An Educational Computer Tool for Simulating Long-Term Soil Erosion on Agricultural Landscapes

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Abstract

Due to its economic and environmental impacts, soil erosion has been a major concern to farmers, engineers and policy makers in recent years. Water and tilling are two of the main agents responsible for this phenomenon and considerable efforts have been made to model them in previous work but not with educational purposes. A computer tool for facilitating any user's simulation of long-term landscape evolution in a plot due to the combined action of water and tillage erosion is presented here. It integrates a graphic user interface with two well-verified erosion models, each one independently devoted to reproduce the effects of water and tilling. This computer tool permits to the student the consideration of the erosivity index and the presence of a crop in the plot, when simulating water erosion, as well as the planning of a different type of tilling each year. Each kind of tilling corresponds to a different combination of tillage tools with their own date, tillage depth and tillage direction. A handy ASCII (XYZ) file is generated containing the long-term soil erosion spatial pattern as result. From this information, the student can derive other results that will help to understand soil erosion. An example is presented here with the aim of showing how to use this computer tool to simulate this phenomenon on an agricultural landscape with a complex topography.

KEYWORDS: simulation, soil erosion, agronomic engineering, agricultural landscape.

1. Introduction

The interest for developing teaching tools for some subjects related with Hydrology, such as the groundwater modelling, has increased in recent years [1, 2, 3]. However, the teaching computer aids for other aspects of the water and soil conservation disciplines, such as the soil degradation by erosion on agricultural lands, are unexplored. Soil erosion is a serious problem and will remain so during the 21st century [4] and the potential agronomic engineers need an adequate learning on this subject in order to take the suitable decisions to dismiss its environmental impact in the future. Erosion affects soil quality [5] and crop productivity [6]. Soil erosion is considered as a main factor of land-use change [7, 8]. The economic and environmental impacts of soil erosion have been the concern of farmers and policy makers in recent years [9, 10]. Considerable effort has been made to model two of the main agents of soil erosion: water and tilling.

Several models have been developed to describe water erosion. Some of them consider the watershed as a set of channel elements and planes [11, 12] so that the effects of landscape convergence or divergence and/or transmission losses between various landscape elements cannot be taken into account [13]. Other models are grid-based and allow for an accurate representation of the spatial structure of the watershed [14]. These are single-event models and require a large number of parameters to run them. According to [15], they cannot be used to simulate effects of changes over a longer period.

The tilling effects on soil erosion have been rediscovered in the last decade after the work of [16]. Tillage or mechanical erosion, as it is called, adds to water erosion, being the most severe type in some cases [17, 18, 19, 20, 21]. Some authors [16, 22] confer an active role to mechanical erosion in the redistribution of soil on agricultural landscapes. Recently, some effort has been made to describe the combined effect of water and tillage on soil erosion [15, 23] but they were not developed with educational purposes. This work introduced a computer tool for facilitating any user's simulation of the long-term soil erosion spatial pattern caused by the action of tilling and water in a land plot. This numerical tool is called TIWERMOD (an acronym of *Tillage and Water Erosion Modelling*). It consists of a graphic user interface (GUI) linked to two models, one devoted to simulate tillage erosion and another devoted to reproduce the effect of water erosion. The tillage erosion model adopted here is based on the one proposed by [16], in which the linear diffusion equation for soil transport was applied. Although non-linear terms were included in that equation by [24], the linear form describes fairly well the experimental findings of [25, 26, 27]. The water erosion model implemented in this work is a modified version of the one-dimensional approach proposed by [28] to describe rill and inter-rill erosion on a hillslope. Thus, the specific catchment area [29] and the influence of the crop presence on the plot are considered. The model proposed by [28], taking into account the specific catchment area or unit contributing area, has been successfully applied [13, 30] to describe the water erosion pattern and to derive the soil erosion rates from the spatial distribution of ^{137}Cs concentration on agricultural landscapes [31].

An example of the application of TIWERMOD is presented in this work to show how this computer tool can facilitate the students' simulation of different long-term soil erosion patterns on an agricultural plot and, thus, to analyze and understanding this complex phenomenon. This software is being used by the authors as a teaching aid in soil and water conservation disciplines. It is recommended that before using the software, the student has basic concepts on soil erosion equations and knows the features of the tillage operations that are simulated.

2. Methods

TIWERMOD has been developed using Borland Delphi Professional (Inprise Corporation, version 4.0) and compiled in an executable file to run under the Microsoft Windows XP operating system. According to Figure 1, this computer tool consists of a graphic user interface that provides the data input required to run the simulation, a module devoted to perform calculations and an output unit which generates a file containing the results obtained with the model.

2.1. Graphic user interface

The GUI has a main window (Figure 2a) which permits the access to the windows for entering the initial data necessary to run the models as well as making it possible to start the simulation once the required information has been supplied.

Regarding the features of the study area, the user has to provide an initial DEM (Digital Elevation Model) file in ASCII (XYZ) format using the window called “DEM” (Figure 2b). Once this file is entered, the information about the number of rows, columns and resolution is displayed on the screen. At this moment it is also necessary to name the ASCII (XYZ) output file. This file will contain the information about the spatial distribution of soil accumulations or losses simulated for the number of years indicated.

The description of the tillage operations to be simulated is made by filling in the form shown in Figure 3. Tillage operations are grouped into categories depending on the tillage tools considered. Thus, TIWERMOD gives the following four options: (i) Intensive tillage (mouldboard, disk harrow and field cultivator); (ii) Medium tillage (disk harrow and field cultivator); (iii) Soft tillage (chisel) and (iv) No tillage. The simulations can be performed with a different tillage category in each year. This planning is introduced using the box ‘Tillage planning’ whose options are: Intensive (I), Medium (M), Soft (S) and No Tillage (O). Tillage operation data include the date (month and day), tillage direction, and tillage depth in m. In the case of the mouldboard plough, it is also possible to take into account the direction of the lateral soil displacement with respect to the advancing direction by marking the box named “Type”. The soil bulk density is also introduced into this window in kg m^{-3}.

The water erosion data are set up by using the screen shown in Figure 4. The user has to enter the monthly mean values of rainfall erosivity, R_j with $j \in [4, 15]$, in MJmm/ha/h. These values correspond to the erosivity index used in the Revised Universal Soil Loss Equation, RUSLE, [32] to calculate the rainfall-runoff erosivity factor. In addition, the data corresponding to the averaged crop height (m) and percentage of soil surface covered in each month are required to perform the calculations.

2.2. Module calculation

2.2.1. Tillage erosion model

The process of soil redistribution due to tillage can be described by a diffusion equation in the form [16]:

$$\rho_b \frac{\partial z}{\partial t} = K_{dif} \frac{\partial^2 z}{\partial x^2} \qquad (1)$$

where z [L] is the elevation, x is the distance along the slope, ρ_b [ML^{-3}] is the bulk density of the soil and K_{dif} [ML^{-1}] is the diffusion constant per tillage operation that consists of two passes in opposite directions. This constant precisely characterizes the intensity of the process. The displacement of the soil by a tillage tool, d_{till} [L] is described by a linear function of the slope.

$$d_{till} = A + BS_L \tag{2}$$

with A [L] and B [L] as coefficients depending on the tool and S_L the slope gradient in the tillage direction.

The tillage tools included in TIWERMOD are the field cultivator, disk harrow, chisel and mouldboard plough. For the first three of these, there is mainly a soil displacement in the direction of their movement forward, d^L_{till}, which depends on S_L, while for the mouldboard plough d^L_{till} there is an additional dependence on S_T, the slope gradient perpendicular to the tillage direction. In the mouldboard plough tillage there is also a lateral displacement of soil, d^T_{till}, which depends exclusively on the slope gradient S_T. Table 1 shows the expressions adopted in this work, obtained experimentally by several authors, for the calculation of net soil displacements as a function of the slope gradients. The convention adopted for these expressions is that positive signs are assigned to the S_L when the tillage is downwards, and to S_T when the lateral soil movement is downwards, while negative signs are assigned in the opposite cases.

For the field cultivator and the disk harrow, the expressions in Table 1 were obtained indirectly from the data of [33], cited by [16]. The relation between the fitted parameters of the previous expressions and the diffusion constant is given by

$$K_{dif} = \rho_b B z_{till} \tag{3}$$

z_{till} [L] being the depth of the tillage. B is the coefficient that times S_L for the field cultivator and the disk harrow, and S_T in the expression for d^T_{till} in the case of the mouldboard plough in Table 1, respectively.

It should be mentioned that in the case of the mouldboard plough, the diffusion model can be used only in the case of soil displacement perpendicular to the tillage, d^T_{till}, and not with the displacement in the tillage direction, as this depends on S_L and S_T [34]. Table 2 shows some typical values of z_{till} and the corresponding K_{dif} derived from (3) assuming ρ_b = 1350 kg m^{-3}.

For each DEM cell, the input and output of the soil is calculated on the basis of the displacement expressions shown in Table 1. The soil mass moved from a DEM cell, *SM* [M], is given by

$$SM = \rho_b z_{till} d_{till} \Delta r \quad (4)$$

with Δr [L] the DEM resolution.

The tillage erosion model is applied so that the summation of soil accumulations is the same as the summation of losses in the plot. Consequently, only a soil redistribution process is considered and not its exportation to neighbouring plots. Due to the tillage operations not being done through field boundaries, there is no soil exportation to neighbouring fields. Thus, the cells near the plot borders always gain or lose an amount of soil. This boundary condition leads to the formation of a linear pile or deep incision at field borders [34]. The results obtained do not smooth the terrain surface as much as is observed in real landscapes. Therefore, in order to include this effect and the smoothing consequences of the one or two harrow passes all around the edge of the field usually carry out by farmers, a levelling tillage operation is simulated in a parallel direction to the plot borders as proposed by [34]. The total amount of soil accumulated or lost in the last cell is redistributed between it and the eight adjacent cells.

2.2.2. Water erosion model

The water erosion is determined by using the model proposed by [28] for describing the rill and inter-rill erosion on a hillslope. Here that model is modified to consider the upstream contributing area per unit of contour length, instead of the horizontal distance from the divide, and the effect of crop presence on the plot. When the sediment load in an overland flow is below transport capacity, the expression for the potential mean rill erosion rate in a DEM cell, E_r [ML^{-2}] is

$$E_r = \rho_b g_r S^m a^n \tag{5}$$

where S is the slope, m and n are exponents with values of 1.45 and 0.75, respectively, and g_r [L] is a coefficient which depends on the normalized rainfall erosivity in the month j, $r_{ej} = R_j \Big/ \left(\frac{1}{12} \sum_{w=1}^{12} R_w \right)$, and the crop cover percentage C_c.

$$g_r = 3 \times 10^{-4} \left[1 - C_c / 40 \right] r_{ej} \tag{6}$$

The factor $\left[1 - C_c / 40 \right]$ reflects that there is no rill erosion when the crop covers more than the 40% of the soil surface. The unit contributing area, a [L], defined as the upslope contributing area per unit length of contour [29], is determined by analyzing the flow pathways calculated by applying the multiple flow direction algorithm proposed by [35]. In this algorithm, the receiving fraction transferred to each cell downslope of the central cell of a moving 3×3 sub-matrix is proportional to the product of the distance-weighted drop and a geometric weight factor, which depends on the direction:

$$A_k = A_u \frac{L_k \tan S_k}{\sum_{i=1}^{v} L_i \tan S_i} \tag{7}$$

where A_k [L^2] is the fraction draining through neighbour k, A_u [L^2] is the upstream area available for distribution, S_i is the slope gradient from the central cell towards neighbour i, L_i is a weight factor (0.5 and 0.354 for a cardinal and diagonal direction, respectively) and v the number of lower neighbours.

The potential mean inter-rill erosion rate for a DEM, E_{ir} [ML^{-2}], is determined by

$$E_{ir} = \rho_b g_{ir} S^l \tag{8}$$

where l is an exponent equal to 0.84 and g_{ir} [L] is a coefficient whose expression is:

$$g_{ir} = 1.104 \times 10^{-3} \left[1 - \frac{C_c}{100} \exp\left(-0.34 h_c\right) \right] r_{ej} \tag{9}$$

with h_c [L] being the crop height. The factor $\left[1 - \frac{C_c}{100} \exp\left(-0.34 h_c\right) \right]$ represents the protection effect of the crop against the inter-rill erosion by considering its height and the percentage of soil surface covered by it in the same way that [36] proposed.

The potential mean transport capacity for a DEM cell, T_c [ML^{-1}], is proportional to E_r [28]

$$T_c = g_t E_r \tag{10}$$

with g_t [L] being a coefficient that equals 740 m [16]. The potential mean water erosion rate, E_w, is calculated as the sum of the rill and inter-rill erosion contributions, $E_w = E_r + E_{ir}$. However, the total soil mass out of a DEM cell is never allowed to exceed the transport capacity.

The proposed water erosion model does not consider any limitation in the amounts of water and sediment that flow across the plot borders. Thus, the plot is not considered to be isolated as happens in the case of the tillage erosion model.

The water erosion is always simulated after the tillage operations in the months in which they are planned. When no tilling is scheduled for a year, the water erosion is simulated considering the non presence of a crop on the plot (C_c = 0 and h_c = 0).

2.3. Module output

As a consequence of the tillage and water erosion simulations there is a soil accumulation or a loss in the cells of the DEM. The output file generated by TIWERMOD is in an ASCII (XYZ) format and contains the information needed to obtain the map of the spatial distribution of soil erosion for the simulated years (Figure 1). From this map, it is possible to derive other results such as the mean and maximum elevation changes.

3. Example of application

A synthetic DEM (Figure 5a) was considered with the aim of showing how to use TIWERMOD and checking its capacity to simulate long-term soil erosion in an agricultural landscape of complex topography. It had as a resolution $\Delta r = 1$ m (110 columns × 90 rows) and the elevation range was 18 m. The map of terrain slopes is shown in Figure 5b. The soil erosion pattern after 50 years was simulated with TIWERMOD when the tillage was carried out in the X and Y directions, taking into account the presence of a wheat crop on the plot. In both cases, a repeated tilling planning that consists of one year of intensive tillage followed by three years of medium tillage and one of no tillage was considered. The features of the tillage operations are shown in Figure 3 and they correspond to those most frequent for a wheat crop in Córdoba (southern Spain). In addition, a soil bulk density of 1350 kg m^{-3} was considered. Regarding the water erosion, the common values of the monthly mean rainfall erosivity in Córdoba shown in Figure 4 were adopted. It is also possible, in the same figure, to verify the typical values of averaged height and soil surface percentage covered in each month for a wheat crop in the same geographical zone.

Figures 6a and 6b show the spatial erosion patterns obtained with TIWERMOD when tillage was simulated in the *X* and *Y* directions, respectively. They were different although it can be seen that the soil accumulation areas (light tones) were located in those sites where the slope was small and a concavity appeared and soil loss zones (dark tones) coincided with steep slopes and convexity. The formation of a gully was also reproduced in the area where the water flow was concentrated. The tendency simulated by TIWERMOD agreed with that observed in the field. A summary of the results obtained from the simulations is shown in Table 3. Soil erosion dominated over soil accumulation in all the cases. The tilling in the *X* direction shows the higher values of the mean elevation changes suggesting that this case is more erosive compared to that in which the tillage is simulated in the *Y* direction.

4. Conclusions

TIWERMOD simulates the long-term soil erosion pattern produced by the combined action of tillage and water erosion on agricultural lands with a complex topography. The software is intended to serve as a teaching aid in water and soil conservation disciplines. It has a graphic user interface that facilitates the input of the plot DEM file in ASCII (XYZ) format as well as the name of the output file containing the spatial distribution of soil erosion. Another GUI window permits the consideration of several options for the tilling by means of combining different tillage tools in each year of the simulation. In addition, the tillage operation date, depth and direction can also be selected and modified from one year to another. The input of water erosion data has to be done by using the corresponding GUI window. Thus, the monthly mean values of rainfall erosivity and the averaged crop height and percentage of soil surface covered are required in order to apply the water erosion model adopted here. This model reproduces the gully erosion in the areas where the water flow tends to concentrate, this fact being in agreement with observations in the field.

From the results obtained, TIWERMOD would seem to be a suitable computer tool for describing the long-term soil erosion pattern in a land plot as a consequence of tillage and water action. The TIWERMOD graphic user interface has been designed with the aim of facilitating the simulation of different scenarios in such a way that the student can use the software after a short training period. The results are saved in a handy file with an ASCII (XYZ) format that permits the performance of several analyses for understanding the soil erosion. This is the previous step to teach the student how to adopt the appropriate decisions to minimize the soil erosion negative effects on environment.

Acknowledgements

The authors gratefully acknowledge the support of the Spanish CICYT Project AGL2006-10927-C03-03/AGR. F.J. Jiménez-Hornero is grateful for support from the Consejería de Innovación, Ciencia y Empresa, Junta de Andalucía (Ayudas para facilitar el Retorno de Investigadores a Centros de Investigación y Universidades de Andalucía).

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Figures

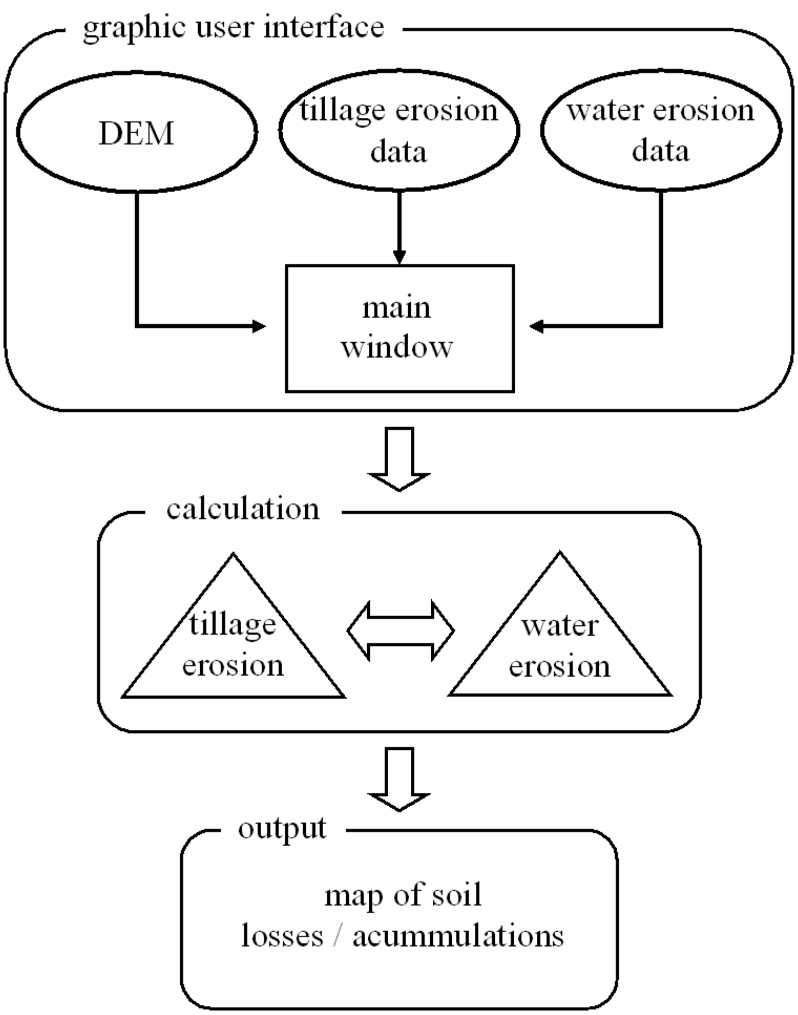

Figure 1. Scheme of the computer tool TIWERMOD proposed to facilitate the user's simulation of the long-term soil erosion on agricultural lands. It consists of three main modules: graphic user interface (data input), calculation (simulation with the water and tillage erosion models) and output (generation of ASCII XYZ file containing the final soil erosion spatial pattern).

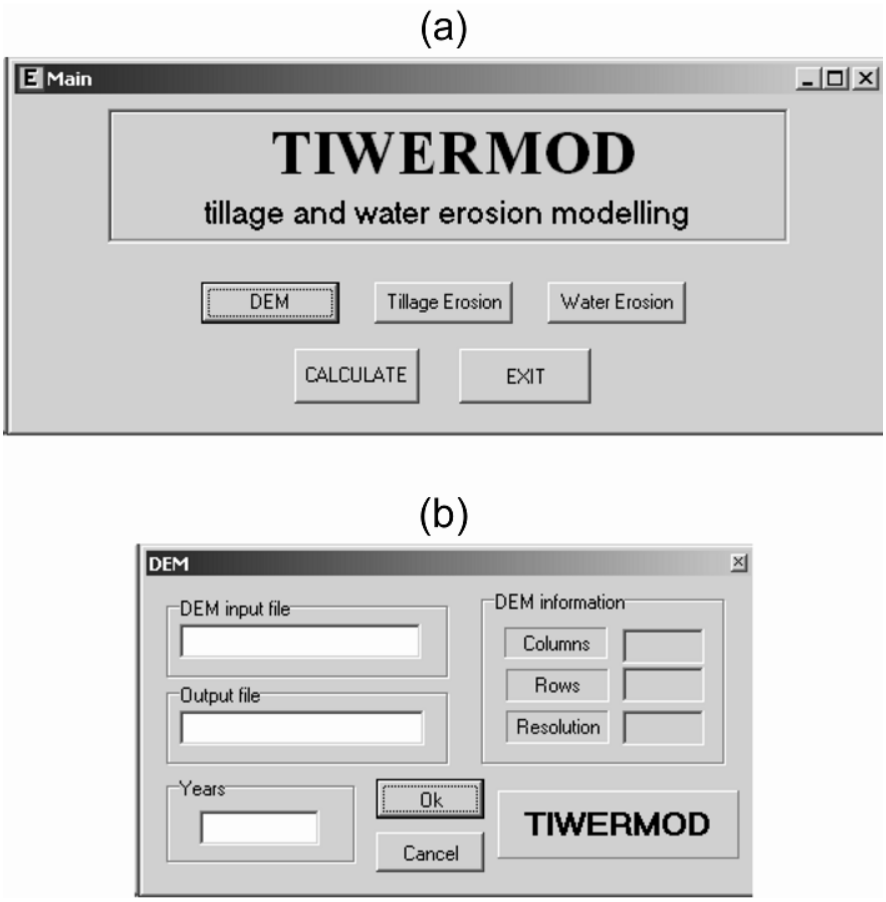

Figure 2. **(a)** Main window of the TIWERMOD graphic user interface. **(b)** TIWERMOD window for the input of the initial digital elevation model (DEM) file in ASCII (XYZ) format. The ASCII (XYZ) output file that will contain the final soil erosion spatial pattern is also named in this window.

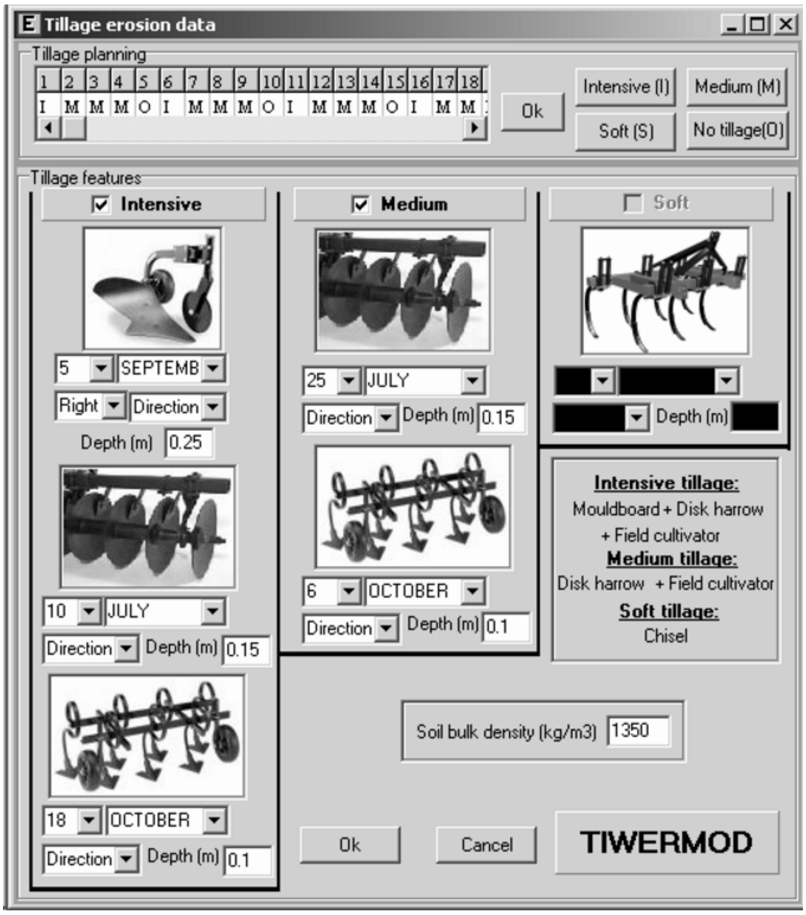

Figure 3. Tillage planning window provided by the TIWERMOD graphic user interface. It permits the input of the features of different types of tilling: soft, medium, heavy or no tillage, in each year. Each kind of tilling corresponds to a different combination of tillage tools with their own date, tillage depth and direction.

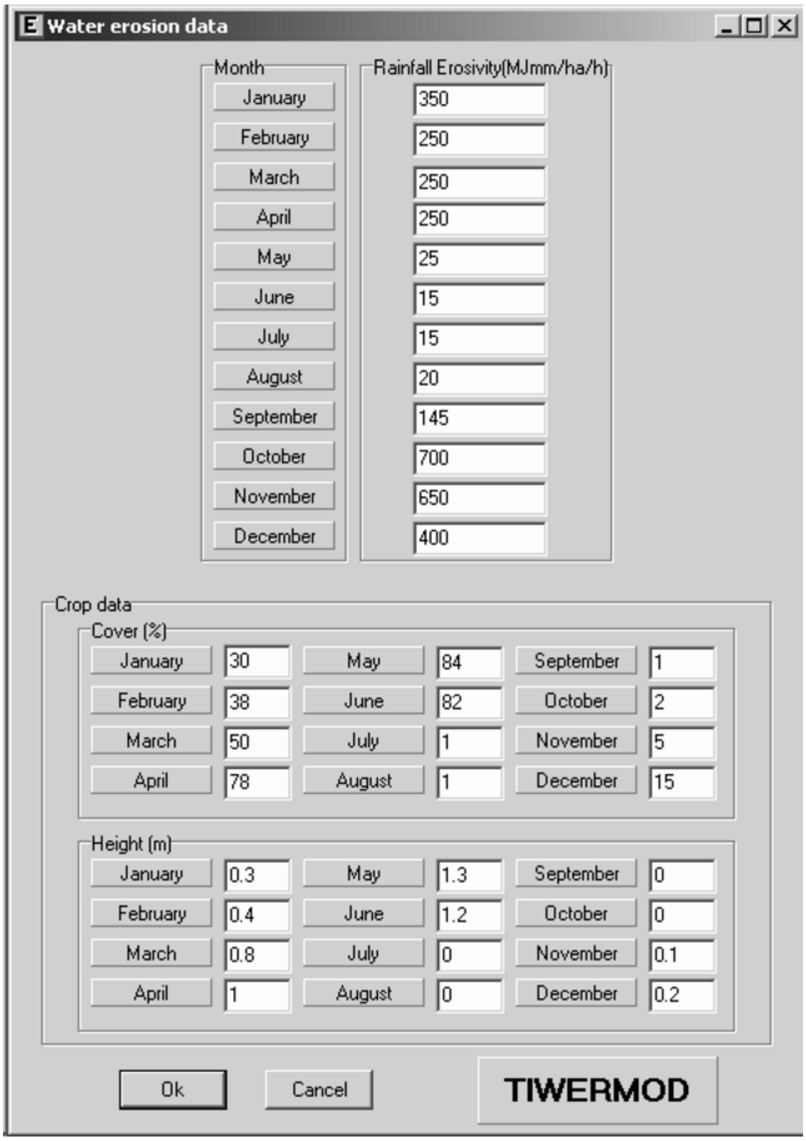

Figure 4. Water erosion data window provided by the TIWERMOD graphic user interface. The data entry corresponding to the erosivity index and the presence of a crop in the plot (height and percentage of soil surface covered) is done by using this window.

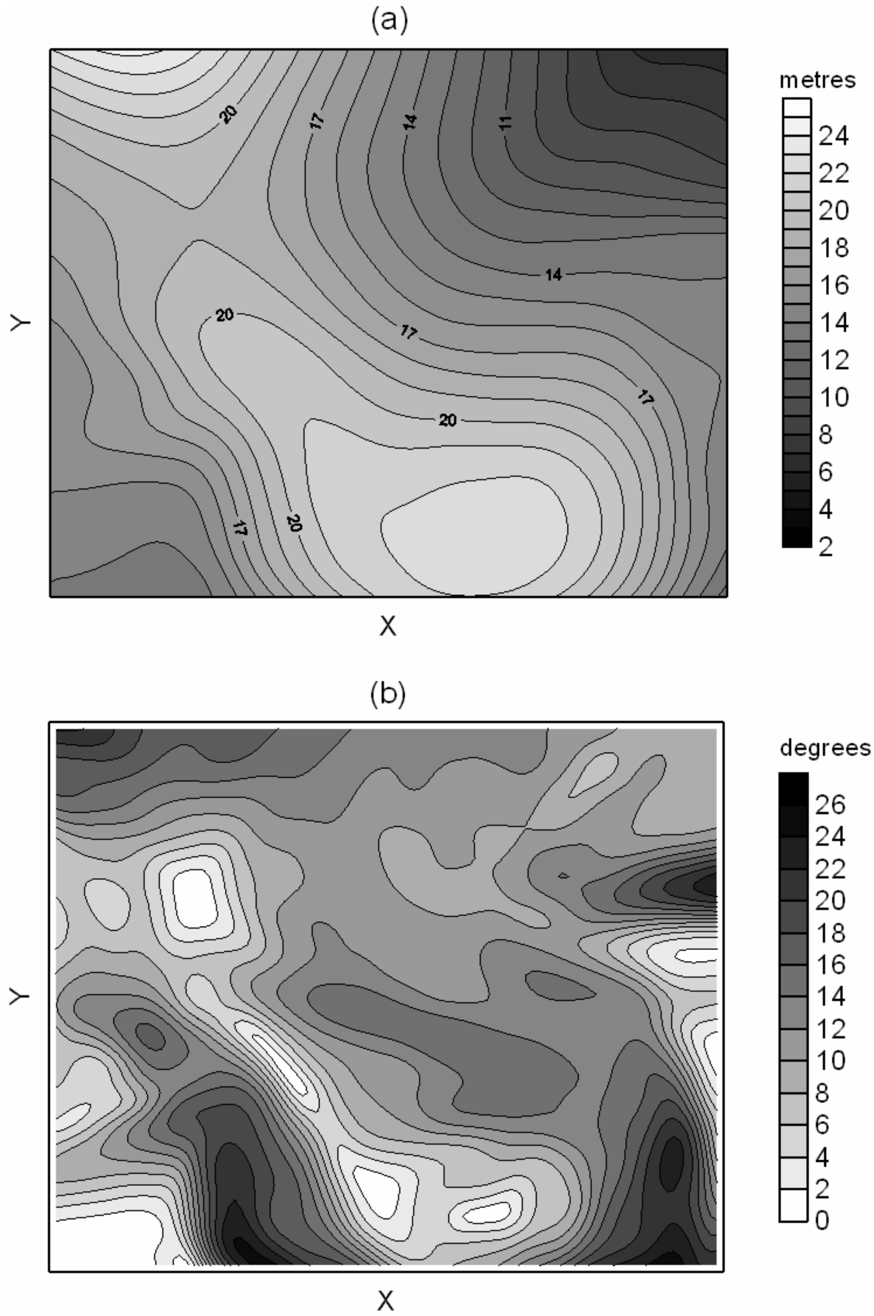

Figure 5. **(a)** Synthetic DEM considered for showing how to use TIWERMOD and verifying its capacity to simulate long-term soil erosion in an agricultural landscape with a complex topography. It has as a resolution Δr = 1 m (110 columns × 90 rows) and the range in elevation is 18 m. **(b)** Map of the DEM terrain slopes.

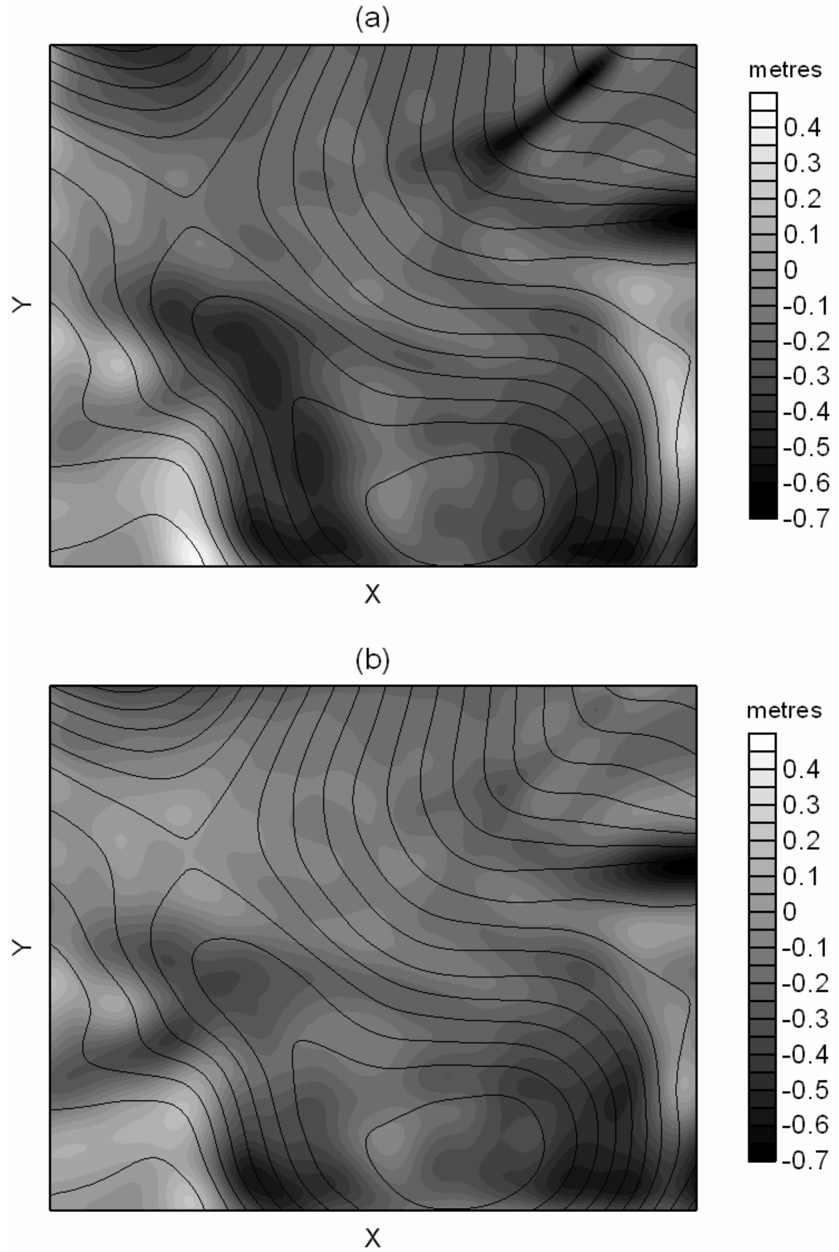

Figure 6. Soil erosion spatial patterns obtained with TIWERMOD for the synthetic DEM representing an agricultural landscape (Figure 5a) after the simulation of 50 years considering the tilling in **(a)** *X* and **(b)** *Y* directions. The data adopted for tillage and water erosion are shown in Figures 3 and 4. The light and dark tones correspond to soil accumulation and loss areas, respectively.

Table 1.

Expressions for the calculation of soil displacement d_{till} (m) in function of the slope gradients S_L and S_T.

Field cultivator	$d^L_{till} = 0.3\ S_L$ [30]
Disk harrow	$d^L_{till} = 0.92\ S_L$ [30]
Chisel	$d^L_{till} = 0.55\ S_L$ [13]
Mouldboard	$d^L_{till} = 0.3803 + 0.62\ S_L - 0.4\ S_T$ [31] $d^T_{till} = 0.414 + 0.5\ S_T$ [31]

Table 2.

Values of the tillage depths z_{till} used in the simulations and diffusion constant K_{dif} derived from (3) assuming ρ_b = 1350 kg m^{-3}.

Tillage tool	z_{till} (m)	K_{dif} (kg m^{-1}) per tillage operation
Field cultivator	0.1	40.5
Disk harrow	0.1	124.2
Chisel	0.15	111.375
Mouldboard	0.25	168.75*

* Perpendicular to the direction of the tilling

Table 3.

Results obtained with TIWERMOD after the simulation of 50 years of soil erosion when the tillage was carried out in the *X* and *Y* directions on the DEM shown in Figure 5a. The presence of a wheat crop is considered for the simulation of water erosion.

	Tillage direction	
	X	Y
	Soil loss	
Area affected (m^2)	8836 (89%)	8989 (91%)
Mean elevation change (m)	0.24	0.21
Maximum elevation change (m)	0.65	0.69
	Soil accumulation	
Area affected (m^2)	1064 (11%)	911 (9%)
Mean elevation change (m)	0.1	0.05
Maximum elevation change (m)	0.42	0.21