Impacts of climate change on regulating nitrogen retention in the River Weiße Elster in Germany

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Abstract In this study, climate scenarios (dry, medium and wet) have been used to characterize changing climatic and flow conditions for the period 2050–2054 in the 4th order River Weiße Elster in Germany. Present and future periods of nitrogen turnover were simulated with the WASP5 river water quality model. Results revealed that, for a dry climate scenario, the mean denitrification rate was 71% higher during summer (low flow period between 2050 and 2054) and 51% higher during winter (high flow period) compared to the reference period. In the 42-km study reach, N-retention through denitrification amounted to 5.1% of the upper boundary N load during summer low flow conditions during the reference period. For the future dry climate scenario, this value increased by up to 10.2%. In our case study, the investigated climate scenarios showed that future discharge changes may have a larger impact on denitrification rates than future temperature changes.

Key words denitrification; climate change; river water quality modelling; River Weiße Elster, Germany

INTRODUCTION

Nitrate input to surface waters has increased in many regions within the last few decades due to increased nitrogen (N) fertilizer application, point discharges, land-use changes, etc. (Zweimüller, 2008). Nutrient retention processes and in-stream retention are mainly attributed to assimilation by suspended and benthic algae, uptake by macrophytes and denitrification. In small agricultural streams in-stream removal of N can range from 10 to 70% of the total N load (Birgand *et al.*, 2007). Only denitrification removes N permanently from the aquatic cycle and, therefore, it is one of the most important processes (Birgand *et al.*, 2007; Mullholland *et al.*, 2008; Schiller *et al.*, 2008; Wagenschein & Rode, 2008; Whitehead *et al.*, 2009).

Many of the environmental factors shown to influence denitrification, such as discharge, temperature and nutrient concentrations, may change markedly over time. Although more nitrate is transported downstream with higher discharge in winter, microbial activity promoting denitrification is controlled by temperature. Therefore, N stream removal rates and efficiency are the highest during summer. Removal efficiency is the lowest during winter in temperate climates due to high flow and loading combined with lowest removal rates (Birgand *et al.*, 2007; Zweimüller *et al.*, 2008).

In most of the above-mentioned studies, climate impacts on in-stream N retention have been either neglected or only simple statistical approaches have been used. These simple approaches do not allow complex interaction between varying discharge, nitrate concentrations and temperature to be assessed. Simulation studies on N loads in mid-sized streams used empirical expressions including in-stream solute travel time and biogeochemical attenuation rates to quantify in-stream N removal (Alexander *et al.*, 2002; Darracq & Destouni, 2005, 2007). Recent studies also include temperature, nitrate concentrations and discharge in empirical equations for in-stream nitrate removal, but these approaches are restricted to small headwater streams (Mulholland *et al.*, 2008; Wollheim *et al.*, 2008). Furthermore, these approaches use empirical relationships between discharge and river width and do not take into account small-scale variability of river cross sections.

Here we explore how denitrification influences N removal in a typical 4th order river with highly variable river morphology. We focus on annual variation of in-stream N removal. Nitrogen transport modelling is based on the WASP river water quality model (Ambrose *et al.*, 1993), which was applied to the River Weiße Elster in eastern Germany in a previous study (Wagenschein & Rode, 2008). The objectives of this study are: (1) to evaluate the impact of climate change on discharge, in-stream denitrification and total N load during low and high flow seasons over a 5-year period, and (2) to assess the influence of river morphology on this N cycling under future climate conditions.

MATERIAL AND METHODS

Study river

The River Weiße Elster is a 4th order stream with a total length of 250 km. It originates in the northwestern part of the Czech Republic and discharges into the Saale River close to Halle, in Germany. Land use in the basin is dominated by agricultural activities (43% cropland, 16% pasture), especially in the lower part, and forest (21%), mainly in the upper part of the basin. Its water quality is characterized by high N concentrations, which are mainly caused by diffuse source pollution from agriculture activities and sewage plant emissions (Rode *et al.*, 2008). This study focuses on the middle part of the River Weiße Elster between Gera and Leipzig. The total length of this river section is 70.6 km (Fig. 1).

The potential natural morphology of the river is characterized by a low-channel slope and a well-defined meandering pattern. The river section upstream from Zeitz has a mean channel slope of 0.89‰, is straighter with a mean sinuosity of 1.43 and has a high width/depth ratio ranging from 20 to 40. In backwater areas at weirs, width/depth ratios are greater than 100. The section downstream from Zeitz has a lower channel slope of 0.60‰, a higher sinuosity of 1.69 and a lower width/depth ratio ranging from 10 to 20, which coincides to stream types C and E (Rosgen, 1996). However, along the entire length of the studied river section, there are only a few unmodified river reaches with natural morphology, for example reach B with a length of 8 km (Fig. 1). Most parts

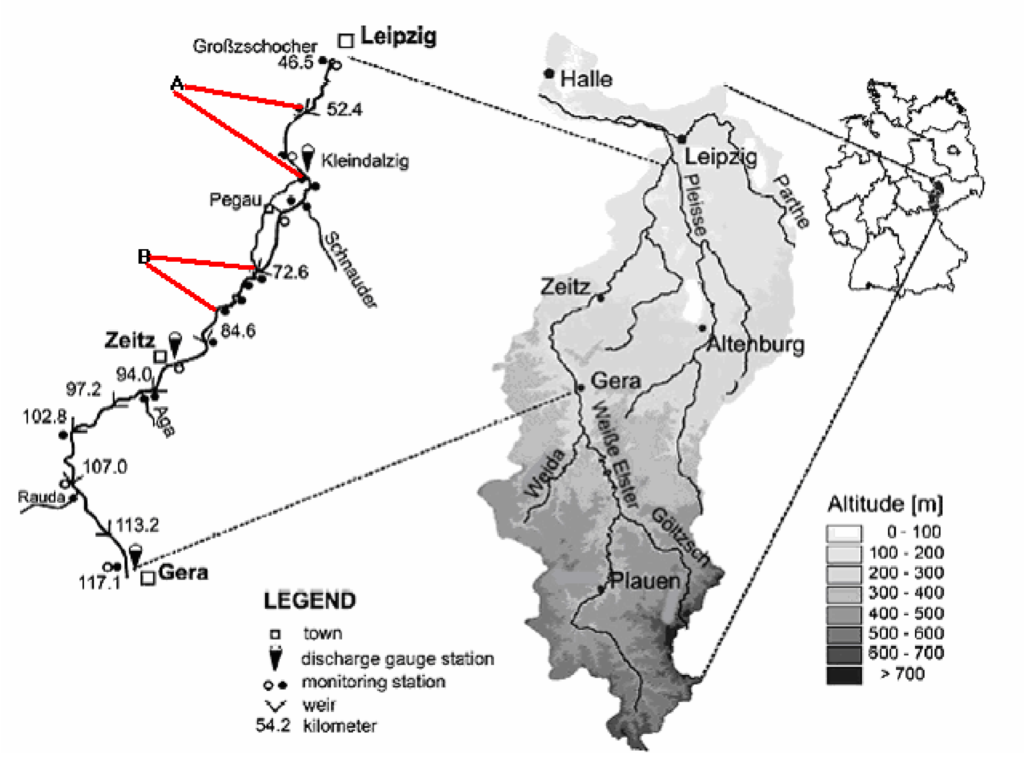

Fig. 1 Map of the Weiße Elster catchment and the studied river section with Reach A (channelized) and Reach B (natural morphology).

of the river are strongly influenced by human activities, especially surface mining and urbanization. A part of the river is completely channelized (Fig. 1, reach A). Nitrogen concentrations are still high with total N concentrations ranging from 4 mg N L^{-1} during summer to 12 mg N L^{-1} during winter. Nitrate uptake in the 70.6-km river reach during low flow conditions is considerable and was observed to amount to a reduction of nitrate-N concentrations of up to 1 mg NO_3-N L^{-1} or 23.4% of the N load of the upper boundary (Wagenschein & Rode, 2008).

Climate and river data

For the reference period (1995–1999), daily discharge, meteorological and biweekly water quality data were obtained from the water authorities and government agencies for the stations Gera Langenberg and Leumnitz. The Potsdam Institute for Climate Impact Research (PIK) provided the required input climate data for the scenario period (2050–2054). The regional climate change data were produced at PIK using the statistical downscaling model STAR (statistical analogue resampling technique) described in Werner & Gerstengarbe (1997). STAR was driven by the ECHAM4-OPYC3 GCM, which was in its turn driven by the IPCC emission scenario. Analogue approaches, such as STAR, assume that observations of a given day from the training period can occur again or in a similar way during the future period. Hence, simulated series are constructed by resampling from segments of a series of observations and in this case, a series of daily observations. The advantage of such resampling is that physical consistency of both the spatial fields and the simultaneous combinations of different weather parameters is guaranteed. STAR resamples in blocks of 12-days, which ensures the projected future time-series with realistic persistence features.

In addition, STAR is able to generate multiple climate projections by implementing a random process (Monte Carlo simulation). Therefore, an ensemble of 100 realizations of the climate change scenario was generated, with the same temperature trend, but different trends in precipitation. Uncertainty of the climate change impact for each climate scenario was evaluated from the ensemble results.

Model descriptions

The dynamic process-based eco-hydrological model SWIM (Soil and Water Integrated Model) (Krysanova *et al.*, 1998) was developed for climate and land-use change impact assessment on the basis of the models SWAT (Arnold *et al.*, 1993) and MATSALU (Krysanova *et al.*, 1989). Previously, SWIM was used to generate river discharge from climate change meteorological data and to investigate changes in crop growth in the Elbe River basin (Krysanova *et al.*, 2007).

Water temperature is an input for the river water quality model. Water temperature data for a future climate were estimated based on a statistical correlation between present climate and observed water temperature. Water temperature was projected using a correlation between observed daily air and water temperatures for the period 1995–1999 at the Gera-Langenberg gauge station. Nitrate-N concentrations in rivers are strongly related to land use, whereas N fluxes may also be strongly influenced by precipitation. We did not use a process-based water-quality model (e.g. like SWIM) to generate nitrate-N concentration input data for future climate conditions because forecasts on land-use distributions and agricultural land-use intensities, management practice, date of fertilizer application, harvest date, etc. are highly uncertain (Eckersten *et al.*, 2001). In the present study we evaluated a linear regression of nitrate-N concentration on discharge for the reference period (1995–1999). We used this regression to predict nitrate-N concentrations and loads for future climate scenarios (2050–2054) based on simulated future discharge from SWIM.

In-stream N turnover was simulated with the Water Quality Analysis Simulation Program (WASP5) (Ambrose *et al.*, 1993). This version of WASP was extended to include discharge over weirs, as described by the Pollini equation (Warwick, 1999). For this study, a modified version of WASP5 (Wagenschein & Rode, 2008), in terms of description of the denitrification process, was used.

For our application, a better representation of benthic denitrification k_{D2} was included in the model and is computed using a maximal benthic denitrification rate k_{D2max}, the mean segment depth (d) and a temperature coefficient Θ_D. In the model, the segment volume is divided by d to provide a dependency with a segment-specific sediment surface area. Total denitrification is calculated by the sum of k_{D1} and k_{D2}. The model was calibrated and validated for the study reach and measured and simulated values agreed well for most water-quality constituents (Wagenschein & Rode, 2008). However, we consider the modelling system adequate for estimating the relative changes in N retention between the reference and the future climate period,

Model set-up

In this study, SWIM was used to generate river discharge from climate change scenario data. The model was calibrated for the period 1983–1987 and validated for the period 1988–1994 to assure that river discharge was satisfactorily simulated (Fig. 2). For implementing WASP5, the river section was spatially subdivided into 283 model segments, with each segment being 250-m long. The mean width and depth were generated using the data from 876 cross-sectional profiles and eight weirs. For hydrodynamic modelling a discharge hydrograph defines the upper boundary and the inflows of the tributaries, for which discharges are low in relation to the discharge of the main stem, were assumed to be constant. To sustain model stability, a time step of less than 2 s was necessary.

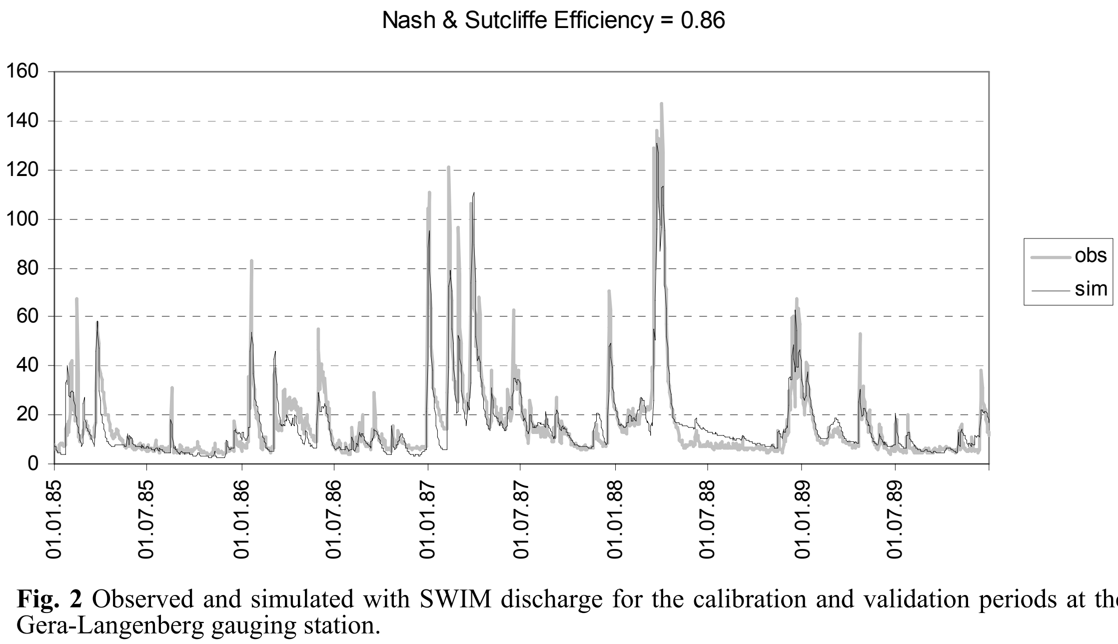

Fig. 2 Observed and simulated with SWIM discharge for the calibration and validation periods at the Gera-Langenberg gauging station.

To evaluate climate change impacts on N transport within the study river, SWIM and the N regression model, described previously, were run to generate discharge and N inputs into the study river reach for the future period 2050–2054 under the dry, medium and wet scenarios. To evaluate the impact of seasonal changes on in-stream denitrification the WASP5 model was run using “weirs removed system” to simulate the river reach between 117 km and 77 km for summer (June–July–August) and winter (December–January–February) seasons. The specific impact of river morphology was investigated by conducting simulation studies for the driest climate scenario during the year for Reach A (53.7–59.4 km reach, the channelized stream section) and Reach B (74.7–80.4 km reach, the unmodified stream section). Furthermore, during low and high discharge periods N source and denitrification were investigated for the 75–117 km reach (for both reference and scenario periods).

RESULTS AND DISCUSSION

Impact of climate change on discharge and denitrification

The climate scenario for the dry, medium and wet realizations analysed with the ecohydrological model, SWIM, was used to characterize changing discharge conditions. Annual and seasonal (summer and winter) mean discharge (at the Gera-Langenberg gauging station), and temperature (at the Gera-Leumnitz monitoring station), during the reference and scenario periods are listed in Table 1.

Winter, summer and annual mean temperatures were higher for all three scenarios than for the reference period. Annual mean discharge was lower for all scenarios compared to the reference period. Due to fluctuations during the year, seasonal means showed slightly different profiles. For example, forecast winter period discharges for the wet scenario are higher than for the reference period but, in contrast, yearly discharges are lower. Variations in denitrification along the river (weirs excluded from the system; 77–117 km reach) were examined for winter and summer conditions for the reference (1995–1999) and future (2050–2054) periods. The results are listed in Table 2.

Denitrification rates are predicted to increase from 0.34 (reference period) to 0.52 mg N L^{-1} day^{-1} during summer, and from 0.16 to 0.27 mg N L^{-1} day^{-1} during winter for the dry scenario. These results correspond to an increase of N-retention by denitrification of 51% (summer) and 71% (winter) for a future climate compared to the reference period. However, the denitrification rate only increased slightly for the medium (4%) and wet (3%) scenarios during summer. In contrast, winter denitrification is lower (9% and 3% for the medium and wet scenarios, respectiv-ely). The variability of denitrification rates is higher during summer than winter. Spatial changes that were determined based on mean daily denitrification along the river are shown in Fig. 3.

Table 1 Observed (1995–1999) and predicted (2050–2054) future river discharge (Gera-Langenberg gauging station) for the River Weiße Elster, and air temperatures (Gera-Leumnitz monitoring station). Annual and seasonal average values are listed.

Variable	Season	Ref. period	Scenarios: Dry	Medium	Wet
Q (m^3 s^{-1})	Winter[a]	19.4±13.7	7.53±6.48	20.2±14.4	18.3±12.6
	Summer[b]	7.68±4.70	4.72±3.49	7.69±4.04	8.65±5.17
	Annual mean	15.4±14.8	6.56±7.90	11.0±10.6	11.7±8.93
T (°C)	Winter[a]	2.00±4.54	3.51±4.62	3.79±4.28	4.20±3.86
	Summer[b]	17.1±3.47	19.4±3.45	18.7±3.44	19.4±3.30
	Annual mean	9.84±7.20	11.6±7.31	11.2±7.09	11.6±6.97

a Winter: Dec–Jan–Feb; b Summer: June–July–Aug.

Table 2 Denitrification rates (mg L^{-1} day^{-1}) for the reference period and for the dry, medium and wet scenarios.

Season	Ref. period	Scenarios: Dry	Medium	Wet
Winter	0.157±0.035	0.269±0.068	0.142±0.031	0.152±0.033
Summer	0.344±0.080	0.521±0.136	0.358±0.083	0.355±0.080

a Winter: Dec–Jan–Feb; b Summer: June–July–Aug.

Nitrogen load reduction through denitrification

Average nitrate-N loads were determined based on daily model runs ("weirs removed") for the summer and winter months in two 5-year periods (1995–1999 and 2050–2054). N source and denitrification in the 75–117 km reach are listed in Table 3. As compared with the reference period, denitrification reduces the total N load of the upper boundary by 1.1% during high flow (winter) and 5.1% during low flow (summer) (Table 3). These values are predicted to increase by 10.2% during low flow, for the dry scenario. Compared to the reference period, a rate decrease

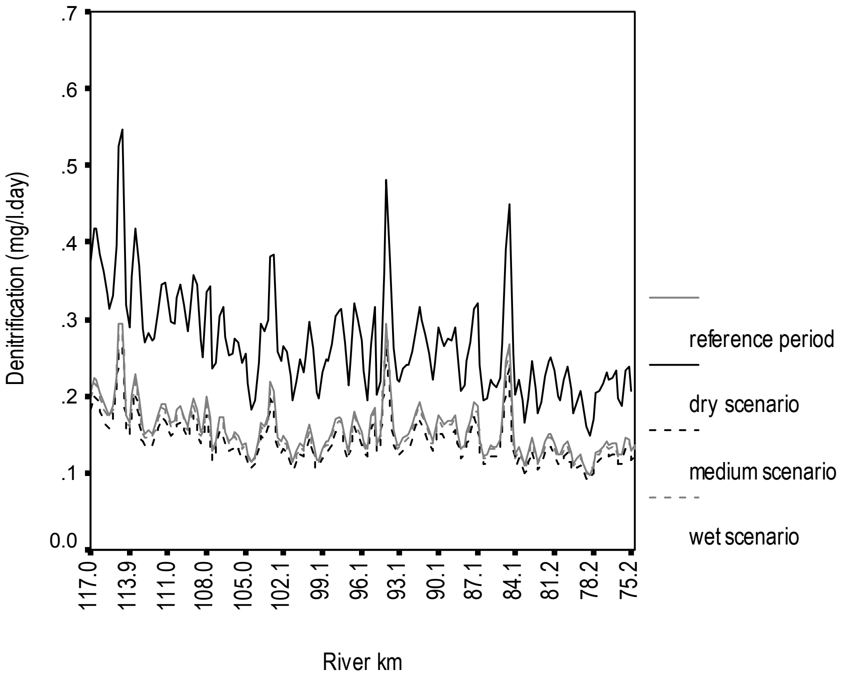

Fig. 3 Comparison of denitrification rates of the reference period and the scenarios for winter flow conditions in the River Weiße Elster (75–117 km reach) for the period 1995–1999 and 2050–2054.

Table 3 Nitrogen input and removal by denitrification (75–117 km reach) during summer low flow period for the reference period and for each of the three scenarios.

Summer June+July+August	Reference period	Dry scenario	Medium scenario	Wet scenario
N input (kg day^{-1})	3720	2130	3690	4330
N removed by de-nitrification (kg day^{-1})	188	218	199	209
% removed by denitrification	5.06	10.2	5.39	4.85

was projected for the summer and the wet scenario (Table 3). The predicted increases in nitrate load removal for future climate conditions are complex functions of decreasing discharge (tending to increase k_{D2} with decreasing water depth and water residence time), decreasing water column nitrate-N concentrations (decreasing k_{D1}) and increasing temperature (increasing k_{D1} and k_{D2}). Therefore, the nitrate removal controlling factors may compensate or strengthen each other, e.g. increasing temperature may be balanced out by decreasing nitrate concentrations. Our findings of a higher percentage of N removal with decreasing discharges are in agreement with the results from Bartkow & Udy (2004) who concluded that during base flow conditions, when N loads to streams are low, the proportion of N removed through denitrification would be substantially higher. Alexander *et al.* (2009) and Wollheimer *et al.* (2008) report high nitrate flux removal during low flow conditions. The high in-stream retention under future climate conditions can be explained by a relative increase in benthic surface area providing contact between water column nitrate and biogeochemically reactive substrate in relation to stream nitrate fluxes and higher temperature induced denitrification rates (compare also Howarth *et al.*, 2006).

The decrease in the denitrification rate along the studied river reach is hypothesized to be caused by a decreasing width/depth ratio of the river cross-sections, and decreasing N concentration along the river is hypothesized to be caused by N removed from the water during transport. The variability can be explained by the impact of river morphology and the changing size of the interface between the water column and stream sediments. These findings are consistent with recent studies (compare e.g. Wollheim *et al.*, 2008; Alexander *et al.*, 2009).

CONCLUSIONS

Seasonal denitrification of the River Weiße Elster, Germany varies depending on the climate scenarios and compared to reference years; the rate is generally higher during summer (with rates of 4% and 3% for the medium and wet scenarios, respectively) and lower during winter (9% and 3% for the medium and wet scenarios, respectively). Furthermore, our study has shown that the denitrification rates for the dry scenario are 51% higher in summer and 71% higher during winter. The ratio of denitrification during summer to winter is about 2.0 in the modified and 2.1 in the unmodified river section. During summer, denitrification amounts to 10.2%, 5.4% and 4.9% of the upper boundary N-load for the dry, medium and wet scenarios, respectively, although the N load is much lower. During the reference period this value is 5.1%. These rates are comparably lower during winter (e.g. 1.1% for the reference period and 3.4% for the dry scenario).

In our case study, the investigated climate scenarios showed that future discharge changes may have a larger impact on denitrification rates than future temperature changes. These findings are restricted to a mid-sized river in a temperate climate, which may be highly affected by decreasing discharge. Thus, denitrification in rivers with less future discharge variations may be less affected by climate change. The study revealed that estimates of nitrate removal through denitrification under low temperature and high flow conditions are highly uncertain because adequate measurements are sparse. This is especially true for mid-size rivers because most river reach studies focus on small streams, e.g. within the LINX project (Mulholland *et al.*, 2008). The approach and results presented here provide a potentially useful way of comparing the expected responses to anthropogenic climate change in different catchments and evaluating ecosystem services provided by river systems. Our application of a model, which has been validated for summer conditions, and then used for other time periods, should be viewed with caution as not all processes are considered in the model. However, this analysis begins to address the importance of N-removal processes under changing climate conditions within a morphologically heterogeneous mid-sized river.

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