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Influence of land use enclave distribution on discharge in a small catchment

Jana Moravcova*, Vendula Moravcova, Pavel Ondr, Tomas Pavlicek

University of South Bohemia, Faculty of Agriculture and Technology, Department of Landscape Management, Studentska 13, Ceske Budejovice, 37005 Czech Republic.
* Corresponding author. Tel.: +420 387 772 773. E-mail: moravcovaj@fzt.jcu.cz

Abstract: According to many authors, hydrological modelling is one of the fundamental techniques for determining the impacts of various environmental changes on the quantitative characteristics of the aquatic environment. This study examines the effects of landscape changes induced by the need to respond to climate change and the natural urban development of the rural setting on the discharge from the small catchment. The SWAT model was applied to a small catchment of Kopaninsky Stream in the traditional agricultural part of the Czech Republic. According to the results, the most effective approach for reducing the consequences of hydrological extremes in the catchment and retaining more water in the landscape is the properly spaced placement of grassland and forest enclaves in the developing urban structure. In practice, each land use category's overall percentage of representation is less significant than its relative arrangement.

Keywords: SWAT; Discharge; Land use change; Environmental change.

INTRODUCTION

Landscapes and river systems in much of Europe and elsewhere have undergone significant changes in the past, and there is no doubt that these environmental changes have altered flood conditions in the region (Baude et al., 2019). These changes have led scientists and managers alike to ask how landscape stability can be restored or improved to prevent flood risk (Rauter et al., 2019). There is only one way, which implies the need to protect landscapes and the behaviour of their users (Van der Hoven et al., 2022). From this point of view, the only way is to change the use of agricultural land to a more ecological form according to the Common Agricultural Policy of the European Union. On this basis, land managers can use financial support to implement measures to increase the stability of the agricultural landscape (Bittner et al., 2020). Landscape process modelling is increasingly becoming a suitable tool for analysing the behaviour of landscape segments and systems (Di Febbraro et al., 2019). We can simultaneously analyse, for example, the short-term response to a sudden or one-off stimulus (rainfall, calamitous deforestation, phytophagous insect gradation, change in river channel morphology) or the long-term response to the action of selected factors (Ahearn et al., 2005). Currently, a significant theme in using hydrological models is to address climate change in the form of drought (Tenagashaw and Andualem, 2022) or flood (Duan et al., 2018). These hydroclimatic extremes have increased significantly due to climate change and could severely impact socioeconomic sectors (Van der Hoven et al., 2022). Quantifying hydroclimatic extremes is beneficial for local authorities and researchers in understanding the status and potential risks of water-related disasters. For local authorities, addressing hydroclimatic extremes can mean easier decision-making when locating different functional components, such as built-up areas or protected areas of water sources, wetlands, or forests in the landscape. Using long-term observations is advantageous as the most reliable source for understanding the hydroclimatic system (Fu et al., 2019).

As demonstrated, for example, by Bittner et al. (2020), hydrological models have served as an effective tool for water resource management planning for many years. According to Beven (2001), these models are a simplified quantitative relationship between a system's input and output parameters. Simulations from such models are then mainly used to assess the impact of proposed scenarios in land-use change and different water management strategies. They are necessary to improve catchment management (Perks et al., 2017). Thus, modelling is the easiest way to determine the influence of natural and human factors on runoff (Parshotam and Robertson, 2019). According to Fu et al. (2019), a wide range of hydrological models are available, and the most suitable simulation tool for specific conditions can be selected. Borah and Bera (2003) state that selecting the most suitable model to solve a particular task involves evaluating several essential factors. These factors may include, first, the purpose of using the model or determining the fundamental problem to be solved by the model (Fu et al., 2019). As Singh et al. (2005) add, another necessary step to correctly select the model to be used is the evaluation of the size of the catchment and the spatial and temporal framework of the required simulation. Finally, Abaci and Papanicolaou (2009) emphasise the importance of considering the required model accuracy, the availability of different models, hardware equipment, and the user's experience.

The hydrological model chosen for this work was the Soil and Water Assessment Tool (SWAT), developed by Jeff Arnold based on years of research by a group of scientists from the US Department of Agriculture - Agricultural Research Service (USDA-ARS). The model and its architecture have been described by Neitsch et al. (2004). It is a continuous semi-distributed model with a daily time step designed to support catchment managers in estimating and assessing the effects of catchment management on streamflow, sediment transport, and pollutant loading at larger-acreage sites. The model is physically based and designed to work with a long, continuous time series of observations. The main components of the model include weather, hydrology, pedology, plant growth, nutrients, pesticides, and landscape management (Gassman et al., 2007). The simulation of the hydrological characteristics of the SWAT model is mainly based on the CN curve method. At the same time, the modelling of nutrient transport is solved through a set of empirical equations.

The objective of this publication was to evaluate the effect of landscape enclaves, as defined by Forman and Godron (1986),

on catchment runoff at different precipitation rates. This approach differs from other published studies as Tenagashaw and Andualem (2022) or Mori et al. (2021) in combining the reaction of the same landscape configuration of the catchment on rainfall sub-normal and above-normal conditions and, on the other hand, the reaction of the different types of landscape configuration on the same amount of rainfall. After this, the landscape reaction was added to flood control measures. Unlike studies such as Zewde et al. (2024) and Nepal et al. (2023) made in a huge catchment, this study was conducted in a small catchment in the inland conditions of the Czech Republic.

Concerning the objective, three research questions were established:

RQ1: What is the catchment runoff under normal (long-term average) rainfall conditions?

RQ2: What is the runoff from the catchment under significantly sub-normal rainfall conditions - drought conditions?

RQ3: What is the runoff from the catchment under significantly above-normal rainfall conditions - wet and flood years?

The study then asked another research question:

RQ4: Can the model respond to including a flood control polder in the study catchment?

MATERIALS

The model site was selected as the Kopaninsky stream catchment (hydrological number 1-09-02-031), located in the central part of the Czech Republic in the Vysocina region (Figure 1). The area lies at an average altitude of 518 m above sea level. The bedrock of the catchment is made up of gneiss and moldanubic volcanic rocks. The most important soil types are cambisols, stagnosols, and gleysols. According to the climatic classification, the Kopaninsky stream catchment area is classified as a moderately warm climatic area. Several private entities and an agricultural cooperative manage the Kopaninsky stream catchment area. The agricultural area represents, according to the Ministry of Agriculture, the cereal-potato production agricultural type with traditional crop production and application of conventional practices.

METHODS

As stated in the Introduction, the hydrological model chosen for this work was the Soil and Water Assessment Tool (SWAT). The model is physically based and designed to work with a long, continuous time series of observations. The main components of the model include weather, hydrology, pedology, plant growth, nutrients, pesticides, and landscape management Gassman et al. (2007). The simulation of the hydrological characteristics of the SWAT model is based on the CN curve method. At the same time, the modelling of nutrient transport is solved through a set of empirical equations.

- Components of the model

Although SWAT is a continuous model for the entire catchment area, to increase the model's accuracy and better describe the water regime, the catchment area is divided into sub-catchments and response units called HRUs (Hydrologic Response Units). This captures mainly differences in evapotranspiration values as well as runoff values for individual soil units and also for individual crops. The runoff and substance concentrations are then modelled separately for each HRU and only then combined into the total runoff and concentration values in the capping profile.

The basis for all operations in the SWAT model is a digital terrain model (DTM), the accuracy of which is one of the

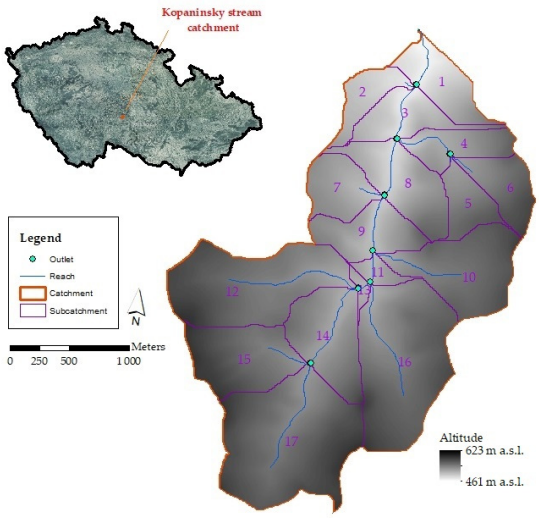


Fig. 1. Localisation of the Kopaninsky stream catchment within the Czech Republic and delineation of the catchment in the SWAT model on the digital terrain model.

variables that determine the resulting degree of agreement of the simulated quantities with the actual measured values, as described in Di Luzio et al. (2005).

In the case of the Kopaninsky stream, the digital terrain model was created according to the elevation map provided by the Czech Office of Surveying and Cadastre. The resolution of the provided model or the pixel size is 2 m. A sub-catchment layer was automatically created in the SWAT environment based on DMT. This layer includes calculating the basic parameters of the sub-catchments and their interconnected hydrological network. The SWAT model allows the watercourse network to be automatically plotted based on the values obtained from the DMT. However, there is also the possibility of including an actual image of the stream network. This work used the first mentioned option, i.e., automatic plotting. There was no significant difference when comparing the existing watercourse network with the model output. A detailed description of the algorithm for plotting the sub-catchment and stream network included in the SWAT model is described in the publication by Di Luzio et al. (2002).

In the simulations with a flood control polder, this reservoir was included in the definition of the catchment topography. It is a multi-purpose polder with a permanent water level. The total floodable area is 1,838 ha with a maximum water volume of up to 60,000 m^3 (at Q100, a water retention of 45,563 m^3 is assumed). The area of the original permanent grassland above the village was converted into a flood control polder area in 2012 by the construction of a 191.28 m long earthen dam with a maximum height of 7.32 m on the valley floor.

The number and size of the areas of each sub-catchment are influenced by the accuracy of the input DMT and the user's wishes, using the parameter "threshold area". According to Arnold and Fohrer (2005), the recommended minimum sub-catchment area is 5% of the total area of the solving unit. In the case of the Kopaninsky stream, the sub-catchment with a total area of 6.9 km^2 was divided into 17 sub-catchments with an average area of 0.39 km^2, whose spatial arrangement is shown in Figure 1. These sub-catchments allowed the following more precise definition of the lower spatial levels in terms of the different topography of the area. The second spatial level is the HRUs. These units represent unique combinations of land cover,

land use, and slope types. In the set of units defined in this way, a generalisation is then made to exclude from the set of HRUs combinations occurring only in minimal areas of the territory, as described, for example, in Neitsch et al. (2004). These units are excluded based on the user's decision on the smallest percentage or area representation of land use, land, and slope. The minor representation of each category was set at 5% of the sub-catchment area. At this value, representation of all crucial combinations of land use and soil types in all slope categories was guaranteed. 87 HRUs with an average area of 0.05 km^2 were defined in the Kopaninsky stream catchment. Figure 2 demonstrates the definition of HRUs.

As modelled in SWAT, the hydrological cycle is based on the general water balance equation. The SWAT model hydrological module's primary and most essential components are surface runoff and evapotranspiration values. Two methods can be used to calculate surface runoff values: the modified SCS CN curves method (Zhan and Huang, 2004) or the Green and Ampt (1911) infiltration method. For this publication, the first mentioned method was used. For the calculation of evapotranspiration, the model offers three options the calculation. The method of Penman-Monteith (Monteith, 1965) was used in constructing the model for the Kopaninsky stream catchment.

The meteorological characteristics consist of moisture and energy inputs determining the importance of hydrological cycle parts. The variables that describe the weather conditions in the modelled catchment are daily precipitation totals, maximum and minimum air temperatures, global radiation, wind speed and relative humidity. These values can be directly measured in the field or determined by the integrated weather generator during the simulation. The territory is located in a temperate climate zone in a moderately warm area. The average air temperature here averages 8.7 °C, and the average precipitation in standard years is 552 mm. For this work, time series of daily precipitation totals from 4 precipitation gauging stations located in the Kopaninsky stream catchment, namely from the stations Velký Rybník, U Turků and U Němců, and the nearby precipitation gauging station K4 were used. The data were supplemented by data from two precipitation gauging stations of the Czech Hydrometeorological Office in Pelhrimov and Humpolec, approximately 6,5 km away. Air temperatures were measured at the meteorological station Velký Rybník, K1 and K4 2 m above the surface of the Earth. These measurements were supplemented with additional radiation and wind speed time series from meteorological stations K1 and K4. All-time series of measured meteorological data were subsequently processed using the weather generator integrated into the SWAT model.

The distribution of individual soil units within the modelled area is used together with slope and land use to define the HRU hydrological units. The defined soil ecological units or central soil units have been used for this work. Their characteristics were repeatedly supplemented by field measurements made directly in the Kopaninsky stream catchment between 2004 and 2007. The results of this survey are presented in (Fucik, 2015). Properties were added to the individual predefined soil profiles in the SWAT database according to the results obtained from physical and chemical analyses of the collected soil samples. For the SWAT model, properties related to soil moisture and water flow through the soil profile are crucial. The data describing the physical properties of the soils were also completed using the freely available software "Soil water characteristics" (Saxton and Rawls, 2006). Based on input information on the percentage of clay (up to 0.002 mm) and sand (0.05 – 2 mm), the software determines, through a regression equation derived from measurements of the physical properties of the world's soils, values of bulk density and porosity, field water capacity, wilting point, saturated hydraulic conductivity and usable water capacity.

SWAT integrates databases with descriptive characteristics of individual land use types. A total of 6 land use categories were identified for the Kopaninsky stream catchment across all scenarios: arable land, permanent grassland, forest and orchards, a built-up area with gardens, and a water area (Figure 2). A cultivated crop group was identified each year based on field surveys for land included in the arable land category. This crop group mainly includes wheat, barley, peas, corn, and potatoes. The necessary plant physiology parameters were taken from the database attached to the SWAT model for each crop, grassland, and forest. All commonly cultivated crop species are described in this database. The individual parameters were determined from measurements made in North America.

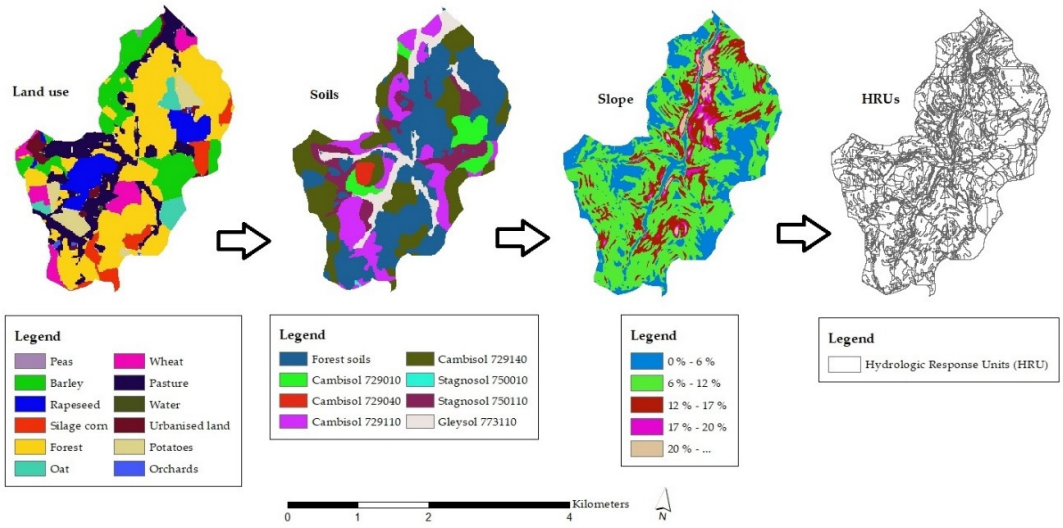


Fig. 2. Processing of Hydrological Response Units (HRUs) – map of particular land use units, map of soil types with soil unit numbers, map of terrain slope [%], final map of delineated Hydrological Response Units.

For this reason, the Kopaninsky stream catchment's characteristics were adjusted based on field measurements directly on the catchment (LAI - leaf area index) and a European database compiled at the University of Giessen for typical Central and Western European crops (Breuer et al., 2003). The Leaf Area Index (LAI) values) were taken from measurements carried out repeatedly in the Kopaninsky stream catchment between 2004–2007 using the LI-COR instrument. For each crop, the dates of each agronomic operation and the doses of applied nutrients in mineral and organic fertilisers were determined based on field surveys, consultations with farmers, and literature sources. For drained sites used as arable land or permanent grassland, the descriptive characteristics of the drainage structures, i.e. the depth of their placement, were also entered into the model.

- Calibration and validation of the model

The SWAT model for the Kopaninsky stream catchment was calibrated using a data series of discharges measured on the T7U Kopaninsky stream catchment profile. A series of average daily discharge values from 2004–2005 were used to calibrate the discharge. For subsequent validation, average daily values from 2006-2007 were used. A time series from 2004 to 2007 was chosen concerning the average rainfall activity in the Czech Republic. These years are characterised by a completely normal distribution of precipitation and total annual precipitation, which in all cases was above the 600 mm threshold (560–570 mm for the selected area) and, at the same time, never exceeded the 800 mm threshold. The selection of years for calibration and validation is consistent with the everyday use of this model, as Neitsch et al. (2004) reported. In these years, watershed responses to a standard distribution of precipitation occur throughout the year, representing both rain-free days and major rainfall-runoff events. This covers both responses to shorter episodes of drought and precipitation events causing rises in water level and, hence, rises in flow. Calibration and validation compare the measured data series with the model output.

The calibration was performed automatically by the calibration module, which is also included in the AvSWATX module. The most critical calibration parameters were selected based on the sensitivity analysis of LH-OAT (Latin Hypercube Sampling - One at A Time) (Van Griensven et al., 2006), an integral part of the SWAT model. As Van Griensven et al. (2002) recommended, multiple parameters were used for calibration. The following list of parameters is ordered according to the sensitivity analysis result in the SWAT CUP environment. The values used for the following calibration parameters will be described in the Results and Discussion section: GWQMIN - shallow groundwater level [mm], ALPHA_BF - baseflow parameter [days], ESCO - evaporation compensation factor, SOL_K - saturated hydraulic conductivity [mm hr^{-1}], CN2 - runoff curve number.

The purpose function describes the degree of agreement between measured and simulated values.

The autocalibration module, called PARASOL (Parameter Solution Method) (Van Griensven et al., 2003), runs the SWAT model with the modified parameter combinations until the simulated and measured values reach the desired agreement or until the defined maximum number of repetitions is exceeded. Changes in parameter values are possible in three ways: by changing and replacing the original parameter value with a new one, by incrementally adding a constant correction factor to the original parameter value or multiplying the original parameter value by a correction factor created as a percentage of the original value.

Three coefficients generally recommended for model evaluation in the literature, e.g., Gassman et al. (2007), were used to compare the model's fit with measured data. These are the coefficient of determination, the Nash-Sutcliffe coefficient of prediction efficiency, and the average error parameter. The coefficient of determination (R^2) indicates the degree of variance in variable Y values, which is explained by changes in the independent variable X values. The higher the coefficient, the better the quality of the resulting model. In the case of linear regression, the coefficient of determination is equal to the square of the Pearson correlation coefficient. The Nash-Sutcliffe coefficient of prediction efficiency (Nash and Sutcliffe, 1970) expresses the strength of the model prediction. It is the most applied dimensionless index for evaluating the performance of hydrological models. The coefficient can take values ranging from $-\infty$ to 1. A value of 1 indicates perfect agreement between the measured and modelled values. A coefficient value of 0 indicates the accuracy of the prediction at the level of the observed values. Efficiency values less than 0 show cases where the average value of the measured data is a better result than the simulated model. The closer the value of the resulting prediction efficiency coefficient is to 1, the more accurate the simulation is.

The average error parameter is a coefficient determining whether the model underestimates (less than 0 or overestimates (greater than) the measured data value.

- Modelled scenarios of landscape structure layout

The study aimed to evaluate the influence of landscape structure in the catchment on the water quantity and quality in the watercourse profile under different rainfall events. The basis of the scenarios is always situation 0, i.e., the catchment configuration at the time of model building and in a typical average rainfall year. From this scenario, three land use configurations were derived regarding land use and distribution over the catchment area. These scenarios are based on the real needs of the study area or the planning procedures applied in the area. The circumstances that led to the development of each scenario are described individually for each scenario. The scenarios are shown in Figure 3.

- Configuration of current land use structure (0)

The land use structure corresponds to the years used to calibrate and validate the built model. In this configuration, the predominant land use is arable land, which accounts for 48.79% of the total area of the catchment area.

- Configuration of the historical land use structure (1)

Landscape structure configuration is based on stable cadastral data from the turn of the 19th and 20th centuries. This model of landscape configuration was chosen as an example of traditional agricultural land use with almost identical ploughing (44.33%) but with a completely different configuration of landscape areas. This variant of land use is still practised in many of the original Austro-Hungarian countries. It is an example of rational, high-intensity farming with due regard for landscape management. This configuration is characterised by the significant presence of permanent grassland, particularly as a transition zone between forests and arable land, around watercourses and reservoirs, and, finally, as an accompanying element of the road network and as a separating element between individual arable land parcels in the form of meadows. The proportion of permanent grassland is 22.99%.

- Configuration of the protective land use structure (2)

This landscape configuration is based on the current strategies of the Czech Republic for responding to climate change and the phenomenon of drought. The land-use concept is based on protecting infiltration-vulnerable areas by promoting the maximum capacity to replenish groundwater supplies and, simultaneously, reduce the environmental burden from high erosion runoff from arable farming in extremely sloping conditions. This scenario foresees grassed areas (slopes between 23–30%) or afforestation of sloping land (slopes above 30%) and infiltration of vulnerable

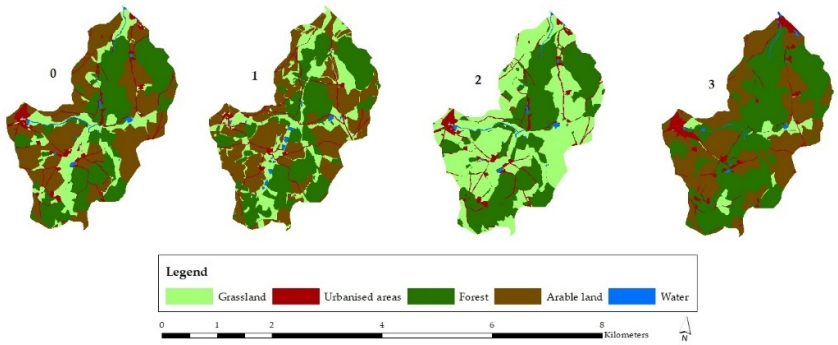


Fig. 3. The scenarios of land use structure within the Kopaninsky stream catchment (0 – present configuration of the landscape; 1 – historical configuration of the landscape; 2 – protective configuration of the landscape; 3 – urbanised configuration of the landscape).

Table 1. Overview of used Scenarios.

Precipitation / Land use	Current use (0)	Historical use (1)	Protective use (2)	Urbanisation use (3)
Average precipitation (A)	A0	A1	A2	A3
Low precipitation (B)	B0	B1	B2	B3
High precipitation (C)	C0	C1	C2	C3

Table 2. SWAT model calibration parameters for calibration of discharges in the Kopaninsky stream catchment (GWQMIN = shallow groundwater level (mm), ALFA BF = baseflow parameters (days), ESCO = evaporation compensation factor, SOL K = saturated hydraulic conductivity (mm/hr), CN2 = runoff curve number).

	Minimal value	Maximal value	Used method*	Final value
GWQMIN	–1 000	1 000	2	–120
ALFA BF	0	1	1	0.38
ESCO	0	1	1	0.01
SOL K	–100 %	100 %	3	17 %
CN2	–100 %	100 %	3	19 %

* 1. changing and replacing the original parameter value with a new parameter value; 2. successively adding a constant correction factor to the original parameter value; 3. multiplying the original parameter value by the correction factor, formed as a percentage of the original value.

areas of Category 1 and Category 2, according to Janglová et al. (2003). In this configuration, arable land almost disappears from the land (5.27%) and is replaced by permanent grassland (52.33%).

- Configuration of urbanisation land use structure (3)

This landscape configuration is based on the current spatial planning documentation of the municipalities included in the study catchment area. Due to the proximity of two large towns (Pelhrimov and Humpolec) and the excellent connection to the nearby D1 motorway, practically all municipalities are aiming to develop built-up areas to be used for housing, supplemented by areas for recreational use, sport, civic amenities, and industrial activities. All these landscape changes will lead to the expansion of paved surfaces, which significantly negatively impact the accelerated runoff of water from the area. The built-up area for all planned developments (considering the maximum possible hardening of land) will reach 8.64%, an increase of almost 2.00% compared to the existing situation.

Each of the four basic landform configurations was then simulated for three rainfall variations during the simulated year.

- Variant A

Variant A uses an average-year rainfall series, with rainfall totals virtually identical to those used in the model calibration and validation. Specifically, 2009, with a total annual rainfall of 552 mm, was used.

- Variant B

Variant B was used for the simulations of a year when the rainfall totals measured at the Velky Rybnik station were significantly below average. This option allows us to monitor the response of the catchment to the ongoing drought. Specifically, 2018 was used with a total annual precipitation of 394 mm.

- Variant C

This last variant describes the catchment's response to a stormy year with high above-normal rainfall causing varying degrees of localised flooding. Specifically 2010, a total annual rainfall of 714 mm in precipitation occurred.

Based on the variations thus generated, 12 scenarios were developed. Their overview is summarised in Table 1.

RESULTS AND DISCUSSION

Calibration and verification of the SWAT model

Since the SWAT model contains many descriptive parameters, it was first necessary to identify the most critical parameters from the model calibration's point of view. For this purpose, the constructed model was first subjected to sensitivity analysis. Six calibration parameters were selected for the discharge rate based on the integrated LH-OAT analysis results. The individual parameters, which have been mentioned in the Methodology section, are listed in Table 2, including the values used.

Other authors generally use the chosen calibration parameters and methods for calibrating discharge rates. The resulting values have been adjusted based on measurements or relevant literature sources.

- Calibration results

After adjusting the input values of the parameters mentioned above, the calibration of the discharge rates for 2004–2005 was carried out first.

After completion of the discharge calibration, the last simulation showed the statistical characteristics described above. The value of the Nash-Sutcliffe coefficient E = 0.887 already demonstrates a reasonably good agreement between simulated and measured discharge values. The high value of the R2 coefficient also evidences the excellent agreement of the data series. The coefficient reaches the value of 0.898 after the calibration. These values are comparable to the recommended results of calibrations of daily discharge values for a catchment of similar size (e.g. Neitsch et al., 2004). Inaccuracies influenced the value of the Nash-Sutcliffe coefficient in the simulation of discharge values for rainfall-runoff events and the short periods that closely follow them. During these periods, peak discharges are typically overestimated. The overestimation is demonstrated primarily by early spring rainfall-runoff episodes when the discharge is overestimated by up to 25% compared to the measured value. These comparisons are confirmed by the mean error parameter ME, which reaches values of 0.001 for the model calibration, indicating a slight overestimation of the simulated data over the entire period. Periods closely following rainfall-runoff episodes tend to be burdened by an error in the simulated discharges due to inadequate model response to short-term reductions in discharge during the recorded episode or to episodes that follow each other in a short sequence. These errors are attributed by Neitsch et al. (2011) to the poor spatial distribution of rainfall gauge station data over the catchment area. This problem likely explains the errors in the discharge simulations in the Kopaninsky stream catchment.

- Validation results

The calibrated model for the Kopaninsky stream catchment was then validated using data from another period before the simulations of the proposed scenarios. First, the validation was focused on discharge values. Data from 2006–2007 were used for validation. The resulting statistical values characterising the completed discharge validation process are presented in Table 3. The resulting values obtained are slightly lower than those obtained in the calibration case. It is a well-known fact that the parameter settings given in the model for the calibration period do not fully match the needs of the validation period, even though this period is chosen as very similar in terms of annual rainfall and discharge distribution.

The modelled values are slightly overestimated during the whole period, as also shown by the positive value of the ME coefficient. The biggest problem is the set of values that, when calibrated, guaranteed a good match of the discharge values during periods with increased discharges. As in the case of calibration, inaccuracies occur during periods of highest discharges. Again, the model must accurately interpret the pattern of rainfall-runoff events that follow each other in a concise time sequence. Similarly, there are inaccuracies in the sudden drop in discharge during rainfall-runoff events, as demonstrated in the calibration process.

A summary of the statistical indices' resulting values after calibration and SWAT model validation for discharges is presented in Table 3.

Based on the results presented in Table 3, the calibration and validation process of the discharge rates can be considered satisfactory, and the model set up in this way is suitable for solving the task set out in the objective of the work.

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

	Calibration	Validation
Nash-Sutcliffe coefficient E	0.887	0.873
Coefficient of determination R^2	0.898	0.896
Mean error ME	0.001	0.002

Simulation of discharges and concentrations under alternative scenarios of a landscape structure arrangement

A total of 4 scenarios of landscape structure arrangement were compared in the Kopaninsky stream catchment in 3 years with different rainfall patterns (from a sub-normal year to an extremely wet year), as described in the Methodology chapter (Table 1).

- RQ 1 What is the catchment runoff under normal (long-term average) rainfall conditions?

First, a runoff simulation from the catchment was carried out under the current land configuration under normal rainfall conditions. This simulation practically corresponds to the calibration and validation setup of the model, and, as a result, the results show similar values to the calibration and validation. The water regime of the catchment in this configuration is very erratic, and the catchment responds with only a very moderate response to increased rainfall. This phenomenon increases significantly during sudden rainfall-runoff events when the response of a poorly stabilised area with a large proportion of intensively used arable land is rapid and pronounced. These results are confirmed in many global studies modelling the behaviour of areas in rainfall-runoff events, such as those of Dakhlalla and Parajuli (2016) for the Mississippi region and Chilkoti et al. (2018).

In the second scenario, the distribution of enclaves in an area corresponding to a traditional agricultural landscape in the early 20th century was simulated. First, a scenario with regular precipitation totals throughout the year and a normal distribution with a peak in the summer months was used. Under this land use and weather pattern configuration, the catchment responded with equalised discharge throughout the year, regardless of increasing precipitation. While there is a short-term increase in discharge in response to higher precipitation, the increase in values is a maximum of 39.01%, and values return to their original magnitude very quickly. This scenario shows the quality of a traditional agricultural landscape comparable to the current configuration of agricultural land in, for example, Austria or Slovenia, which have very similar topographical characteristics to the study site. Thus, the absolute percentage of the land cover of each land type, which is practically identical to the current situation, but rather its spatial distribution, does not play a role in the balance of discharge. In particular, the narrow strips of grassland in the form of gaps separating the individual blocks of arable land play a significant role. In the past, these areas were generally used as grazing areas for small livestock. Due to the potentially increased retention capacity and the more significant presence of water storage reservoirs (13 more reservoirs in the area, with a total area of 3.43 ha), this situation led to a balance of discharges throughout the year. These results are also supported by studies conducted in countries with similar agricultural land arrangements, such as Austria, as mentioned earlier by Grath (2016), Slovenia Glavan and Pintar (2012) or Curk et al. (2020).

The third simulated scenario was the afforestation of the most vulnerable zones according to the soil and slope infiltration capacity. In this scenario, no significant changes occur under regular rainfall activity. Contrary to expectations, strengthening and protecting infiltration zones and displacing intensive arable

farming to only land with favourable slope conditions did not mitigate the catchment response to rainfall-runoff situations associated with spring melt or summer convective rainfall. The discharge reduction predicted in the cumulative totals reached only 49.79%, and the catchment response is still quite abrupt. The simulation result confirms the conclusions of researchers Van der Ploeg et al. (1997) and Pebesma and Kwaadsteniet (1997), who describe the positive effect of grassed and forested sites in infiltration areas on the discharge values, which are reduced due to these management changes. At the same time, there is no significant fluctuation in flow values throughout the year, and peak values decrease during rainfall-runoff events. At the same time, however, the authors draw attention to the extensive use of these grassed areas observed in the simulation.

The last simulated scenario shows the response of the catchment area to the development of the municipalities as they are strategically included in the long-term spatial plans of each municipality. The development mainly foresees an increase in built-up and often associated paved areas. The catchment response to rainfall is compounded by faster runoff from these areas. Contrary to the assumption of the municipality's representatives, there is no significant reduction in discharges in connection with the newly constructed and planned areas of water features in the form of polders and small water reservoirs directly above the village of Velký Rybník. On the contrary, compared to the current situation, there is an increase in discharge by an average of 71.05% (the maximum recorded discharges are almost three times higher). The explanation is practically identical to the historical distribution of the landscape structure simulation results. The absolute percentage representation of water bodies and other landscape enclaves does not play such a role as their exact location and localisation (Curk et al. (2020)).

- RQ2 What is the runoff from the catchment under significantly sub-normal rainfall conditions - drought conditions?

The first simulated scenario modelled the current land use pattern under significantly lower annual rainfall conditions. In this situation, the runoff simulations show a significant reduction in runoff from the catchment, particularly in the summer months, with meagre rainfall totals well below average. The catchment thus responds to a lower capacity to retain water and subsidise the absence of atmospheric precipitation. A significant problem is very high evaporation from areas of intensive agricultural use, but overheating areas with a high proportion of paved areas also play a role (Fang et al., 2020). In this situation, the health of the forest stands, especially related to their species composition, also does not contribute to stabilising the water regime.

The second simulated scenario under low rainfall is a structure corresponding to the state of the landscape at the beginning of the 20th century. Discharge equilibrium is significantly improved compared to the previous simulation under the current catchment configuration. While discharge values also decreased slightly from the normal precipitation condition (by an average of 25.75%), the values remained balanced throughout the simulation, with significantly little response to any sudden convective storms in the summer period. The maximum discharge values achieved are only 15.43% of the customarily achieved maxima. In contrast, the minimum discharges are 50% higher than the typically achieved hydrological minima in the comparison year. The equilibrium of discharges concerning the stable catchment is also described in studies (Prokopova et al., 2019) during the dry season. Particularly crucial to these results is the arrangement of enclaves of wet grassland and water bodies in the landscape, which form a 'reservoir' of water in the soil for times of low rainfall. At the same time, woodlands, which have an increased water retention capacity due to a higher proportion of deciduous trees, are also crucial. Thus, the catchment can increase water storage and retention in rainy episodes and gradually release in drier parts of the year. As a result, the total runoff is balanced throughout the year, and there are no extreme increases or decreases (Lin et al., 2022).

The third simulated scenario is a variant of grassland and forest management on extremely sloping parts and in infiltration vulnerable areas of the catchment. This land configuration should, at least according to the assumptions of the expert panels on drought management, lead to the mitigation of drought impacts in agricultural landscapes and associated problems. Based on simulations, it can be shown that when rainfall is significantly reduced, landscapes with a larger area of grassland and forest cover, mostly in continuous complexes, lead to a levelling of discharges only very sporadically. The longer the period of low rainfall lasts, the more difficult it is for the landscape to cope with it, and discharges fall even in the summer period to the values of the hydrological minimum. With more extended periods of drought, this situation likely leads to the drying up of more exposed watercourses. Discharges have declined by an average of 76.77% compared to normal water levels. These results are confirmed by studies from the Ruscom River in Ontario (Rahman et al., 2010).

The last scenario simulated in the drought impact assessment was the municipal development scenario under the land use planning concept. The situation in the catchment was shown to worsen slightly, especially in terms of runoff from the catchment (Dixon and Earls, 2012). The discharge values decrease throughout the simulated period of low rainfall, reaching minimum hydrological values in late summer and early autumn. However, the abrupt responses to potential rainfall-runoff events differ from the previous scenario, caused mainly by convective precipitation. Due to the higher percentage of dispersed paved areas for housing, transport and industry, the catchment has less capacity to infiltrate the dry land surface. Water discharges away from the catchment very quickly with virtually no benefit, which is reflected even under hydrological drought conditions in the rapid onset of the hydrograph.

- RQ3 What is the runoff from the catchment under significantly above-normal rainfall conditions - wet and flood years?

The first simulation again depicts the behaviour of the catchment in the current configuration of landscape features. However, it responds to highly wet years with higher rainfall-runoff situations this time. The simulations show that the catchment has problems coping with high rainfall events, especially in relatively short periods. Discharges at the closure profile are several per cent higher with each additional rainfall event. These are due to the saturation of the catchment and return to their original values only very slowly after the runoff event has passed. They often fail to reach them due to the additional rainfall subsidy. In this case, the total increase in runoff from the landscape is quantified at 452.96% compared to what was expected. In this configuration, higher rainfall totals are problematic, and there is a sharp increase in discharge values by tens of per cent in a brief period (Maghsood et al., 2019).

The second simulation again shows the response of the catchment in a traditional landscape configuration from approximately one hundred years ago. The catchment in this configuration of landscape elements has an excellent buffering capacity, which causes a significant reduction in discharge virtually regardless of the evolution of rainfall patterns (Jodar-Abellan et al.,

2019). Even with this type of catchment arrangement, individual rainfall-runoff events are evident. A flash flood wave cannot be ruled out during extreme rainfall events and when the catchment is fully saturated, but its occurrence is significantly less likely. The simulations did not capture a similar situation during the simulated rainfall events.

The third simulated scenario shows the response of a catchment with a higher proportion of grassland and woodland. In this case, the assumption of better water management in the landscape is partially fulfilled by managing areas with greater infiltration vulnerability and areas unsuitable for traditional crop production in terms of topography. Although the discharge values are not as balanced as in the previous case, if the rainfall intensity did not reach high values in a short period, the runoff wave was insignificant, as described for the Minnesota catchment by Mori et al. (2021). Discharges decreased slightly (38.87%) compared to the simulated current use over a more extended period.

The last simulated scenario to answer the third research question concerns the development of a community or an increase in the area developed with facilities for recreation, housing, manufacturing, or communication networks. In this case, the response was expected: a significant increase in runoff from the catchment. When the community is not protected by good quality flood protection, the increase in peak discharges over the current terrain configuration when modelling an extreme water year was only an average increase of 165.62% over normal. Similar management functionality in urbanised areas is also described by Purwitaningsiha et al. (2020), who describe a decrease in peak discharges of tens of per cent from regular for large catchments.

A comparison of the results obtained after running all simulations is summarised in the following Figure 4.

- RQ4: Can the model respond to including a flood control polder in the study catchment?

The final research question focused on comparing the model response to the presence of flood protection in the form of a multi-purpose flow-through polder, the parameters of which are described in the Methods chapter. When comparing the simulation of the different types of land use arrangements chosen as simulation scenarios in the selected year with above-normal rainfall, the difference between the simulated flows was satisfactorily significant. If the presence of this reservoir did not protect the community, the increase in peak flows within the total runoff would be 39.17% higher than if the reservoir had already been implemented. At the same time, the total volume of water diverted from the catchment would be significantly higher without this measure in place. Even with this finding, runoff from the basin is still significantly higher than in a typical rainfall year. There is also an expected increase in runoff compared to the current terrain configuration, but also, due to the implemented flood protection measure, this increase is lower. When compared to the runoff during an average rainfall year, without the use of flood protection in the current land use configuration, there would be an increase in total runoff of 452.96%, while in the model scenario with the use of flood protection, on average only 156.35%. The functionality of flood protection in urbanised areas is also described by Mori et al. (2021), who describe a decrease in peak flows by tens of per cent compared to the values recorded for large catchments. In order to confirm the hypothetical functioning of the modelled scenario with flood protection, a comparison of the simulation under the current land use condition, including a localised flood protection polder, was performed for the meteorological conditions of above-normal rainfall in 2017. The polder had already been in operation for under five years and was thus stabilised and fully functional. When comparing the total annual runoff between the actual measured data and the model scenario, it was found that the model deviates from the actual runoff by only 24.15% on average and upwards.

In comparison, the model overestimated the peak flows by 28.46% on average. A comparison of the simulation of a typical summer rainfall-runoff episode under the model solution with and without the inclusion of the polder in the year used in the actual land use scenario for the above-normal rainfall year (Scenario C0) and the simulation already after the implementation of the polder in 2017 is presented in Figure 5). These results show that, similarly to the assessment of Purwitaningsiha (2020), the SWAT model is highly suitable for simulating possible alternative flood protection solutions in the flood protection planning process.

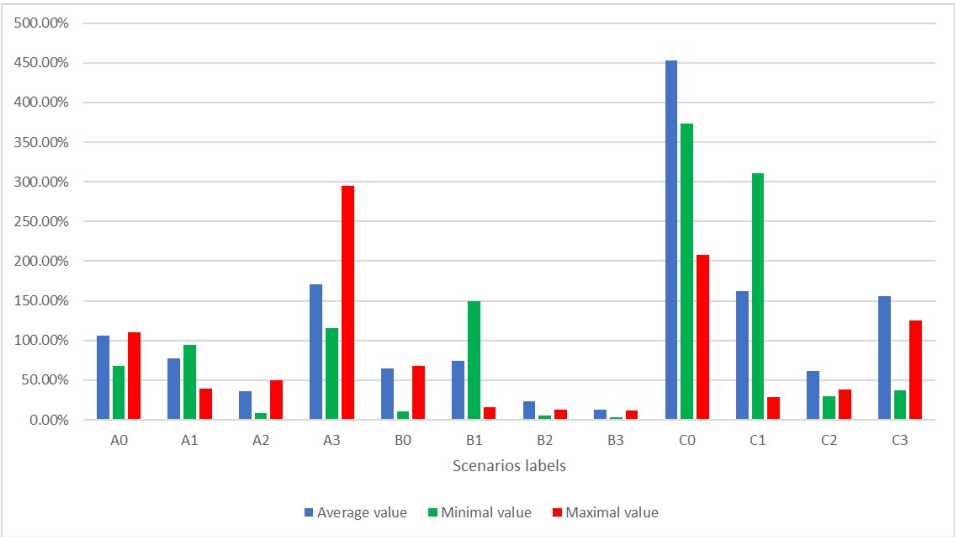


Fig. 4. Comparison of the results of simulations of discharges with the actual measured data from 2009 (Scenarios are labelled following Table 1).

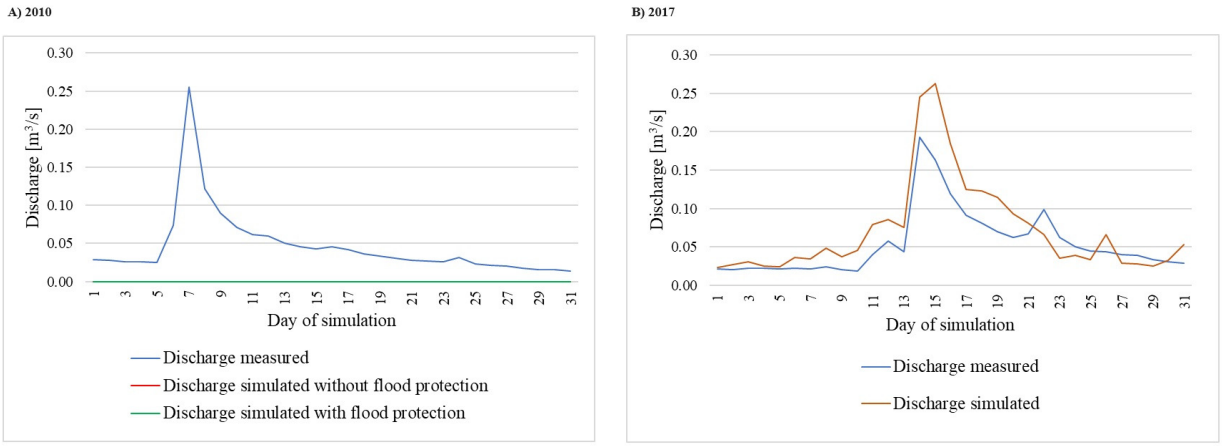


Fig. 5. Comparison of the results of simulations of discharges with the observed discharge from A) 2010 and B) 2017.

CONCLUSIONS

When comparing all simulated scenarios, the absolute magnitude of discharge and total runoff from the catchment is influenced not only by the absolute percentage of each land use type, the health and management of vegetation, or the percentage of hardening of individual areas. It is primarily affected by the configuration of individual areas and enclaves in the landscape. In an average rainfall year, but also when the catchment responds to extremely low or high rainfall events, a land use configuration corresponding to the turn of the 19th and 20th centuries is the most appropriate. This land configuration represents the landscape with a relatively high level of ploughing, which is practically the same or even slightly higher than today, but with a completely different land layout, where individual plots are arranged in the landscape as strips of arable land separated by grassed boundaries. In addition, large grassland areas are distributed around water features so that there is virtually never direct contact between the arable land and the water component. This scenario is very effective in dealing with drought and flooding in the agricultural landscape, but it is not feasible in light of modern farming techniques. The variant resulting from the Czech Ministry of Agriculture's strategy for mitigating the impact of drought in the agricultural landscape is closest to this scenario. However, this scenario is less effective for balancing the discharges. This scenario, however, needs to meet the expectations of the developers, particularly concerning the fight against drought, i.e., in years with subnormal rainfall. The reason may be an inappropriate landscape structure, notwithstanding the significant increase in grassland and forest cover in the catchment area. Contradictory results were then provided by the last simulated scenario resulting from the zoning configuration of the selected site. This scenario proves to be ineffective in terms of addressing the balance of discharges on the catchment.

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