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"Gheorghe Asachi" Technical University of Iasi, Romania

APPLICATION OF GIS TECHNIQUES FOR THE QUANTIFICATION OF LAND DEGRADATION CAUSED BY WATER EROSION

Gabriela Biali[1*], Cristian Valeriu Patriche[2], Vasile Lucian Pavel[1]

[1] "Gheorghe Asachi" Technical University of Iasi, Faculty of Hydrotechnical Engineering, Geodesy and Environmental Protection, Iasi, Romania
[2] Romanian Academy, Department of Iasi, Geography Group, Iasi, Romania

Abstract

Land decay processes caused by erosion are very serious by their long term impact on the quality of soils, surface waters, environment and living standards. This article presents the results of a spatial erosion modelling. A new methodology is hereby proposed to estimate the soil losses caused by water erosion. The method is based on using GIS techniques, and its novelty consists in applying the mathematic calculation model on the pixel/ cell level, by using the "overlay" technique, which grants a high level of accuracy for the results. The input data used are four site plans (topographical survey, land use layout, soils layout, and erosion control plan map). Upon processing, seven information layers resulted, which are included in the calculation model, representing actually the factors triggering and maintaining the erosion process. The scope of erosion modeling is to determine the actual and potential erosion in the hydrographical basin considered for the study. Results show an average annual soil loss much above the tolerable limit in our country. In-house developed software application for erosion simulation (in Fortran language) was run under Geo-Graph software, that was used for the entire project development. At the end of the work it is shown that erosion modeling suggested by this software is balanced (through comparison / test) by the erosion measurements and tests performed by researchers from the Research and Development Center for Soil Erosion Control, Perieni, Romania.

Key words: Geographic Information Systems (GIS), land degradation, layer, water erosion

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1. Introduction

In our country and worldwide, erosion decay processes affect agricultural land plots in particular, because of a lower "coverage" of such land plots in terms of agricultural use, as well as impossibility to perfectly adjust agricultural practices to soil protection and conservation requirements, as soil is subject to the above mentioned decay processes. In Romania, such processes denoted as "pollution" in the modern environmental protection terminology, is extended to almost 47% of the country's agricultural area, namely around 7 million ha (Biali and Popovici, 2006). In Tutova Hills region taken as study area, the improper human activity, mainly the up and down hill farming and inadequate road network resulted in a significant land degradation especially through the development of soil erosion, and to a lesser extent of landslides (Niacsu, 2012).

Negative effects of erosion and torrential processes (Clinciu et al., 2010) are significant for Romania, especially by continuous decrease of soil fertility, by sediment clogging in river beds and reservoirs, dammage of transportation roads and certain social - economic objectives located in localities or at slopes base or by environmental degradation by pollution, damage of the microclimate, geographical landscape, people's living standards, depopulation (Berghoff et al., 2014, Dumitrescu et al., 2014; Stătescu et al., 2013; Ungurașu et al., 2013). A full definition of Geographical Information Systems would be: a GIS

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[*] Author to whom all correspondence should be adressed: e-mail: gbiali@yahoo.com

is both a system of databases with specific spatial data capabilities, and a set of operations used for working with spatial data. From a certain point of view, a GIS can be seen as highly-organized map (Chendes, 2011).

The use of Geographic Information Systems techniques for the management of certain environment-related parameters became a routine. These techniques can be used for both the studies related to small areas (few ha) and for studies of regional or even national impact (Cotiușcă et al., 2009. If we refer to the *determination of erosion risk*, in particular for large areas, this implies the thorough knowledge of all factors involved in the degradation process, (Burrough, 1988, Iacobescu et al., 2012, Popiţa et al., 2014), namely the parameters that characterize the climate, landscape, soil, manner of the land use, agricultural exploitation technologies etc. Considering, however, that all such parameters have a spatial distribution, namely a certain value in each spatial point, the complex monitoring action can only be performed under a spatial IT system (Biali and Statescu, 2013; Cochrane and Flanagan, 1999; Williams, et al., 1990).

In this context, the implementation of Geographic Information Systems technique in our country is required and justified not only due to economic reasons, but also for the safe and fast acquisition of real time data.

The main scope of this study is to apply a mathematic model in order to determine the water erosion generated on land by using a GIS technique. The project scope covers the setting up of spatial and attribute based databases, connection of such databases, designing the simulation model required and interpreting the information obtained. This study mainly aims to estimate soil losses by water erosion using a different method compared to the classical one, by various areals, selected areas according to the type of land coverage and use. The benefit of the method suggested by the study is that all calculations are made up to the pixel / cell level where all parameters are homogeneous. Moreover, the results obtained are much more detailed and closer to the on site situation.

Upon modeling, erosion risk maps were obtained for the watershed studied. Our long-term plan is to simulate erosion risks by variation of certain agricultural management parameters, such as cultures structure or erosion control systems. That would be possible and very feasible as soon as spatial and attribute based (alphanumeric) databases are already set up.

The implementation of these techniques can also ensure an *integrated ecologic monitoring*, through which the competent bodies can continuously monitor the status of natural resources, in particular of environment factors and anthropic impact, based on spatial and temporal parameters and indexes, which ensure the informational framework required for the prevention strategy and tactics related to the impact of environmental factors and human activities, for the development of forecasts and exercise of the operative control on ecological status remedy actions.

2. Materials and methods

2.1. Study area

This paper sets out a study, performed through GIS techniques, concerning the evolution of land degradation process through erosion in the reception basin of Antohesti water catchment area, of Berheci river higher water catchment area, Bacău County (Fig. 1). The reception area is of 3963 ha, with a highly fragmented relief, hilly type and average slopes of more than 15 %. Absolute altitudes ranging between 549.5 m (Hill Dorosanu) and 200 m in the dam accumulation, resulting an energy relief 349.5 m. The slopes are affected by surface erosion, deep and. The sloping land was affected by sheet erosion, gully erosion and by active landslides. Dominant soils are chernozems and brown soils, and the most extended uses are: arable land – 47.2 %, pasture land – 26.78 % and forest - 16.8 %, (Biali and Popovici, 2003).

Graphical input data are supplied from the site plans on the scale of 1:10000 as shown by Fig. 2. Descriptive (non-graphical) input data are provided based on analogy with similar documentations and using data collected on site.

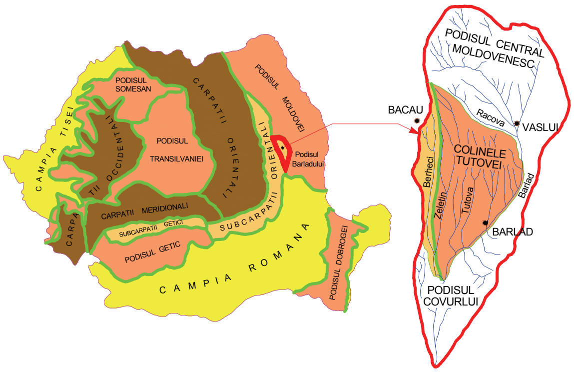


Fig. 1. Location of research (Berheci catchment)

2.2. Data and methodology

Under the GIS project, the geo-referential data is represented as layers, which facilitates the analysis of space variables and distribution of entities on the reviewed surfaces, and the overall analysis of the acquired information, which implies the concomitant approach of several layers, was performed through the so-called "*overlay"* technique.

The "overlay" technique is based on overlaying or combination operations of several layers (based on specific algorithms – determined by the user), which generates new layers and data and attributes, respectively. These operations may be algebraical, logical, topological etc. and have graphic and non-graphic effects. *The "overlay" technique* enables the performance of multiple spatial analyses because it refers to the spatial entities and associated databases belonging to an unlimited number of layers. Cartographic algebra and Boolean algebra represent the basis of *overlay* operations. Because *overlay* does not mean merely the overlaying of thematic maps (certain operations being performed with the layer-related data), the current GIS application gives special attention to the type of layers, quality of acquired data, resolution thereof, geo-referencing, scale of the projection system, data structure changes.

2.3. Structure of the GIS project

The general chart of stages performed under the project (with respect to the set out topic) is set out at Fig. 2. The application used a GIS-type Romanian software Geo - Graph, intended for work operations with digital maps and database interrogation.

The mathematical model used in order to determine the soil loss is based on USLE equation (Universal Soil Loss Equation – developed in the USA by Wischmeier),(Wischmeier and Smith, 1978; Renard et al., 1996) and in Romania in the form of ROMSEM model – Romanian Soil Model (Moţoc, 1983). Due to the fact that the "*relief*" factor has a significant weight in the erosion process for gradient areas, the development of the Digital Elevation Model (DEM) represented an important step within GIS project, and generated (according to Fig. 2) three information layers included in the computation algorithm of erosion-related soil loss. The Digital Elevation Model was obtained by means of interpolation, based on "*weighted average method*" for local interpolation (Haidu and Costea, 2012.

In view of creating a georeferenced database included in the Romanian Soil Model (ROMSEM), raster procedure was used, which enabled to overlay a rectangular grid of square 25 x 25 m sized cells on the land survey documentation. Therefore, both the thematic layers included in the mathematic model and the calculations for water erosion in the researched basin were completed up to the cell level.

The raster procedure was used in order to develop the geo-referential database included in the above mentioned equation, and this enabled the overlay of a rectangular grid of square cells of 25 x 25 m on the cartographic documentation. Thus, the computation of water erosion in the reviewed basin was performed on approximately 63,408 cells.

Based on the map with level curves, the obtained Digital Elevation Model (DEM) provided fundamental layers for the GIS project, such as:

Layer 1 – Hypsometric map (Fig. 4)
Layer 2 – Flowing direction map (Fig. 5)
Layer 3 – Gradient map (Fig. 6)
Layer 4 – Topographical factor map (Fig. 7)

Digital Elevation Model is based on the calculation own program in Fortran language, then run in Geo-Graph software. The first information layer (Fig. 4) is the average rates for each cell / pixel. The average was determined by applying a local interpolation (by *weighted average method*). Knowledge the quota is very important because it is calculated on based on the following parameters topographic (drainage directions, slope, drainage length). The second information layer resulting from DEM is layer with drainage directions.

The flowing/draining directions of the reviewed water catchment area were also laid out by means of the land raster form alphanumeric model. Under this procedure, the draining network of the reviewed area has an arborescent structure (Fig. 3). By transiting it pixel by pixel, the flow from upstream towards downstream was represented by means of irregular lines, with lengths reduced at the confluence points, (Moore and Wilson, 1992).

In the distributed flowing model, the integration computation organizing manner is based on the determination of associated draining local directions, and the other topographic information was used in particular in order to partially verify the accuracy thereof.

The water flow from a hydrographic unit takes place by means of a complex of paths that unite the high altitude points with the closing point of the basin. Thus, in the basin, one can see the source type pixels – to which no other pixel is drained, the confluence pixels – where at least two upstream pixels are drained, and the closing pixel – passed by all draining paths of the basin.

The raster representation considered that the current pixel can be drained based on one of the eight possible directions, depending on the positioning of the lowest altitude adjacent pixel (Fig. 3a). When analyzing the vicinities of the central pixel, in order to determine the draining direction thereof (Fig. 3c), the altitude of diagonal ones are reconsidered in order to maintain the same distance from the reference pixel (Biali and Popovici, 2003). The third layer resulting from the application of DEM is the slope determined for each pixel.

The land gradient, I, was determined based on the value of I gradient (expressed in percents - %), according to the USLE equation (1) (Wischmeier and Smith, 1978; Renard et al., 1996):

$$I = \frac{0.17 + 0.12i + 0.017i^2}{6.613} \qquad (1)$$

The parameter that marks the versant length on the gradient direction was determined based on Eq. (2):

$$L = \left(\frac{\lambda}{22.14}\right)^m \qquad (2)$$

where: λ - length of the gradient on horizontal projection (m); *m* – parameter with a value ranging between 0.3 and 0.6; m = 0.5 was taken into consideration (because the average slope of the land is between 10 – 20 %).

The mathematical model of water erosion - related soil loss forecast (E per ha) – ROMSEN equation (3) (Motoc, 1983):

$$E = K \cdot L^{0.4} \cdot i^{1.4} \cdot S \cdot C \cdot C_s \qquad (3)$$

where: K is the pluvial aggressiveness; in the proposed mathematical model, the pluvial aggressiveness coefficient is expressed through a value constant for the entire water catchment area; $K = 0.15$, according to the erosion mapping in Romania (Biali and Popovici, 2006); i – average gradient along the flow (%); L – length on the flowing direction (m); S – correction factor for soil erodibility (non-dimensional); C – influence factor of land use, crops and works (non-dimensional); C_S – influence factor of soil preservation and protection works (non-dimensional).

3. Results and discussion

During the first stage, the information layers that characterize the landscape were created (because relief-related information is critical for the modeling of erosion processes on gradient land). Quotas ranging from 200 m to 550 m. 3D DEM is made with Microstation 97, where quota ranges and colour codes are different than in Geo-Graph. The computation of gradients and orientations was performed on eight directions (Fig. 5), based on the average altitude of pixels, and both parameters were estimated by means of a 3 x 3 pixel window. The information layer of flowing directions, grouped per colour codes associated to cardinal points and arrow-type representation (detail) are represented in Fig. 5. Informational layer of average pixel gradient, in according to equations (Eq. 1 and Eq. 2) are represented in Fig. 7.

The next phase included vectorization of site layout plans on a scale of 1:10.000 with data related to land coverage (uses), soil and types of land improvement coverage. An important phase consisted in setting up a polygon topology for each graphical object, which is represented as a use outline or an improvement type. The topology structure (to ensure vector data storage model) is based on proximity properties and spatial relations between elements (objects) defining a vector data model.

That will enable developing the structure of spatial data base files, which are mandatory to ensure operation of the information system: updating, zones overlapping, entity outline by overlapping intermediate boundaries, generalizing boundaries outline etc.

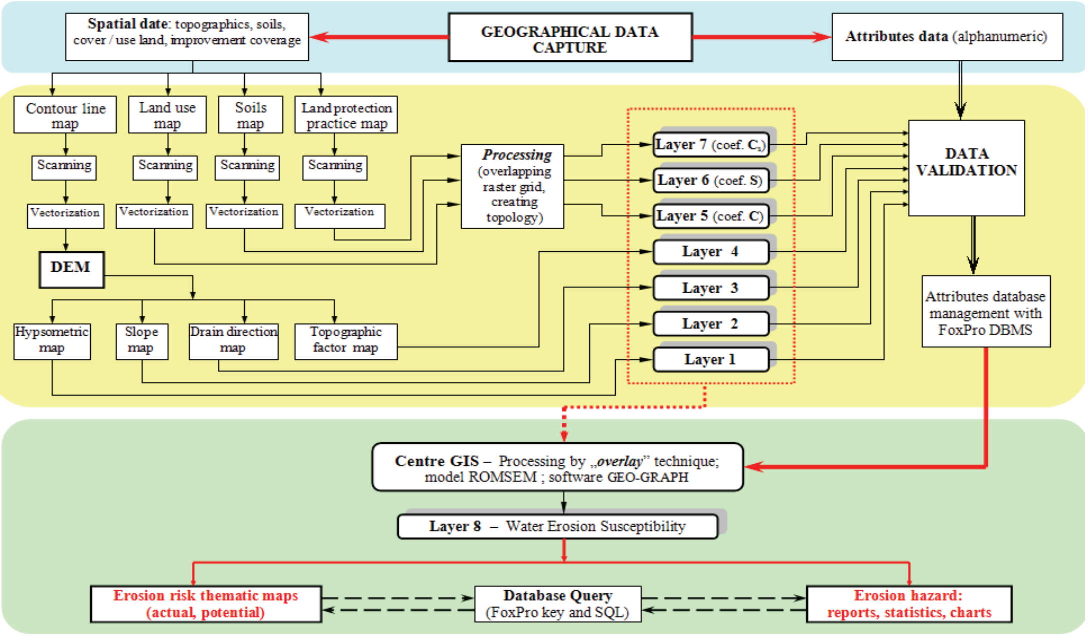
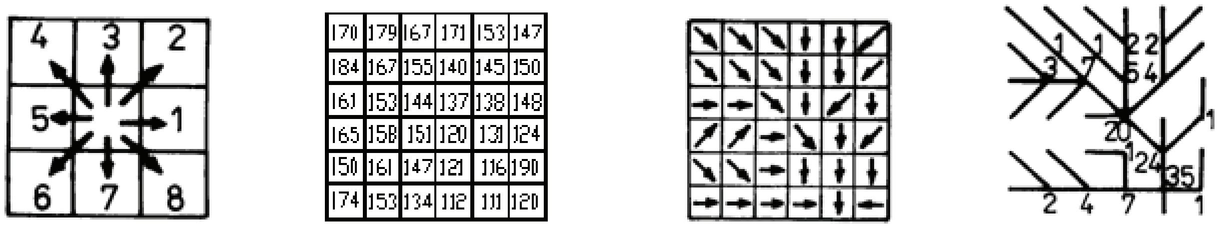


Fig. 2. Data flow in GIS project



170	179	167	171	153	147
184	167	155	140	145	150
161	153	144	137	138	148
165	158	151	120	131	124
150	161	147	121	116	190
174	153	134	112	111	120

(a) **(b)** **(c)** **(d)**

Fig. 3. Analysis of versant flow based on GIS raster method: (a) estimating the flow direction (of the 8 possible options); (b) representation of the land surface in raster model (average quotas); (c) flowing directions related to the grid of (b); (d) flowing concentration grid equivalent with (c) and (d).

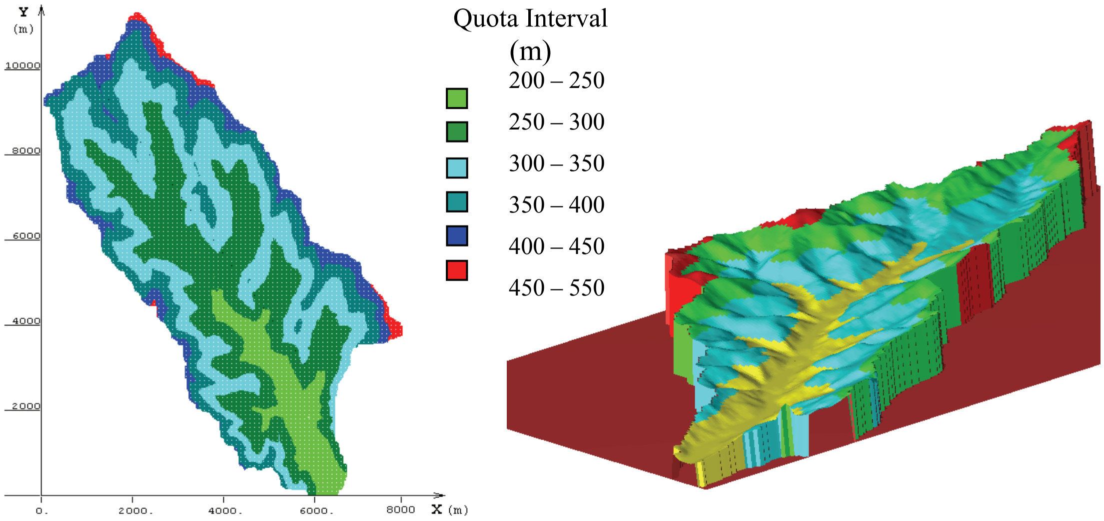


Fig. 4. Hypsometric map: “*layer 1*” and DEM in 3D format

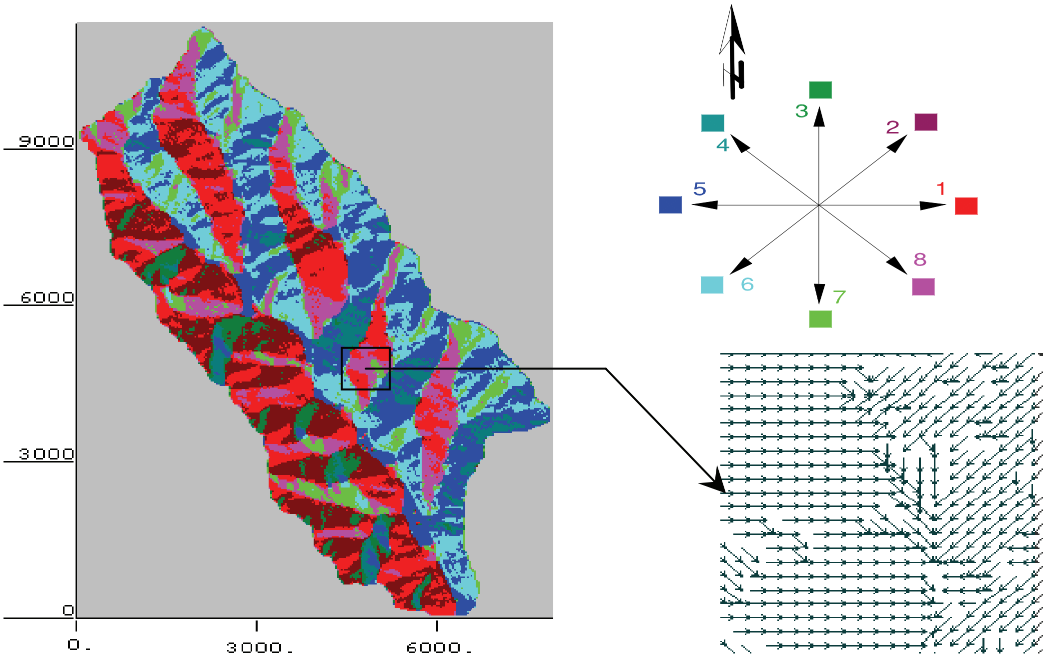


Fig. 5. Map of drain directions “*layer 2*”

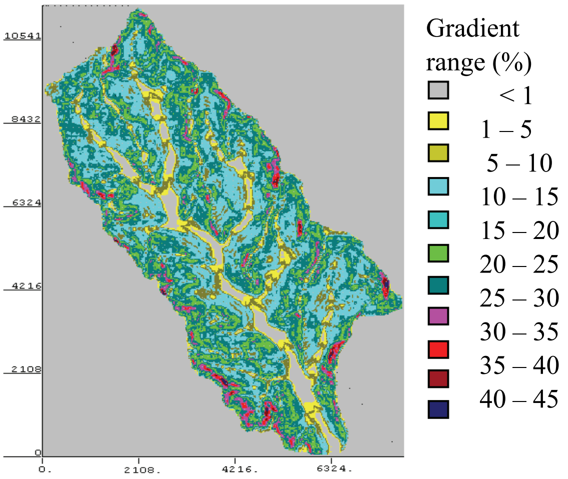


Fig. 6. Relief declivity map: “*layer 3*”

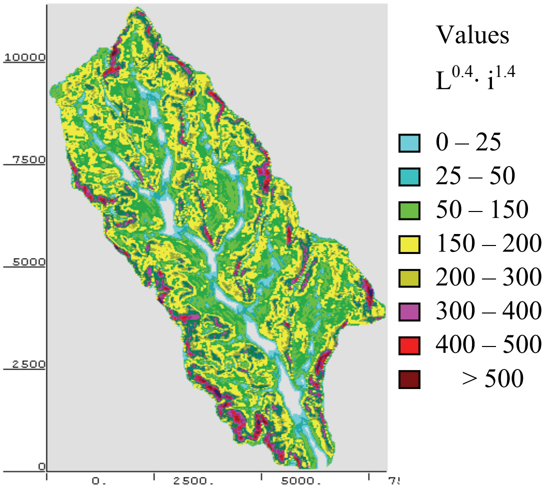


Fig. 7. Topographical factor map: “*layer 4*”

Based on the status layouts of uses (cover) on sloping land, types of soil and types of land improvement coverage, the spatial topology methods (Biali and Popovici, 2003) generated the following information layers:

Layer 5 – Land coverage and agricultural management (Fig. 8);

Layer 6 – Soil erodibility factor (Fig. 9);

Layer 7 – Effect of soil protection and preservation actions and works (Fig. 10).

By integrating the above mentioned seven layers in ROMSEM equation (in according to equation 3), under Geo-Graph software, we obtained the information layer of the erosion risk (*Layer 8*) (Figure 11), in two simulation versions, namely the *actual erosion risk* (determined by the combined action of all parameters of USLE equation) and the *potential erosion risk* (where the factors that can be controlled in the intake basin - layer 5 and layer 7 – were disregarded).

Actual erosion results from applying the mathematic model that takes into account the combined (joint) action of all parameters in ROMSEM equation (Eq. 3) including structure of cultures and erosion control protection systems on slope land plots – which lead to decrease of erosion values, as C and C_s < 1.0; C_s = 0.15 for terrace farming on arable land or terraces in vine areas and orchards; C_s = 0.30 – 0.60 for strip farming or grass filter strips on arable land; C_s = 0.50 – 0.90 for works along the land contour lines overall direction;.

Potential erosion results from applying the same model, but parameters C and C_s have no impact on the equation (it is considered that the arable land has the most unfavourable structure, therefore C=1.0 and there are no erosion control systems C_s = 1.0):

Actual erosion is lower than the potential erosion, as resulting from the thematic maps obtained by using the GIS as well as by data query and processing as presented in Table 1 and Fig. 12.

5. Validation of results obtained through erosion modeling

In view of validating the method for estimating the soil losses by erosion using the Geographical Information Systems technique, the data obtained were compared with those resulting from a study of the sediments clogging rate in Antohesti reservoir performed by Research and Development Center for Soil Erosion Control, Perieni, Romania (Nistor and Hurjui, 2010).

This study aiming to establish the sediments clogging extent (by alluvial deposits and annual sediments clogging rate) included the following operations:

➪ bathymetric and level - related measurements to determine the water volume in reservoirs;

➪ assessments of the alluvial deposits thickness and lithological features;

➪ sampling and test of water samples in order to assess water turbidity going in and out of the reservoir and in its various areas.

The study performed revealed the clogging rate (as an average clogging rate for a 10 year – period (1992 – 2002) and alluvial deposit flow rate was calculated as 3.64 m^3 / ha per year for Antoheşti reservoir (Nistor and Hurjui, 2010). Starting from the results obtained under this study the alluvial deposit flow rate was calculated, in the following phases:

a) Calculation of average weighted erosion (E_s) in the hydrographic basin studied (Eq. 4):

$$E_s = \frac{\Sigma E_i \cdot S_i}{\Sigma S_i} \quad (t/ha \cdot year) \tag{4}$$

where: E_i – actual erosion (specific soil loss) annual average rate quasi-consistent on various surfaces (S_i) in the hydrographic basin of a reservoir (t/ha·year);

E_s = 12.64 (t/ha·year)

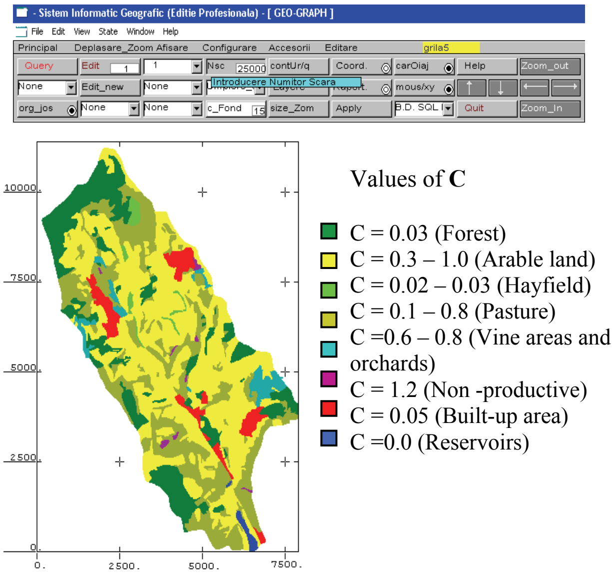


Fig. 8. Distribution of factor C: „*layer 5*"

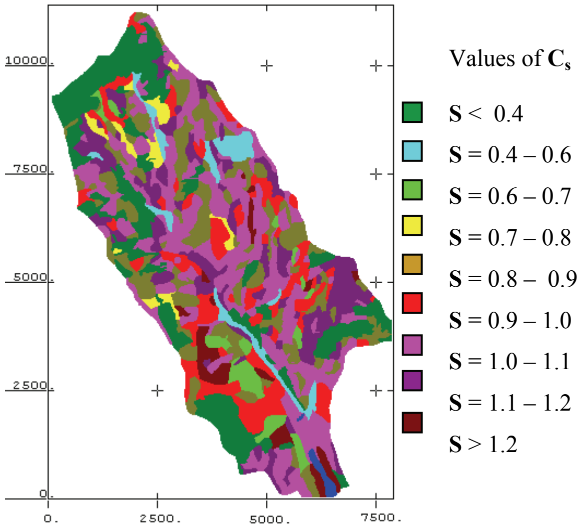


Fig. 9. Distribution of factor S: *„layer 6”*

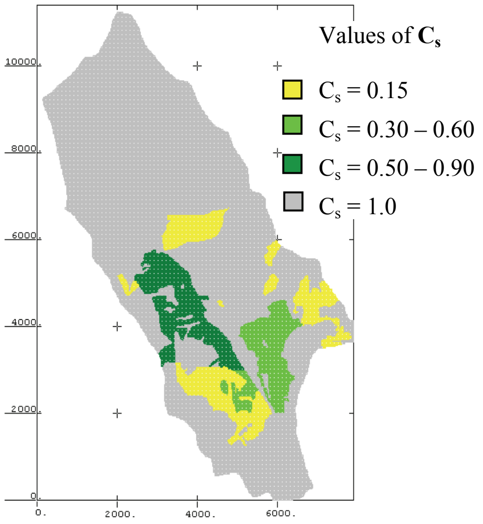


Fig. 10. Distribution of factor C_s: *„layer 7”*

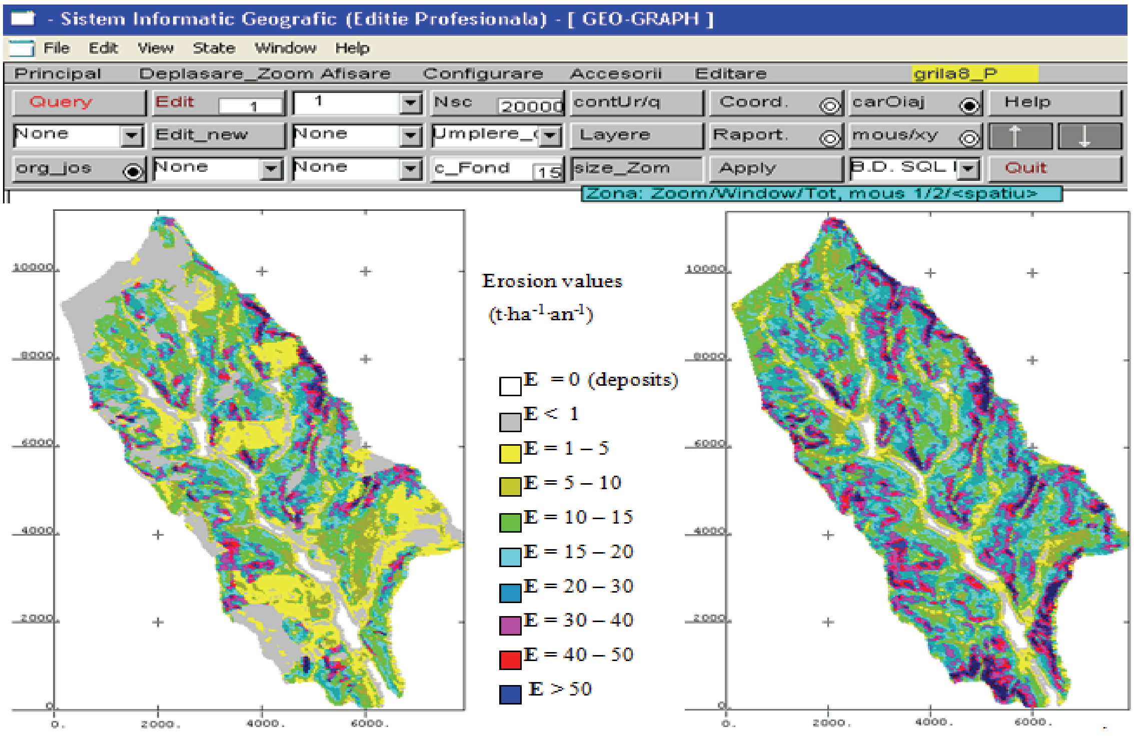
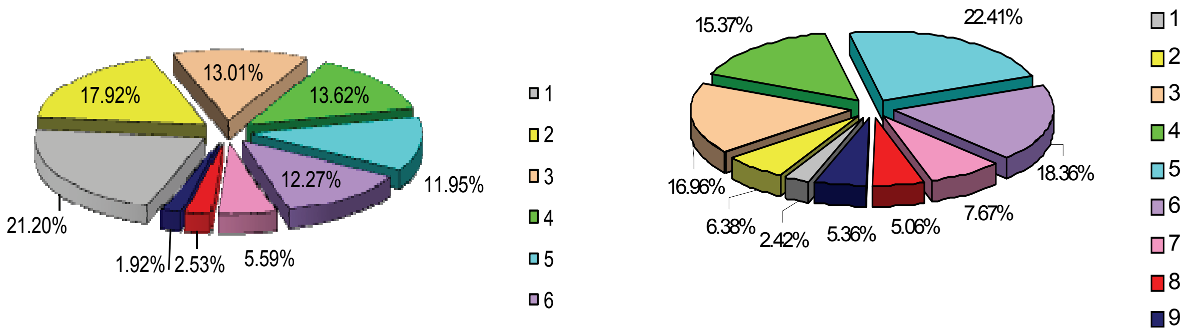


Fig. 11. Soil loss due to water erosion, at pixel level, in Antoheşti basin. Information “*layer 8”* concerning erosion risk: a. actual; b. potential

Table 1. Distribution of actual erosion and potential erosion in Antoheşti basin

			Actual erosion		*Potential erosion*	
Code		*Erosion values (t/ha·year)*	*Surface (ha)*	*% of the total surface*	*Surface (ha)*	*% of the total surface*
1	⬜	< 1	844.43	21.20	96.43	2.42
2	🟨	1 – 5	713.62	17.92	254.25	6.38
3	🟧	5 – 10	518.12	13.01	675.67	16.96
4	🟩	10 – 15	542.43	13.62	612.35	15.37
5	🟦	15 – 20	475.81	11.95	892.72	22.41
6	🟦	20 – 30	488.75	12.27	731.31	18.36
7	🟪	30 – 40	222.81	5.59	305.57	7.67
8	🟥	40 – 50	100.85	2.53	201.65	5.06
9	🟦	> 50	76.43	1.92	213.30	5.35
Total			3983.25	100.00	3983.25	100.00



(a) **(b)**

Fig. 12. Percentage distribution of erosion in Antoheşti watershed: (a) actual erosion; b. potential erosion

b) Estimating alluvial deposit flow rate in multiannual average values (E_{al}) on the exit of the hydrographic basin (Eqs. 5, 6):

$$E_{al} = E_{total} \cdot C_{ef} \tag{5}$$

where:

$$E_{total} = E_s + E_{ad} + E_d + E_h \tag{6}$$

where: E_{total} is total erosion (t/ha·year); E_s – sheet erosion (t/ha· year) (Eq. 4); E_{ad} – gully erosion (t/ha· year); E_d – erosion on the road network of the hydrographic basin (m^3/ha·year); E_h - sediments resulting from erosion of unconsolidated river banks or erosion caused by rural localities or increasing depth of the river network beds (t/ha·year); C_{ef} - alluvial deposit (reduction) flow.

The value of such coefficient is calculated using the known area of the catchment basin considered for the study (Biali and Popovici, 2006). Based on the on-site research (Nistor and Hurjui, 2010) the following relation resulted:

$E_{ad} + E_d + E_h \approx 0.2\ E_s$

$E_{total} = 12.64 + 0.2 \cdot 12.64 = 15.16$ (t/ha·year) (according to Eq. 6):

$C_{ef} = 0.34$ – corresponding to the surface of 3983 ha of the water catchment area Antoheşti

$E_{al} = 15.16 \cdot 0.34 = 5.15$ *(t/ha·year)* (according to Eq. 6):

By using $\gamma_{al} = 1.45$ t/m^3 for clay-sandy alluvial deposits, it results:

$$E_{al} = \frac{5.15}{1.45} = 3.55\ (m^3/\text{ha·year})$$

The values of alluvial effluence estimated through the GIS technique, in case of Antohesti water catchment area, are significantly close to those obtained through on-site measurements by Research and Development Center for Soil Erosion Control, Perieni, Romania (Nistor and Hurjui, 2010).

6. Conclusions

This study sets out the geo-spatial data flow (from acquisition to obtaining graphical and non-graphical information) in view of estimating erosion risk in a hydrographic basin.

A Digital Elevation Model (DEM) was drafted, based on a mapping database consisting of site layout plan of land contour lines and altimetry data. As terrain data are critical for modeling erosion processes on slope land plots, displaying such data in numeric format has significant benefits depending on the fast processing and quality of information obtained (slopes, flow directions, distances).

A mathematic water erosion calculation model was set up, based on the Universal Soil Loss Equation. The information obtained is stored in a system based on information layers, each layer containing a certain dataset. Such approach enabled to perform a spatial analysis of parameters considered for the model.

Computerized processing, review and further exposure of information acquired in various forms (maps, charts, tables, text etc.) provide certain special benefits, including:

- obtaining thematic maps (major benefit)
- the possibility to handle large, multilayer, heterogeneous databases, of spatial reference;
- high flexibility concerning the IT system configuration, thus enabling the adjustment thereof to a large variety of applications and users;
- the possibility to integrate data concerning various objects;
- analysis of information acquired through computerized processing of the initial data;
- diversified presentation (display) or editing of information.

This paper proves the computation accuracy of water erosion. Compared to classic procedures (where the computation areas are larger and with variable size), in this case the determination of water erosion takes place at elementary surface level (pixel / cell). Another great benefit of GIS technique consists of the possibility to incorporate/enter all factors (natural and anthropic) at cell level. The computerized data processing that characterizes the factors which determine the initiation and maintenance of water erosion process generate multiple possibilities of erosion simulation on sloping land.

Higher accuracy of the research performed on time degradation of land due to erosion by means of GIS techniques can also be acquired by diversifying the data acquisition methods (including photogrammetry and remote detection), development and permanent update of the databases, but also by using certain recent mathematical models of erosion simulation, such as WEPP, EPIC, GRASS, AGPNS.

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