SIMULATION OF SEDIMENT TRANSPORT IN CATCHMENT USING ARCSWAT 2005 DYNAMIC EROSION MODEL EXEMPLIFIED BY THE CATCHMENT OF THE OSTRAVICE RIVER

MODELOVÁNÍ TRANSPORTU SEDIMENTŮ V POVODÍ POMOCÍ DYNAMICKÉHO EROZNÍHO MODELU ARCSWAT 2005 NA PŘÍKLADU POVODÍ OSTRAVICE

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Abstract

Soil is one of the most important natural sources on earth. The same way as all parts of the environment, and the global ecosystem generally, it suffers from several kinds of human activities in the landscape. One of the most serious environmental problems of our present days is accelerated soil erosion and related processes. In the past, the most of soil erosion studies and researches took place in the field, on experimental plots or in laboratories. The problem of these studies is the fact that they take quite a long time and are expensive. Nowadays, in the age of computers and information technologies, the soil erosion and sediment transport studies can be managed by new effective tools – numerical models. There are lots of numerical models being able to solve several tasks in the field of soil erosion and sediments. One of the most complex numerical models is the SWAT model (Soil and Water Assessment Tool). This physically based semi-distributed model can be used to analyze the complex watershed management and soil erosion, and sediment transport is only a fraction of the tools offered by the model. The main goal of this contribution is to introduce the basic abilities of the model as a tool of soil erosion analyses and sediment transport in watersheds.

Abstrakt

Eroze půdy, zejména ve své akcelerované podobě, patří mezi nejzávažnější problémy spojené s aktivitou člověka v krajině a v souvislosti s tempem růstu světové civilizace a nerovnoměrným rozmístěním zdrojů na Zemi je tato hrozba čím dál naléhavější. Člověk se o půdu, jakožto základní zdoj, zajímal již od samotného vzniku zemědělské společnosti, tedy i poznání v oblasti eroze půdy si prošlo dlouhým obdobím bádání. V dnešní době tak v návaznosti na prudký rozvoj jiných oborů, zejména IT, disponujeme pestrou paletou numerických modelů řešících erozi půdy. Jedním takovým je i právě model SWAT (Soil and Water Assesment Tool). Jedná se o fyzikálně podložený semidistribuovaný kontinuální dynamický model poskytující řadu nástrojů pro řešení poměrně obsáhlé problematiky managementu povodí, zejména pak s ohledem na vodní složku, erozi půdy a rostlinnou produkci. Nápní tohoto příspěvku je pak testování nabídky modelu v oblasti eroze půdy a transportu sedimentů a na ně vázaných látek v povodí. Model byl testován na schematizovaném povodí Ostravice.

Key words: soil, erosion, model, SWAT, GIS

1 INTRODUCTION

SWAT (Soil and Water Assessment Tool) 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 the complete evaluation of landscape potential in relation to runoff rates, soil erosion, and sediment transport, or to other geo-ecological characteristics (energy balance of the ecosystem, accessibility of moisture and nutrients in soil, etc.).

The SWAT model belongs to a group of physically based models. This means that in calculating the soil erosion rate the model respects the physical principles of genesis and formation of surface runoff, and also the consequent process of erosion, transport and deposition of soil particles. Using the SWAT model we can simulate a lot of processes not only in the field of hydrology, but also in the field of soil management. The model can reveal water, nutrient and energy factors being stressful for plant growing. The fact the model can simulate the movement of important chemical elements in basin, especially nitrogen and phosphorus, is very important for agricultural planning. The ability of the model to simulate the movement of pesticides by surface and subsurface runoff is also very important. The SWAT model is used mainly for the assessment of impacts of agricultural activities on water, soil and agricultural landscape in the long term.

In term of time, it is a continuous model, in term of the spatial distribution of numerical units, it is a semi-distributed model. By semi-distribution we mean the division of spatially heterogeneous area of interest into a network of spatial units, which can be considered homogeneous with regard to important morphological, hydrological and other parameters. These units are individual subbasins and related river reaches.

We used the ArcGIS Desktop program as a graphic user interface of the SWAT model. The SWAT model works as an extension of this program referred to as ArcSWAT. Nowadays, there are more versions of the ArcSWAT extension for ArcGIS Desktop available on the internet completed with their documentation.

2 STUDY AREA

In our study we focused on the simulation of sediment transport in the study basin of the Ostravice River. The Ostravice basin was selected as a model area due to the accessibility of necessary input data.

The basin of the river is situated in the north-eastern part of the Czech Republic. The Ostravice River is a right-hand tributary of the Odra River, so it is a kind of the second stream order with an 816 km^2 large fan-shaped catchment.

The main draining artery of the basin is the Ostravice stream with its main tributaries, the right-hand Morávka River and the left-hand Čeládenka and Olešná Rivers. The Ostravice River is a typical gravel-bearing stream of the Beskydy mountain range and from the spring to the confluence with the Morávka River it has the character of white water. In these sections the dynamics of runoff is given by quite a craggy relief on the flysch of the Beskydy Mountains. A distinctive alternation of erosion and gravel sedimentation is characteristic for this part of the Ostravice River. This is one of the reasons, why the stream of the river is anthropogenically regulated to a great extent [1], [3].

Approximately 15 km far from its beginning, that is created by the confluence of the Rivers Černá and Bílá, the transverse valley of Ostravice, which crosses the main ridge of the Moravskoslezské Beskydy Mts., opens. It continues into the flatter forefront of Beskydy and its stream leads to the north, into the basin of the city of Ostrava. On the territory of Ostrava it flows into the Odra River.

The relief of the Ostravice basin and the region climate are the main factors that influence other components of land, for example, the soil conditions, land cover or the general structure of land and land use. In the upper part of the basin, in the Moravskoslezské Beskydy Mts., the soil is composed mainly of Cambisols and Podzols, sporadically also Histosols occur. The land cover is created predominantly by forests, especially coniferous ones. The land is used extensively.

In the lower parts of the basin, in the forefront of the Beskydy Mts., the pedologic conditions and the cover of land are more varied. The dominant soil types of these parts are mostly Luvisols, Fluvisols occur in the floodplains, and there are also Orthic Luvisols, Pseudogleysols, Pararendzinas and others. The land here is used much more intensively and a large part of it is formed by differently cultivated agricultural farms and urbanized areas.

Geographical conditions of the watershed are quite various, which considerably influence the heterogeneity of erosion processes.

3 BASIC MATHEMATICAL APPARATUS OF THE MODEL

Regardless to the problems that are actually being solved, the driving force of all the actions in the Ostravice catchment is represented by the processes of hydrologic cycle and the water balance. If we want to simulate the movement of water, sediments, nutrients, pesticides or other substances in watershed, it is

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necessary to use such a model being able to simulate the complicated hydrologic cycle running there. In the SWAT model the cycle is divided into two steps.

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

In the SWAT model the hydrologic cycle is managed by a complicated system of differential equations that could be summarized into the balance equation as follows [2]:

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

Where:

SW_t - final soil water content [mm],

SW_0 - initial soil water content [mm],

t - time [days],

R_{day} - amount of precipitation per day *i* [mm],

Q_{surf} - amount of surface runoff per day *i* [mm],

E_a - amount of evapotranspiration per day *i* [mm],

w_{seep} - amount of percolation and bypass flow exiting the soil profile bottom per day *i* [mm],

Q_{gw} - amount of return flow per day *i* [mm].

Since the only required input into the model, which is related to the hydrologic cycle, is precipitation, it is evident that the individual parameters of the equation above are processed by their own equations, whose presentation is beyond this contribution.

First, the runoff is calculated for HRUs (Hydrologic Response Units) which could be understood as areas with a unique combination of soil and land covers that, together with the slope of relief, could be considered homogeneous within the bounds of HRUs. We get HRU in the 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 watershed and also the final characteristics of monitored processes.

Second, 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 figure 1.

Erosion itself is managed through the use of the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975 In: [2]), as follows [2]:

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

Where:

Sed - sediment yield of a given day [t],

Q_{surf} - surface runoff volume [$mm \cdot ha^{-1}$],

q_{peak} - peak runoff rate [$m^3 \cdot s^{-1}$],

$area_{hru}$ - area of HRU [ha],

K_{USLE} - USLE soil erodibility factor,

C_{USLE} - USLE soil cover factor,

P_{USLE} - USLE support practice factor,

LS_{USLE} - terrain shape factor (slope and length of slope),

$CFRG$ - coarse fragment factor.

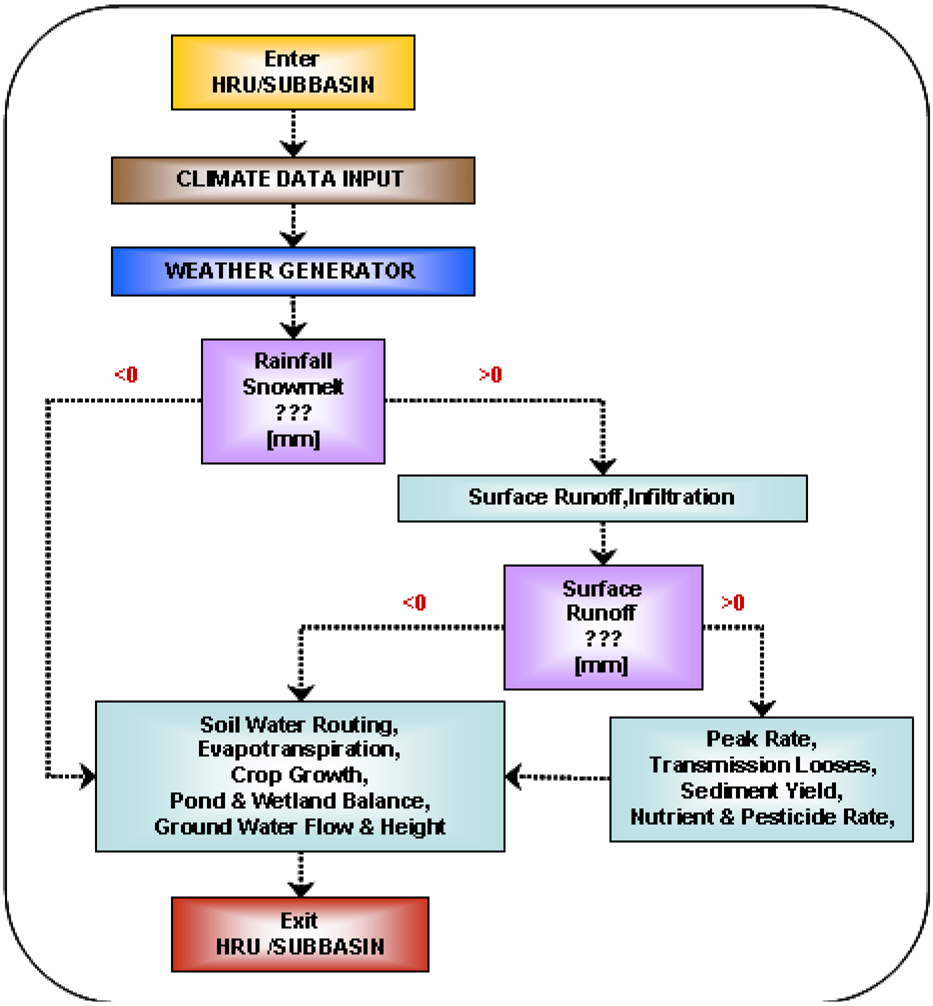

Fig. 1 Cascade of calculations in the SWAT model for HRU/Subbasin. Adapted according to [2].

4 INPUT DATA

Fundamentally, the SWAT model is a physical model. The fact that physical models generally respect the physical essence of simulated processes sets these models apart from empirical models. This is due to their higher accuracy and better representativeness of their outputs and because these models have a wider range of use concerning the parameters of study area. In contrast to the empirical models, the group of physical models is much more demanding for input data, which logically results from the structure of the model as a complicated system of differential equations, which define the individual factors of complex rainfall-runoff and erosion processes in a simplified way.

The demand of the SWAT model for input data is quite high. The model has a certain rate of robustness, which means that after specifying the basic input variables and their accurate equilibration we can expect quality outputs of simulations, even if the whole capacity of input database is not filled.

In order to get satisfying outputs it is necessary to specify the parameters of static variables properly, especially the relief, runoff network, soils and land cover. It is needful to describe the climatic conditions from dynamic variables during the simulation and if necessary also the water management parameters of reservoirs in watershed and operating with them.

The digital elevation model (DEM), vector layers of soils and land cover and data on climate and reservoirs can be regarded as the basic inputs into the model [4]. Then the model has an internal database, which refers to a relevant input layer and describes its parameters necessary for observed processes.

4.1 Relief

Relief is involved in an erosion-sedimentary process by way of its morphometric parameters like slope, length, curvature, orientation and others. Relief is one of the most important factors influencing the movement and placement of substances and energy in space [5].

The relief of watershed enters the model in a form of DEM, which is the main input into the process of watershed schematization, in which the catchment under study is divided into a network of subbasins and their river reaches. Afterwards important morphometric parameters, taken out from DEM, are put into the attribute tables of individual subbasins and reaches of the river network. These parameters play a part in the next calculation of water erosion.

The use of a grid type of DEM is easier for this kind of analyses. This type of DEM is more suitable for the watershed schematization than other data formats of DEM, especially due to its structure. An important feature of this type of DEM is its hydrologic correctness, which guarantees that each drop, fallen on the surface of watershed, will flow through its closing profile.

4.2 River network

Runoff network is one of the basin parameters entering the building of the model. It is not a compulsory parameter, as the runoff network is taken out from input DEM by semiautomatic way during the schematization process. In our case, we approached an option to use the already existing vector layer of runoff network, in order to specify the localization of valley lines in the process of basin schematization. In the next phases of the model building it is possible to define the value of the Manning coefficients by way of the main and also the side reaches of the river network.

4.3 Soils

Soil factors belong to the most important factors and are primary. The impact of other factors on the progress of erosion is not often straight and it is mediated by an elicited change of certain features of soil (physical or chemical). The soil factors are presented by having an impact on the amount and progress of infiltration into soil and by the resistance of soil against the destructive effect of rain drops and surface runoff (resistance against erosion) [6], [7].

The impact of soil, as the source of sediments, is quite precisely recorded in the SWAT model. The layer of soil types and subtypes enter the process of simulation after finishing the watershed schematization. In this step quite a large database is assigned to individual areas, which represent their soil types and subtypes. The data on soil depth, soil hydrologic group, soil bulk density, efficient water capacity, granulometric characteristics, volume of humus and many other data related to a soil unit are registered in this database.

In a more precise approach the data is recorded even for particular soil horizons of a given soil unit.

4.4 Land cover

The type of land cover considerably influences the total values of sediment transport and transport of other substances. The conditions of vegetation have a strong impact on the structure, permeability, moisture regime and stability of soil and cause the roughness of surface. The vegetation cover protects the soil surface from the straight fall of raindrops and it also considerably slows down the surface runoff of rainfall water. The existence of vegetation cover works against erosion [6], [7].

Principally, forest areas are typical for their high protective effect against erosion. Especially the density and the dense canopy contact of vegetation cover type play an important role. The thicker the vegetation cover, the gentler effect of raindrops on soil. An opposite case is farmed areas with a low density and weak canopy contact. These areas succumb to accelerated water erosion the most.

The way of cultivation of these localities, the kinds of crops grown here and the duration of vegetative period of these crops also have a distinctive impact on erosion. The area cover is a factor, by which a man can influence the progress of erosion the most, either in a positive or in a negative way.

The data on land cover enter the model as an individual layer, whose particular category is reclassified according to the internal database of the model. Each kind of cover is defined in the database in detail by a lot of parameters.

4.5 Climatic data

One of the most important and necessary data entering the model is the data on climate. The character of climate is given mainly by the location and relief of watershed.

The climatic data is gained by measurements at weather stations of CHMI (Czech Hydrometeorological Institute). In case of the Ostravice basin, the data entering the model were taken from the weather stations Bílá, Lysá hora and Lučina, situated immediately in the basin, and the weather stations Frenštát p. R., Dolní Bečva and Ropice, located near the basin area. The data on rainfalls and temperatures have the biggest impact on the sediment transport simulations.

This data enters the SWAT model in a form of long-term monthly averages of maximum and minimum temperatures and a long-term average of rainfall height in particular months. It is important to mention also the data on the height above sea level of individual weather stations and their geographical coordinates. The number of years, during which the data on temperatures and rainfalls were measured, is important for an integral weather generator (see below). Except these data it is possible to set the data related to the speed of wind, solar radiation, and relative air moisture or other climatic data.

The already mentioned weather generator is a module integrated within the bounds of the SWAT model, whose role is to generate the information on the progress of weather from the climatic data. The model has quite a complicated mathematical-statistical device, in order to complete this task. It plays the most important role in the case, when we require simulation outputs in a more fine time step than the climatic inputs used before, or if we have only a limited quantity of input meteorological data.

4.6 Reservoirs

Also the reservoirs situated at streams have a great impact on the sediment transport in watershed. The importance of reservoirs is mainly in their ability to keep the transported sediments that would normally travel down the flow. This leads to a sudden change of a suspended load regime.

The impact of reservoirs can be factored in quite an effective way during the simulation in the SWAT model. The outlets of the subbasins, where the monitored reservoirs are situated, are marked during the process of watershed schematization. In the next step a database, which contains specific data related to these reservoirs, is assigned to them.

The important parameters of reservoirs and their regime entering the model are the amount of their supply and retention volume, volume of permanent holding, area of these volumes, average daily flow rate through a principal spillway and minimal daily outflow from the reservoir in particular months of a year.

The valley reservoirs are an important part of the hydrological and water management systems in the Ostravice basin. The 5 largest reservoirs of the basin were included in the watershed schematization. These are the Šance, Žermanice, Morávka, Olešná and Baška reservoirs (from the largest to the smallest).

5 PROGRESS OF MODEL BUILDING AND INITATION OF SIMULATION

The first step is the above mentioned watershed schematization. The SWAT model offers a device for the semiautomatic watershed schematization referred to as „Watershed Delineator“. During the schematization a draining network is generated and the study area is defined by selecting an outlet. As the SWAT model is a semi-distributed model, the whole basin is divided into several subbasins. It is possible to choose the minimal size of subbasins during the schematization. The result of our model watershed schematization is 67 subbasins with subsistent outlets.

The next step of simulation is setting the data on soils, land cover and slope conditions of the study area. The basic internal units for counting the surface runoff, above mentioned HRUs, are defined by way of overlapping this data.

The climatic data of area and the data describing the parameters of reservoirs enter the model as the last one. After this step it is possible to initiate the simulation itself. In this step it is necessary to set mainly the duration of simulation and the time step of outputs. The results of simulation are shown in attribute tables and they are exported into the *.dbf format. The scheme of model building is illustrated in figure 2.

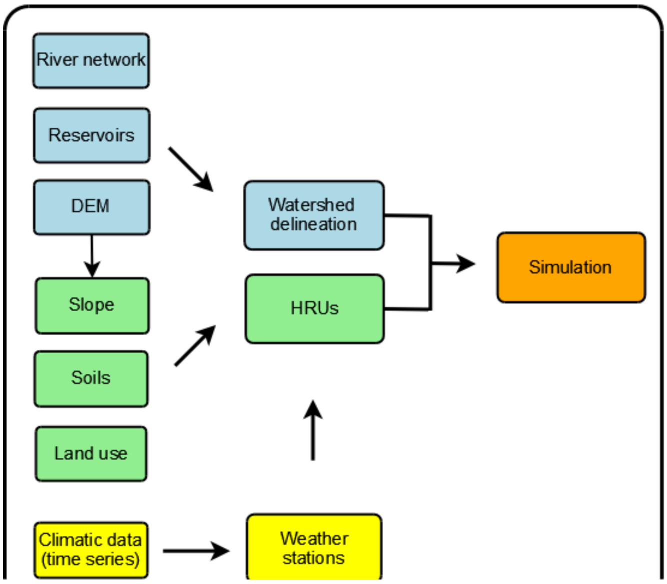

Fig. 2 Scheme of SWAT model building.

6 SELECTED RESULTS AND THEIR INTERPRETATION

The SWAT model offers a whole range of outputs exported into *.dbf tables related to subbasins, river reaches and others. Afterwards each subbasin, or reach, is characterized by different attributes, which represent the values of computed quantities. Three selected output characteristics of model calculation are discussed and interpreted below.

6.1 Assumed sediment routing from the Ostravice basin

One of the outputs of the SWAT model is the sediment routing from subbasins related to a unit of area [t/ha/year]. The subbasins with minimum values of this quantity are situated predominantly in the Beskydy part of the Ostravice basin, which is given by an almost continuous forest cover in this part of the basin. In the lower parts of the basin laying lower at the stream, the values of sediment routing are higher. This fact could be explained by the reality that this area is used in a way, which exposes the surface to erosion much more. The subbasins with maximum values of sediment routing are coated by a cover, which is susceptible to erosion from a great part. These covers are mainly agricultural soils or discontinuous urban areas. Moreover, the subbasins below the reservoirs Morávka and Šance are typical for considerable slant of slopes in the relief, which is connected not only with a deep cutting of the valley into the ridge of Moravskoslezské Beskydy, but also with their passage to the steep front slopes of the nappe of the Moravskoslezské Beskydy mountain range. The sediment routing simulation results are shown in figure 3.

6.2 Assumed average concentration of sediments in the watercourse of the Ostravice basin

The second illustrated output is an average concentration of sediments in the river reaches of subbasins [mg/l]. In the case of this quantity, the spatial distribution of the values is more complicated than in the previous characteristic. The important facts influencing the sediment transport are the land cover and soil erodibility and also the dynamics of stream. In this way, it is possible to explain the quite high values of sediment concentrations in the river sections of the Beskydy mountain range.

On the contrary, it is possible to monitor a considerable impact of reservoirs on the values of simulated phenomenon. The values of sediment concentrations are minimal in the river reaches directly bordering the reservoirs and in the river reaches below these reservoirs, where the flow dynamics is reduced and sediments are held by the reservoir. It is possible to give arguments for the presence of maximum values of monitored quantity in the subbasins of the Beskydian forefront in the same way as in the case of the characteristic already discussed, it means by way of soil features combination and land use. The pseudo-cartogram of the discussed erosion characteristic is shown in figure 4.

6.3 Assumed average routing of nitrogenous substances from the Ostravice basin

The transport of substances like $N_{org.,}$ $(NO_3)^-$ and others is closely connected with the above discussed characteristic of sediment transport. The monitored characteristic is an assumed average routing of nitrogenous substances from the Ostravice basin specific routing of nitrogenous substances from a subbasin in a year [t/ha/year] (see figure 3).

The model comes out from the general assumptions of the occurrence of these substances in particular components of the environment, especially in the individual categories of vegetation cover. The model is also able to quantify the migration of monitored substances, draining water and transported soil particles from these output characteristics.

7 SUMMARY

The aim of the presented work is to verify the abilities and possibilities of the ArcSWAT model device on a selected watershed. The model offers quite a great amount of useful outputs utilizable in practice. However, quite a big number of quality input data is needed for getting credible results. The model is very sensitive to the existence of quality and precise input data, which is a limiting factor for its real use in many cases. After all, the model, because of its robustness, is able to give quite quality outputs if its setting is done finely and the number of available data is more limited.

An important offer of the model is the possibility to calibrate the outputs that has not been tested yet. This is the subject of further interest of the collective of the authors.

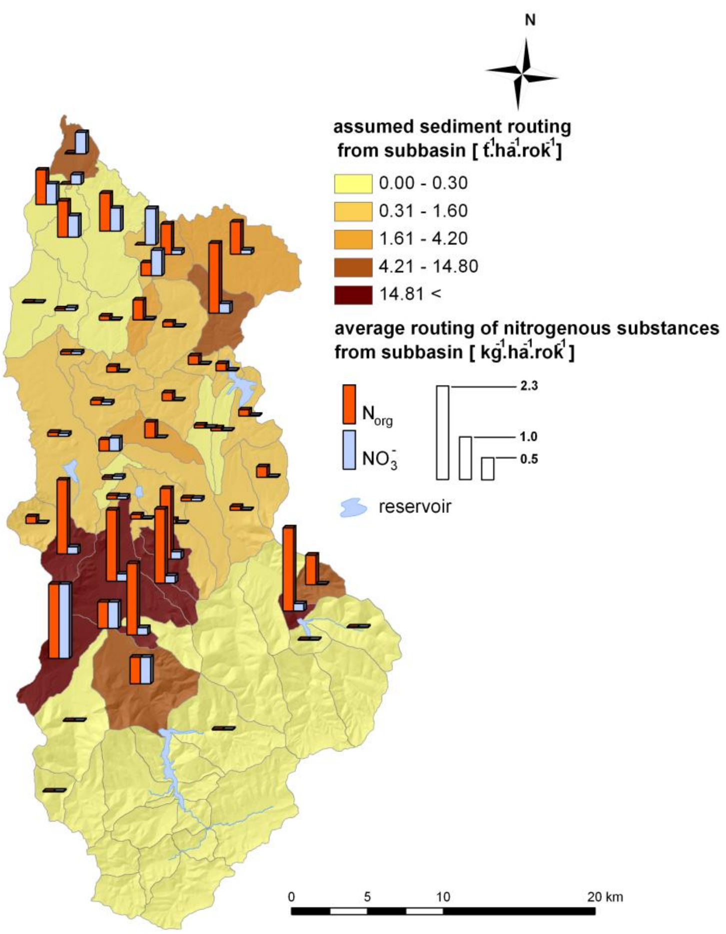

Fig. 3 Assumed sediment routing and average routing of nitrogenous substances from the Ostravice basin

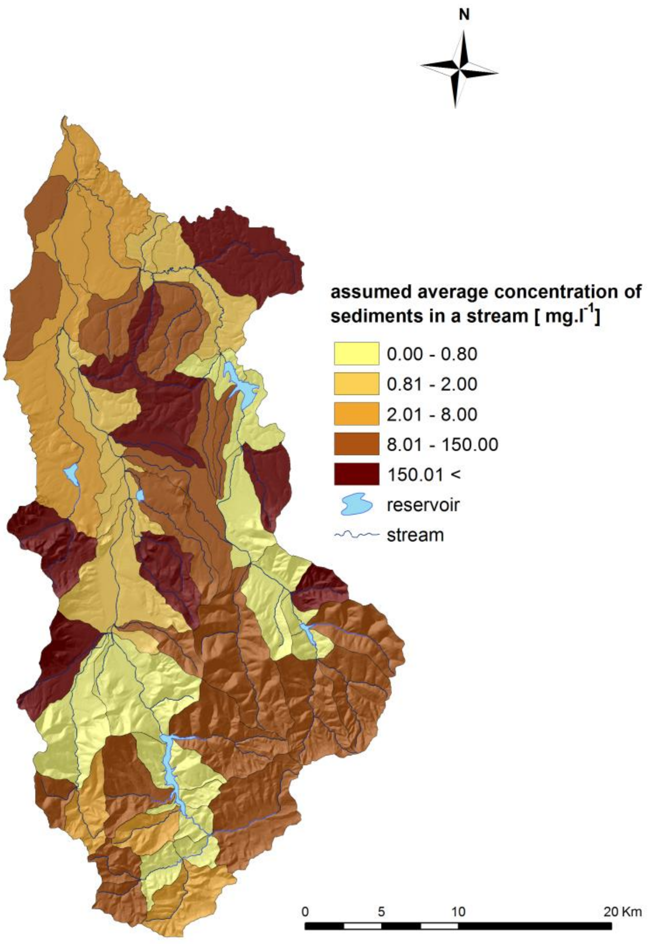

Fig. 4 Assumed average concentration of sediments in the stream of the Ostravica basin

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RÉSUMÉ

Eroze půdy, zejména ve své akcelerované podobě, patří mezi nejzávažnější problémy spojené s aktivitou člověka v krajině a v souvislosti s tempem růstu světové civilizace a nerovnoměrným rozmístěním zdrojů na Zemi je tato hrozba čím dál naléhavější.

Člověk se o půdu, jakožto základní zdoj, zajímal již od samotného vzniku zemědělské společnosti, tedy i poznání v oblasti eroze půdy si prošlo dlouhým obdobím bádání. V dnešní době tak v návaznosti na prudký rozvoj jiných oborů, zejména IT, disponujeme pestrou paletou numerických modelů řešících erozi půdy. Jedním takovým je i právě model SWAT (Soil and Water Assesment Tool).

Jedná se o fyzikálně podložený semidistribuovaný kontinuální dynamický model poskytující řadu nástrojů pro řešení poměrně obsáhlé problematiky managementu povodí, zejména pak s ohledem na vodní složku, erozi půdy a rostlinnou produkci. Nápní tohoto příspěvku je pak testování nabídky modelu v oblasti eroze půdy a transportu sedimentů a na ně vázaných látek v povodí.

Model je spouštěn jako extenze GISovského programu ArcGIS 9.x a veškeré operace počínaje tzv. preprocessingem, neboli schematizací povodí, přes spuštění simulací až po tzv. postrocessing, čili zpracování, vizualizace a analýzy výsledků simulací, se tak děje v uživatelsky přívětivém a odborné veřejnosti notoricky známém grafickém uživatelském rozhraní zmiňované GIS aplikace.

Model byl testován na schematizovaném povodí Ostravice. Toto povodí bylo vybráno z důvodu dostupnosti potřebných vstupních údajů. Základními statickými vstupy do modelu byl DEM, vektorová vrstva vodních toků, dále vektorové vrstvy půdních typů a krajinného krytu. Jednotlivým tématickým jenotkám těchto vrstev (půdním typům a kategoriím LULC) byly v interní databázi modelu přiřazeny atributy popisující z hlediska studovaných procesů důležité parametry. Do modelu též vstupovaly data dynamického charakteru, a to data popisující parametry a průměrné manipulační údaje na vodních dílech a především pak data o klimatu, zejména dlouhodobé průměrné měsíční údaje o srážkách a teplotách na vybraných pozorovacích stanicích ČHMÚ.

Vkládání dat do modelu je velice intuitivní a po jejich nastavení je možno spustit simulaci. Výstupem z modelu jsou tři *.dbf tabulky obsahující celou řadu atributů popisujících chování povodí jednotlivých krocích simulace z celé řady hledisek. Jednotlivé tabulky jsou vztaženy k subpovodím, říčním úsekům a HRU, neboli jednotkám hydrologické odezvy (angl. hydrologic response unit).

S ohledem na prostor příspěvku byly interpretovány pouze tři vybrané výstupy, a to předpokládaný roční specifický odnos sedimentů ze subpovodí [t/ha/rok], průměrná koncentrace sedimentů v říčních segmentech daných subpovodí [mg/l] a průměrný specifický roční odnos dusíkatých látek $N_{org.}$, $(NO_3)^-$ ze subpovodí [t/ha/rok]. Výsledné výstupy jsou vizualizovány formou pseudokartogramů a pseudokartodiagramů.