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EFFECT OF LAND USE CHANGES ON WATER RUN-OFF FROM A SMALL CATCHMENT IN THE CZECH REPUBLIC

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Abstract

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The changes in the landscape during past years were affected mainly by political and financial conditions in the agricultural sector as well as the future changes probably will be. For this study various scenarios of changes in land use in the small catchment caused by human activity were simulated. Several scenarios were focused on changes of agricultural area to urbanized landscape and also on industrial use of several plots. The aim of this study was to model and assess the impact of human-induced landscape changes on run-off from small catchments in the traditional agricultural area. It can be said, that more than the change of land use itself, changed management of these areas affects the water run-off more. The hypothetical transfer of significant part of the catchment area or the localities with infiltration vulnerable zones into urbanized paved space is the only exception. This change mainly affects the rate of discharge.

Key words: SWAT, discharge, infiltration vulnerable zones, land use change, urbanization.

Introduction

The aim of this study was to model and assess the impact of human-induced landscape changes on run-off from small catchments in the traditional agricultural locality. As stated by Franczyk and Chang (2009) and Novaes Váchalová et al. (2010), the land use change is a very important factor affecting hydrological conditions of the catchment and mainly the run-off conditions. The same finding is confirmed also by Bernetti et al. (2006) and Du et al. (2013). Bulygina et al. (2009) or Jiang et al. (2011) showed that all landscapes are dramatically changed under the influence of various factors as demography, climate change, national policies and subsidies, economic conditions, among others.

Urbanization is one of the most significant changes of land use (Váchal et al., 2006, 2009a; Mihalčíková et al., 2010). Currently, a significant trend of urban population is migration to safer locations nearby rural areas, where conditions are suitable for life, close to nature and offer an unspoiled environment (Louženská et al., 2011, Moravcová et al., 2013). For these new inhabitants of small villages near cities, mass construction of new houses occurs on the greenfield sites. Similar trend has been described through the whole world (e.g. Antrop

(2004), Jayasinghe-Mudalige et al. (2007) or Pacione (2001)). At the same time, there is a need for the construction of new amenities such as kindergartens, etc. (Antrop, 2000). In some cases, there is also a full reorientation of traditional agriculture to other forms of economic activity, and thus it leads to the construction of commercial buildings, such as storage facilities, factories, solar power stations and so on (Pečenka et al., 2014). This phenomenon is well described mainly in post-Communist countries and countries in transition as documented by Sýkora and Ourednek (2007) or Moravcová et al. (2014) for the Czech Republic, by Timár and Váradi (2001) for Hungary, by Tosics (2004) or Raagmaa et al. (2009) for Baltic states.

As stated in Alig et al. (2004) and Chin (2006), globally the urban population increased in the last 40 years by 100% and the trend will continue for a minimum of the next 30 years. Such dramatic changes, according to Majid (2009), lead to radical changes in the hydrological behaviour of catchments (Hampicke, Roth, 2000). The regions are facing serious problems with water quality and also quantity (Lacroix et al., 2006, 2007; Martinez et al., 2007; Moravcová et al., 2009). The growth of impervious surface in urbanized catchments, according to Aronica and Cannarozzo (2000) and Zhou et al. (2013), leads to local decreases in infiltration, canopy interception and the water-holding ability (Spaziante, Murano, 2009). Consequently, there is a huge potential of flooding risk and also of water shortage. As showed by Dixon and Earls (2012) or Moravcová et al. (2014), this poses challenges to emergency and disaster management and planning efforts.

Brandmeyer and Karimi (2000) as well as Green et al. (2006) show that the hydrological and hydrochemical models have been serving for many years as an efficient tool for the planning of water resources management. Abu El-Nasr et al. (2005) describes these models as a simplified quantitative relationship between input and output parameters of a system. Simulations of these models are then used primarily to assess the impacts of the proposed scenarios in land use change and different water management strategies. Singh et al. (2005) considers the modelling of hydrological properties necessary for understanding processes in the catchments (Buzek et al., 2009). Arnold et al. (1998) adds that it is a necessary step to improve the management of the catchment. Also Heuvelmans et al. (2005) and Le Grusse et al. (2006) describe the modelling as the easiest way to determine the influence of natural factors and human factors on run-off and water quality (Brouwer et al., 2001). The application of such modelling approach can be confirmed by studies such as Guo et al. (2008), Palamuleni et al. (2011) or Ren et al. (2002).

Currently, according to Borah and Bera (2003), a wide range of hydrological models were developed, from which the most suitable simulation tool for the particular condition can be chosen. From these wide range of models, we have chosen the Soil and water assessment tool (SWAT). SWAT is a continuous model in scale catchment, which, in its basic version, works with a daily time step and is designed to predict the impact of management on the hydrology, sediment and chemicals associated with agricultural activities (Fohrer et al., 2005). The model is physically based and designed to work with long time series of continual monitoring. The main components of the model include weather, hydrology, soil science, plant growth, nutrients, pesticides and landscape management (Gassman et al., 2007).

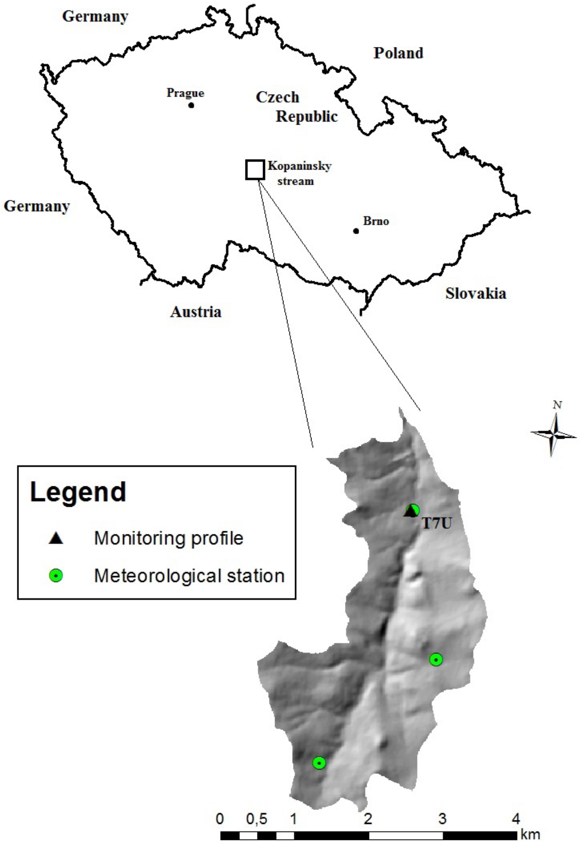

Fig. 1. Localization of Kopaninsky stream catchment in the Czech Republic.

Material and methods

Material

All activities associated with the preparation of the study were focused on Kopaninsky stream catchment. Kopaninsky stream catchment, covering 6.9 km^2, is located in the central part of the Czech Republic (Fig. 1), Vysocina County, in the district Pelhrimov, cadastral areas Chvojnov, Kletecna u Humpolce, Onsovice u Dehtar, Velky Rybnik u Humpolce and Zirov.

The area lies at an altitude of 467–624 m above the sea level, the highest peak Pavlickuv kopec with an altitude 624 m above sea level is located in the south-western part of the catchment. The area is under the geomorphologic structure in the Czech Highlands province, subprovince of the Czech-Moravian system, the Bohemian-Moravian Highlands, Kremesnicka Highlands, Zelivska hills, Horepnicka hills. Bedrock consists of biotitic-muscovitic schist, Moldanubian mica schist with inter-layer of quartzite and quartritic gneisses. The most important soil types are Cambisol modal, Cambisol gleyed and modal, which cover most of the catchment area Kopaninsky stream. Kopaninsky stream catchment lies in the moderately warm climate. The Kopaninsky stream catchment is managed by more private farmers and agricultural companies. Agricultural area represents the type of potato-rye production area. Agricultural production is mostly based on the traditional method of agricultural production with application of traditional agro-technical practices.

Closing profile of this sub-catchment is equipped with a Thomson weir with a rectangular cut-out and is equipped with an ultrasonic device for continuous measurement and recording of flows and water levels. More detail desription of this catchment can be found in Kvítek et al. (2009, 2012).

Methods

For the modelling of runoff and the concentration of nitrate anions, semi-distributed model with continuous daily time step SWAT (Soil and Water Assessment Tool) designed for medium to large basins (Abbaspour et al., 2007; Arnold, Fohrer, 2005) was chosen. This is partially physically based model, which allows the simulation at a very high degree of spatial resolution by distribution of the catchment into a large number of small facets.

The basis of all operations in the SWAT model is a digital terrain model. In case of Kopaninsky stream catchment a total area of 6.9 km^2 was divided into sub-catchments with an average area of 1.7 km^2. The second spatial level is hydrological response unit HRU. Altogether the Kopaninsky stream catchment is defined by 87 HRUs with an average

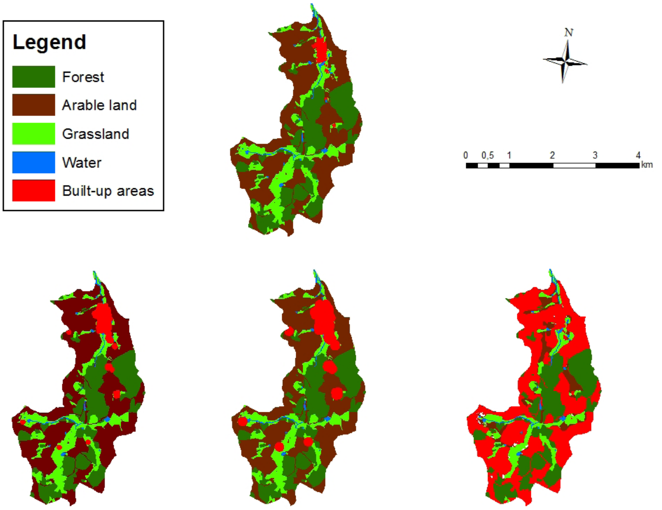

Fig. 2. Scenarios with different types of land use arrangement in the Kopaninsky stream catchment, as they are included in the model SWAT.

area of 0.05 km^2. Hydrological cycle, as modelled in the SWAT, is based on the general water balance equation. The principal and most important components of the hydrological module of SWAT model are the values of surface run-off and evapotranspiration. Penman-Monteith method (Monteith, 1965) is used to calculate evapotranspiration. Meteorological characteristics of the basin provide moisture and energy inputs that determine the relative importance of different parts of the hydrological cycle. Variables that describe the weather in the river catchment model are daily rainfall, maximum and minimum air temperature, global radiation, wind speed and relative humidity. For this study, time series of daily rainfall totals of four rainfall stations were used. These are located on the Kopaninsky stream catchment, stations Velky Rybnik, U Turku and U Nemcu, and the nearby rain gauge station K4 located on the Dehtare catchment (Fig. 1). The distribution of individual soil units within the modelled area are used together with slope and land use for the purpose of defining the hydrological units HRUs. For the purposes of this study, there were used main soil units. For each pre-defined soil profile, the results obtained by the physical and chemical analyses of collected soil samples were added into the SWAT database. Database with descriptive characteristics of each type of land use is also integrated in the SWAT program. On the Kopaninsky stream catchment, five categories of land use, namely arable land, permanent grassland, forest, built-up area and water area were identified. The land included in the category of arable land was then described by cultivated crops based on field research in each year. This group includes crops such as winter wheat, spring barley, winter barley, winter oilseed rape, potatoes and corn. The required parameters of the physiology of plants were taken for each crop, but also for grassland and forest. The database connected to the SWAT model was completed by the database, which was compiled at the University of Giessen for a typical Central European and Western European crops (Breuer et al., 2003), and also by field measurements.

SWAT model for basin Kopaninsky flow was calibrated using a data series of discharges measured at the closure profile of Kopaninsky stream catchment marked T7U. To calibrate the discharges, time series of average daily discharge values from hydrological years 2009–2011 (1 November 2008 to 31 October 2011) were used. For subsequent validation, daily average discharge rates of the hydrological year 2012–2013 (1 November 2011 to 31 October 2013) were used. Calibration and validation involves comparing actual measured data series with the output of the model. Calibration was performed by automatic calibration module, which is also included in the module AvSWATX. Based on the sensitivity analysis of the LH-OAT (Latin Hypercube Sampling - One At A Time) (van Griensven et al., 2006), which is an integral part of the SWAT model, the most important calibration parameters were selected. For comparison, the conformity of the model with real measured data, three coefficients generally recommended for the evaluation of the models in the literature as Gassman et al. (2002) or van Griensven and Bauwens (2003) were used. This is the coefficient of determination, Nash-Sutcliff coefficient of predictions performance and the average error parameter.

The modelled scenarios of different land use layout in the catchment

All the following scenarios are shown in the Fig. 2. In the Kopaninsky stream catchment, arable land, which is intensively used for agriculture, is clearly dominant Arable land is conventionally used with crop rotation including both spring and winter variants of commonly cultivated cereals and root crops. This arrangement with the land use management has been identified as a baseline (Variant 0). Subsequently three possible alternative scenarios of land use were established, with a focus on human-induced changes. The scenarios are related to new built-up areas. Variant 1 assumed double expansion of built-up areas in the surrounding of present municipalities. Variant 2 assumed a four-fold expansion of built-up areas and the last Variant 3 described the hypothetical complete built-up of all infiltration vulnerable sites, according Janglová et al. (2003). In each scenario, the newly urbanized plots were simulated in five different variants according to the type of urbanization. The particular variants were defined according to the SWAT database with regard to fraction of impervious land and their connectivity. Each new variant was labelled by the letter A–E. The classification of the urbanized plots is summarized in Table 1.

Table 1. Range and average impervious fractions for different urban land types (Neitsch et al., 2004).

Variant	**Urban land type**	**Average total impervious**	**Average connected impervious**
A	Residential - High density	0.60	0.44
B	Residential - Medium density	0.38	0.30
C	Residential - Low density	0.12	0.10
D	Industrial	0.84	0.79
E	Transportation	0.98	0.95

Results and discussion

Firstly, the SWAT model was calibrated and validated for the discharge rates. Different scenarios were subsequently inserted in the calibrated and verified model and finally their impact on the indicators of water quantity were evaluated.

Calibration and validation of the model SWAT

Since the SWAT model contains a large amount of descriptive parameters, there is the need to determine the parameters that are key from the perspective of the model calibration at first. For these purposes, SWAT model was firstly assembled to sensitivity analysis. Based on the results of integrated LH-OAT analysis, six calibration parameters were selected for discharge rates. Individual parameters, including the initial values, arelisted in Table 2.

It can be concluded that then chosen calibration parameters and methods are generally used to calibrate the discharges (van Griensven et al., 2002). The resulting values were adjusted according to the actual measurements, or the available relevant literature.

After adjustment for baseline values of the parameters mentioned above, the model was calibrated for discharge. The final comparison of data series measured at closure profile T7U during the hydrological year 2009–2010. Last recorded simulation characteristics gained after completion of the calibration of discharge are described in Table 3. Nash-Sutcliff coefficient value E = 0.932 is demonstrating the relatively good agreement between the simulated and measured discharge rate. The good agreement between data series is evidenced by the high value of the coefficient R^2, which after calibration reaches 0.944. Nash-Sutcliff coefficient was mainly affected by inaccuracies in the simulation of discharge in the time of rainfall-run-off events and the short period that followed them closely. In these periods, the peak

Table 2. Setting of the calibration parameters for the SWAT model for calibration of discharge in the Kopaninsky stream catchment (T7U).

	Value			Used method [g]
	Minimal	**Maximal**	**Final**	
GWQMIN [a]	-1000	1000	-118	2
ALFA_BF [b]	0	1	0.35	1
ESCO [c]	0	1	0.01	1
SOL_K [d]	-100%	100%	15%	3
CN2 [e]	-100%	100%	18%	3

[a]The water level of shallow groundwater, [b]Parameters of the base flow, [c]Evaporation compensation factor, [d] Saturated hydraulic conductivity, [e] Run-off curve number; [g] 1. Change and replace the original parameter value by new. 2. Gradual count up the constant correction factor to the initial value of the parameter; 3. Multiplying the original value by the parameter correction factor generated as percentage of the original value.

Table 3. Statistical indicators describing the results of calibration and validation of SWAT model for discharge and concentration of nitrate anions.

	Calibration	Validation
Nash-Sutcliff	0.932	0.912
R^2	0.944	0.901
Mean error ME	0.012	0.003

discharges are typically overestimated. This fact is demonstrated especially in early spring rainfall-run-off episodes, when the discharge is overestimated by up to 25% compared to the measured value. The average value of the parameter errors ME is confirmation of these comparisons, which after calibration of the model reaches values of 0.012, thus pointing to a slight overestimation of simulated data over the entire time period.

Periods, which closely follow the rainfall-run-off episodes, are in some cases the source of error in the discharge simulation, because of the unsatisfactory response of SWAT model for short-term reduction in discharge during recorded episodes, or episodes that follow each other in short sequences.

The calibrated model for Kopaninsky stream catchment was, before running the simulation of the proposed scenarios, tested on data from another time period.

***First, the discharge rate was chosen for verification. For the validation process, the data from hydrological year 2008 were used. The final statistical values characterizing the completed validation process for discharge are shown in Table 3. Achieved final values are slightly lower than in the case of calibration. This confirms the generally known fact that the parameters that were specified for the model calibration period, not entirely cover the needs of the validation.

***The modelled values are almost for the entire period slightly overestimated, as evidenced by a positive coefficient ME. The biggest problem is the setting of calibration values that guarantee good agreement of discharges in periods with higher discharge rates. Again, it showed that the model incorrectly interprets the course of rainfall-run-off events that follow each other in rapid succession. Likewise, there are inaccuracies in the sudden drop in discharge during rainfall-run-off events, as it has already been shown in the process of calibration.

Based on the results shown in Table 3, the results of calibration and validation process for discharge and concentrations of nitrate anions can be regarded as satisfactory and thus set model is suitable for solving the tasks set out in the aim of the study.

Results of scenario simulations

Gradually, increase of building area in the vicinity of existing small municipalities in the catchment twice and four times of the original size was simulated. In the last seventh simulated variant, hypothetical possibility of occupation of the arable land in the catchment was simulated. A similar trend was described in many countries around the world and similar study was described, for example, by Dixon and Earls (2012).

According to the results shown in Fig. 3, it is clear that all the three variants will lead even to a small increase in flow.

In the first simulated variant, the increase of flow is practically only very slight, only about 3.5%. When doubling the area of present built-up areas, there will be no significant threat of flood in the village and the risk of significant damage during rainfall-runoff events should not even be increased. By comparing the particular variants of these scenarios all the simulated variants give approximately the same results in the range of 5.3%. The best simulated variant from the point of view of discharge is low-density residential urban land. Similar conclusions were achieved by Majid (2009), who described the growth of flow of 2.5% by doubling the impervious localities in the watershed, or Koulová et al. (2011), Váchal et al. (2009b) and Franczyk and Chang (2009) who described the increase by 2.3–2.5% by doubling the urbanized landscape in the Rock Creek catchment in Oregon, USA. They also described the linear trend between the growth of urban land and discharge. Very similar results were also described by Brun and Band (2000) for Baltimore Metropolitan area where no significant change in outflow was recorded by 20% increase in urbanized impervious localities. Also Chang (2007) described very low increase in discharge (less than 2%) in Pennsylvania catchment with change of land use from agricultural landscape to low density suburban landscape.

For the second simulated variant of four-fold increase in the paved areas, already a marked increase in average annual flow rates up to about 50% occurred. The most significant increase was recorded mainly in the values of peak flows during rainfall–run-off events. The increase in discharge rates was sometimes more than 100%. In the simulation scenario 2, individual variations are rather different.

The variance of individual values range between 126.3 and 162.7% of recorded flows. In this scenario, the two variants showed a significant variation. The first one recorded a higher increase of the flow at the development of medium-density than in high-density residential areas. The cause of the anomaly is especially significant in areas with wastewater sewer system, which draws water from the surface and therefore do not contribute to an increase in natural water run-off from the territory. The second abnormality compared with other simulations is lower simulated run-off from the land affected by transport infrastructure. The reason is again seen in the good drainage of wastewater from communications to a closed space (Ciml et al., 2015).

The risk of damage to property and the health of the population are therefore disproportionately increasing. The rapid increase in discharge mainly in downstream urbanized

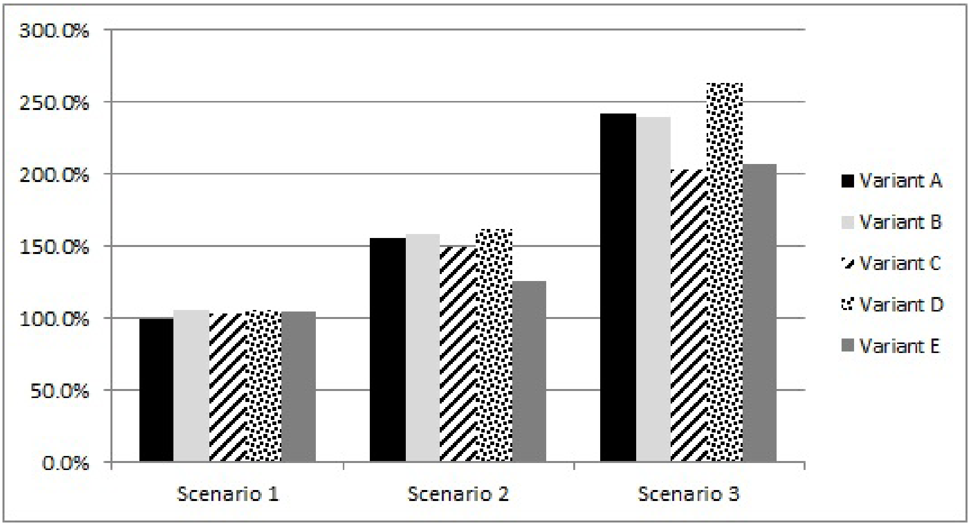

Fig. 3. Simulations results of different scenarios.

localities was described also by Petchprayoon et al. (2010) for catchments in Thailand and the results were supported also by study Niehoff et al. (2002) made in Germany or Koupilová et al. (2008) and Pavlíček et al. (2014) in the Czech Republic.

In the last scenario, the simulated complete building up of current arable land would report very alarming discharge rate. This option is only hypothetical, and its implementation cannot be expected, with the sole exception of the expansion of areas of solar power stations. In the case of implementation of this variant, the simulation of model SWAT showed the increase of discharges more than double of the current values. These results cannot be compared with any other studies because any author simulates such scenarios with the enlargement of the urbanized areas in similar conditions of infiltration vulnerable zones according to Janglová et al. (2003). In all variants of simulated flow This scenario shows the increase of over 200% of the original value. From Fig. 3, there is also an apparent fluctuation of the individual values from 203.4 to 263.2%. Increase in flow variations with industrial land use is particularly alarming. A recorded increase in average annual flow rates has been up to 263.2%. This scenario has become more important especially with a steady increase in the area of solar power plants. This trend is described also in Moravcová et al. (2008) or Váchal et al. (2010).

Conclusion

It can be said that more than the change of land use itself, changed management of these areas affects the water run-off more. The hypothetical transfer of a significant part of the catchment area or the localities with infiltration vulnerable zones into urbanized paved space is the only exception. This change mainly affects the rate of discharge.

Completely building up of the whole catchment vulnerable zones was the worst variant, which would lead to almost doubling of the discharge and will lead to increasing of potential flood risk. This scenario is only hypothethical but it could be assumed that the present significant trend of urban population migration to safer locations of nearby rural areas, where conditions are suitable for life, close to nature and unspoiled environment, will lead to construction of new houses on greenfields. The pressure will be created to strengthen the weakened natural flood protection of the landscape mainly in localities vulnerable to infiltration of rainwater.

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