Analysis of the impact of land cover spatial structure change on the erosion processes in the catchment

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Soil erosion is one of the main environmental problems of this time. Erosion in its recent accelerated form is the reflection of the human activities in the landscape. Soil erosion is a complicated process. Its behaviour and final rate are results of an interaction of whole group of factors. One of these factors is the character of land cover whose main role in the erosion process consists in its protective function. Intensive land use do not dispense with the land cover change and the change of its spatial distribution thus the main content of this contribution is the study of the influence of the land cover change on the erosion processes in the catchment. To quantify that the dynamic erosion SWAT model was used together with the GIS tools. As a study area the Stonávka river catchment was chosen and the erosion processes were analysed using the three CORINE Land Cover layers (specifically CORINE Land Cover of the years 1990, 2000 and 2006) as a model input. The outputs of the analyses in the form of average annual specific sediment loss from the catchment were relativized to the reference years 1990 and following 2000 and were cartographically visualized in the form of cartograms.

Key words: *Soil erosion, land cover, SWAT, model, GIS, the River Stonávka catchment*

Introduction

Soil is one of the basic natural resources. It is key resource of the agriculture and food production thus it is necessary to protect it from all the processes contributing to its degradation. One of these processes is soil erosion. The role of the soil erosion among these processes is nowise marginal. Contrariwise it could be understood as a process most seriously endangering the soils, both in the sense of the process intensity as well as of its spatial extent.

Soil erosion at the present extent is mainly a result of human activities and not a product of natural processes. Without human impact, the earth's soil surface would be almost completely covered by permanent vegetation with the exception of extreme climatic environments, such as deserts, polar or high mountainous areas. The main natural hazards such as natural fires, storms, volcanic eruptions and others may cause erosion under natural conditions but only in limited spatial and temporal scale. The use of soil by man, in particular for agriculture, constraints to remove natural vegetation cover and to replace it by crops. Thus it results in more serious erosion hazard, both in spatial and temporal scale (Schmidt, 2000).

Soil erosion is the process occuring in space and a whole set of factors is being applied at them. Because of erosion solution, this complex of factors is more or less reduced to a selection of easily describable main factors, which are hydro-meteorological situations, qualities of soil and land cover, configuration of relief and application of anti-erosion protection. As stated above, the one of the human activities participating on the erosion acceleration are particularly the processes leading to the land cover structure change. Almost any natural or nature close land cover type is characterised in considerable protective effect against the erosion. However the areas of these qualities are rather residual enclaves in the recent intensively used landscape. Thus the landscape management should follow the principles of the prevention and man should be able to manage his steps in the way not endangering the soils for the next generations.

Nowadays numerous environmental models appear to be the appropriate tools of the landscape management. Together with geographical information systems (GIS) they offer wide range of the application possibilities and they are capable to solve several spatial problems. One of these models is SWAT (Soil and Water Assessment Tool), which were used to analyse the impact of the land cover change on the erosion processes in the catchment, specifically the Stonávka river catchment.

Description of study area

The watershed of the Stonávka river in the Moravskoslezský region, Czech Republic, was selected as the area of our interest. The Stonávka river is a left-hand side tributary of the Olše river, so it is a stream of the III. order. The Stonávka river is a stream starting on the northern slopes of the Moravskoslezské Beskydy mountains and in its upper part it has a character of a mountain stream. Its confluence with the Olše river is located in the area of Karviná city, after 33 km of its length. The spring is approximately 750 m above sea level and the confluence is 220m above sea level. The area of its watershed is about 131 km^2 large.

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In its upper part the dynamics of the stream is given by a considerable high gradient of the northern slopes in the front of the nappe of the Moravskoslezské Beskydy Mts. In its lower part the gradient conditions are much more gentle, and furthermore, the hydrologic regime is significantly anthropologically influenced by the presence of the Těrlicko dam. Under the dam, above the confluence with the Olše river, the Stonávka riverbed meanders through a flat, but not wide, valley with high edge slopes with scattered built-up of Stonava village. The natural runoff conditions in the lower part, especially in the part of the last 3 kilometres, are significantly influenced by mining (Brosch, 2005).

From geological and geomorphological point of view the Stonávka watershed in its lower part belongs to the Outer Northern Carpathian lowering parts and it is formed mainly by quarternary sediments. In its upper part the watershed belongs to the Outer Western Carpathians formed by Carpathian flysch. The soil cover of the watershed is quite varied, in the upper parts cambisols and podzols dominate, in the lower parts there are various subtypes of cambisols, but also several types of luvisols, dystrict planosols, gleysols, calcaric regosols and fluvisols. The land cover of the watershed is also quite varied with its 14 categories of CORINE Land Cover classification. The higher Beskydian areas are covered with forest vegetation and mountain pastures, so the lower submontane areas are used much more intensively.

According to Quitt's climatic classification (1971) the watershed belongs to the areas CH6, CH7 (cold regions) and MT2, MT9, MT10 (moderate regions). The Stonávka watershed is a sub-watershed of the Olše river basin. According to the division of surface streams into the districts that was made by ČSAV (former Czechoslovak Academy of Science), the Stonávka watershed falls into III-B-4-d category, what means an area with medium water availability and runoff generation, with the maximum of runoff in March and April. The specific runoff from the watershed is 6-10 $l/s.km^{-2}$, the runoff from the watershed can be evaluated as a heavily fluctuating and the value of a runoff coefficient varies from 0.21 to 0.7 (Unucka, 2008).

Methods

Initial idea of this contribution was the relative quantification of the land cover spatial structure change impact on the erosion processes in the catchment. Land cover is one of the landscape components protecting the soils against the erosion. The human activities in the landscape lead to change of spatial distribution of land cover types and thus the landscape could often become more vulnerable to soil erosion.

To solve the problem SWAT model and the GIS tools were used. One of the basic model inputs is the properties of land cover. The analyses of the land cover spatial configuration influence on the erosion processes were done using the three different data layers representing the distribution of CORINE Land Cover categories in the catchment in the years 1990, 2000 and 2006. These years were chosen simply because of the data availability and their readiness to be used in the analyses. All the other model settings were used same in all three analyses. Erosion was studied using the automatic internal weather generator of the SWAT model with the long-term average climatologic characteristics specified. The model outputs have the character of the long-term annual averages.

Model SWAT

SWAT model could be briefly characterized as a tool for the assessment of soil and water sources. It is a complex dynamic numerical model which can be used for a complete evaluation of landscape potential in a relation to rainfall-runoff relations, soil erosion and sediment transport or to other geoecological characteristics (energy balance of the ecosystem, accessibility of moisture and nutrients in soil, etc.).

SWAT model belongs to a group of physically based models. This means that to calculate soil erosion rate the model respects the physical principles of the genesis and formation of surface runoff, and also a consequent process of erosion, transport and deposition of soil particles. With a help of SWAT model we can simulate a lot of processes from the field of hydrology, but also from the field of soil management. The model can reveal water, nutrient and energy factors that are stressful for plant growing. The fact that the model can simulate the movement of important chemical elements and substances, such as nitrogen and phosphorus or pesticides in a basin, is very important for agricultural planning. SWAT model is used mainly for the assessment of the impacts that agricultural activities have on water, soil and agricultural country in long terms.

From the aspect of time, it is a continuous model, from the aspect of spatial distribution of numerical units, it is a semidistributed model. By semidistribution it is meant the division of spatially heterogeneous area of interest into a network of spatial units, which can be considered homogeneous from the aspect of important morphological, hydrological and other parameters. These units are individual subbasins and river reaches that belong to them.

The work with the SWAT model is based on the graphical users interface (GUI) of GIS environment. Older model versions are implemented in the ArcView 3.x, the newer ones in the ArcGIS 9.x environment, but some versions exist for other GIS platforms (e.g. GRASS GIS, AGWA) as well. ArcGIS Desktop program as a GUI of SWAT model was used in our works. SWAT model works as an extension of this program under a term

ArcSWAT. Nowadays, there are more versions of ArcSWAT extension for ArcGIS Desktop available on the internet together with their documentation.

Basic mathematical apparatus of SWAT soil erosion model

Without regard to problems, that are actually being solved, the driving force of all the actions in the catchment is the processes of the hydrologic cycle and the water balance. If we want to simulate the movement of water, sediments or other substances in a watershed, it is necessary to use a model that is able to simulate a complicated hydrologic cycle in it. In SWAT model the cycle is divided into two steps.

The first is a simulation of hydrologic transformation of rainfall in a catchment, what is closely connected with the movements of water, sediments and substances from the slopes of a watershed into streams. The second one is a simulation of hydraulic transformation in the streams what solves the problems of the movements of water, sediments and substances in the reaches towards an outlet of a subbasin.

In SWAT model the hydrologic cycle is managed by a complicated system of differential equations that could be summarized into one balance equation of the following form (Nietsch et al., 2002):

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}); \qquad (1)$$

where SW_t is final soil water content [mm],
SW_0 is initial soil water content [mm],
t is time [days],
R_{day} is amount of precipitation on a day *i* [mm],
Q_{surf} is amount of surface runoff on a day *i* [mm],
E_a is amount of evapotranspiration on a day *i* [mm],
w_{seep} is amount of percolation and bypass flow exiting the soil profile bottom on a day *i* [mm],
Q_{gw} is amount of return flow on a day *i* [mm].

It is evident that individual parameters of the equation above are elaborated by their own equations, which presentation is beyond the contribution.

Firstly, runoff is calculated for HRU (Hydrologic Response Units) which could be understood as areas with a unique combination of soil and land covers that, together with a slope of a relief, could be considered homogeneous within the bounds of HRU. We get HRU in a process of model building by overlapping the maps of soil and land covers. Each such a unit specifically influences the final simulated movement of water in a watershed and also the final characteristics of monitored processes.

Secondly, the runoff from HRU is summarized for individual subbasins and finally for the outlet of the whole watershed. The scheme of the cascade of calculations is shown in the figure 1.

Erosion itself is managed by the use of Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975 In: Nietsch et al., 2002), which has the following form (Nietsch et al., 2002):

$$Sed = 11{,}8\,(Q_{surf} \cdot q_{peak} \cdot area_{hru})^{0{,}56} \cdot K_{USLE} \cdot C_{USLE} \cdot P_{USLE} \cdot LS_{USLE} \cdot CFRG; \qquad (2)$$

where *Sed* is sediment yield on a given day [t],
Q_{surf} is surface runoff volume [$mm \cdot ha^{-1}$],
q_{peak} is peak runoff rate [$m^3 \cdot s^{-1}$],
$area_{hru}$ is area of a HRU [ha],
K_{USLE} is USLE soil erodibility factor,
C_{USLE} is USLE soil cover factor,
P_{USLE} is USLE support practice factor,
LS_{USLE} is terrain shape factor (slope and length of a slope),
CFRG is coarse fragment factor.

SWAT model building and its setting

The necessary data inputs of SWAT model are digital elevation model (DEM), data about the land cover, about the soils and minimally long-term monthly averages of selected climatologic characteristics such as precipitation depth, extreme daily temperatures etc.

The process of model building is go on in several steps which are watershed delineation, land cover (use) and soils definition, HRU definition, definition of data about weather and finally the simulation run. If there are some measured data series available they can be used to calibrate the model. It the case of this contribution three parallel models were built different in the land cover definition. Scheme of SWAT model building is on the figure 2.

The model outputs are related to individual subbasins, river reaches, water reservoirs and HRUs representing surface accumulations of water such as ponds or wetlands. In the case of this contribution the output of interest was the sediment loss from the subbasin.

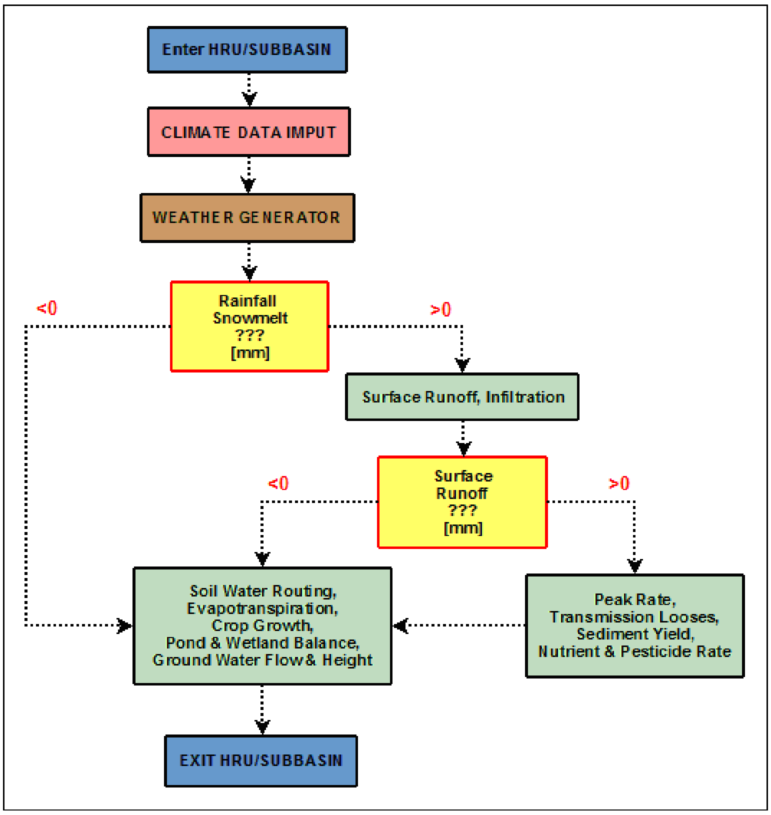

Fig. 1. Cascade of calculations in SWAT model for HRU/Subbasin. Adapted according to (Nietsch et al., 2002).

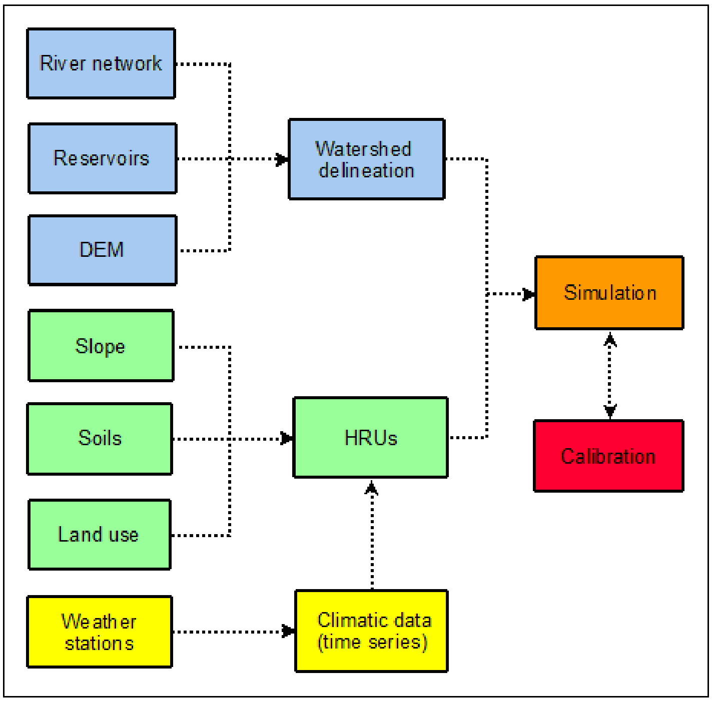

Fig. 2. Scheme of SWAT model building.

Results

The land cover changes and simulation results are visualized on the figures 3 and 4. As a reference years the year 1990 was chosen and thus the changes of erosion processes (potential sediment loss from the subbasin) are related just to this year possibly to the following year 2000 (succession of change).

If look at the Fig. 4b., it is evident that the land cover changes during the decade 1990 – 2000 resulted to the decreasing of the potential sediment loss rate practically in the half of all the subbasins (20 from 41). In the case of six subbasins the potential rate of the sediment loss decreased about 1 – 10 % as against the state of the year 1990, the decrease in another nine subbasins was about 11 – 20 %. Two of the subbasins belong to the potential sediment loss decrease of about 21 – 30 % and the decrease in another three subbasins exceeded 30 %. There are no subbasins with the increase of the potential sediment loss. The rest of the subbasins (altogether 21) could be classified as the subbasins with no change in the rate of potential erosion processes.

If look at the Fig. 4c., it is apparent that in comparison with previous studied period some of the land cover mosaic changes between the years 2000 and 2006 resulted in the increase of potential sediment loss, some of them contrary in the decrease if it. Thus in the case of six subbasins in the year 2006 it came about increase of potential sediment loss in the interval 1 – 10 % as against the year 2000. In one of the subbasins the increase of sediment loss numbered 22 %, in another one 37 %. In the nine of the subbasins it came about decrease of potential sediment loss in the interval 1 – 10 %, another six subbasins comes under the following interval, thus 11 – 20 %. One of the subbasins is distinguished by the decrease of about 27 %, another one of about 32 %. The rest of the subbasins (16) could be classified as the subbasins with no change.

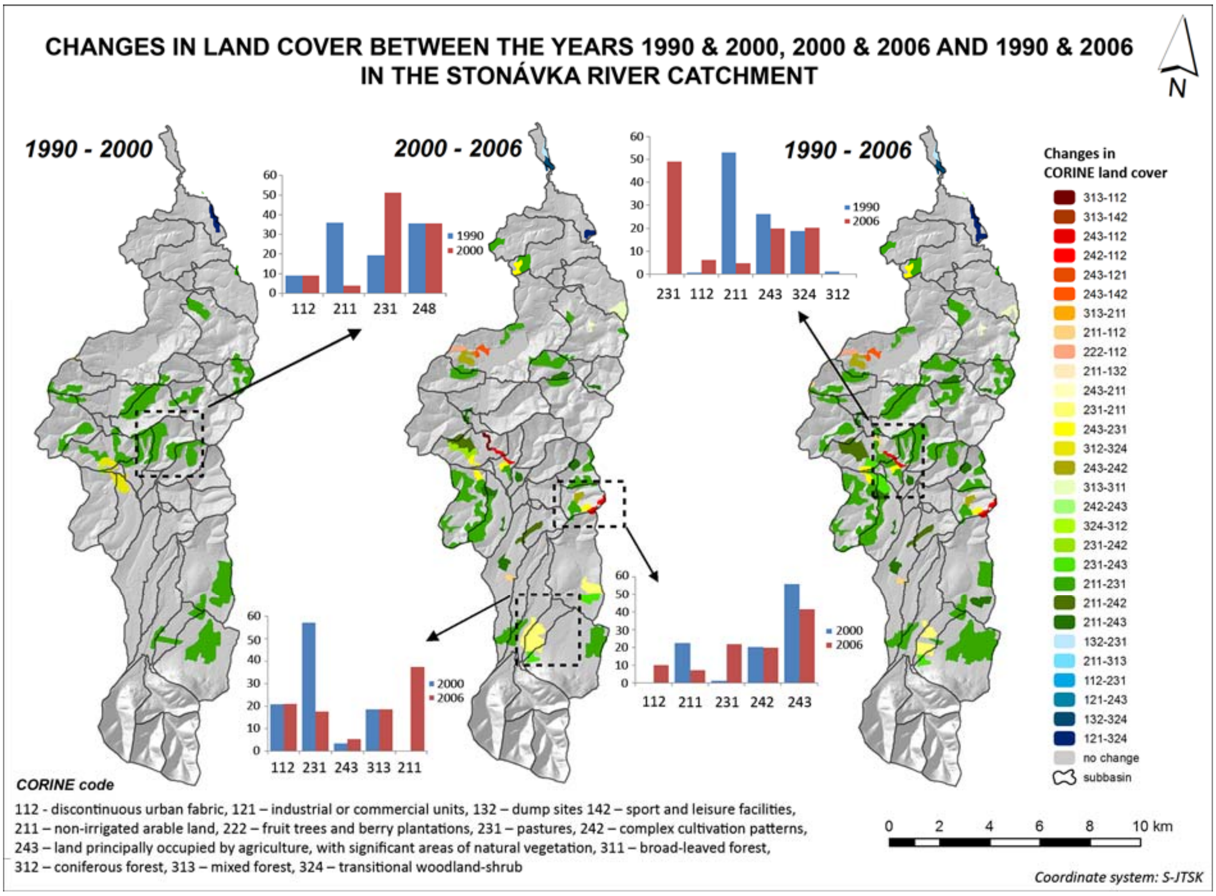

Fig. 3. Land cover change.

If we focus on the complete classification of potential erosion processes in the catchment as a consequence of the spatial distribution of the land cover categories between the years 1990 and 2006 (see the Fig. 4d.) then it is evident, that just only one subbasin reflected the increase of potential sediment loss risk as a result of its internal land cover change. The rate of this relative increase is 22 % as against the state of the year 1990. Twelve of the subbasins can be classified as the subbasins with no change of potential erosion risk, the rest of the subbasins can be in the aspect of erosion risk assessed positively. Six of these subbasins belong to the interval of the decrease about 1 – 10 %, following decrease interval (11 – 20 %) numbers fourteen subbasins, five of the subbasins come under the interval of 21 – 30 % of decrease and in the case of the rest three subbasins the sediment loss decrease exceeded 30 %.

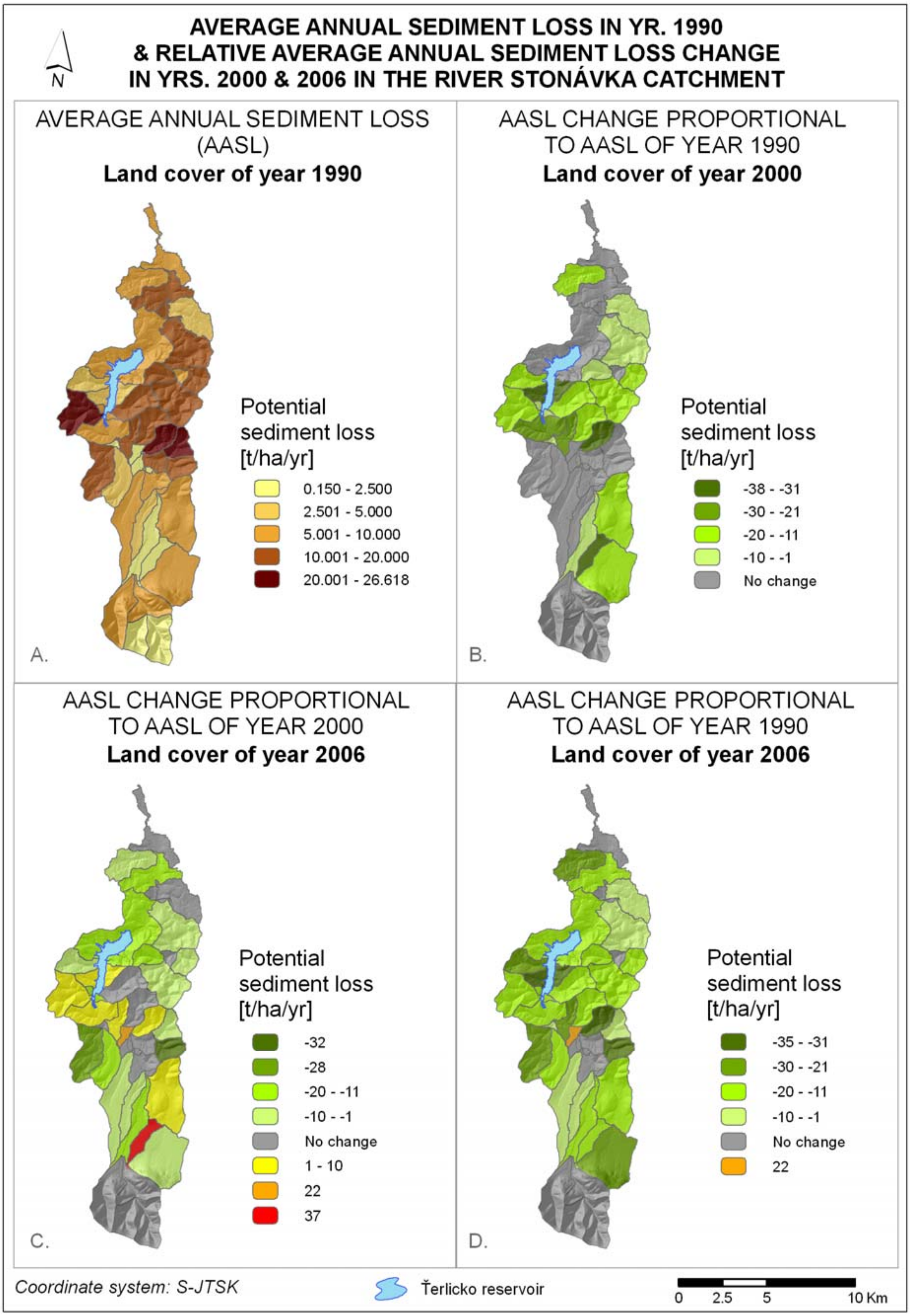

Fig. 4. SWAT model simulations results.

These results could be generally interpreted in the way that in the subbasins with the potential erosion decrease the extent of the land cover categories with the high protective properties increased while the spatial extent of erosion vulnerable land cover categories decreased. In these subbasins the increase of the extensively managed areas (for example pastures and forests) is evident. Extent of intensively managed agriculture areas decreased. Contrary the subbasins with the increase of the potential sediment loss prove by the increase of the arable land extent and decrease of the meadow, pastures and forests. This intrepretation key could be used in all the analysed cases.

Discussion

Resultant rate of soil erosion is given by the synergic influence of the whole group of erosion factors. One of these factors is land cover whose structure and properties more or less protect the soil against the erosive effects of rain and surface runoff. In the aspect of time this parametr is stationary. Used SWAT model belongs among the physically based erosion models thus it is based on the physical description of the processes leading to soil erosion. In spite of this there is to word „potential“ sediment loss (erosion) deliberately used in the interpretation of the results. It is because of the internal weather generator of SWAT model was used nay the real meteorologic series. However it is fully sufficient to analyse the influence of the stationary factor change on the erosion rate and the results could be considered as relevant.

Conclusion

Under this contribution the influence of the land cover spatial structure changes on the resultant erosion processes rate was studied. The Stonávka river catchment was chosen as a study area. Erosion processes were simulated using SWAT model paralelly by three models different in the land cover input data representing the land cover state of the year 1990, 2000 and 2006. Generally it could be said that after the year 1990 it came about the positive changes in the spatial distribution of the land cover. The land cover categories presdisposed to the soil erosion origination were replaced by the catgories with stronger protective properties. It is related to the transition from the strongly intensive landsape management to the less intensive and extensive one. Particulary the extent of pastures, meadows and forests increased on the detriment of the agriculturally managed arable land. Just only in the case of few subbasins it came about the incrase of the potential erosion rate between the years 2000 and 2006, but the decrease of potential erosion processes rate predominates.

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