A., Flanagan, D.C., 1999. Assessing water erosion in small watersheds using WEPP with GIS and digital elevation models. Journal of Soil and Water Conservation 54, 678–685.

de Jong van Lier, Q., Spavorek, G., Flanagan, D.C., Bloem, E.M., Schnug, E., 2005. Runoff mapping using WEPP erosion model and GIS tools. Computers and Geosciences 31, 1270–1276.

De la Cruz, J., Zorogastúa, P., Hijmans, R.J., 1999. Atlas digital de los Recursos Naturales de Cajamarca. Production system and natural resources management. Working paper No. 2. CIP - CONDESAN. Lima, Peru, 49 pp.

Flanagan, D.C., Frankenberger, J.R., Engel, B.A., 2004. Web-based GIS application of the WEPP model. Paper No. 04–2024. American Society of Agricultural Engineers, St. Joseph, MI, 12 pp.

Flanagan, D.C., Livingston, S.J., 1995. Water Erosion Prediction Project (WEPP) version 95.7 user summary. NSERL Report No. 11, USDA-ARS National Soil Erosion Research Laboratory. West Lafayette, IN, 139 pp.

Flanagan, D.C., Nearing, M.A., 1995. USDA-Water Erosion Prediction Project (WEPP). WEPP user summary. NSERL Report No. 10. USDA-ARS National Soil Erosion Research Laboratory. West Lafayette, IN.

Ghidey, F., Alberts, E.E., Kramer, L.A., 1995. Comparison of runoff and soil loss predictions from the WEPP hillslope model to measured values for eight cropping and management treatments. ASAE Paper No. 95–2383. ASAE, St. Joseph, MI.

Hartkamp, A.D., White, J.W., Hoogenboom, G., 1999. Interfacing geographic information systems with agronomic modelling: a review. Agronomy Journal 91, 761–772.

He, C., 2003. Integration of geographic information systems and simulation model for watershed management. Environmental Modelling & Software 18, 809–813.

INRENA, 1998. Estudio integrado de caracterizacion de recursos naturales renovables en microcuencas altoandinas para el alivio a la pobreza en la sierra. Microcuenca La Encañada, Cajamarca. Ministerio de Agricultura. Lima, Peru, 108 pp.

Jimenez, M., 1996. Estudio de Suelos de la Microcuenca ‘‘La Encañada’’ (semi-detallado). ASPADERUC/CONDESAN, Camajarca, Peru (in Spanish).

Kramer, L.A., Alberts, E.E., 1995. Validation of WEPP 95.1. Daily erosion simulation. ASAE Paper No. 95–2384. ASAE, St. Joseph, MI.

Lu, H., Moran, C.J., Prosser, I.P., 2005. Modelling sediment delivery ratio over the Murray Darling Basin. Environmental Modelling & Software 21, 1297–1308.

Merrit, W.S., Letcher, R.A., Jakeman, A.J., 2003. A review of erosion and sediment transport models. Environmental Modelling & Software 18, 761–799.

Metternicht, G., Gonzales, S., 2005. FUERO: foundations of a fuzzy exploratory model for soil erosion hazard prediction. Environmental Modelling & Software 20, 715–728.

Miller, S.N., Semmens, D.J., Goodrich, D.C., Hernandez, M., Miller, R.C., Kepner, W.G., Guertin, D.P., 2007. The automated geospatial watershed assessment tool. Environmental Modelling and Software 22 (3), 365–377.

Monmonier, M., 1982. Computer-Assisted Cartography: Principles and Prospects. Prentice Hall, Englewood Cliffs, NJ.

Nearing, M.A., Foster, G.R., Lane, L.J., Finkner, S.C., 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Transactions of the ASAE 32, 1587–1593.

Overmars, K.P., 1999. Developing a method for downscaling soil information from regional to catena level. Thesis, Soil Science and Geology, Wageningen Agricultural University - CIP, Wageningen, Netherlands, 146 pp.

Parks, B.O., 1993. The need for integration. In: Goodchild, M.F., Parks, B.O., Steyaert, L.T. (Eds.), Environmental Modelling with GIS. Oxford University Press, pp. 31–34.

Pellegrini, G.J., 1995. Terrain shape classification of digital elevation models using Eigenvectors and Fourier transforms. UMI Dissertation Services.

Proyecto PIDAE, 1995. La Encañada: Caminos hacia la sostenibilidad. Centro Internacional de la Papa. Lima, Peru.

Pullar, D., Springer, D., 2000. Towards integrating GIS and catchment models. Environmental Modelling & Software 15, 451–459.

Ranieri, S.B.L., de Jong van Lier, Q., Sparovek, G., Flanagan, D.C., 2002. Erosion database interface (EDI): a computer program for georeferenced application of erosion prediction models. Computers and Geosciences 28, 661–668.

Renschler, C., 2003. Designing geo-spatial interfaces to scale process models: the GeoWEPP approach. Hydrological Processes 17, 1005–1017.

Renschler, C., Flanagan, D.C., Engel, B.A., Frankenberger, J.R., 2002. GeoWEPP – The Geo-spatial interface for the Water Erosion Prediction Project. ASAE meeting paper No. 022171, St. Joseph, Michigan.

Romero, C.C., 2005. A multi-scale approach for erosion assessment in the Andes. Dissertation thesis, Wageningen University and Research Centre, The Netherlands.

Romero, C.C., Baigorria, G.A., Stroosnijder, L., Changes of erosive rainfall for El Niño and La Niña years in the northern Andean Highlands of Peru: the case of La Encañada watershed. Climatic Change, in press.

Romero, C.C., Baigorria, G.A., Stroosnijder, L., Validation of the hillslope version of WEPP in La Encañada watershed, northern Peru. Ecological Modeling, submitted for publication.

Rudloff, W., 1981. World-Climates: With Tables of Climatic Data and Practical Suggestions. Wissenschaftliche verlagsgesellschaft mbH, Stuttgart.

Santhi, C., Srinivasan, R., Arnold, J.G., Williams, J.R., 2006. A modeling approach to evaluate the impacts of water quality management plans implemented in a watershed in Texas. Environmental Modelling & Software 21, 1141–1157.

Savabi, M.R., Flanagan, D.C., Hebel, B., Engel, B.A., 1995. Application of WEPP and GIS-GRASS to a small watershed in Indiana. Journal of Soil and Water Conservation 50, 477–483.

Singh, V.P., 1995. Computer Models of Watershed Hydrology. Water Resources Publications, Highlands Ranch, CO.

Tiwari, A.K., Risse, L.M., Nearing, M.A., 2000. Evaluation of WEPP and its comparison with USLE and RUSLE. Transactions of the ASAE 43, 1129–1135.

United States Department of Agriculture (USDA) and Natural Resources Conservation Service (NRCS), 1998. Keys to Soil Taxonomy, eighth ed. Soil Survey Staff, Washington, DC.