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MODELING OF SOIL EROSION HAZARDS AS A RESPONSE OF LAND USE CHANGES

V. Voženílek, J. Demek: *Modeling of soil erosion hazards as a response of land use changes.* Geografie – Sborník ČGS, 105, 2, pp. 166 – 176 (2000). It is generally accepted that land use changes influence fluvial regime, especially generation of surface runoff, water discharge in water courses, and soil erosion. The disturbances in fluvial systems of old cultural landscapes caused by land use changes bring many difficulties in landscape management (floods, accelerated soil erosion, silting of river beds, etc.). The land use structure in the Trkmanka River catchment in the Czech Republic consisted until 1953 of fragmented plots (small patches of land, ribbons) and later has been changed into large fields with agricultural monocultures. The catchment is known for the highest values of soil erosion in the Czech Republic. Testing of common soil erosion models showed that they are not fitted for the catchment. A new model of soil erodibility is proposed in this paper.
KEY WORDS: soil erosion – modeling – GIS.

Introduction

The Trkmanka River is the left tributary of the Dyje River, which is the right tributary of the Morava River (Danube Basin). The catchment is situated in the south-eastern part of the Czech Republic to the SE from the city of Brno in territory called Moravia.

The Trkmanka catchment is situated at the natural boundary between Outer Western Carpathians and Pannonian Basin (Vienna Basin). The NW part of the catchment (Outer Western Carpathians) is composed of deposits of outer flysh of Paleogene age. Deposits (clays, marls, claystones, sandstones, and conglomerates) form most of flysh area. A small part between villages of Velké Pavlovice and Stavěšice is built by sandstones and claystones. Flysh deposits are strongly folded and overthrusted. Those places are also divided into blocks by faults. The SE part of the catchment which belongs to Vienna Basin is part of a large tectonic depression filled by Neogene (Miocene and Pliocene) marine and lacustrine deposits (mostly sands and clays). The basin is divided into blocks by many faults. Folded and faulted flysh rocks and Neogene deposits are covered by Pleistocene loess and slope deposits.

The highest point of the catchment is a hill called U slepice (438 m a. s. l.), the lowest is at the confluence of the Trkmanka and Dyje River (158 m a. s. l.). About 16 % of the catchment in its southern part and in the central part in vicinity of the village Čejč is classified as plain (relative amplitude from 0 to 30 m). About 40 % of the catchment have the relief of flat hillyland (30 to 75 m) and about 43.8 % of undulating hillyland (75 – 150 m). Only 0.2 % (about 1 square kilometer) has relief amplitude over 150 m.

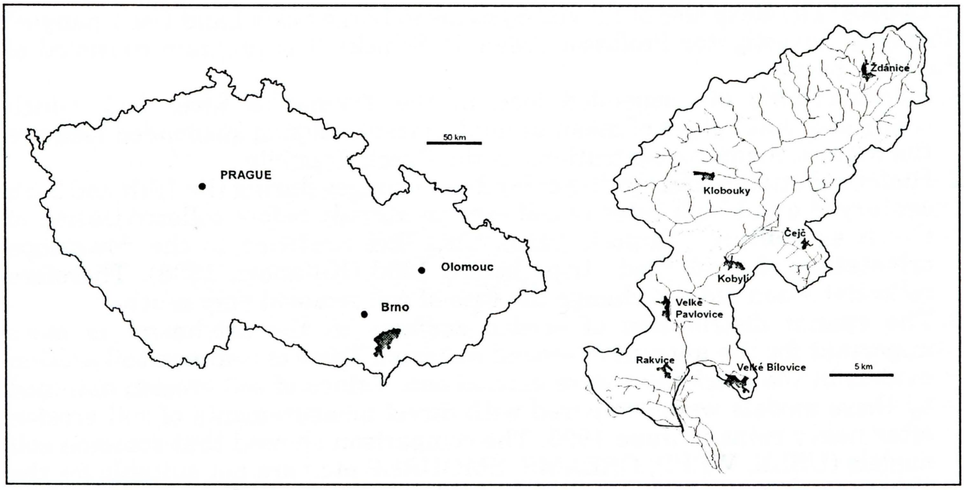

Fig. 1 – The Trkmanka catchment – area of study

The Trkmanka River spring is situated on the southern slopes of the Ždánický les Highlands NW of Ždánice at 300 meters a.s.l. It empties from the left side into the Dyje River near village of Podivín in 158 meters a.s.l. Long-term average annual discharge of the Trkmanka River at its mouth is QA 0.387 $m^3.s^{-1}$. Daily discharges have their maximums in March and minimums in August (see Figure 1).

The original vegetation cover was mixed Central European forest. Large deforestation occurred already in 12th century. Today there is only 72 sq. km of forest in the catchment (about 20 % of area). At present agroecosystems typical for cultural landscape (fields, vineyards, orchards, meadows, etc.) prevail; altogether these land use types cover 280 sq. km (about 78 % of area). Until 1953 the land use structure of studied area consisted of fragmented plots (small patches of land and ribbons oriented downslope); since 1953 most agricultural land has been transformed into large fields with monocultures.

It is generally accepted that land use changes influence fluvial regime of the land, especially generation of surface runoff, water discharge in water courses, and soil erosion. The disturbances in fluvial systems of old cultural landscapes caused by land use changes are supposed to bring many difficulties in landscape management (floods, accelerated soil erosion, silting of river beds, etc.) The earlier studies and measurements of suspended load in the Trkmanka River (Vaníček 1959) revealed that very intensive recent slope and fluvial processes are in effect in the catchment (e.g. the largest measured intensity of soil erosion in the whole Czech Republic).

Due to the dimensions of narrow ribbons these fields were tilled from water divides downslope. Under the old conditions slopes of almost the same length existed as exist today on the large co-operative fields. Balks separating ribbons were naturally also oriented downslope and represented no obstacle against accelerated soil erosion. Due to limited number of crops cultivated in the area there are no greater differences in amount of soil erosion among different types of crops either on narrow ribbons or on large fields.

The research in the Trkmanka catchment started in December 1993 in co-operation with the Czech Hydrometeorological Institute, Branch Brno in the framework of U.S. – Israel CDR Program – Grant No. HRN-5544-G-00-2060-00

(C12-090) "The Response of Fluvial Systems to Large Scale Land Use Changes" (Principal Investigator Professor Asher P. Schick). The program consisted of the basic parts:

1. Measurements of suspended load in the Trkmanka River bed, which confirmed that values of mean annual concentration of suspended load are the highest mean concentrations in the Czech Republic.
2. Historical studies and studies of land use changes during the 19th and 20th century showed high rates of soil erosion already before collectivization of Czech agriculture (Vaníček 1959). This fact conforms to the downslope orientation of most filed strips before 1956 (Kilianová 1998). Therefore collectivisation did not change the rate of soil removal very much.
3. The spatial distribution of eroded surfaces in the catchment is more important for the amount of eroded material. Tests of common soil erosion models in the catchment were carried out. Values of soil erosion obtained by these models were compared with direct measurements of soil erosion after heavy rains in June 1995. The comparison showed that common soil models (USLE, WEPP, CREAMS, SMODREP etc.) are not suitable for the Trkmanka River catchment (Knisel 1980, Laften et al. 1991, Voženílek 1999b). The following new model of soil erosion is proposed.

GIS and Models

Computer-based, mathematical models that realistically simulate and predict spatially distributed, time-dependent landscape processes in nature are increasingly recognized as fundamental requirements for reliable, quantitative assessment of complex environmental issues of local, regional and global concern (Goodchild et al. 1993). This environmental analysis and modeling are one of the strongest and most successful application areas for geographical information systems (GIS). GIS is rapidly developing technology for handling, analyzing, and modeling geographic information (Voženílek ed. 1996, Chou 1997). The spatial analysis and dynamic modeling has been used as a principal research methods. The geographical information system technology became the basic platform to solve investigated issues.

MODEL PEG – assessment of potential erodibility of georelief

The concept of the PEG model is based on a different understanding of the concepts of erosion and erodibility. Erosion is the acquisition of material by geologic agencies (running water, glaciers, wind, etc. – Fairbridge ed. 1968, p. 317). Erosion is defined as the set of processes of denudation, transport and accumulation of solid particles on the Earth surface by water, glaciers, and wind. Erosion processes are studied as a system of landscape elements and relationships among them. Erodibility is a feature of georelief representing potential conditions for erosion processes. Erodibility is studied as one of several characteristics having a wide range of expression (constant or probable). Its estimation is called potential erodibility.

The PEG model was completed to assess the potential amount of material outflowing from the Trkmanka River catchment (Voženílek 1999b). The model is based on analysing of all erosion processes that are active in the studied area using the following factors:

1. *Soil grain size:* The soil grain size factor reflects the characteristic proportion of solid particles (grains) and space among them. Erodibility rises with higher ratio of gaps in soil due to soil consistency. The classification of soil grain size for implementation in the PEG model was taken from 1:50 000 soil maps.
2. *Stability of soil particles:* The stability of soil particles factor is a complex factor involving various soil characteristics, which take part in soil consistency, stratification and depth. The factor is derived from soil types in basic pedological classification.
3. *Soil moisture regime:* Soil moisture describes the moisture content of the soil intones of underground water saturation. The greater the wetness of the soil the lower risk of erosion occurrence. Permanent saturation almost eliminates erosion on the surface.
4. *Slope angle:* This is the most relevant factor. The steeper slope the bigger outgoing energy and the higher potential erodibility on the slope. Slope angle was expressed in degrees.
5. *Surface forms:* The factor of surface forms in the project substitutes slope length which is problematic in both its definition and calculation. This substitution seemed to be very useful as the surface forms factor involves changes of slope trajectories on planar convex forms on slope which is outcome of either convergent or divergent combining of energy (Voženílek 1996). Surface forms of the Trkmanka catchment was generated from grid based DEM. Individual categories were determined by combination of planar and profile curvatures.
6. *Land use structures of 1877, 1953 and 1995:* Land use has a strong impact on the erodibility. This factor involves a surface roughness, density of vegetation, the type of cultivation (farming), the root consistency of relief, etc.

Factors 1, 2, 3, 4, and 5 are factors of outgoing energy, factor 6 is factor of surface features changes. The input parameters were weighted according to scheme that is based on field observation and experimental evidence (Figure 2).

The model was constructed by following steps:
- the input factors were classified into interval/ratio scales
- the coverages representing the factors were evaluated according to the above mentioned scales
- using the procedure of polygon overlay, the coverage of polygons ("model coverage") – each with its individual set of factors – was produced
- the model coverage was processed according to a theoretical model using equations to get the potential erodibility of relief – for each polygon
- areas with the highest potential erodibility were investigated in more detail using geomorphologic mapping, network analysis etc.
- the results of the detailed investigations of selected areas were used for the calibration of the model in the Trkmanka catchment
- the calibrated model equations were applied for the entire Trkmanka catchment to obtain the potential erodibility of relief.

The PEG model provides answers to questions such as how individual parts of the surface contribute to the sediment loss in the catchment. This contribution is only a potential one because of the elimination of real input factors from field works such as precipitation, which are highly specific for the catchment (Voženílek 1999a). The PEG model was generated as a preliminary

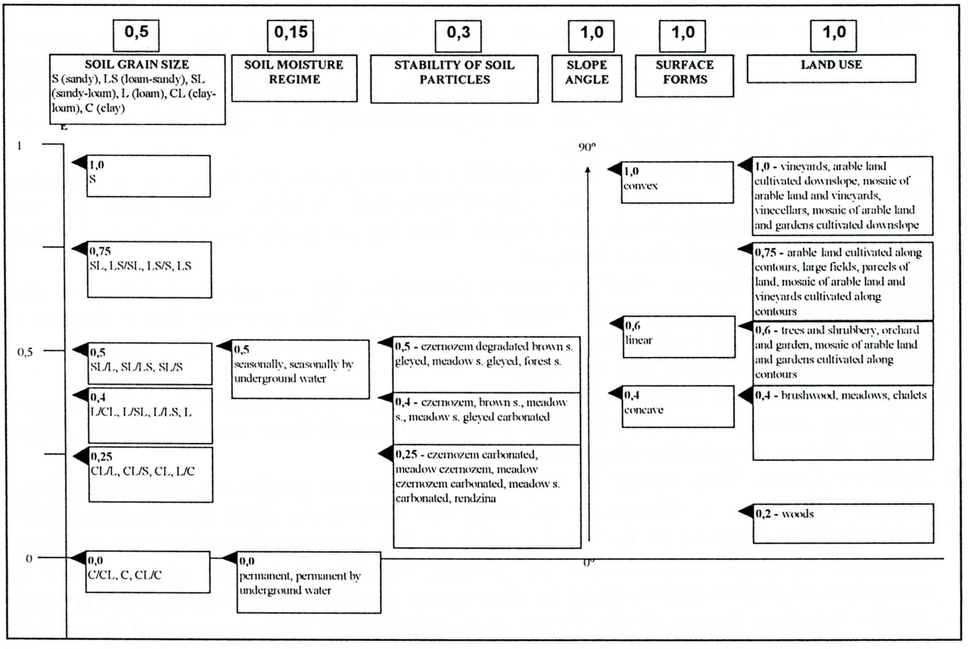

Fig. 2 – Structure and evaluating of input parameters for PEG model

step prior to dynamic modeling, giving better information for final conclusions.

The aim of PEG model generating was to estimate erodibility in the Trkmanka catchment and then to assess the amount of material outflowing from the catchment.

MODEL dPEG – dynamic modeling of georelief erodibility

The dPEG model (dynamic PEG model) introduces concepts of time and climate into the PEG model. The implementation improves the model outcomes by giving the model more in terms of real rather than potential erodibility.

There were two types of time involved in the model: annual variability (for land use categories and climatic parameters) and long-term changes (for landscape structure and climatic regime). Annual variability represents the changing conditions for soil erosion during the year. It concerns both land use distributions and climatic parameters.

Land use

Different land use categories create different conditions for erosion processes during the year. The changes take place according to a regime defined by the type of cultivation in the individual land use categories. Four different seasons were distinguished:

– spring – is typified by snow melting and intensive field work (mainly ploughing) which makes the surface rough, loose and subject to material transport

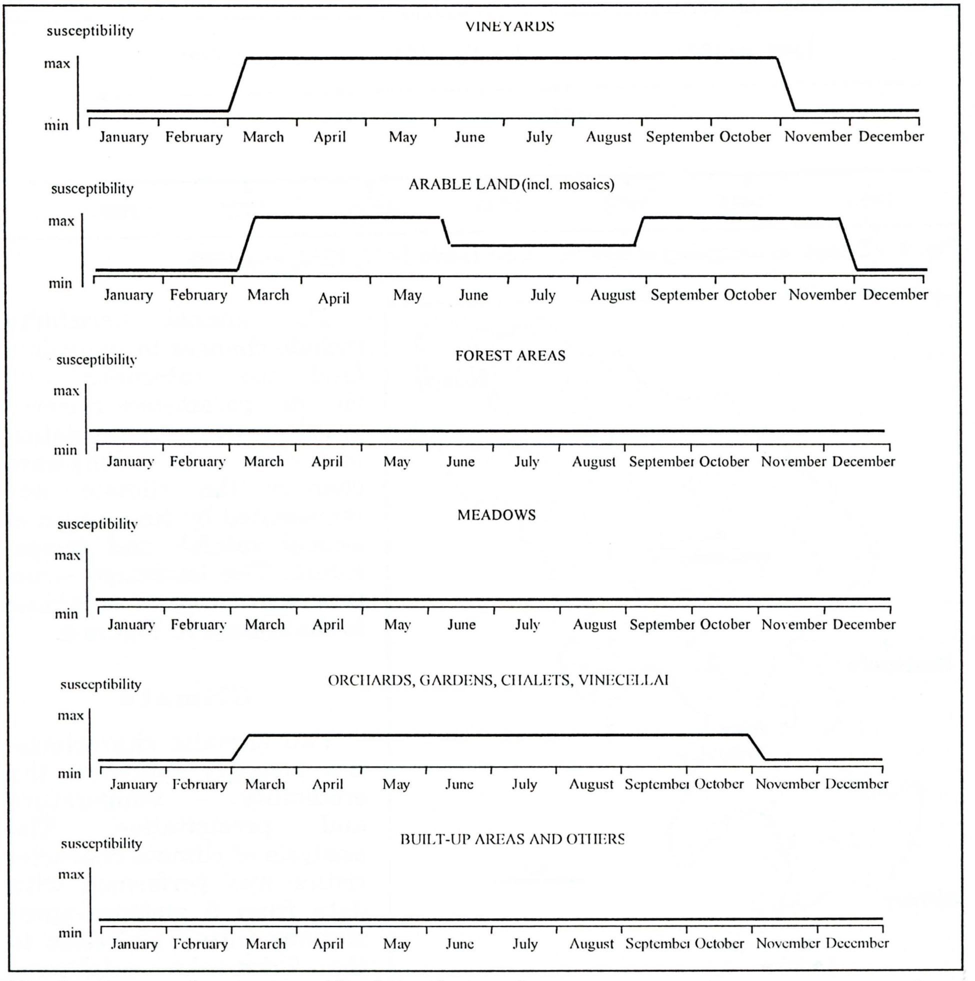

Fig. 3 – Temporal assigning of land use during the year

- summer – is mostly the period of high vegetation which stabilises the surface and saves soil particles from transport
- autumn – brings harvesting which means baring of the surface, ploughing and creation of conditions for high erosion
- winter – is cold, sometimes with frost and often covers the surface with snow which is a good protection against erosion.

The charts in Figure 3 show the distribution of susceptibility to erosion during the year. Maximal susceptibility is concentrated in months with little or no vegetation on the non-frozen surface. Minimal susceptibility occurs during the winter with snow cover or frozen soil. The quantitative expression of the charts in the model distinguish different surface conditions for erosion over the time. The vertical axis represents susceptibility of surface (from minimum to maximum) and the horizontal axis is time (months in a year). The thresholds in the charts reflect climatic seasonal changes (frozen soil vs. temperature over 0 °C) and cultivation works (ploughing, harvesting etc.).

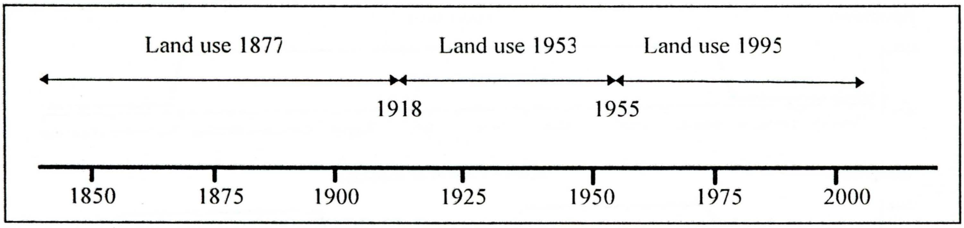

Fig. 4 – Temporal assigning of land use time levels 1877, 1953, and 1995

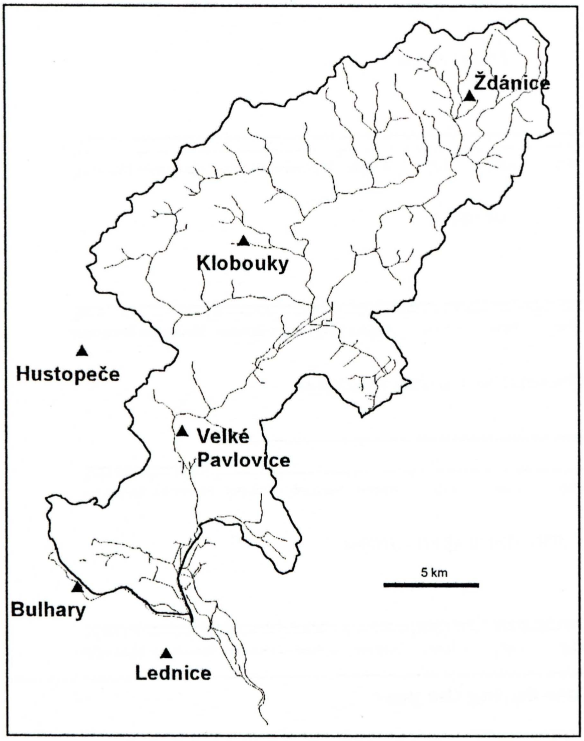

Fig. 5 – Meteorological stations used in the project

The annual variability include changes in individual land use categories and climatic parameters (investigated by interpolation methods). In long-term changes the climate was represented by time series of annual rainfall and temperature. The landscape structure was assigned according to the scheme in Figure 4.

Climate

Two climatic characteristics strongly influence the erodibility – temperature and precipitation. The analysis of climate characteristics was performed with data from 6 meteorological stations within and close to the Trkmanka catchment (Figure 5).

The regime of *temperature* is not as important as are the changes around the freezing point. Frozen soil protects the surface. Figure 6 shows long-term series of annual temperature means of two of the closest meteorological stations with continuous temperature measurement. Despite the variability in the graph the changes of temperatures around the freezing point in the catchment stay almost unchanged. The spatial distribution of temperature in the catchment shows only minimal differences, which are irrelevant to the model. That is why the changes of temperature were eliminated from the set of model factors. The only participation of temperature was involved in land use changes where the period with temperature under 0 °C (from the first half of November until the beginning of March) is included (see Figure 6).

Precipitation plays a key role in the erosion processes. It starts the processes of entrainment, transport, and accumulation. The graph in Figure 7 shows annual rainfall means at meteorological stations involved in the study. It shows how similar precipitation patterns in the catchment area are.

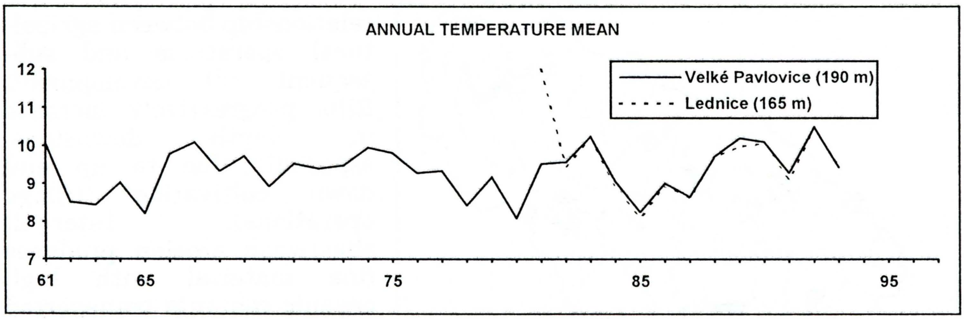

Fig. 6 – Long-term series (1961 – 1993) of annual temperature mean (°C) of Velké Pavlovice and Lednice stations

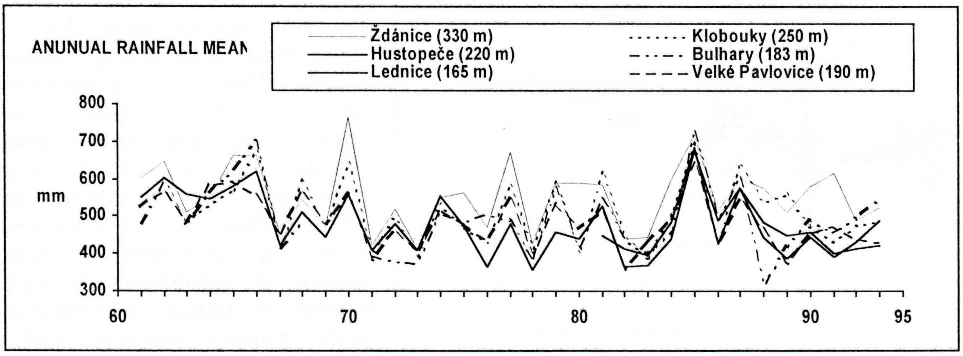

Fig. 7 – Mean annual rainfall at selected meteorological stations from 1960 to 1994

A close correlation was determined by regression analysis between annual rainfall mean and altitude. The equation of linear regression for the Trkmanka catchment calculated from datasets of 6 meteorological stations is:

$$Y = 401{,}1315 + 0{,}4207X$$

where Y is annual rainfall mean (in mm) and X altitude (in metres a. s. l.).

The dPEG model allows the assessment of the changes in erodibility over the time and its relationships to land use changes (Figure 8).

Field observations of soil erosion versus computer modeling

The computer model was compared with field soil erosion observations and measurements, especially soil erosion features after heavy rain in June 1995. On broad watersheds belt of sheet erosion were observed. On long and steep slopes developed microchannels (rills) that were small enough to be removed by normal tillage operations. Concentration of erosion in channels essential to rill development is attributed to length and inclination of slopes and to slight accidental variations in topography, which produce local increase of runoff depth and shear stress. Rills commonly occur on bottom of dells.

Observations on remnants of areas with narrow ribbons of land oriented downslope and bordered by vegetated balks revealed that ribbons concentrated runoff and limited cross-grading. Field study indicates a close

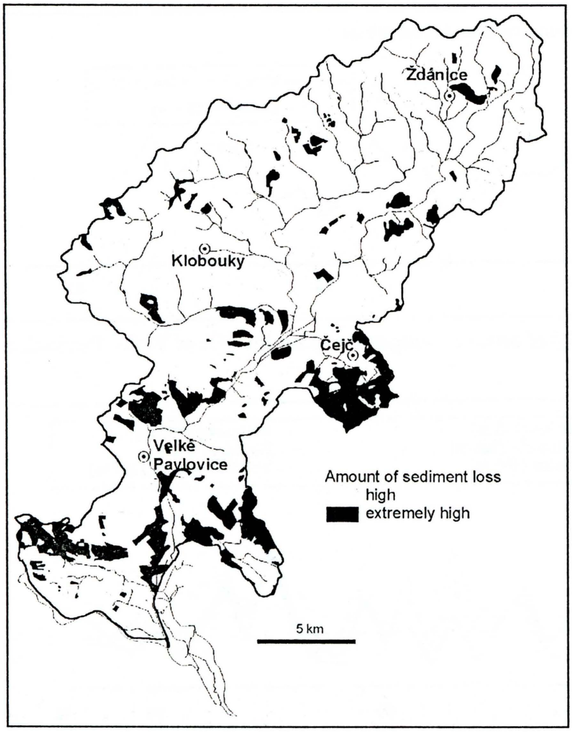

Fig. 8 – Sediment loss in the Trkmanka catchment predicted by dPEG model

relationship between agricultural operations and subsequent rill development. Rills progressively increase in depth downslope, especially due to up and down cultivation (tillage operations). Inter-rill sheetwash erosion produces fine material with high organic contents transported farther into brook channels.

In the contrary, on large co-operative fields rills become broader and shallower with increasing slope length, disappearing eventually in braided washes. Rills appear both on convex and concave parts of slopes. Especially concentrations of rill erosion on cultivation lines (e.g. on tractor passes) posses a problem. Tillage operation along horizontals rank among positive anti-erosion measures.

The spatial distribution of soil erosion features in the Trkmanka catchment well corresponds to the generated model.

Conclusion

High values of accelerated soil erosion in the Trkmanka River catchment are partly results of natural condition (slope inclination, thunderstorms) and partly of agricultural use of landscape (land use). Before 1953 the land use structure consisted of numerous small patches of land mostly oriented downslope. This land use pattern changed after 1953 into large fields managed by collective farms. Due to downslope orientation of field strips in the previous period, however, the changes in values of eroded material were only small. More important is the spatial distribution of soil erosion. Tests of common soil erosion models are not suitable for the catchment. Therefore new models based on GIS techniques have been proposed. The dPEG model developed as part of the project brought new aspects into modeling of spatial environmental phenomena by involving seasonal regimes of climate and farming. The new models of soil erodibility were compared with soil erosion features measured after heavy rain in June 1995.

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especially to Principal Investigator Prof. A. P. Schick, The Hebrew University of Jerusalem, Israel.

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Shrnutí

MODELOVÁNÍ OHROŽENÍ EROZÍ PŮDY JAKO ODEZVA ZMĚN VYUŽITÍ ZEMĚ

Je všeobecně přijímán názor, že změny ve využití země ovlivňují odtokové poměry zemského povrchu, zvláště při vytváření povrchového odtoku, průtoku vody v korytech a půdní erozi. Narušení fluviálních systémů historických kulturních krajin způsobené změnami ve využití země přináší mnoho problémů při tvorbě, ochraně a řízení krajiny (povodně, zvýšená eroze půdy, zanášení říčních koryt atd.).

Trkmanka je levostranný přítok řeky Dyje. Povodí Trkmanky (377 km^2) se rozkládá na jihovýchodní Moravě, přibližně 40 km jihovýchodně od Brna (obr. 1). Je situováno na rozmezí Vnějších Západních Karpat a Panonské pánve. Severozápadní část povodí (Karpaty) je budována silně zvrásněnými sedimenty vnějšího flyše paleogenního stáří (jíly, slíny, jílovce, pískovce a slepence) rozdělenými zlomy do bloků. Jihovýchodní část povodí náležející do Vídeňské pánve (Panonská pánev) je součástí tektonické deprese vyplněné neogenními (miocenními a pliocenními) mořskými a jezerními sedimenty (převážně písky a jíly). Pánev je rozlámána zlomy do bloků. Pokryv tvoří pleistocenní spraše a svahoviny.

V povodí Trkmanky se skládala krajinná struktura před rokem 1953 z velkého počtu malých polí. V následujících několika málo letech došlo k výrazné změně ve struktuře krajiny – vznikla velká, rozlehlá pole pro pěstování zemědělských monoklutur. Povodí je známé nejvyššími naměřenými hodnotami eroze půdy v ČR.

Studie University Palackého v Olomouci zpracovávaná v letech 1993 až 1999 v rámci realizace mezinárodního grantu (Izrael, ČR, Slovensko) CDR "The Response of Fluvial Systems to Large Scale Land Use Changes" (odpovědný řešitel Asher P. Schick) řešila odezvu fluviálních systémů na změny využití země v povodí Trkmanky. K základním poznatkům studie patří:

Měření unášeného materiálu v korytě řeky Trkmanky potvrdilo, že hodnoty průměrné roční koncentrace unášeného materiálu jsou nejvyššími hodnotami v ČR.

Dřívější práce a studie změn využití země v 19. a 20. století ukázaly vysoké tempo eroze půdy již před kolektivizací českého zemědělství (Vaníček 1959). Šlo o důsledek orientace většiny zemědělských pozemků po spádnici již před rokem 1956 (Kilianová 1998). Kolektivizace tedy nezměnila příliš výrazně rychlost odnosu půdy.

Důležitější pro množství erodovaného materiálu je plošné rozšíření erodovaných ploch v povodí. Testování obecně používaných erozních modelů (USLE, WEPP, CREAMS, SMODERP atd.) ukázalo v povodí Trkmanky jejich nepoužitelnost. Proto byl se staven nový model pro modelování odnosu sedimentu z modelového povodí.

Modely PEG (Potential Erodibility of Georelief) a dPEG (dynamic PEG) jsou založeny na odlišném pojetí pojmů eroze a erodibilita. Eroze je chápána jako proces, zatímco erodibilita jako vlastnost (georeliéfu). Realizace obou modelů probíhala v prostředí GIS. Model PEG byl sestaven k ohodnocení potenciální erodibility georeliéfu. Je koncipován jako konceptuální model a jako vstupní proměnné využívá zrnitost půd, stabilitu půdních agregátů, vlhkostní režim půd, sklon georeliéfu, povrchové tvary a využití země. Model byl použit třikrát, a to pro tři různé časové horizonty s odlišnou strukturou krajiny – roky 1877, 1953 a 1995. Kvantifikace vstupních proměnných na úrovni poměrových digitálních dat je obsažena v obrázku 2.

Model dPEG je rozšířením modelu PEG o dynamické proměnné, a to o změny klimatických charakteristik a kategorií využití půdy. Časový aspekt byl pojat ve dvou úrovních – změny krátkodobé (roční proměnlivost) a dlouhodobé (období od 1877 do 1995). Roční změny dílčích kategorií využití půdy (podle způsobu obhospodařování zemědělských pozemků) vyjadřují schémata na obrázku 3. Prahy dlouhodobých změn jsou vyjádřeny na obrázku 4. Na základě analýzy klimatických charakteristik z 6 meteorologických stanic v povodí a nejbližším okolí (obr. 5), byl zahrnut do modelu roční chod teplot (obr. 6) a srážek (obr. 7).

Výsledky modelování erodibility georeliéfu (obr. 8) v povodí Trkmanky v modelu dPEG vykazují shodu s naměřenými hodnotami a potvrzují skutečnost, že kolektivizací nedošlo z výraznému zrychlení erozních procesů v povodí Trkmanky.

Obr. 1 – Modelové území povodí Trkmanky
Obr. 2 – Struktura a evaluace vstupních parametrů pro model PEG
Obr. 3 – Změny dílčích kategorií využití půdy v průběhu roku
Obr. 4 – Prahy dlouhodobých změn využití půdy v časových horizontech 1877, 1953, a 1995
Obr. 5 – Meteorologické stanice, jejichž měření byla v projektu využívána
Obr. 6 – Dlouhodobé řady (1961 – 1993) průměrných ročních teplot (°C) naměřených na stanicích Velké Pavlovice a Lednice
Obr. 7 – Roční úhrn srážek naměřený ve vybraných meteorologických stanicích v letech 1960 – 1994
Obr. 8 – Předpokládaný odnos sedimentu v povodí Trkmanky pomocí modelu dPEG

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