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Evaluation of the SWAT model as an integrated management tool in the Švihov drinking water supply catchment

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Abstract: Švihov dam, the largest drinking water source in the Czech Republic and Central Europe, has problems with eutrophication. The Švihov dam catchment spreads over 1200 km^2 and supplies over 1.5 million people in the capital of Prague and the Central Bohemian region with drinking water. Due to intensive agricultural activities and a lack of wastewater treatment plants in small settlements, the water quality is deteriorating. As a result, corrective measures need to be taken. Technological Agency of the Czech Republic supported this research which proposes different scenarios for a reduction of water quality degradation in the dam. The Trnávka dam watershed was chosen for study purposes as it occupies one quarter of the Švihov dam watershed. Hydrological balance was established using measured data. Point and non-point sources of nutrients were determined by field research and included in a Soil and Water Assessment Tool (SWAT) model. This study aims to propose complex watershed management to improve the state of the environment in the entire area and to reduce eutrophication. Different management practices would reduce nutrient loads of streams and increase water quality which is the critical factor in dam eutrophication. This research brings methodology and systematic approach to integrated management, and can be applied not only for the Švihov dam, but also for other watersheds, including those which function as drinking water supply.

Keywords: hydrological balance; phosphorus balance; river basin management; SWAT

The rapid rise of industry, household consumption, and the intensification of agricultural practices over the past century have led to a significant increase in the volume of discharged sewage with high nutrient content. Since the second half of the 1990s, improvements in farming practices and reduction of nutrient content in municipal waste waters have been achieved through more thorough cleaning, and the sale of detergents and washing powders without phosphates has been encouraged, but these measures appear to be inadequate. In addition, in sparsely populated areas, especially settlements of up to 250 inhabitants, an adequate degree of sewage treatment is not usually provided.

Waters that are loaded with excessive nutrient intake are changing their nutrition (e.g. from oligotrophy to eutrophication) (Smith *et al.* 1999). An essential element of eutrophication is phosphorus and its compounds. An increased input of phosphorus into the basin of the reservoir may result from both point and diffuse sources of pollution. The most frequent accompanying phenomenon in such polluted waters is the massive development of cyanobacteria and green algae (Steinberg & Hartmann 1988; Novotny 2011). This kind of pollution cannot be avoided even for drinking water sources. High concentrations of cyanobacteria and algae in drinking water sources are causing problems in waterworks,

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mainly due to deterioration of organoleptic properties of treated water. Another negative impact is the production of toxic substances that cause health problems (Falconer 1999). If a given drinking water source is affected, its further usability for water purposes is at risk, and if the issue is not resolved, the water source may be lost.

Reducing the input of nutrients into the dam, it is essential to identify the sources of pollution in the river basin. Nutritional elements may come into the river from point sources and diffuse sources of pollution. In order to evaluate and identify different sources of pollution in the river basin, it is necessary to carry out detailed monitoring of the area and to distinguish the share of diffuse and point sources of total pollution. It is essential to apply a sophisticated approach to the problematics of nutrient input. Elimination of point sources of pollution will not guarantee the achievement of the required water quality in the dam, because there is a prevalence of diffuse pollution as well. The most appropriate approach to drinking water supply is limiting the entry of nutrients into the water dam via prevention, as a long-term sustainable way. Technological updates of drinking water treatment plant should not be encouraged when sources of pollution and the way to eliminate them are known.

In order to solve problems with eutrophication in a drinking water supply dam, we chose a representative part of the water catchment area of the Švihov dam, Trnávka dam river basin with a water catchment area of 339.3 km^2 (Figure 1). There are significant watercourses Trnava and Kejtovský stream with the Pacov Wastewater Treatment Plant (WWTP), which is the largest point source in Trnávka dam watershed. The entire catchment area of the Švihov dam covers an area of 1188 km^2 and the chosen catchment area occupies 28% of the entire catchment area and is intensively farmed and populated. This research deals in particular with the identification of sources of pollution by reactive forms of phosphorus and nitrogen. It serves as a basic assumption for the formulation of corrective measures to achieve a good ecological and chemical status of surface water. (Novotny 2011)

METHODS

For modelling purposes, we used the Soil and Water Assessment Tool (SWAT) model. It is a continuous-time, semi-distributed, process-based river basin model which was developed to quantify the impact of land management practices in large complex watersheds (Arnold *et al.* 2012). Specific information about topography, land use, soil types and weather was used

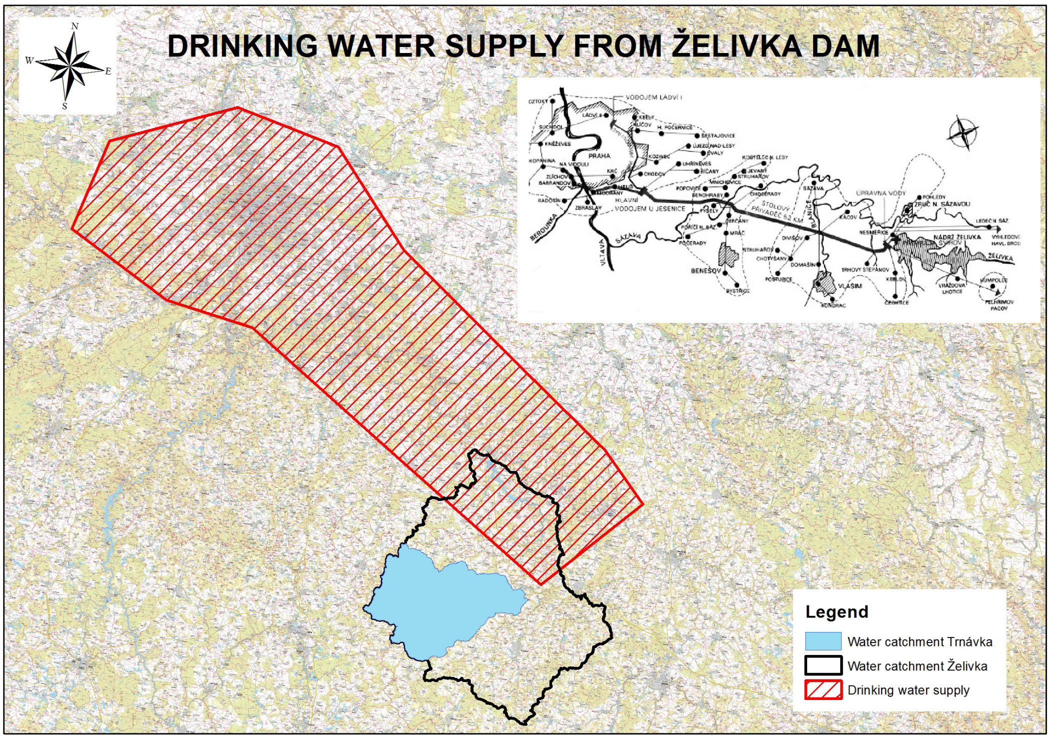

Figure 1. Drinking water supply from the Želivka dam

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to create hydrological response units (HRUs) – unique combination of these parameters specifying a characteristic part of the watershed (Arnold *et al.* 2012).

After creating HRUs, more detailed information was entered into the model to cover point sources, non-point sources and management practices. These were measured during a three-year monitoring period when hundreds of samples were taken from streams, analysed and used for calibration purposes. Phosphorus and nitrogen concentrations were measured as well as water flow. The annual amount of N and P was calculated from simple Eq. (1).

$$M_{\mathrm{P,\,N}} = C_{\mathrm{P,\,N}} \times Qy \qquad (1)$$

where:

$M_{\mathrm{P,\,N}}$ – final annual amount of phosphorus or nitrogen (kg)

$C_{\mathrm{P,\,N}}$ – average annual concentration of phosphorus or nitrogen in stream ($\mathrm{kg/m^3}$)

Qy – total annual water outflow ($\mathrm{m^3}$)

Sources of pollution – inputs. No particular procedure for the quantification of phosphorus and nitrogen input into the overall balance was used for forested areas. For the restoration of forested areas (in terms of P and N deposition in biomass), the 60 years period was calculated. As the forests form a significant part of the Trnávka dam watershed, they play an essential role in stabilizing the total balance of P and N, but in the long-term balance, they do not constitute a significant source of P and N in the outflow of these areas.

Individual input values for WWTPs were obtained from their operators. A particular case is the Pacov WWTP, where the impact of the reconstruction of this treatment plant on water quality in the Kejtovský stream influenced the total balance of P and N as flow into the Trnávka dam. To reduce P and N in runoff from these point sources, different management simulations were executed and hypothetical data series (based on the best available technologies) were calculated at the outflows from individual WWTP.

The basic idea of determining unidentified diffuse sources of nutrients was to analyse the number of inhabitants in individual smaller settlements not equipped with central wastewater treatment technology. The analysis was conducted for both permanent residents and seasonal visitors (this is a relatively important recreational area with seasonal fluctuations in the number of equivalent inhabitants (EI)). According to the Plan of Public Utilities Development of the Vysočina region, individual WWTPs were analysed. For the overall estimation of P and N inputs from these sources, the conversion of the daily values of pollution output for one EI was calculated, which has been adjusted in terms of prevailing individual purification technologies, in particular, three-chamber septic tanks. The calculated values were used as P and N sub-watershed inputs.

For diffuse agricultural resources, the calculation of P and N inputs from areas with agriculture, the standard fertilization values for individual crops in the Land Parcel Information System (LPIS) layout were used. In order to verify the accuracy of the data, inputs in the database received from individual economic entities were processed for more than 20% of the area. Crop rotation corresponds to real conditions on a global scale.

Atmospheric deposition values were not calculated due to their negligible share in the overall balance of the model.

Control measurements of individual sub-basins in Trnávka dam watershed ‒ monitoring network. A water quality monitoring system was established for the runoff from individual sub-basins. Hundreds of instream samples were collected and analysed (Figure 2). Together with data from WWTPs and agricultural companies (Figure 3), this data was used for the calculation of mass balance.

All data, including inputs and outputs, were processed in open-source environment Q-GIS (Quantum GIS), SWAT, Q-SWAT (Q-GIS interface for SWAT) and SWAT-CUP (calibration/uncertainty or sensitivity program interface for SWAT). In the Trnávka dam, point sources, change of land use, diffuse agricultural sources and unidentified diffuse sources were determined after the evaluation of individual partial simulations.

Scenarios

In order to design comprehensive management of the Trnávka dam watershed, four scenarios were defined on the basis of the calibrated hydrological model. The baseline scenario was verified on measured data (measured by Povodí Vltavy (PVL), State Enterprise) at the watershed outlet. The impact of using the best available technologies for wastewater treatment, reduction of fertilizer amounts used in a crop cycle and afforestation of all agricultural areas (excluding grassland) are individual scenarios used for designing the complex management.

Basic scenario – real state. The basic scenario of nitrogen and phosphorus balance reflects the

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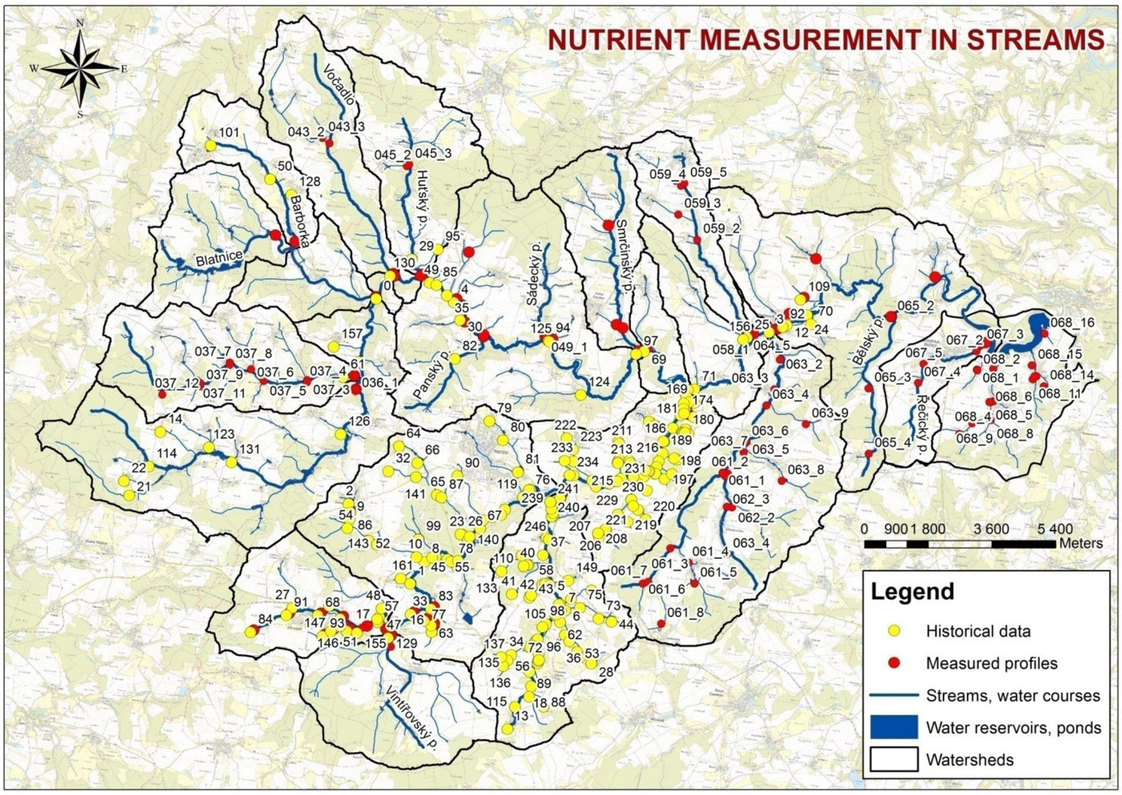

Figure 2. Nutrient measurement in streams

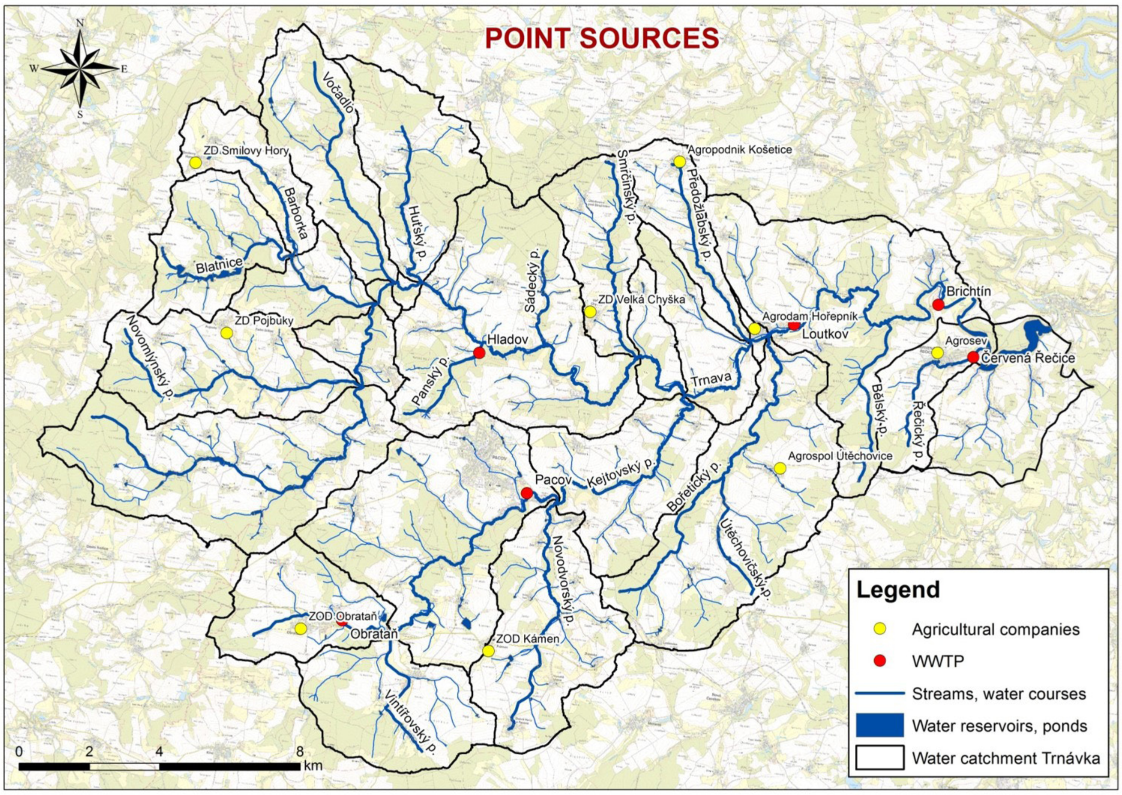

Figure 3. Point sources in the Trnávka dam watershed

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real conditions in the Trnávka dam watershed. The inputs are reflecting the actual conditions in the catchment area, not only in point sources, but also in agricultural and unidentified diffusion sources of pollution. The model was calibrated according to the measured N and P concentrations carried out by the PVL at the inlet to the Trnávka dam and the data were verified accordingly to the measured concentrations from the own monitoring network at the individual sub-basins. The Balance of phosphorus shows values corresponding to assumptions in this management method (Hanák & Ryšavý 2015).

Scenario 1. The scenario is based on the real state when values based on the best available technologies were used for point and diffuse unidentified sources of pollution. These values were verified at the Pacov WWTP during the testing of the pilot technology for phosphorus reduction at the WWTP outflow. These values were transposed to point and diffuse unidentified sources of pollution according to the quantity of EI in each settlement. The simulation uses the best available technologies for waste water treatment in all municipalities and settlements in the Trnávka dam watershed area, even when there is no WWTP.

Scenario 2. Another simulated scenario was a reduction of the amount of applied fertilizer in the agricultural part of the Trnávka dam watershed. This model is based on Scenario 1, the amount of applied fertilizer was reduced by 50%, and applied according to land use.

Comprehensive management. Complex management is based on scenarios 1 and 2, when the introduction of wetlands in order to reduce the flow of nutrients into the flow (Duras 2015) was simulated by a change of land use. Wetlands were designed in the areas of floodplains, which gives them enough water sources to prosper.

Scenario – VISION. According to an example of the management of the water catchment areas of the city of Vienna, where the entire drinking water catchment area was afforested at the end of the last century, and these water resources have long-term excellent water quality. Simulation of afforestation of the whole agricultural land in the Trnávka dam watershed was carried out to reduce erosion, reduce nutrients in streams and increase precipitation storage (Kim *et al*. 2017). Scenario 1 (best possible technologies) was retained.

Table 1. Types of input data

Land use	Soil	Slope (%)
RNGB	Eutric Cambisol	0–3.0
PAST	Gleyic Fluvisol	3.0–7.0
URLD	Dystric Cambisol	7.0–0.0
AGRL	Stagno-gleyic Cambisol	10.0–max
FRSE	Dystric Planosol	
FRST	Eutric Gleysol	
UIDU	Histo-humic Gleysol	

RNGB – range scrubland; PAST – pasture/hay; URLD – low-density urban land use; AGRL – agriculture generic; FRSE – evergreen forest; FRST – mixed forest; UIDU – urban industrial

RESULTS AND DISCUSSION

The area of the watershed was divided into 34 sub-basins using Q-GIS, which were then subdivided into 1002 HRUs combining seven types of soils, seven types of land use and four types of slope (Table 1). The most common threshold for large watershed modelling using SWAT was 10/10/10% (Larose *et al.* 2007; Meng *et al.* 2010; Srinivasan *et al.* 2010; EPA 2013). The threshold of 0/0/5% was used due to a smaller watershed and the need of having land use, soils and slopes in detail.

Model calibration and validation were performed for monthly outflow data. Measured data were from the years 2007–2014, and the data set was split into two three-year sets. The years 2011–2014 were used for

Table 2. Phosphorus concentrations

	Scenario			Complex management	Scenario VISION	PVL measurement
	basic	1	2			
P total (kg/year)	5464	3608	2419	1613	391	5350
Ø total concentration (mg/l)	0.08771	0.05792	0.03883	0.02589	0.00628	0.08782
Diffuse sources (kg/year)	3542	3542	2353	1547	325	
Point sources (kg/year)	1922	66	66	66	66	

PVL – Povodí Vltavy, State Enterprise

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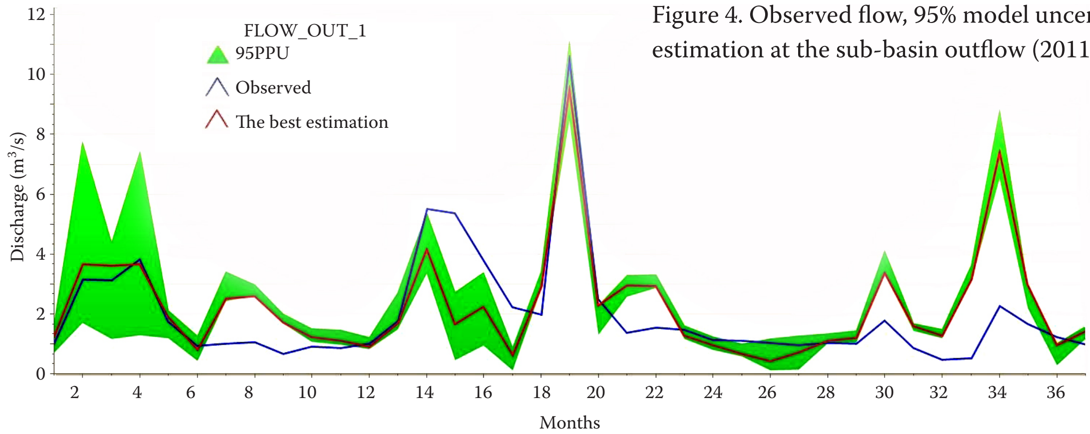

Figure 4. Observed flow, 95% model uncertainty, and best estimation at the sub-basin outflow (2011–2014)

calibration purposes and the years 2007–2010 were used for validation purposes (Arnold *et al.* 2012).

Parameter sensitivity was performed using SUFI-2 (Sequential Uncertainty Fitting Version 2) to assess what parameters are sensitive to a change (Arnold *et al.* 2000; Eckhardt & Arnold 2001; Santhi *et al.* 2001, 2003; Bracmort *et al.* 2006). In previous studies, the most sensitive parameter was ground water delay, when the use of tile drainages resulted in faster outflow from the top soil profile.

With Kling–Gupta efficiency (KGE) equal to 0.69, goodness of fit (R^2) equal to 0.53 and Nash-Sutcliffe (NS) coefficient 0.44 which according to Engel *et al.* (2007) is a satisfactory result (Figure 4). For better performance of the SWAT model, tile drainages were calculated, improving the overall hydrological balance. According to Koch *et al.* (2012), eliminating tile drainages can lead to underestimation of the total flow. However, subsurface tile drainages can have an essential effect on phosphorus transportation (Qi & Qi 2017). Monthly data were measured with insufficient accuracy and, therefore, it was difficult to obtain better calibration results for a watershed of this size. The daily data, recalculated into monthly averages, would make the model perform better, with a possibility of more accurate calibration.

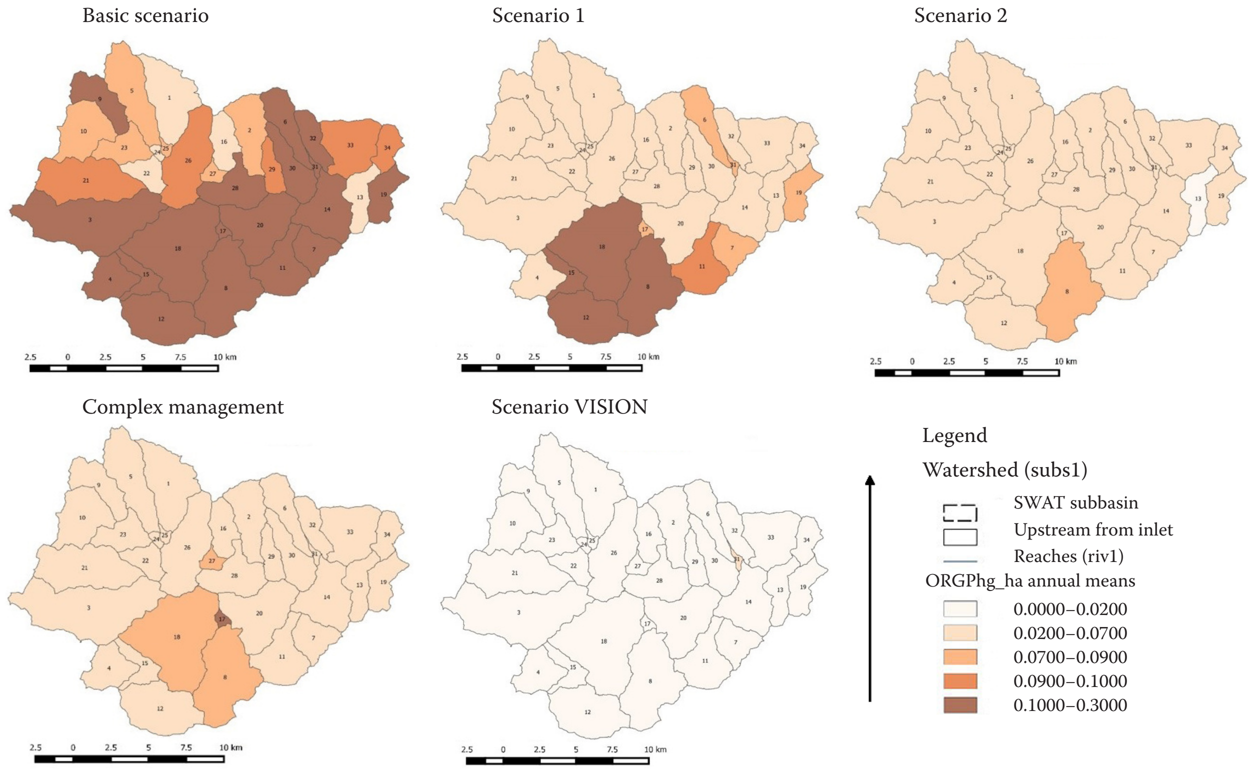

Figure 5. Scenarios – phosphorus outflow from sub-basins (kg/ha)

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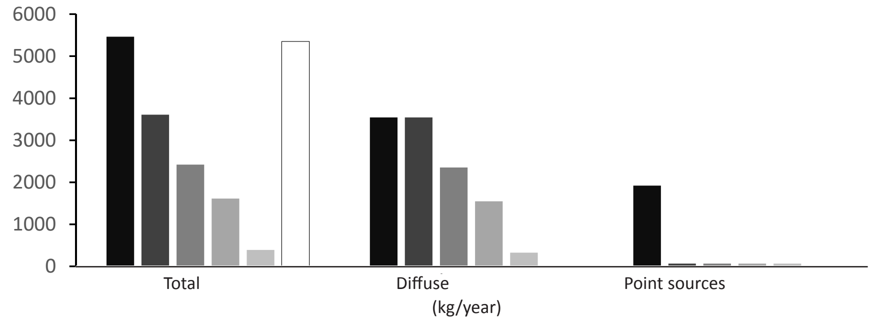

	Total	Diffuse	Point sources
■ Basic Scenario	5464	3542	1922
■ Scenario 1	3608	3542	66
■ Scenario 2	2419	2353	66
■ Complex Management	1613	1547	66
■ Scenario - VIZION	391	325	66
□ PVL	5350		

Figure 6. Comparison of different scenarios according to phosphorus concentrations at the watershed outlet

After calibration, different scenarios were explored and the outputs are summarized in Table 2. For comparison, data measured by Povodí Vltavy were added as well. The basic real-world simulation was performed for calibration purposes and to enable to calculate different phosphorus concentrations by comparing different strategies – scenarios (Figures 5 and 6). By ensuring the best available technologies for wastewater treatment, including phosphorus outflow, even for settlements that do not yet have any effective phosphorus removal (Scenario 1), there was a dramatic reduction in the phosphorus concentration, and hence, in the total annual amount of phosphorus. According to this scenario, the phosphorus concentration is reduced from 0.0877 to 0.0579 mg/l. At the same time, reducing the amount of fertilizer applied onto agricultural land (Scenario 2), there is a further significant decrease in total annual inputs, which is reflected by a reduction of the total phosphorus concentration to 0.0388 mg/l. By afforestation of agricultural parcels (VISION Scenario), there is a further significant drop in nitrogen and phosphorus outflow to 0.00628 mg/l. This scenario drastically decreasing phosphorus is the most stable in the long run, and at the same time, it eliminates some other negative effects, for example, pesticides and erosion. The design of the complex management uses Scenarios 1 and 2, with the simultaneous construction of wetlands in the floodplains. Wetlands have been chosen as a stabilizing element of the landscape, which at the same time reduces the amount of nutrients transported by sediment. The final total phosphorus amount is 1613 kg/year, which is 0.0259 mg/l on the inflow to the Trnávka dam. This concentration has a high chance to eliminate the risk of eutrophication.

CONCLUSIONS

Running the SWAT model raised additional questions about the quality of input data. We can conclude that having low-quality input data may result in a decreased possibility of calibrating the model properly and achieving high quality results (Malago *et al.* 2015). A number of partial simulations has been carried out. After evaluating these outputs, a scenario based on the real possibilities of its implementation was chosen for the complex management proposal. The cost of its implementation (investment, human resources, organizational, operational, etc.) has not been calculated given the fact that the issue of phosphorus, as the main eutrophication factor, is not the only problem in the water reservoir basin. Afforestation of agricultural land might not make sense to farmers, but it is a great way to reduce nutrients, even with only partial afforestation. Other substances of anthropogenic origin entering the watercourses (i.e., reservoirs), such as pesticides and pharmaceuticals, represent (for sources of drinking water) a much more complex problem than simple eutrophication. For the river basin management to be called complex, it must include these already known negative phenomena. The results of this study, addressing the problem of eutrophication, should be part of the design of comprehensive watershed management of the Švihov reservoir. The approach of progressive elimination of known causes of water quality degradation, including eutrophication, should take precedence

https://doi.org/10.17221/46/2018-SWR

and priority, or at least, the same weight before starting an action to remove the consequences directly in water treatment plants.

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