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Watershed Modeling with ArcSWAT: Calibration and Validation for the Prediction of Flow, Nitrate and Phosphorus load

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ABSTRACT

The European Water Framework Directive requires that all surface waters and groundwater within defined river basin districts must reach at least 'good' status by 2015. Thus, the directive requires the development of management strategies to restore rivers and lakes to "good" status within a specified timeframe.

Simulation models are essential tools to evaluate potential consequences of proposed strategies and to facilitate management decisions. One of the most commonly used river basin model is ArcSWAT, a combination of the simulation model SWAT with a GIS user interface.

To test the application of ArcSWAT under German conditions, a relatively small watershed (52 km²) with sufficient data on soils, land use, climate, water flow and river water quality was selected. The watershed shows a wide variety of land use (intensive farm land, extensive pasture, and forest), soils (light sandy soils and heavy loams), surface slopes (flat to 30 % slope) and a few potential point sources of nutrients, like fish ponds, wastewater treatment plants and a public compost plant. The measured Phosphate concentration over a period of 20 years was relatively uniform and low (0.2 mg/l), whereas the Nitrate concentration varied considerably between 10 and 50 mg/l.

The model was calibrated and validated for the prediction of flow, Nitrate and Phosphate concentration and load at the main basin outlet. Sensitive model parameters were determined and adjusted within feasible ranges to minimize model errors monthly flow and quality data. The calibration resulted in good model predictions of the monthly discharge, whereas the error in Nitrate and Phosphorus concentration and load was much larger.

Possible reasons for the poor simulation results for the nutrients are incorrect amounts of fertilizers in the automatic fertilization option of ArcSWAT. This resulted in incorrect yield and biomass production in the model. For a further improvement of the simulation quality, different arable crops and adequate model fertilization values have to be considered.

The model can be used for German conditions with data usually available in Germany without too much calibration work for simulating and predicting the monthly and annual discharge. To simulate nutrient concentration and load, much more calibration work is necessary.

INTRODUCTION

The European Union passed the European Water Framework Directive in the year 2000. Subsequently, it was transposed into national law by 2003. An assessment of the contamination risk for all water bodies in the European Union had to be finished by 2006. The development of measures to improve the state of the water bodies has to be finished by 2009 and the measures must be implemented by 2012.

The final goal is that all surface waters and groundwater within defined river basin districts must reach at least ‘good’ status by 2015.

Simulation models are essential tools to evaluate potential consequences of proposed strategies and to facilitate management decisions. One of the most commonly used river basin model is ArcSWAT, a combination of the simulation model SWAT with a Geographical Information System (GIS) user interface (Winchell et al., 2007).

ArcSWAT and its predecessors have been intensively used to simulate surface and groundwater quality by several authors in the last two decades (review by Gassman et al., 2007). However, the program has been developed for American conditions and most studies have been carried out in the United States. Relatively few studies have been carried out in Central Europe or particularly in Germany. One working group in Germany concluded that the program had to be adjusted severely with respect to Nitrate related processes to reflect the conditions in Germany correctly (Eckhardt et al, 2002; Pohlert et al., 2005).

Background of the present study was that many official sites in Germany own a lot of data on water quantity and quality for sometimes periods as long as several decades. This data could be used to calibrate watershed models and, in case a calibration is successful, later significantly help to determine the effect of water protection measures. However, official sites do usually not have the resources to invest very much time into the calibration process of watershed models for the many catchments the have to take care of.

Therefore, the present study was carried out to evaluate the effort necessary to calibrate and use the watershed model ArcSWAT with usually in Germany readily available data.

MATERIALS and METHODS

The basic model SWAT is a watershed-scale model that operates on a daily time step and is designed to predict the impact of management on water quantity and quality and sediment load in groundwater and surface waters. Major model components include weather, hydrology, soil properties, plant growth, nutrients, pesticides, bacteria and pathogens, and land management. In SWAT, a watershed is divided into multiple sub watersheds, which are then further subdivided into hydrologic response units (HRUs) that consist of homogeneous land use, management, and soil characteristics (Neitsch et al., 2005). A review of the development of the model system is given by Gassman et al. (2007). The interface between the model SWAT and ArcGIS is called ArcSWAT. ArcGIS is used to calculate basic hydrologic information for the model (i.e. surface slope, water flow paths), calculates the position and the size of the hydrologic response units and provides the necessary files which are used by the SWAT model (Winchell et al., 2007).

Climatic Data

The model SWAT requires daily precipitation, maximum/minimum air temperature, solar radiation, wind speed and relative humidity. The weather data was taken from the weather station of University of Applied Sciences at the Haste Campus which is situated a few kilometers south-west of the watershed area for the years 1996-2007. The available data were daily minimum and maximum temperatures measured 2 m above the ground (°C), temperatures at 14.00 hrs measured 2 m above the ground (°C), daily precipitation (mm), maximum rainfall intensity in one hour for any month, relative humidity at 14.00 hrs (%), and total daily sunshine duration (hrs). Additional data for daily average wind speed were taken from a weather station in Osnabrueck for the years 2003 to 2007. The solar radiation was calculated from the total daily sunshine duration with the Angstrom equation.

The model SWAT additionally needs long term monthly statistical data (mean, standard deviation) to generate representative daily climate data when measured data is missing. The statistical parameters were calculated from the available daily weather data.

Soil Data

The soil data for the watershed were taken from the official digital soil map at the scale 1:25.000 or were estimated based on this map. In the digital soil map a few soil units had 7 or more layers. In these few cases, some thin layers were discarded and the neighboring horizons were used instead so that a maximum of 6 layers was used in the soil profiles. The necessary parameters are the

• Soil hydrologic group (calculation based on the texture of the first horizon)

• Maximum rooting depth (Generally, a maximum rooting depth of 200 cm was used. Only in those cases where the rooting depth was obviously reduced due to bed rock in the description of the digital soil map, the depth to the bed rock was used)

• Bulk density (g/cm^3; values were recalculated from the classes of the digital spoil map according to the German classification (AG Boden, 1994)

• Available water capacity (cm^3/cm^3; estimated from the textural class, the bulk density humus content classes according to the German classification system (AG Boden, 1994). For organic soils, the available water capacity (AWC) was estimated from the type of organic material and the decomposition status. The AWC used in ArcSWAT is the American AWC, i.e. the difference of the water contents between pF 4.2 and the American field capacity (pF2.5). The AWC estimated with the procedure outlined above is the German AWC, i.e. the difference of the water contents between pF 4.2 and the German field capacity (pF1.8). Therefore, the estimated AWC is slightly larger than the American AWC. Therefore, a procedure was developed to transform the German AWC to the American AWC which increased the quality of the calibration significantly.

• Saturated hydraulic conductivity (mm/hr; estimated from the textural class and the bulk density according to the German classification system (AG Boden, 1994). For organic soils, the saturated hydraulic conductivity was estimated from the type of organic material and the decomposition status).
• Organic carbon (%weight; the central values of the humus content classes divided by 1.72 were used as organic carbon values. For organic soils, a value of 30 % organic carbon was used).
• Clay content, silt content and sand content (%weight; textural classes are available in the digital soil map. The central values of the clay, silt and sand content of the textural classes were used according to the tables of the German classification system (AG Boden, 1994).
• Coarse particles (%weight): the amount of coarse particles (> 2mm) in classes is available in the digital soil map. The central values of the classes were used as an approximation of the coarse particles.
For bedrock, a value of 90% coarse particles was assumed.
• Soil albedo (fraction): The soil albedo (moist) was calculated from the sand content (%).
• Erodibility factor (.013tm²h/m³tcm; the erodibility factor was calculated according to Williams (1995) from texture and organic carbon data.

Land Use

The land use was taken from the digital soil map. The eight different land uses from the digital soil map were transformed into the respective land uses classes of the SWAT model: arable land (AGRL), permanent pasture (PAST), coniferous forest (FRSE), deciduous forest (FRSD), forest in general (FRST), soil pits and lakes (WATR), and villages and urban areas (URBN).

Slope

The slope was calculated in ArcGIS from digital elevation data at a distance of 50 m. Two slope classes of 0 - 2.5% and >2.5% were defined.

Hydrologic Response Units

The Hydrologic Response Units (HRU) will be defined in ArcSWAT by overlaying soils, land use and slope classes. This overlay resulted in a total of 557 HRU for the Nette catchment. Some of the HRU, however, were very small. Therefore, the final HRU were defined based on a threshold percentage, i.e. only those land use classes, soil units and slope classes in a sub-catchment were taken into account, which were larger than the respective threshold value. Threshold values of 20% for land use, 20% for soils and 10% for slope classes resulted in a reduction to 111 HRU for the whole Nette catchment.

Sensitivity Analysis, Calibration and Validation

The SWAT model has many parameters which can be optimized in the calibration process. To make the time consuming calibration process most effective, a sensitivity analysis of the main parameters influencing the water discharge and the water quality were carried out. The most sensitive parameters were later used to calibrate the model. For the calibration with respect to water discharge, a period of three years from 2001 to 2003 was used (plus one initial year as a "warming up" period for the model). A model run for the ten year period 1997 to 2006 was used with the optimum parameters as validation period. The same procedure was used for the water quality.

RESULTS and DISCUSSION

The basic information, i.e. soil data, land use classes, slope and river reaches and sub basins for the model is given in Fig. 1.

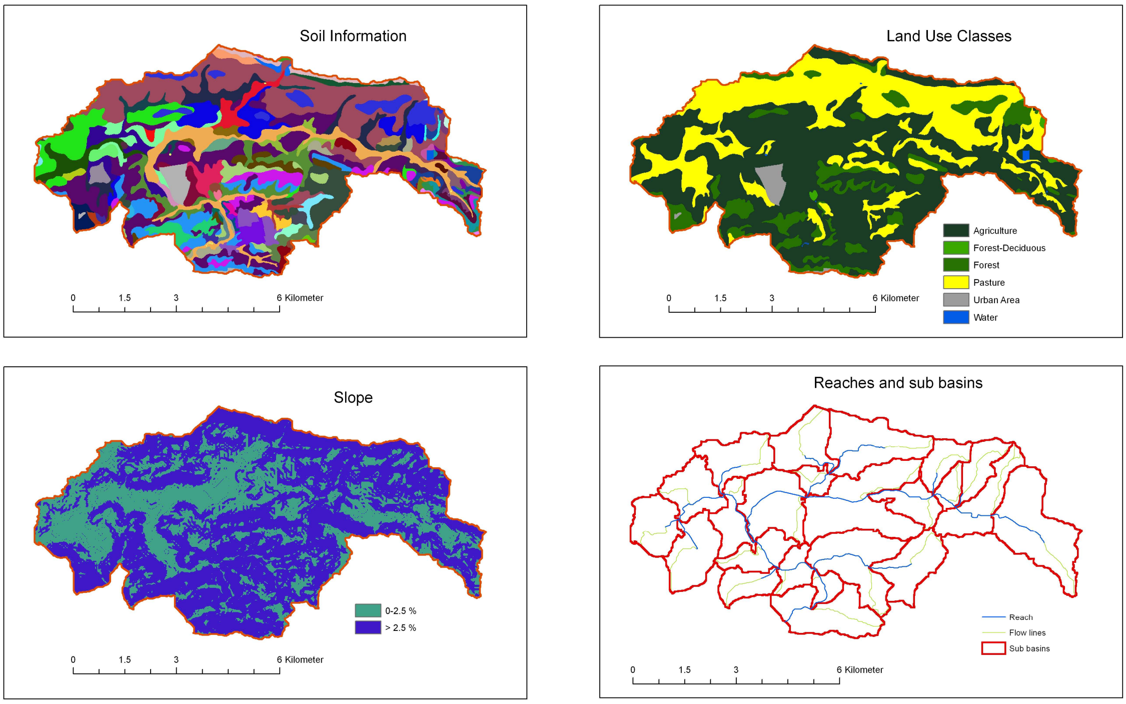

Fig: 1: Soil data, land use classes, slope and river reaches/sub basins

The sensitivity analysis for the river discharge showed that four parameters were the most sensitive ones: the baseflow recession constant determining the relation between baseflow and surface flow, the runoff curve number determining the surface flow, the soil depth determining the amount of seepage water and surface flow, and the soil evaporation compensation factor determining the amount of evaporation from the soil. The sensitivity analysis for the nutrients NO_3 and P showed that the runoff curve number was the most important parameter for both.

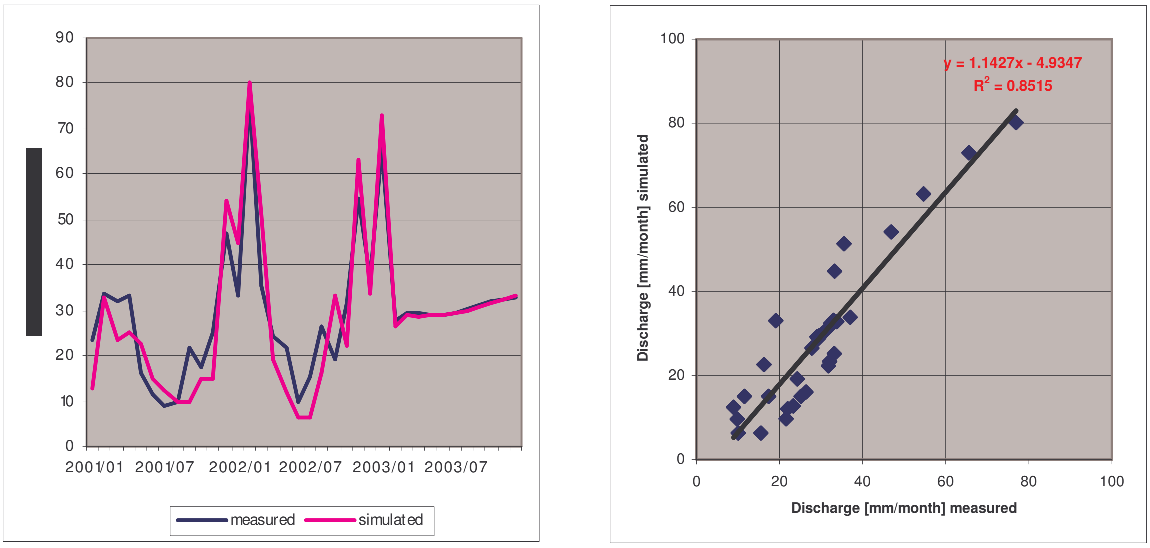

Fig. 2: Measured and simulated discharge (calibration period): discharge versus time (left) and simulated versus measured (right)

After calibration, the simulation showed good results for the monthly average discharge values with a slope of the simulated versus measured values close to unity, a high R^2 of 0.852 and a Nash-Sutcliffe efficiency ENS of 0.75 (fig. 2). The daily discharge, however, showed less accurate simulation with some major discrepancies and a R^2 of only 0.433 and a Nash-Sutcliffe efficiency ENS of only 0.46. The peak values were at times too high or too low, but the peak position was generally correct (not shown). Table 1 show the final parameters used in the calibration.

Table 1: Calibrated Values for Parameters determining the river discharge

parameter	default value	calibrated value	parameter	default value	calibrated value
CANMX		7.5	**RCHRG_DP**		0.20
CHN2		0.02	**TIMP**		0.45
CHK2		115	**ESCO**		0.5
CH_COV		0.8	**EPCO**		1.0
GW_Delay		0	**EVLAI**		3.0
ALPHA_BF		0.1885	**SURLAG**		2.5
GWQmn		0	**MSK_CO2**	3.5	7
GWRevap		0.05	**MSK_CO1**	0	2
RevapMN		90			

After calibration, the simulation was extended to a 10 year period 1996 to 2006. The simulated monthly averaged discharge was sufficiently well with a $R^2 = 0.756$ and a Nash-Sutcliffe efficiency ENS of 0.63 which shows that the calibration parameters were chosen correctly to describe the behavior of the hydrologic system (fig. 3).

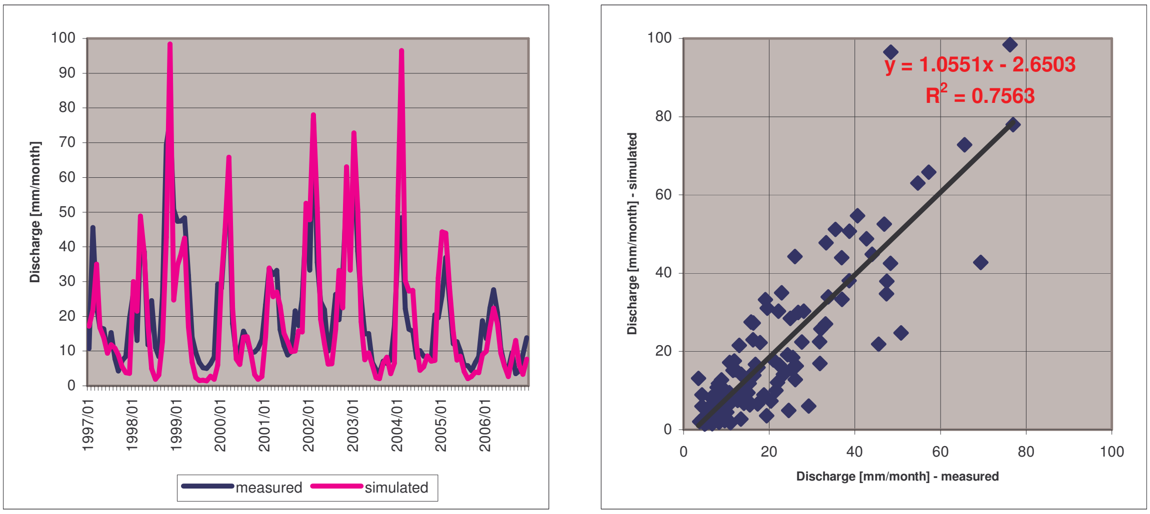

Fig. 3: Measured and simulated discharge (validation period): discharge versus time (left) and simulated versus measured (right)

The Nitrate concentration and load was simulated in a next step. The results for the monthly averaged values were poor. The correlation between measured and simulated monthly averages showed a R^2 of 0.37 and a Nash-Sutcliffe efficiency ENS of 0.29 only. The positions of the high and low peaks were correct; the fluctuation, however, was much too high. The monthly averaged Nitrate load showed better results. The correlation between measured and simulated monthly averages showed an R^2 of 0.45 and a Nash-Sutcliffe efficiency ENS of 0.43. The position of the high and low peaks was correct but the agreement of the peak height is poor.

The average annual values (fig. 4) showed that the overall level of the Nitrate concentration is simulated relatively well (5.3 mg/l Nitrate-N simulated versus 5.8 mg Nitrate-N measured. The same is true for the Nitrate-N load (258 kg/day for the whole catchment simulated versus 203 kg/day measured).

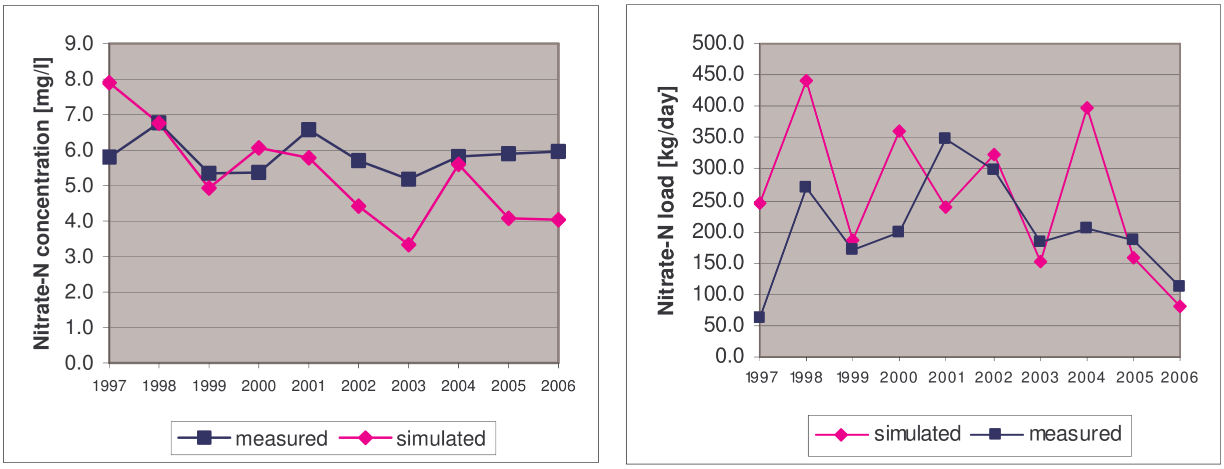

Fig. 4: Measured and simulated Nitrate concentration (left) and load (right)

The monthly averaged phosphorus concentration and load showed an inferior quality of the results compared to Nitrate. The correlation between measured and simulated monthly averages showed an R^2 of 0.02 and a Nash-Sutcliffe efficiency ENS of -0.29. The position of the high and low peaks was partly wrong and the fluctuation was much too high. The phosphorus load also showed an insufficient simulation quality with a correlation between measured and simulated monthly averages of $R^2 = 0.04$ and a Nash-Sutcliffe efficiency ENS of -0.46. The position of the high and low peaks was partly correct but the agreement of the peak height was poor.

The average annual values (fig 5) showed that the overall level of the phosphorus concentration is simulated relatively well (0.16 mg/l Phosphate-P simulated and 0.17 mg/l measured). The average annual Phosphate-P load (5.2 kg/day simulated and 5.6 kg/day measured) was simulated correctly with a correlation coefficient $R^2 = 0.56$ and a Nash-Sutcliffe efficiency ENS = 0.42.

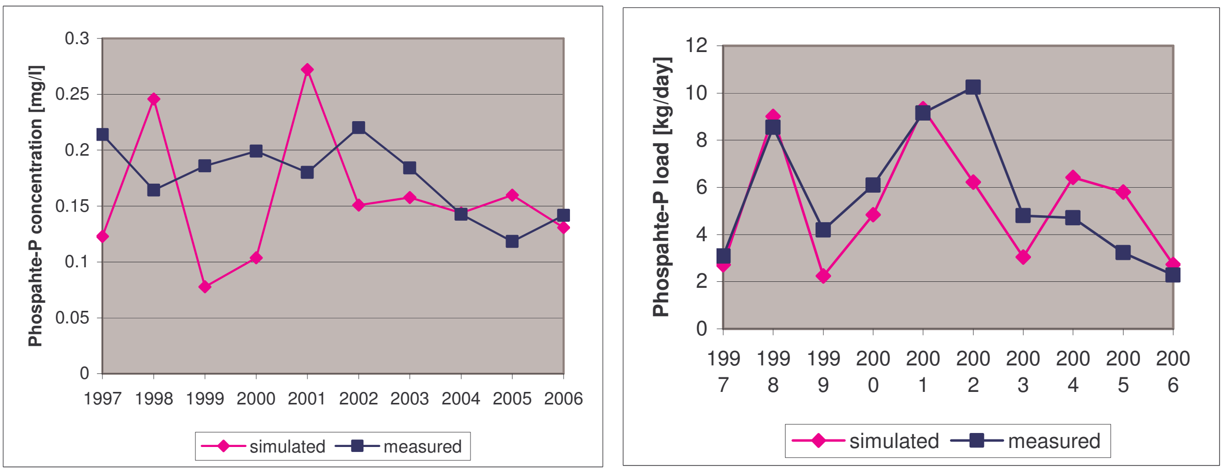

Fig. 5: Measured and simulated Phosphate-P concentration (left) and load (right)

Possible reasons for the poor simulation results are wrong amounts of fertilizers applied in the model and an incorrect amount of nutrients taken up by the plants. The fertilizer used in the SWAT model runs were applied automatically dependent on the simulated plant growth in that way, that there are always sufficient nutrients for plant growth in the model, i.e. never nutrient stress. The simulated yield on arable land is based on parameters for winter wheat, although other crops are planted as well, such as oil rape, barley, corn. The simulated yield for winter wheat is too low compared to the yield of farms in that region. The amount of automatically applied N-fertilizer in the model for winter wheat is much too low, i.e. only 139 kg N/ha instead of up to 200 kg/ha normally used on farms. The simulated biomass (forest and grass) is too low compared to values expected in that region.

CONCLUSIONS

The results show that the ArcSWAT model simulates the monthly and yearly averaged discharge correctly. The quality of the monthly averaged simulated Nitrate concentration is poor; the peak position is correct but the high peaks are too high and the low peaks are too low; the general level is correct. The simulation quality of the monthly averaged Nitrate and Phosphate load is better, but the peaks too high. The simulation of the yearly averaged Nitrate and Phosphate concentration and load was correct in that sense that the overall level was simulated correctly. The simulated grain yield for winter wheat and biomass (Pasture and Forest) is too low. The N fertilizer applied with the "automatic" option is too low.

In a next step plant parameters must be adjusted so that yield and biomass production will be simulated correctly. Only after that, a further calibration of N and P related parameters can be carried out to adjust N and P concentration and load.

The introduction of further land use, i.e. splitting the arable land use to winter wheat, barley, corn and oil rape must be evaluated in order to increase the accuracy of the simulation.

Potential point sources, such as fishponds, a waste water treatment plant and a compost plant will be incorporated in the model in order to increase the accuracy of the simulation.

The model can be used for German conditions with data usually available in Germany without too much calibration work for simulating and predicting the monthly and annual discharge. To simulate nutrient concentration and load, much more calibration work is necessary.

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