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A modeling framework to assess water and nitrate balances in the Western Bug river basin, Ukraine

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Abstract. The objective of this study was to assess the utility of the eco-hydrological SWAT model (Soil and Water Assessment Tool, Arnold et al., 1998) for representing water balance and nitrate fluxes given limited input and calibration data. The investigated catchment is located in Western Ukraine with an area of approximately 2616 km^2. Land use is currently dominated by agriculture with significant areas of pasture, and has undergone a high degree of changes in land-use and agricultural practice since the end of the Soviet Union. Model application produced a fitted water balance (calibration: $R^2 = 0.52$, NS = 0.46; validation: $R^2 = 0.47$, NS = 0.51) and plausible ranges and dynamics of nitrate in stream loadings. Groundwater parameters were found to be highly sensitive. The results indicate that SWAT is an appropriate tool for water resource investigations in the Western Bug catchment, and can provide a useful tool for further ecohydrologic research in the region (i.e. diffuse pollution impacts).

1 Introduction

The aim of the Water Framework Directive is to achieve clean water across the European Union. Under this directive, water management is based on river basins (rather than administrative boundaries), and as a result some watersheds covered by the Directive are partially contained within non-EU countries. The Western Bug basin located between the north-western part of Ukraine, south-western Belarus and the central eastern part of Poland is an example of one of these cross-border watersheds. The Western Bug is the second largest tributary of the Vistula which empties into the Baltic Sea. The political transformations associated with the dissolution of the Soviet Union resulted in significant changes in and cover and land-management practices in the Western Bug watershed after Ukrainian independence in 1991. (Schanze et al., 2012). Due to out-of-date sewage treatment infrastructure as well as diffuse pollution sources from agricultural activities, the Western Bug river basin is currently experiencing pronounced pollution of its surface water bodies (cf. Ertel et al., 2012). Therefore, there is a need to adapt land management to minimize leaching of nutrients and other chemicals while taking into account the complexity of the economic, social, and ecological processes. The integrated project IWAS "International Water Research Alliance of Saxony – Water Research in the Ukraine" aims to contribute to an Integrated Water Resources Management approach in hydrologically sensitive regions by developing specific system solutions as a response to some of the most pressing water-related problems of our time. Within the IWAS Framework a IWAS-Toolbox is being developed to combine and extend existing modeling software in order to address coupled processes in the hydrosphere, especially for the analysis of hydrological systems in sensitive regions (Kalbacher et al., 2012). Furthermore, this Toolbox will allow a more realistic picture of hydro-systems to be developed; incrementally increasing the degree of process complexity and number of available tools for the integration of changing natural and socio-economic boundary conditions, such as climate change, land use or future population growth (Kalbacher et al., 2012). As a contribution to this Framework, the Soil Water Assessment Tool (SWAT) was applied to simulate water and matter fluxes in the catchment area.

The overall aim of our working group was to assess how pollution from diffuse sources has impacted water quality in the Western Bug catchment by means of spatially distributed water and matter modeling. The objective of this study is to assess the applicability of the eco-hydrological model SWAT for representing water balance and nitrate fluxes given limited input and calibration data.

2 Methods and material

2.1 Study site

The total area of the Western Bug river basin is 39 400 km^2, which is 19.3 % of the Vistula basin. The total length of the river is 755 km, of which 184 km are located on Ukrainian territory and further 185 km mark the border between Ukraine and Poland (TACIS, 2001). In our work we focus on the Ukrainian portion of the Bug river basin until the Dobrotvir Reservoir. Therefore, we denominated the watershed in focus of Dobrotvir catchment area. The study area (Fig. 1), covering about 2616 km^2, is predominantly a rolling plain with elevations between 200–250 m, which has a hilly topography and elevations of 300–400 m at its western and southern periphery (Schanze et al., 2012), a temperate continental climate with an average precipitation of 800 mm per year and an average temperature of 7.1 °C. Highly cracked and karsted limestone, marls and loess from the Upper Cretaceous form the hydrogeological structure of the Dobrotvir catchment (Terekhanova, 2009).

Due to the presence of fertile soils, this area underwent large scale deforestation and replacement of forests with agricultural activities currently occupying approximately half of the catchment's area (Tavares Wahren et al., 2012). There is one important tributary in the eastern section of the watershed, the Poltva, which flows through L'viv, the largest city in the Bug catchment with a population of approximately 750 000. Within the study area, nutrients enter the river systems from agricultural activities and from obsolete or overloaded waste water treatment plants (WWTPs) which impairs surface water quality. In contrast to the poor water quality status, the river's hydromorphology is primarily of good quality for large stretches (Zingstra, et al., 2009; Ertel et al., 2012; Scheifhacken et al., 2012).

2.2 Data availability and time period

Lack of data availability and poor data reliability are major issues confronting environmental research in the Ukraine (Blumensaat et al., 2012; Tavares Wahren et al., 2012). In our previous work (Tavares Wahren et al., 2012) we dealt with data limitations due to limited spatially distributed soil information by applying a fuzzy-logic mode to predict soil spatial attributes. In this research paper we continue to address data limitation issues by evaluating the data adequacy

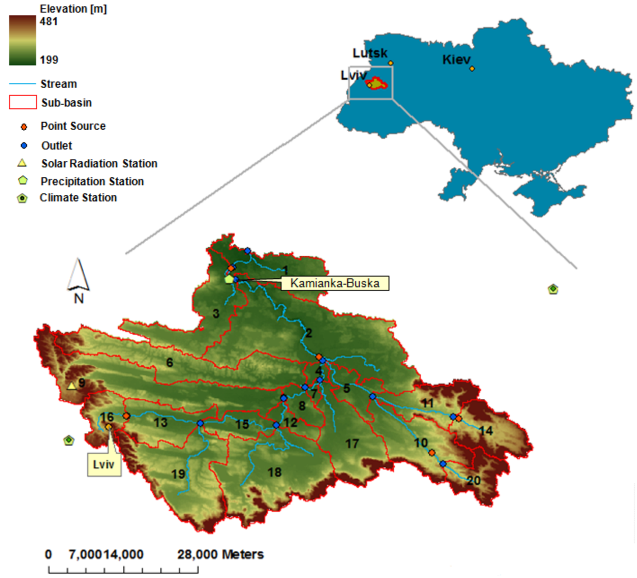

Fig. 1. Dobrotvir catchment study area in Western Ukraine, meteorological stations location and watershed delineation.

for representation of diffuse pollution sources and to analyze the feasibility of future efforts.

A common constraint to model development and verification is that water quality and discharge data are often not simultaneously collected at a temporal/spatial resolution which is useful for analysis. This situation was the case for this study; with only the monitoring point Kamianka-Buzka having both daily discharge measurements and water quality measurements available. A further limitation is that the water quality measurements were conducted from only once per month to once per quarter year. Further, there were four different institutions responsible for the monitoring of water quality throughout the period from 1978 to 2009. As an example for the recorded data, the empirical distribution function of ammonium based on different measurement campaigns during 1978 to 2009 is shown in Fig. 2. It is therefore unclear how much of the observed temporal dynamics in water quality is due to changes in land-use and system dynamics caused by the political turnover, and how much is due to the measurement technique of each institution. Table 1 presents the input data used by the model in the Dobrotvir catchment. Further constrains to the modeling process are due to that the presence of only one precipitation station within the study area, and by the lack of information available regarding to the karst aquifer underneath our catchment.

The study period covers 1978 to 2010, which experienced a significant politic turnover which led to a series of changes which ultimately affected the catchment's hydrological processes and matter fluxes. The socio-economic modifications experienced resulted in dramatic agricultural practice modifications with rapid land-use changes and decreases in fertilizer application. The import of mineral fertilizers and forage

Table 1. Overview of input data for hydrological and nutrient modeling.

Data	Year	Resolution	Obtained from
Digital elevation model	–	30 m	METI and NASA: ASTER GDEM (2009)
Land cover	1989	15 × 15 m	Landsat-7 ETM+, cf. Schanze et al. (2012)
Soil	–	1 : 200 000	Krupskyi M.K. L'viv Land Planning Institute, cf. Tavares Wahren et al. (2012)
Climate data (temperature, precipitation, wind speed, humidity, sunshine duration)	1971–2010	Time series – daily values	ECA&D (2010) and NOAA (2011); Climate Station University L'viv
Stream flow	1980–1998; 2006–2010	Time series – daily values	Hydrometeorological Services Lviv
Water quality	1978–2009	Daily values Irregular periodicity	cf. Fig. 2
Sewage disposal	1976–1986	Annual averages	Vodokanal L'viv

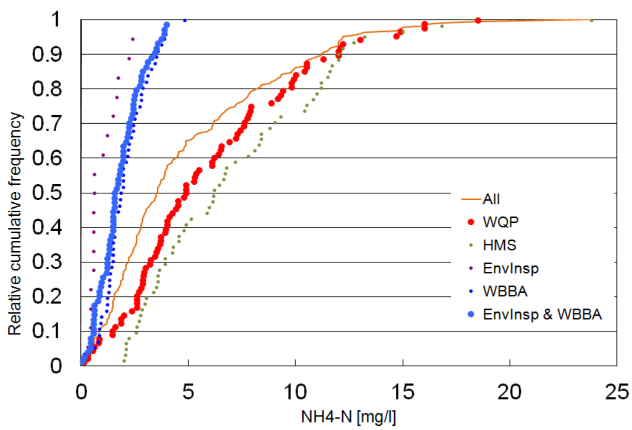

Fig. 2. Empirical distribution function of ammonium daily measurements for the different monitoring campaigns. Legend: WQP = Water Quality Project (monitoring campaign: 1980–1990); HMS = Hydro- Meteorological Services (monitoring campaign: 1990–1995); WBBA = Western Bug Basin Authority (monitoring campaign: 1994–2008) and EnvInsp = Environmental Inspectorate (monitoring campaign: 2001–2008).

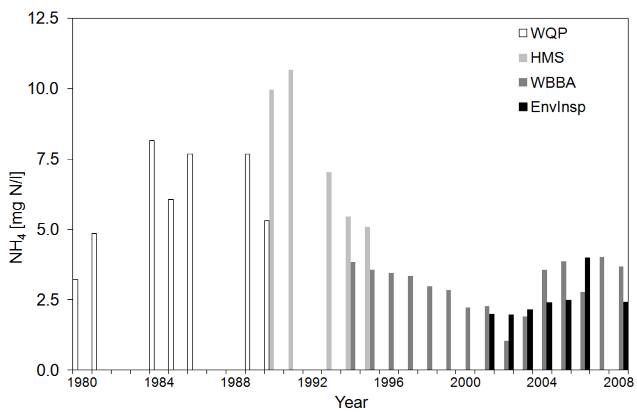

Fig. 3. Water quality improvement after the political turnover. The example of ammonium concentration year average at the Kamianka-Buzka outlet. Different monitoring campaigns. Legend: WQP = Water Quality Project; HMS = Hydro- Meteorological Services; WBBA = Western Bug Basin Authority and EnvInsp = Environmental Inspectorate.

was almost entirely eliminated, and the extensive slaughtering of livestock reduced the amount of available manure (Stalnacke et al., 2003). These changes are representative of the agricultural dynamics observed in many other eastern European countries undergoing similar transitions during this time period (Mander et al., 2000; Pekarova and Pekar, 1996). Similar changes also occurred in the former German Democratic Republic, as the reunification of Germany led to fundamental structural changes in agriculture (Meissner et al., 1998). These studies show that the changes brought about by the political turnover inevitably affected the nutrient export to water bodies. Similar changes can be seen in the Ukraine, such as in the Dobrotvir catchment, where a rapid improvement in water quality can be observed after 1993 (Fig. 3). In more recent years the continued reorganization of agriculture has led to increased fertilizer usage and therefore to higher nutrient concentrations. Since significant changes in nutrient fluxes occur after 1991 with the collapse of organized agriculture, we chose to perform model calibration and validation for the period until the dissolution of the Soviet Union, from 1980 to 1985 and from 1986 to 1990 respectively. Therefore, the modeling work here presented focuses on the period 1980 to 1990.

2.3 Eco-hydrological model setup and calibration

SWAT is a basin-scale, semi-distributed, and continuous-time model that operates on a daily time step. It was designed to simulate the impact of various agricultural management practices on water, sediment, and nutrients in large and complex watersheds, over long periods of time (Arnold et al., 1998; Neitsch et al., 2005). Main model components consist

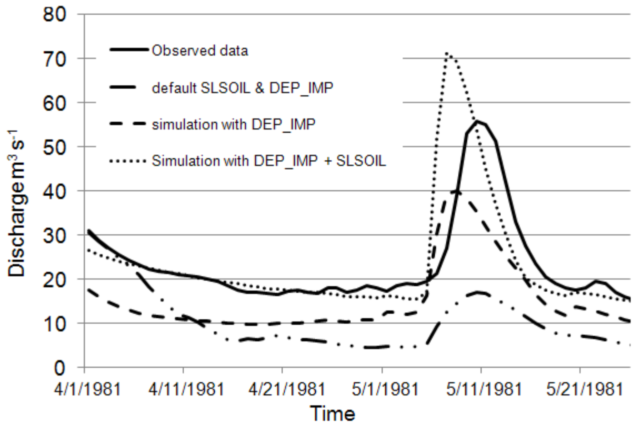

Fig. 4. Comparison of 3 model runs during the calibration process: default values for the parameters SLSOIL and DEP_IMP; DEP_IMP = 1500 (mm) and DEP_IMP = 150 (mm) + SLSOIL = 20 (m). DEP_IMP = Depth of impervious layer for perched water tables in mm; SLSOIL = Slope length for lateral subsurface flow in m.

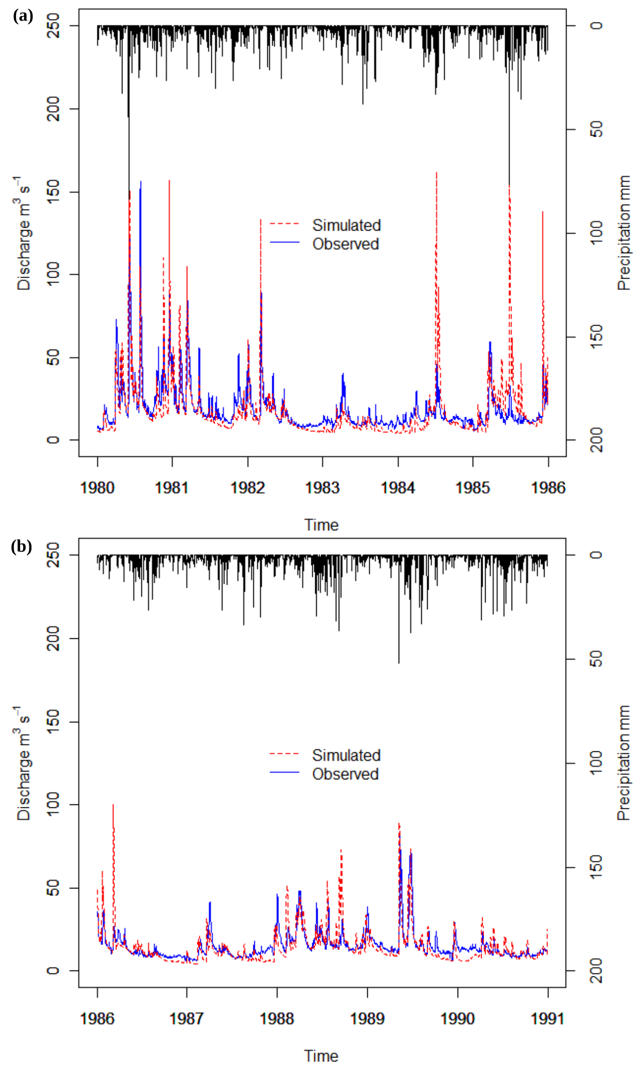

Fig. 5. (a) Comparison of daily observed and simulated discharge during the calibration (1980–1985) in the Dobrotvir catchment area at the gauge Kamianka-Buzka ($R^2 = 0.52$, NS = 0.46). **(b)** Comparison of daily observed and simulated discharge during the validation period (1986–1990) in the Dobrotvir catchment area at the gauge Kamianka-Buzka ($R^2 = 0.47$, NS = 0.51).

of weather, hydrology, soil temperature, plant growth, nutrients, pesticides, land management, bacteria and pathogens (Arnold et al., 1998; Neitsch et al., 2005; Gassman et al., 2007). The majority of soil management practices can be simulated in SWAT through direct changes in parameter values (Ulrich and Volk, 2009). Many studies have used SWAT to assess the effects of land use change and management practices (Shanti et al., 2001; Ulrich and Volk, 2009; Lam et al., 2010). SWAT monitors five different pools of nitrogen in soils: two inorganic (ammonium, NH_4^+, and nitrate, NO_3^-) and three organic; fresh organic nitrogen associated with crop residue and microbial biomass, and active and stable organic nitrogen associated with soil humus (Ulrich and Volk, 2009). Nitrogen is added to the soil through fertilizer, manure or residue application, fixation by bacteria, and precipitation (Neitsch et al., 2002). Nitrogen losses occur through plant uptake, transport with surface runoff, lateral flow, percolation and with eroded sediment (Neitsch et al., 2002; Ulrich and Volk, 2009). In this study, we applied ArcSWAT version 2009.93.7b in the ArcGIS (version 9.3) environment.

The Dobrotvir catchment was divided into 20 sub-basins, and calibration and validation of the water balance was conducted using data from the gauge at Kamianka-Buzka. For the period until 1991, we assumed a traditional agricultural management scheme; including corn silage, wheat, barley, sugar beet and potato cultivation. Conventional plough tillage and disk bedder operations were applied. Both daily fresh and mineral fertilizers were applied to the agricultural field according to the approach of Pospelova (1997), Pospelova and Schinke (1997) and von Cramon-Taubadel and Striewe (1999).

As in other groundwater-influenced lowland regions, drainage systems are important landscape features, which have a major impact on hydrological flow pathways (Stone and Krishnappan, 2002). Kiesel et al. (2010) show the importance of taking such systems in hydrological modeling by comparing how flow components were affected through the incorporation of drainage in the model setup. Drainage system distributions in the study catchment were analyzed by Terekhanova (2009). Based on this spatial distribution, drainage systems were applied to all agricultural and pasture land-use classes.

We added five point sources to the model to represent the five waste water treatment plants (WWTPs) present in

Table 2. SWAT parameters used for calibration, fitted values and sensitivity statistics (downward sensitivity increase).

Parameter (SWAT IO 2009 manual, Arnold et al., 2011)	Fitted value	t-Stat	P-value
Minimum snowmelt rate (mm H_2O/°C day)	1.555	0.029	0.976
Groundwater recession coefficient (days)	0.114	0.117	0.906
Time to drain soil to field capacity (h)*	24	0.362	0.717
Lateral flow travel time (days)	29	−0.413	0.679
Threshold depth of water in the shallow aquifer for movement to the unsatured zone to occur (mm H_2O)	202	0.421	0.673
Plant uptake compensation factor	1	−0.455	0.649
Maximum snowmelt rate (mm H_2O/°C day)	8.2	−0.616	0.537
Snow melt base temperature (°C)	−0.8	0.766	0.443
Depth to impervious layer in soil profile (mm)	259	1.156	0.247
Initial SCS runoff curve number for moisture condition II[b]	0.161	−1.515	0.129
Depth to subsurface drain (mm)[a]	722	−1.800	0.072
Capillary rise coefficient	0.12	−1.862	0.063
Drain tile lag time (h)[a]	10	−2.318	0.021
Soil evaporation compensation factor	0.23	2.927	0.003
Groundwater recession coefficient for bank storage (days)	0.421	3.106	0.001
Effective hydraulic conductivity in the main channel (mm h^{-1})	74	−3.645	0.000
Minimum snow water content that corresponds to 100 % snow cover (SNOCOVMX) (mm H_2O)	116	3.704	0.000
Fraction of snow volume represented by SNOCOVMX that represents 50 % snow cover	0.3	−3.903	0.000
Depth of impervious layer for perched water tables (DEP_IMP) (mm)	902	7.738	0.000
Slope length for lateral subsurface flow (SLSOIL) (m)	14	−13.323	0.000
Maximum canopy storage (mm H_2O)	6	21.029	0.000
Groundwater delay time (days)	447	−21.871	0.000
Threshold depth of water in the shallow aquifer for return flow to occur (GWQMN) (mm H_2O)	51	−31.012	0.000

[a] Only applied to drained HRU's. [b] Initial parameter value is multiplied by (1+ a given value) (Abbaspour, 2007).

the catchment. However, introduction of only the existing WWTPs is not adequate to represent human pollution since a large part of the population is not connected to the WWTP network. Therefore, a virtual fertilizer application to urban areas which do not surround the WWTPs was carried out.

The Sequential Uncertainty Fitting, ver. 2 (SUFI-2) procedure of Abbaspour (2007) was used for calibration and sensitivity analysis, which has been shown by numerous studies to be an efficient method for watershed model calibration (Abbaspour et al., 2007; Schuol et al., 2008; Faramarzi et al., 2009). For the auto-calibration process the parameters listed in Table 2 were included based on the sensitivity analysis. The t-stat value provides a measure of sensitivity whereas the P-value determines the significance of the sensitivity (Abbaspour, 2007). Value ranges for the selected parameters were based on field surveys (e.g. Tavares Wahren et al., 2012), local expert knowledge, and literature review (e.g. Spruill et al., 2000; Terekhanova, 2009; Ulrich and Volk, 2009).

3 Results

3.1 Parameterization and sensitivity analysis

The parameter controlling groundwater flow from the shallow aquifer to the reach was the most sensitive parameter in model calibration, followed by the groundwater delay time parameter. The importance of the groundwater parameters is not surprising due to the hydrogeological characteristics of the watershed. Similar results have been found in previous SWAT studies dealing with groundwater influenced catchments (Holvoet et al., 2005; Schmalz and Fohrer, 2009; Kiesel et al., 2010). In the SWAT model, water balance is represented by several storage volumes, including: canopy storage, snow, soil profile, shallow aquifer, and deep aquifer (Eckhardt et al., 2002). Therefore, it is reasonable that parameters directly related to storage components will have a high sensitivity. Soil related parameters were parameterized according to previous field campaigns (cf. Tavares Wahren et al., 2012). As shown in Fig. 4, significant improvement in model performance occurred when parameters were included to account for the "Depth of impervious layer for perched water tables in mm" (DEP_IMP) and "Slope length

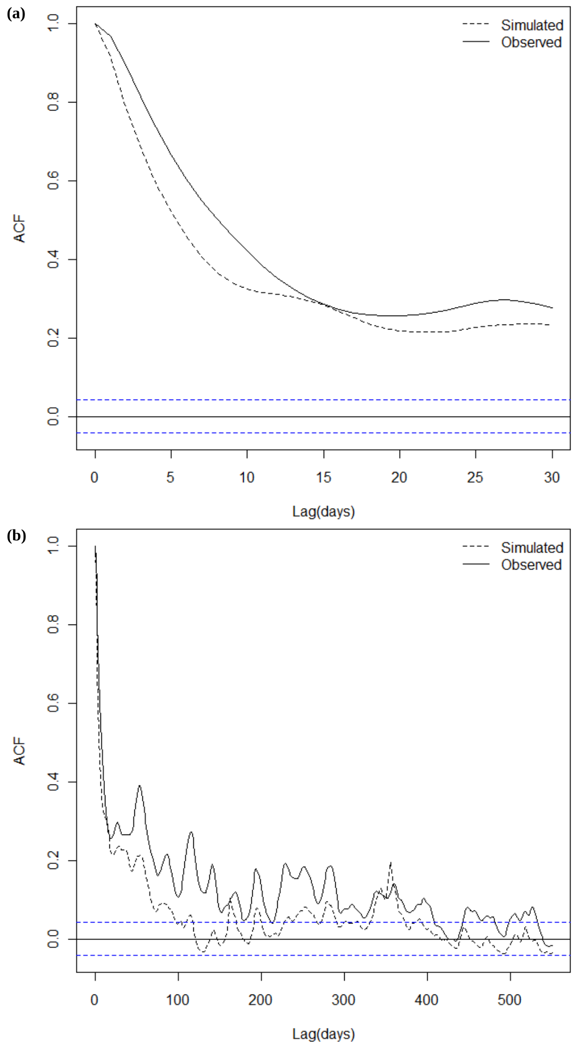

Fig. 6. Autocorrelation Function (ACF) of daily observed and simulated discharge values, during the calibration period 1980 to 1985, for the gauge Kamianka-Buzka, Dobrotvir catchment area, for a time lag of **(a)** 30 days and **(b)** 550 days. Dashed lines depict the 95 % confidence intervals.

for lateral subsurface flow in m" (SLSOIL). Inclusion of these parameters allows for representation of a perched water table which enables the regulation of water percolating out of the soil profile. The default parameterization of SWAT assumes slope length for lateral subsurface flow to be equal to the average sub-basin slope length; however several studies have shown the importance of adequately parameterizing slope length (e.g. Spruill et al., 2000; Lenhart et al., 2002). Therefore the SLSOIL parameter was further adjusted in this study, producing a more reliable base and interflow simulation, and resulting in a better estimation of vertical and lateral soil flow.

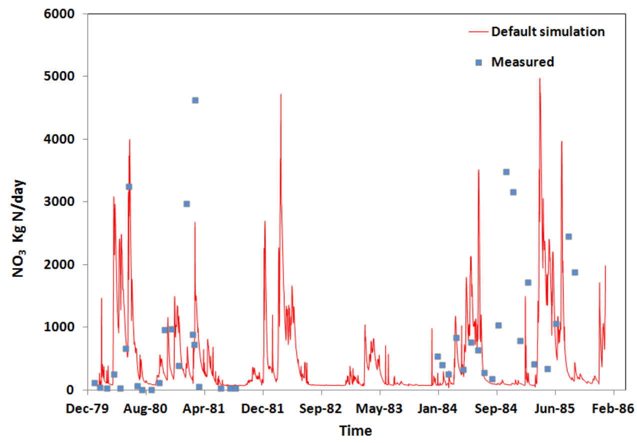

Fig. 7. Comparison of measured and modeled daily nitrate loads at the Dobrotvir catchment at the gauge Kamianka-Buzka during the calibration period 1980 to 1985.

3.2 Calibration and validation of water balance

In Table 2 the calibrated parameters and their optimized values are listed. Ultimately 23 different water balance related parameters were subject to calibration. Figure 5a and b show the results of calibration and validation respectively. Both Nash-Sutcliffe Index (NS) and Coefficient of Determination (R^2) for the calibration (NS = 0.46, $R^2 = 0.52$) and validation (NS = 0.51, $R^2 = 0.47$) periods indicate a reasonable fit of the water balance. The relatively low NS and R^2 might be due to the fact that there was only one precipitation station inside the catchment, as several studies have indicated that an under-representation of spatial rainfall variability may result in added model uncertainty (Kirsch et al., 2002; Inamdar and Naumov, 2006; Strauch et al., 2012). For example, the over estimation of the peak flows in 1984 and 1985 may be a consequence of a localized precipitation event occurring near the gauge, which was incorrectly taken as representative of conditions over the entire catchment in terms of extent, duration, or intensity. In such cases, an improvement in precipitation input data would clearly allow better model performance. The calibration of base flow was both time consuming and complex in this study, and was not successful in some cases, as shown in Fig. 5. A significant source of the difficulty in calibration may be the very long storage times present due to the hydrogeological characteristics of the catchment (i.e. karst aquifer). Figure 6a and b show the Autocorrelation Function (ACF) (Venables and Ripley, 2002) of observed and simulated discharge values for a time lag of 30 and 550 days respectively. It can be seen from Fig. 6a that there was still a significant correlation after 30 days, and only after 550 days did the ACF enter the range of the 95 % confidence interval about zero. The slowly declining values in the correlogram may be indicative of a long-range autocorrelation in stream flow, although the source of this autocorrelation is not certain (Szolgayová et al., 2012). One possible explanation for this behavior is the presence of a hydrologic system with a very large storage component, which is consistent with previous findings of high long-term ACF in a karst system by Fiorillo and Doglioni (2010). Nevertheless, further work is needed in order to investigate possible influencing factors.

3.3 Nutrient export simulation

Figure 7 shows the initial modeling results for in-stream nitrate loading, which indicates reasonable model output both in terms of simulated load range and temporal dynamics. However, the limited amount of observed nutrient data makes application of an objective function to the simulation output infeasible. In order to further verify the simulation outputs, nitrate percolation and humus mineralization processes is the target of subsequent investigation. To bridge the gap brought by the data scarcity, nutrient exports will be studied by means of a simple mass balance approach.

4 Conclusions and outlook

In this study, the SWAT model was successfully fitted to simulate runoff in the Dobrotvir catchment area. The dominating hydrological processes were found to be mainly controlled by groundwater dynamics and lateral subsurface flow, and as a result, groundwater parameters were found to be highly sensitive. Two important modifications in SWAT setup for improving model performance were the implementation of an impervious layer within the soil profile to simulate perched water tables, and specification at the HRU level of a slope length for lateral subsurface flow. Model calibration was complicated in this study by the limited amount of available precipitation data, and by the hydrogeological characteristics of the watershed (i.e. karst aquifer). To address the first point, an improved rainfall dataset will be tested in the following study. The initial nitrate simulations presented in this study show plausible load ranges and dynamics. However, further investigations on matter balance will be needed in order to adequately evaluate nutrient entry pathways into surface waters from diffuse sources. Overall, the findings of this study indicate that SWAT has potential to provide a base for assessing how diffused pollution impacts the Western Bug catchment.

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