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MODELLING SPATIAL AND TEMPORAL CHANGES OF SOIL WATER EROSION

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The paper presents a dynamic approach in physically based soil water erosion modelling in GIS coming out of the unit stream power and physical fields theories. Dynamics of the phenomenon is studied in both short-term and long-term scales considering relief and Manning's surface roughness. Morphometric parameters of relief are computed of digital model of relief and Manning's surface roughness coefficient was derived of visually interpreted aerial photographs of two contrast time horizons (1955 and 1990). The method is tested on a small catchment selected in Myjava hillyland.

Key words: soil water erosion modelling, geographic information systems, aerial photographs, computer assisted visual interpretation

INTRODUCTION

Soil water erosion depends on various natural factors and human activities and its inherent feature is an enormous complexity. It is broadly accepted that changes in land use during the last four decades (collectivisation, enlargement of agricultural plots, monoculture production etc.) have lead to its acceleration and spatial increase.

At present questions of soil/land susceptibility to soil erosion/deposition and total effect of the process in hilly areas for the period of past 40-50 years are discussed. Different research approaches have been applied, e. g. complex pedo-geomorphic

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research (Stankoviansky 1995), analysis of radioactive isotope Cs^{137} (Lehotský et al. 1993) or rule-based modelling (Solín and Lehotský 1996). The broader overview of the methods applied in soil erosion/protection research in Slovakia is available in the report by Čurlík et al. (1995). The geographic information system (GIS) is an appropriate tool for the problem analysis and modelling. It is quite obvious as it assumes the use of various data (vegetation, soil, relief, climatic data etc.) that can be effectively processed in GIS (see Flacke et al. 1990, Mitášová et al. 1996, Pilesjö 1992).

The Universal Soil Loss Equation (USLE model, Wischmeier and Smith 1978) is being frequently applied in agricultural practice but the application of this model within a GIS is limited because of its properties. For example, the USLE model predicts only soil loss (not deposition) and therefore in the stage of computation the deposition areas must be *a priori* excluded. It is only one-dimensional, static empirical model with limited possibilities for the analysis of the phenomenon dynamics. The physically based models consider subtle spatial and temporal changes of contributing factors and are more appropriate for dynamic modelling.

The aim of the paper is to analyse changes of spatial and temporal distribution of soil water erosion/deposition by application of the ERDEP model based on the physical fields and the unit stream power theories. Dynamics of the phenomenon is studied at erosion event level with the implications for modelling longer time periods. Changes of spatial and temporal distribution of erosion/deposition due to relief and land use interpreted from aerial photographs (time horizons 30. 5. 1955 and 12. 7. 1990) are considered. The method is tested on the study area Kostolné located in agricultural landscape of the Myjava Hillyland.

DYNAMIC APPROACH IN SOIL WATER EROSION MODELLING

Soil water erosion is very dynamic and spatial phenomenon. Its dynamics strongly depends on relief geometry and surface properties influencing overland flow. Other erosion components (e.g. soil infiltration characteristics, rainfall intensity) are also spatially and temporally variable and have strong impact on overland flow and water erosion process (Ogden and Julien 1993, Saghafian et al. 1995). But the assessment of these input model parameters requires statistically significant series of costly precise field measurements.

Some of the well-known water erosion models (e. g. WEPP, Flanagan and Nearing 1995) use static approach describing a steady-state erosion/deposition caused by overland flow in dynamic equilibrium. However, this situation is rather rare in real landscape due to relief configuration and/or land cover roughness properties. Also the equilibrium in overland flow on slopes within a catchment is reached at different time. Therefore it is clear that exact soil water erosion modelling must be spatial and also dynamic in all its components.

Moore and Burch (1986a, 1986b) have shown that Yang's unit stream power theory (Yang 1973, see Moore and Burch 1986a, 1986b) can be used in sediment flux modelling for overland flow as well as in erosion/deposition modelling for less cohesive soils on slopes. It has been shown that this approach in combination with the theory of physical fields, GIS and remote sensing can provide valuable results for evaluating water erosion/deposition rates in agricultural areas (Hofierka and Šúri 1995). This method was named the ERDEP model. In comparison to the USLE, the ERDEP is a two-dimensional physically based model allowing dynamic water erosion modelling.

Moore and Burch (1986a, 1986b) have shown that the sediment *flux per unit flow width* at a given point on relief and given time q_s can be expressed as:

$$q_s = \frac{\rho\gamma}{n^{0.6\beta}} q^{1+0.4\beta} \sin(\theta)^{1.3\beta}, \quad [1]$$

where ρ is the water density $[kgm^{-3}]$, n is the Manning's surface roughness coefficient, β and γ are the physically based coefficients characterising properties of soil particles and flowing water, θ is slope steepness at a given point, q is the water flux per unit flow width (specific water discharge) $[m^3s^{-1}m^{-1}]$.

This equation is principally the same as general sediment transport equation by Julien and Simons (1985). In the case of erosion resistant soils the equation [1] can be multiplied by factor $1-P_c/P$ where parameters P_c and P are the critical unit stream power and unit stream power or the critical shear stress and shear stress, respectively.

Then the erosion or deposition rate E $[kgm^{-2}s^{-1}]$ is computed as a divergence of 2-dimensional dynamic vector field representing the spatial distribution of the sediment flux per unit flow width [1]:

$$\mathbf{q}_s = \mathbf{q}_s((x,y)\ t), \quad [2]$$

$$E((x,y),t) = div(\mathbf{q}_s) = \nabla \mathbf{q}_s = \frac{\partial q_s}{\partial x} + \frac{\partial q_s}{\partial y}, \quad [3]$$

where x, y are the cartesian horizontal coordinates and t is time. The similar result can be obtained by computing the net erosion/deposition rate as a directional derivative of the scalar field representing intensity values of the sediment flux per unit flow width in direction of the flow [1]:

$$E(x,y) = \frac{\partial q_s}{\partial s} = \frac{\partial q_s}{\partial x}\cos\alpha + \frac{\partial q_s}{\partial y}\sin\alpha, \quad [4]$$

where α is a direction of the flow (approximated by anti-gradient direction) $[deg]$ and s is a section of the slope curve. The equation [4] is very close to the steady-state equation published by Moore (1993) which has been derived as a directional derivative of the sediment flux.

The cumulative effect of erosion/deposition process E_b $[mass/area/time]$ is expressed by the integral:

$$E_b = \int_{t_0}^{t_k} E\ ((x,y),\ t)\ dt, \quad [5]$$

where $E[(x,y),t]$ is spatially and temporarily variable erosion/deposition rate $[kgm^{-2}s^{-1}]$. In practice, the integral is solved as a sum of erosion/deposition rates at time horizons with appropriate time step Δt.

The specific water flux (specific water discharge) is approximated by product of specific contributing area A_s $[m^{-2}m^{-1}]$ and rainfall excess i $[ms^{-1}]$. The equation [3] models a simplified steady-state water erosion/deposition and predicts erosion/deposition rates near the equilibrium in overland flow. However, this situation is often rare in landscape and depends strongly on relief configuration, rainfall excess and land use. During an obvious rainfall event with erosion/deposition impact it occurs especially on upper parts of catchments with bare soils (see fig. 2).

The Saint-Venant differential equations describing overland flow have the following 2D form (Saghafian et al. 1995):

$$\frac{\partial h}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = i, \qquad [6]$$

where h is the surface flow depth $[m]$, q_x, q_y are the specific water discharge in the x and y directions, respectively, i is the rainfall excess, t is time.

The diffusive wave approximation of the momentum equation in the x direction, for example, is

$$S_{f_x} = S_{o_x} - \frac{\partial h}{\partial x}, \qquad [7]$$

where S_{f_x} is the friction slope and S_{o_x} is the bed slope.

Analytical solution for these equations is not known. Therefore, a numerical approximation of their solution is required. For example, Saghafian (1993) has implemented a 2D diffusive wave approximation of the equations as r.hydro.CASC2D command in GRASS GIS using a finite difference method. Mitáš et al. (1996) have presented a stochastic approach using Monte Carlo method for a steady-state situation.

The simplified version of the ERDEP model called *the index of topographic potential for erosion and deposition* (Mitášová et al. 1996) considers only the influence of relief and models a sediment transportation capacity of overland flow. Its relation to the LS factor of the USLE model (Moore and Wilson 1992) is known. The results of the topographic potential are very close to the ERDEP model in areas with transportation limited case of erosion and minimum spatial change in land cover/land use and soil properties (Hofierka and Šúri 1995).

REMOTE SENSING FOR SOIL WATER EROSION IDENTIFICATION AND MODELLING

The broad spectrum of visual and digital interpretation techniques of remote sensing data is applied in erosion studies at various scales as summarised by Šúri (1996).

Aerospace data are often used for *direct identification of eroded areas* on unvegetated soils as they allow to determine soil properties that can directly indicate sheet erosion (Irons et al. 1989). These are mostly changes in humus and water content, mineral composition and soil structure (Mulders 1987). In visible wavelengths of electromagnetic radiation these appear as changes of soil surface colour (Escadafal 1993). Dramatic changes in vegetation cover can be also used as an indirect indicator of sheet erosion (Price 1993). Linear erosion forms can be identified using prevailingly large scale aerial photographs (Alam and Harris 1987) and occasionally - for larger forms - also SPOT data (Bocco et al. 1990).

Aerospace data are also used to derive *input parameters* into erosion models as they can be effectively integrated and analysed in GIS. The most prevalent applications are focused to the assessment of actual land cover/land use factors (e.g. see Lantieri et al. 1990, Pilesjö 1992, Hofierka and Šúri 1995).

The aerial photographs are valuable source of information for erosion modelling in large scale studies. They provide information on actual state of landscape in required time horizons. Visual interpretation - alternatively supported by digital image processing - is a generally applied methodical approach based on the understanding of the state of landscape components, their mutual links, position and the way of their interaction with electromagnetic radiation. Landscape objects are represented on photographs by interpretation features that are considered at the identification of physiognomic patterns of land cover (Feranec and Oťaheľ 1984, Feranec and Oťaheľ 1993). Adding functional properties and the method of realisation of the material-physiognomic forms of land cover it can be said about the land utilisation or land use. With regard to the soil erosion models the interpreted information on land cover/land use can be used for the assessment *of surface roughness, vegetation and soil surface properties* as well as for the analysis and implementation of *landscape spatial structure* and *overland flow barriers.*

APPLICATION TO MYJAVA HILLYLAND STUDY AREA

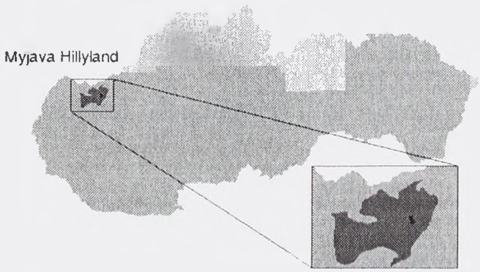

Fig. 1. Position of the study area.

To test the approach of the ERDEP dynamic modelling, a small catchment (1.69 km^2) in the Myjava Hillyland (West Slovakia) was selected. A predominant part of the catchment is characteristic by a typical hillyland relief, the uppermost part shows plateau-like subupland character. The smoothly shaped relief with elevation 230 to 372 metres is disturbed only by presence of gullies and ravins, concentrated in some areas. The catchment is typical for finger-like convergence of dells and dell-like valleys and is without any permanent water course. Due to low resistance of parent rocks (sandstones and claystones), considerable thickness of regolith, as well as the character of land use it was strongly affected by soil erosion. Two soil units are recognised in the study area - the uppermost part is covered by typical Dystric Planosols, the rest of the catchment by Stagno-gleyic Luvisols with deposition forms in dell parts.

Various factors influence water erosion and deposition. In this study only two of them were considered - *relief* and *Manning's surface roughness coefficient.*

Digital model of relief (5 metres raster resolution) was computed in GRASS GIS using *s.surf.2d* command from digitised contour lines at scale 1:10 000. The following morphometric characteristics of relief controlling overland flow were computed - slope steepness, aspect, profile and tangential curvatures and specific upslope contributing areas. On Fig. 2 the slope steepness and the estimation of time to equilibrium in overland flow (assuming bare soil) are presented. Using the estimation of the time to equilibrium in overland flow for the whole catchment we can predict a hydrologic behaviour of different areas within it. This is very important when applying steady-state water erosion models. The expression has the following simplified form (Saghafian et al. 1995):

$$t_e = \frac{n^{0.6} l^{0.6}}{i^{0.4} S^{0.3}}, \qquad [8]$$

where t_e is the time to equilibrium in overland flow [*sec*], n is the Manning's surface roughness coefficient, l is the flowpath length [*m*], i is the rainfall excess [ms^{-1}], $S = \sin(\theta)$ where θ is the slope steepness.

The spatial distribution of water depth of overland flow needed for the specific water discharge q was computed using *r.hydro.CASC2D* command (Saghafian 1993). As the climatic and pedologic data (concerning especially rainfall intensity and infiltration rates) had not been available the *r.hydro.CASC2D* command was applied with constant rainfall excess i set to 10 mm/hr for 15 minutes overland flow with a time step 1 second used in approximation. Soil parameters β and γ had been set *ad hoc* as constants for the whole catchment to 1.3 and 5.0 respectively. Then the specific water discharge q was computed using r.mapcalc command (GRASS 4.1 Reference Manual) and depth-discharge relationship:

$$q = \frac{1}{n}(\sin\theta)^{0.5} h^{1.67}, \qquad [9]$$

where h is the water depth [*m*]. The ERDEP model [3] was computed by shellscripting using *r.mapcalc* and *r.deriv* commands in GRASS GIS.

The first example demonstrates only the influence of relief on spatial and temporal distribution of erosion/deposition. The spatial changes in land use and soil surface properties were neglected. An erosion event was modelled with a time step 1 second, starting from 0 to 14th minute. The 14th minute stage is close to the dynamic equilibrium in overland flow and the resulting pattern is similar to the spatial distribution of topographic potential for erosion and deposition of the study area. For better understanding the erosion/deposition rates are presented on the profile 1 (Fig. 3 and 7a) positioned in south-western part of the catchment. The figure shows growing erosion/deposition rates with erosion/deposition boundary moving downslope. The difference between 10th and 14th minute is very low as the overland flow is close to equilibrium (the profile is located close to the catchment divide). The lower parts of the profile are overloaded by water at that time and overland flow changes to stream flow temporarily. Therefore the increase of computed erosion intensity is rather overestimated. These parts of the catchment should be modelled separately using models for stream flow in channels.

The next example documents the influence of the Manning's surface roughness parameter on erosion/deposition. This parameter indicates soil surface properties and land cover/land use. The changes of soil properties for the study area were neglected and we have focused on the latter parameter. The aerial photographs depicting two contrast time horizons (30. 5. 1955 and 12. 7. 1990) were selected. Based on computeraided visual interpretation in Topol GIS the land use classes (Fig. 4, Tab. 1) were derived. For the studied catchment these classes reflect the most relevant differences in land use that strongly control spatial and temporal distribution of erosion and deposition. To consider the distinct changes of influence of arable land management

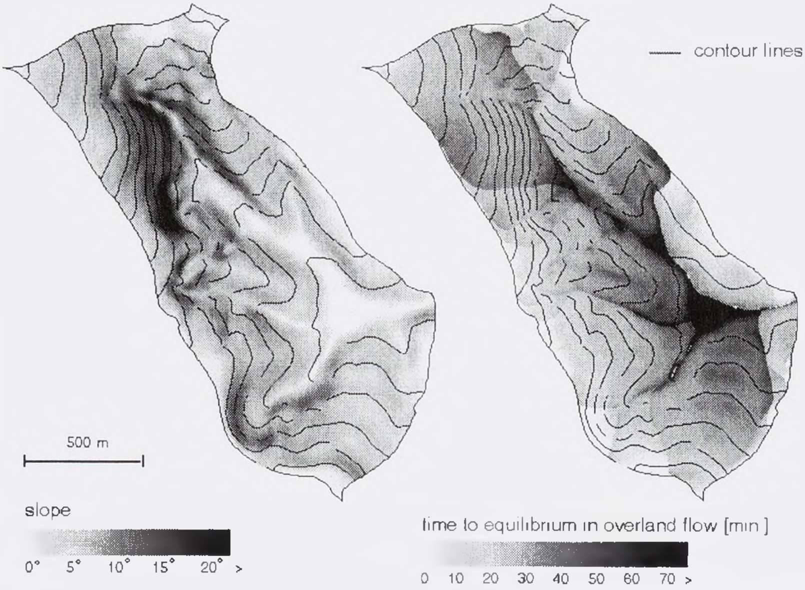

Fig. 2. Slope steepness and time to equilibrium in overland flow.

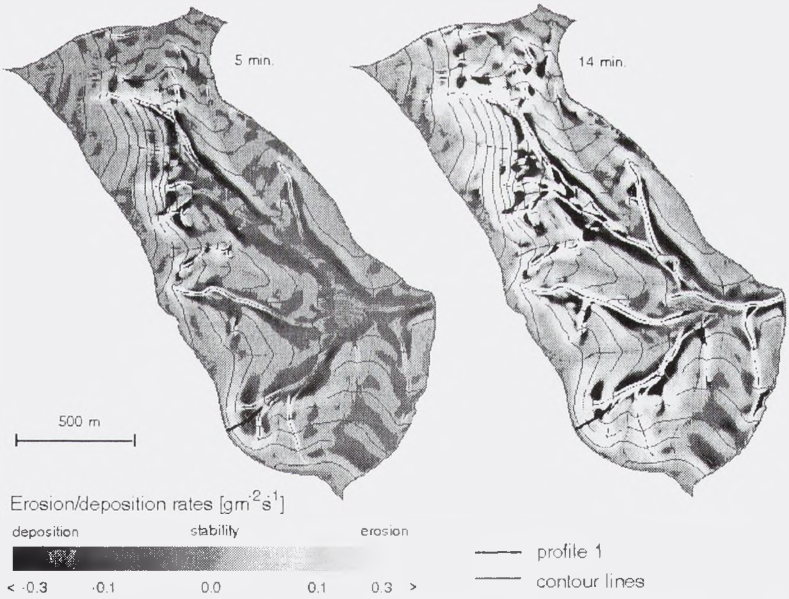

Fig. 3. Influence of relief on changes of spatial and temporal distribution of erosion and deposition during one erosion event (5th and 14th minute).

on water erosion, the class 'small-size plots of arable land' was divided based on orientation of the plots in relation to the direction of slope lines. Interpreted land use polygons were converted to raster format in GRASS GIS and reclassified to the values of Manning's surface roughness coefficient (Tab. 1) empirically assessed based on values published in Young et al. (1987). From the point of view of barrier effect of the land use classes, the asphalt road (with parallel ditches and ramparts vegetated by shrubs) as well as the built areas can be considered as ideal barriers for overland flow.

Tab. 1. Assessment of Manning's surface roughness coefficient from land use classes

1. Large-size plots of arable land	0.035
2. Medium-size plots of arable land	0.035
3. Small-size plots of arable land with furrows and terraces - in the direction of slope line	0.030
4. Small-size plots of arable land with furrows and terraces - perpendicular to the direction of slope line	0.100
5. Small-size plots of arable land with furrows and terraces - diagonal to the direction of slope line	0.300
6. Cultivated grassland area	0.080
7. Natural grassland with petches of shrubs and wood	0.300
8. Forest, compact patches of wood	0.500
9. Orchards	0.020
10. Built area	1.000
11. Asphalt road	1.000

Thus results of the dynamic modelling on Fig. 5 present short term changes of spatial and temporal distribution of erosion/deposition for one model erosion event considering only relief and land use for the 30. 5. 1955 time horizon. The quantitative description of the effects of radical change in land use to erosion/deposition distribution are documented on the second profile (Fig. 7 b). The figure shows that the influence of land use is very dominant. Almost all parts of the profile are far from the steady state during the whole erosion event. The intensity of the erosion/deposition process is continually rising. The most exposed parts are arable areas on convex parts of the profile and grasslands on the steepest slopes (about 20 degrees). There are visible sharp boundaries between forest and arable land or grasslands with strong deposition strips. The intensity of this deposition depends also on convexity/concavity of relief. For example the boundary at 400 metres distance (in horizontal direction) is associated with a rapid change in slope steepness (from 20-21 deg. to 10-15 deg.) and therefore the deposition is very high. The high values at the end of the profile are influenced by stream flow-like water process. This part of the profile is in local valley with a temporary stream flow similarly to the situation described in the first example.

The same approach was applied for the 12.7.1990 time horizon.

The final cumulative net erosion/deposition effect for one possible erosion event (the resulting erosion/deposition balance) for the given two time horizons was obtained integrating the net erosion/deposition rates of the erosion event over time (15 minutes) [5]. The results (Fig. 6 and 7c) document that changes of land use (joining and compaction of arable land plots, elimination of overland flow barriers) which are

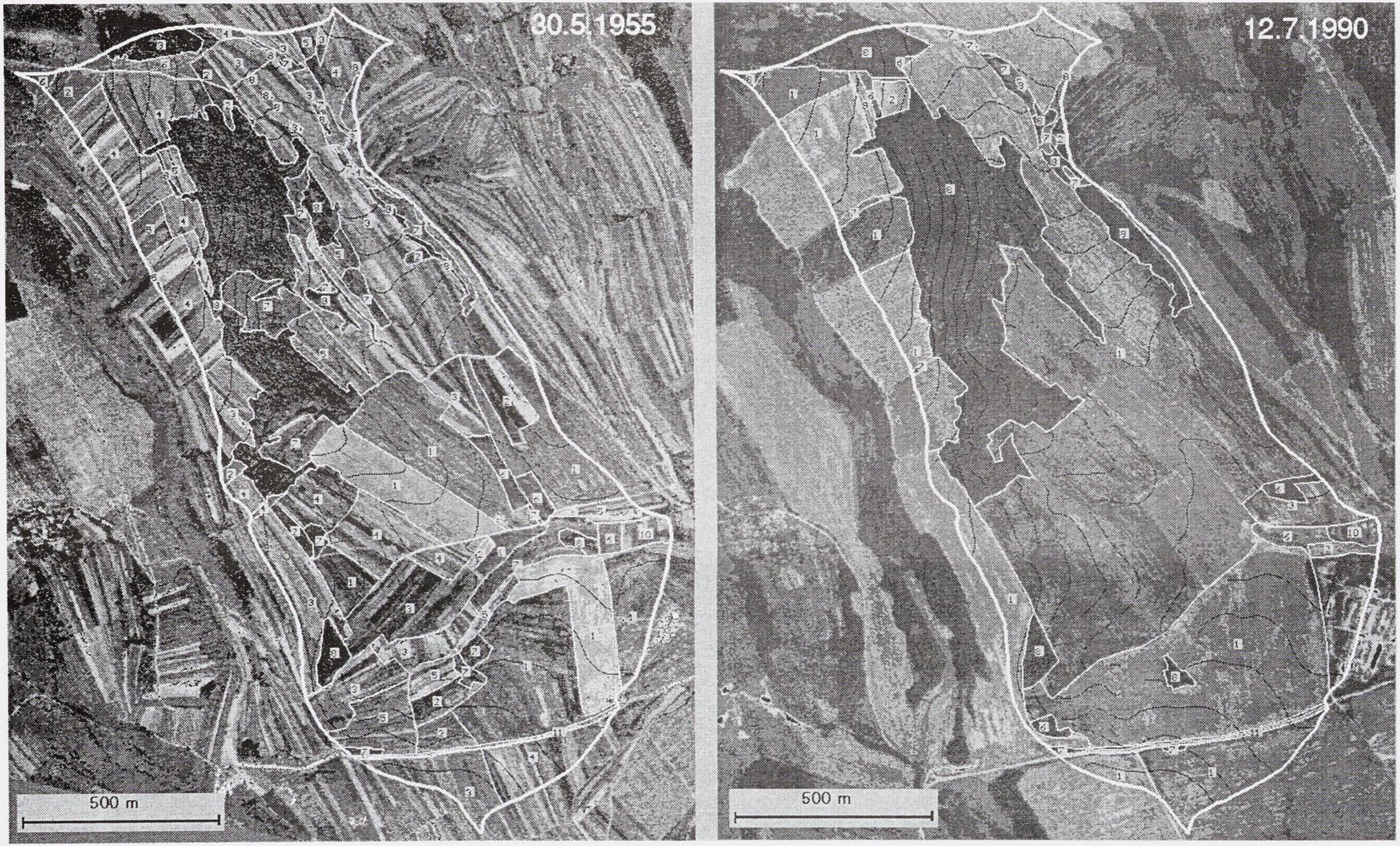

Fig. 4. Land use visually interpreted from aerial photographs.

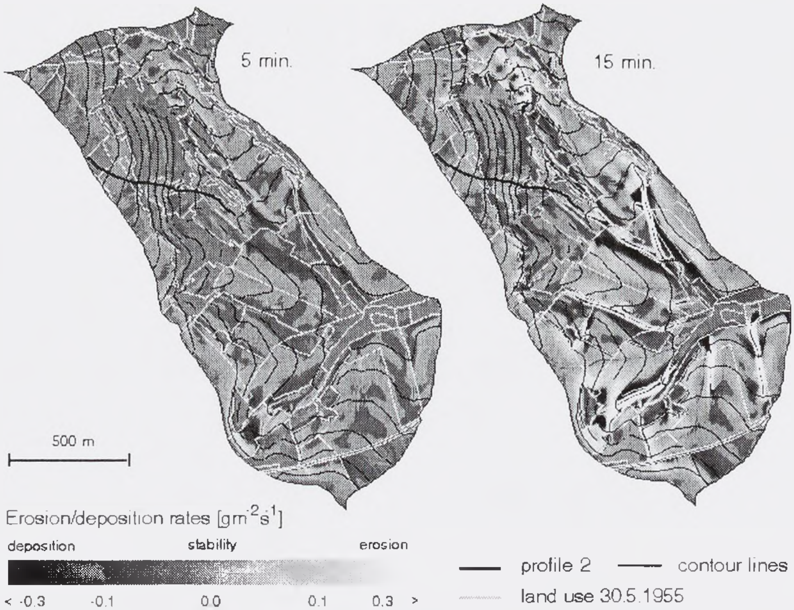

Fig. 5. Influence of relief and land use for 30. 5. 1955 time horizon on spatial and temporal distribution of erosion and deposition during one erosion event (5th and 15th minute).

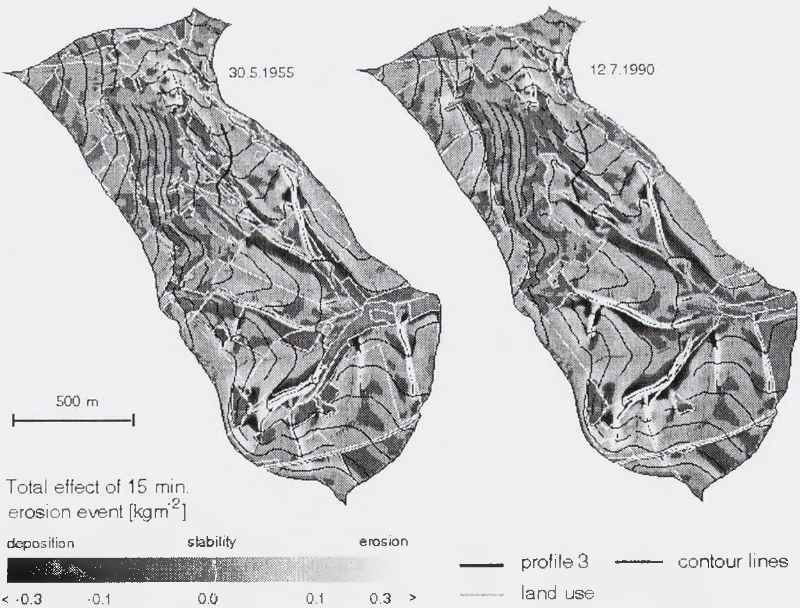

Fig. 6. The final cumulative net erosion/deposition effect for one possible 15 minute erosion event for two time horizons 30. 5. 1955 and 12. 7. 1990.

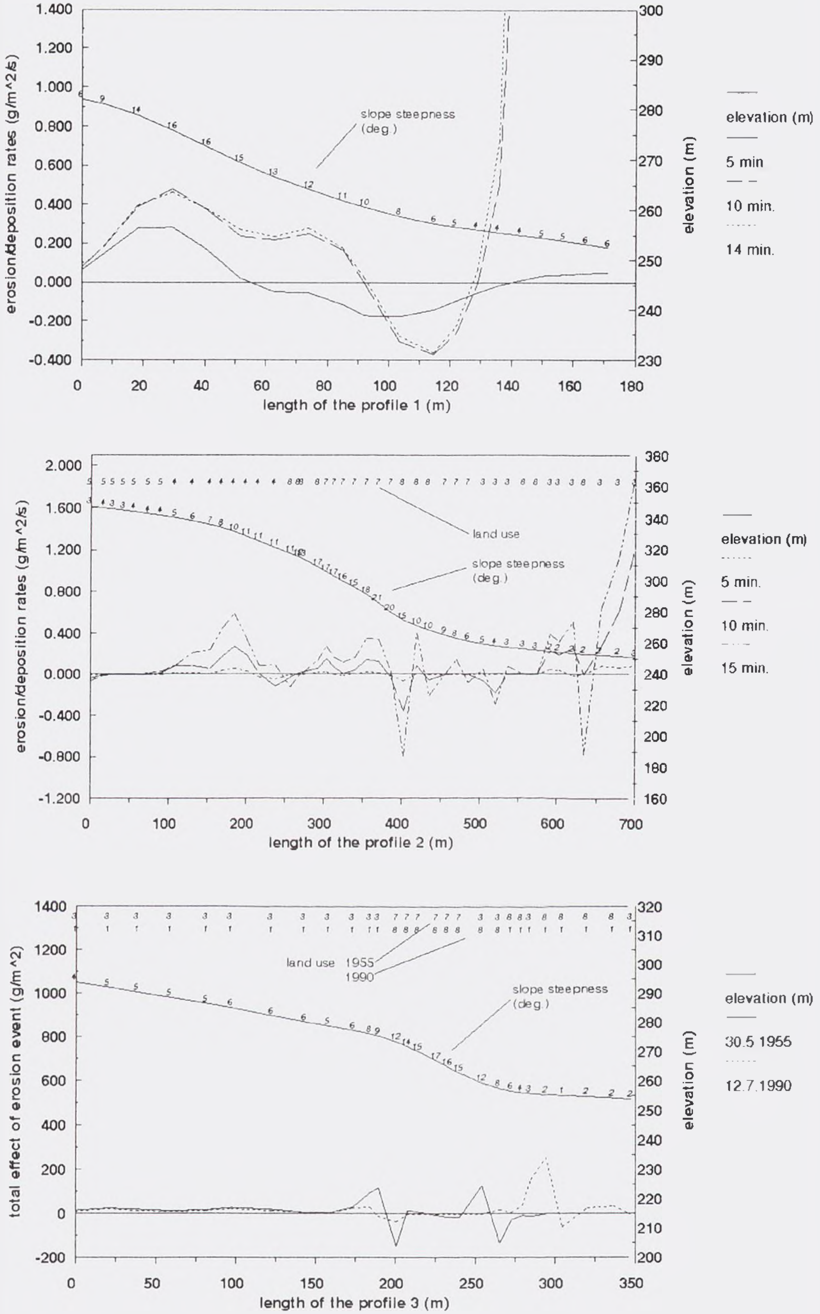

Fig. 7. Erosion/deposition rates for the three selected profiles:
a) three stages of one erosion event (only relief considered),
b) three stages of one erosion event (considered relief and land use in 30. 5. 1955),
c) the final cumulative net erosion/deposition effect for one possible 15 minute erosion event for two time horizons 30. 5. 1955 and 12. 7. 1990.

evident for the two studied time horizons could have basically accelerating effect on water erosion process, namely in areas with lower surface roughness and longer overland flow zones. On the other hand, some parts of the catchment were aforested after year 1955 and hence showing improved stability in 1990.

Longer time periods (e. g. years) can be modelled providing the necessary parameters for all erosion events during the period under consideration are available. Techniques of digital image interpretation can provide much deeper analysis of subtle temporal and spatial changes of model input parameters as documented e. g. in Šúri and Lehotský (1995) and Hofierka and Šúri (1995). When assuming mid-term changes (e. g. weeks and months over one year), the seasonal variability of surface roughness (soil properties and land cover/land use), as well as the variability in rainfall excess should be considered. The cumulative effect of the erosion events over years, based on the series of remote sensing data, meteorological and field measurements, is a good assumption for the assessment of long-term changes of erosion/deposition pattern.

CONCLUSION

Soil water erosion is a very dynamic phenomenon. This fact should be also reflected in modelling techniques. The presented method - ERDEP model - is an example of the possible solutions. Dynamic modelling at the level of erosion event is basis allowing to model the changes in spatial distribution of erosion/deposition pattern and based on this also to model more precisely the mid-term changes (during one year) and long-term changes (over decades) of erosion/deposition effects. Remote sensing data are valuable source of information that can be used to assess spatial and temporal changes of the parameters influencing erosion/deposition process.

In the next stage the ERDEP modelling approach will be tested with assessments based on field measurements and mapping.

NOTE

The full-colour figures and graphs used in this study can be retrieved in from internet location http://savba.savba.sk/~geogsuri/gc 96/model.htm.

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MODELOVANIE PRIESTOROVÝCH A ČASOVÝCH ZMIEN VODNEJ ERÓZIE PÔDY

Vodná erózia pôdy je veľmi komplexný fenomén, ktorý závisí od mnohých prírodných, ako aj človekom podmienených faktorov. Pôsobí v priestore, pričom jeho výraznou vlastnosťou je veľká dynamika počas eróznej udalosti a pôsobenie v dlhších časových obdobiach. Prístupy reprezentované napríklad modelmi USLE a WEPP majú isté obmedzenia a nedostatočne rešpektujú priestorovosť a dynamiku javu.

V príspevku je prezentovaný priestorový, dynamický prístup v modelovaní vodnej erózie pôdy, ktorého podstata spočíva v kombinácii teórie jednotkovej sily toku a teórie fyzikálnych polí. Táto metóda bola nazvaná model ERDEP (Hofierka a Šúri 1995). Metódy diaľkového prieskumu Zeme majú významné miesto jednak v procese identifikácie erodovaných pôd a jednak pri odhade vstupných parametrov potrebných pre existujúce modely vodnej erózie pôdy.

Tento prístup v modelovaní vodnej erózie pôdy bol aplikovaný na vybranom povodí v okolí obce Kostolné v Myjavskej pahorkatine. Povodie je postihnuté eróziou pôdy, akcelerovanou najmä spôsobom využitia krajiny. Z celkového súboru parametrov vstupujúcich do procesu vodnej erózie sme sa sústredili iba na analýzu vplyvu reliéfu a využitia krajiny. Ostatné parametre v modeli boli konštantné. Zo zdigitalizovaných vrstevníc bol v prostredí GIS-u GRASS vytvorený digitálny model reliéfu, ktorého súčasťou je súbor morfometrických parametrov - sklon, orientácia, krivosti, špecifické prispievajúce plochy. Na zachytenie zmien využitia krajiny v dlhšom časovom období boli použité letecké snímky z rokov 1955 a 1990. Vizuálnou interpretáciou v prostredí softvéru Topol boli vyčlenené triedy využitia krajiny, na základe ktorých sme odvodili hodnotu fyzikálneho parametra - Manningovho koeficientu n - charakterizujúceho drsnosť povrchu. Tieto vstupné údaje boli použité v aplikácii modelu ERDEP v prostredí GIS-u GRASS. V troch etapách bola modelovaná dynamika procesov vodnej erózie pôdy pre teoretickú eróznu udalosť v celkovej dĺžke trvania 15 minút s časovým krokom 1 sekunda. V prvej etape sme zo vstupných údajov využili iba digitálny model reliéfu a sústredili sme sa len na analýzu vplyvu reliéfu na priestorové a časové zmeny vodnej erózie. V druhej etape sme okrem reliéfu uvažovali aj vplyv využitia krajiny prostredníctvom Manningovho koeficientu drsnosti povrchu n. Cieľom tretej etapy, v rámci ktorej sme uvažovali oba už spomínané parametre, bolo analyzovať celkový výsledný efekt po ukončení 15 minútovej eróznej udalosti.

Výsledky ukazujú, že v rámci jednej eróznej udalosti dynamika javu spôsobuje zmeny v priestorovom rozložení zón erózie a akumulácie a takisto sa mení intenzita týchto procesov. Táto dynamika na úrovni eróznej udalosti vyplýva z geometrie reliéfu, ako aj vlastností krajinnej pokrývky a spôsobu jej využitia. Z toho vyplýva, že aj pri modelovaní výsledných efektov vodnej erózie pôdy za dlhšie časové obdobie je potrebné vychádzať z postihnutia dynamiky tohto javu na úrovni jednotlivých eróznych udalostí a ich efekty integrovať za celé skúmané obdobie.

Obr. 1. Poloha študovaného územia.

Obr. 2. Sklon reliéfu a čas potrebný na dosiahnutie rovnovážneho stavu v povrchovom toku.

Obr. 3. Vplyv reliéfu na zmeny priestorového a časového rozloženia erózie a akumulácie pre jednu eróznu udalosť (5. a 14. minúta).

Obr. 4. Využitie krajiny interpretované z leteckých snímok.

Obr. 5. Vplyv reliéfu a využitia krajiny pre 30. 5. 1955 na priestorové a časové rozloženie erózie a akumulácie počas jednej eróznej udalosti (5. a 15. minúta).

Obr. 6. Výsledný kumulatívny erózno-akumulačný efekt pre jednu modelovú 15-minútovú eróznu udalosť pre časové horizonty 30. 5. 1955 a 12. 7. 1990.

Obr. 7. Intenzita erózie a akumulácie pre 3 vybrané profily: a) 3 stavy eróznej udalosti (uvažuje sa len vplyv reliéfu), b) 3 stavy eróznej udalosti (uvažuje sa reliéf a využitie krajiny pre časový horizont 30. 5. 1955), c) výsledný kumulatívny erózno-akumulačný efekt počas eróznej udalosti pre dva časové horizonty - 30. 5. 1955 a 12. 7. 1990.

Tab. 1. Odhad Manningovho koeficientu drsnosti povrchu z tried využitia krajiny.