

Groundwater–surface water exchange fluxes in a Pleistocene lowland and the impacts on riparian zone water balance and nitrate conditions

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Abstract Water balance and groundwater nitrate dynamics within the riparian flood plain of the Havel River in northeast Germany are investigated by experimental analyses as well as by model simulations, using a coupled soil water balance and groundwater model approach. The model simulations indicate a substantial impact of exchange fluxes across the groundwater–surface water interface on the riparian water balance, the river discharge, as well as on the nitrate dynamics within the groundwater and river. Experimental and model-based results give evidence that the impact of groundwater contributions and associated nitrate fluxes from the riparian flood plain are temporally very variable. Substantial seasonal variations in the riparian groundwater-borne nitrate contributions to river discharge are observed. Hence, nitrate contributions from the groundwater represent a significant proportion of the observed loads in the Havel River during summer, when discharge and nutrient conditions in the surface waters are crucial for the ecological health of the lowland river.

Key words riparian; flood plain; nitrate; groundwater; surface water; coupled model

INTRODUCTION

Riparian zones in the river corridors and flood plains in the Central European lowlands represent an important buffer for the landscape water balance and nutrient dynamics.

The hydrological and ecological functions provided by riparian zones cover a broad variety from regulation of runoff generation (Woessner, 2000; Butturini *et al.*, 2002), retention during hydrological extremes (Butturini *et al.*, 2002; Sophocleous, 2002) and biogeochemical transformations, including natural attenuation of nutrients and pollutants (Lowrance *et al.*, 1984; Hill, 1996; Brunke & Gonser, 1997). In light of the demands of the European Water Framework Directive (WFD; 2000/60/EU) on the regulatory functions of water bodies and their associated catchments, the impact of riparian flood plains on water balance and chemistry, especially during dry periods, becomes of increasing interest for research and management (Woessner, 2000; Krause *et al.*, 2007). Many of the eco-hydrological functions of riparian flood plains are strongly related to the dynamic interactions between the shallow groundwater of flood plains and the surface water of the usually well-connected lowland rivers (Butturini *et al.*, 2002; Hayashi & Rosenberry, 2002).

The intensity of these interactions and the resulting exchange fluxes between groundwater and surface water depend on pressure head gradients between the flood

plain groundwater and the river, as well as on the connectivity between both water bodies (Woessner, 2000; Sophocleous, 2002).

In this study, we report on an experimental and model-based investigation of the spatially and temporally heterogeneous exchange fluxes between groundwater and surface water and their implications for water balance nitrate budgets.

MATERIALS AND METHODS

Study area

The riparian flood plain of the Havel River, which covers an area of 24 000 km² in the North German lowlands, is representative of the typical lowland flood plains of Central Europe. The flood plain extends over a mean altitude of 25–28 m a.s.l. The Pleistocene moraines surrounding the flood plain reach heights of up to 120 m a.s.l. The mean precipitation is 540 mm/year with higher rainfall intensities in autumn and spring. Because the riparian flood plain of the catchment has been characterised for centuries by periodic inundation, a dense and cross-linked drainage network has been developed (Krause *et al.*, 2007). The riparian flood plain of the central and lower Havel River with its numerous groundwater dependent wetlands represents an area of outstanding ecological value. Thus, wide areas of the flood plain are protected by German and European nature conservation laws. An extended description of the field site characteristics can be found in Krause & Bronstert (2004, 2007) and Krause *et al.* (2007).

The research presented in this study focuses on the “Direct Catchment” of the lower and central Havel River (Fig. 1) which is characteristic of the specific part of the riparian flood plain of the Havel River between the Potsdam and Garz gauges, where the water balance is directly affected by the surface water dynamics (Krause & Bronstert, 2005). The Direct Catchment represents the maximum spatial extent of direct interactions (i.e. quick responses) between groundwater and surface waters (Fig. 2). It is assumed that the groundwater dynamics beyond the direct catchment boundary are not significantly influenced by the fluctuation of surface water levels (Krause & Bronstert, 2005). An algorithm based on local simulation results in smaller subcatchments of the Havel River was applied to delineate the boundaries of the Direct Catchment (Krause & Bronstert, 2005).

Experimental setup

Experimental investigations within several subcatchments of the lower and central Havel River were based on observations of groundwater levels in 22 boreholes, nine of which were monitored at higher temporal resolution (hourly) than the fortnightly observations made at all boreholes. Soil moisture conditions were monitored at up to four depths, and hydroclimatic data were also measured at four stations. Detailed discharge and water-level measurements made on an irregular basis complemented the discharge and surface water level series which were obtained for 14 gauges from the Brandenburg State Environment Agency and from the nature conservation administration “Westhavelland”. Additional rainfall data for four stations were

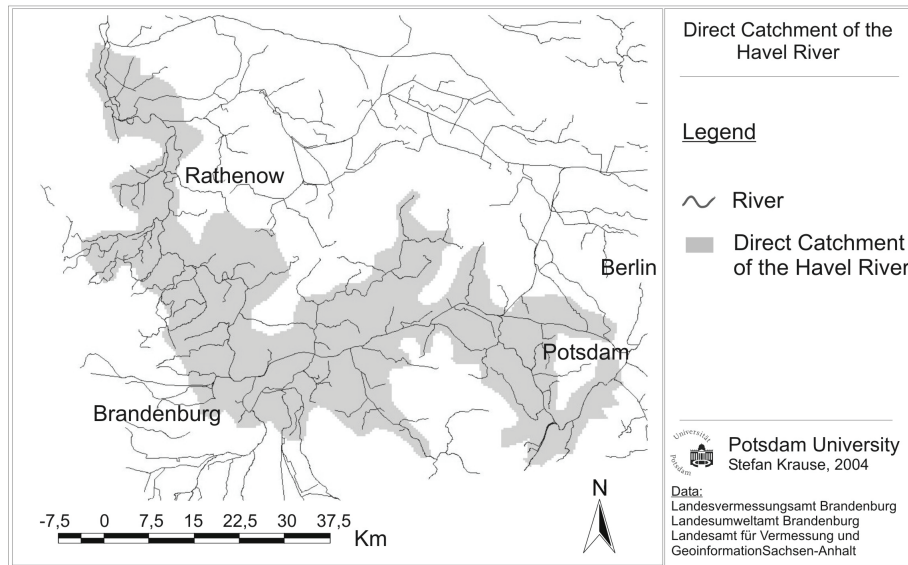
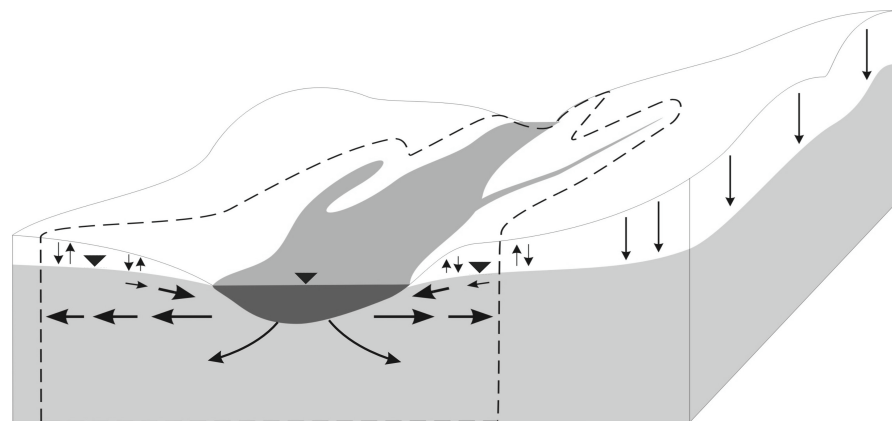


Fig. 1 Location of the research area, the direct catchment of the lower and central Havel River.



--- Boundary of Direct Catchment (limited by max. extend of river dynamic influences)
 □ Unsaturated soil zone ■ Groundwater ↔ GW-SW exchange fluxes

Fig. 2 Boundary of the Direct Catchment, representing the part of the riparian flood plain where the water balance is controlled by quick and close interactions between the groundwater and the surface water.

obtained from the German Weather Service (DWD). A comprehensive description of the experimental setup and monitoring network can be obtained from Krause & Bronstert (2004, 2007).

The IWAN model

The IWAN model for simulating “Integrated Water Balance and Nutrient Dynamics” (Fig. 3) was set up for the Direct Catchment. This considers vertical water balance

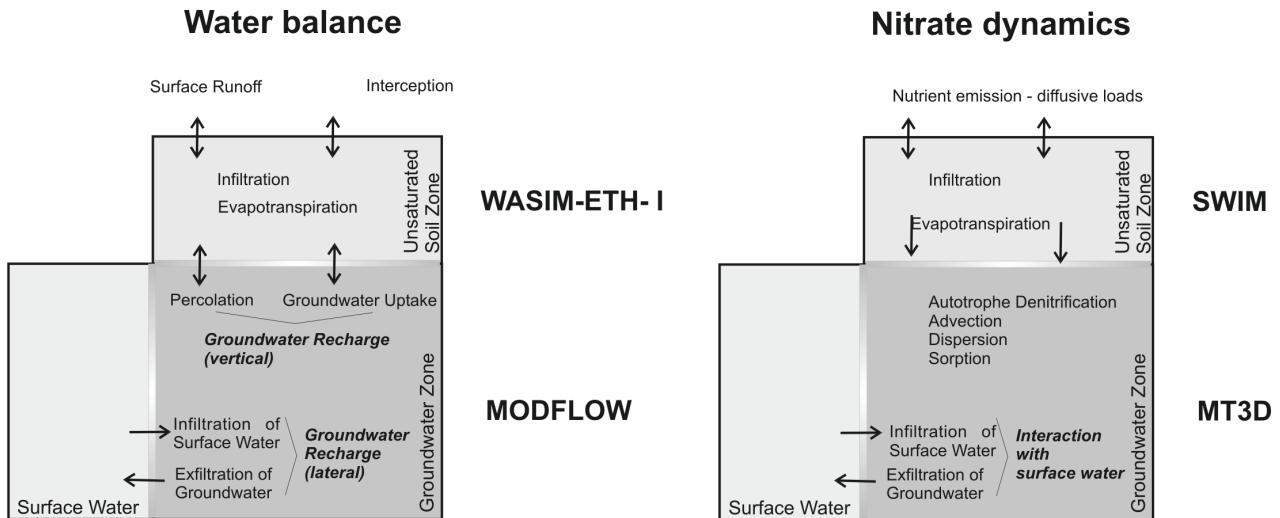


Fig. 3 Concept of the coupled groundwater, water balance and nitrate dynamics routines within the IWAN model: WASIM-ETH for the vertical soil water dynamics in the unsaturated zone and MODFLOW for the lateral groundwater flow and for the interaction between groundwater and surface water (left); MT3D for the nitrate dynamics in groundwater including SWIM that delivers vertical leachate rates as the upper boundary condition (right).

processes in the unsaturated part of the flood plain soils and lateral flow processes in the groundwater. Furthermore, it takes into account the temporally and spatially variable exchange fluxes at the groundwater–surface water interface (Fig. 2).

The model is based on the coupling of already existing routines. It is composed of two main water balance components (Fig. 3), which have been coupled in a two-way mode, i.e. feedback effects are taken into account in both directions:

- vertical soil water dynamics including unsaturated zone fluxes and groundwater recharge/abstraction are simulated by using the routines of the deterministic, spatially distributed hydrological model WASIM-ETH-I (Schulla, 1997; Niehoff *et al.*, 2002);
- the flow in the saturated zone and its interactions with the channel systems are modelled by using the 3-dimensional finite element-based numerical groundwater models MODFLOW (Harbaugh & McDonald, 1996) and Processing MODFLOW (Chiang & Kinzelbach, 2001).

The exchange between surface water and groundwater (Fig. 2) is approximated in the model-environment of Processing MODFLOW by using the “River Routine” (Prudic, 1988) applying a standard leakage approach.

The solute transport model MT3D (Zheng & Wang, 1999) is used for the simulations of nitrate transport and dynamics within the groundwater of the flood plain (Fig. 3). The model is incorporated in the Processing MODFLOW package (Chiang & Kinzelbach, 2001), where the flow velocities derived by MODFLOW are used for the simulation of the advective–dispersive nitrate transport. The nitrate degradation by bacterial denitrification is incorporated by applying a non-reversible first-order decay reaction. Values for the decay rates or half times are taken from the literature (Van Beek, 1987; Wendland & Kunkel, 1999). The model further considers exchange of nitrate due to transport through boundaries of the groundwater body. These are the

exchanges via the interface between the groundwater and the surface water, as well as the infiltration/uptake of nitrate from/into the root zone (Fig. 3). Both boundary conditions are considered to be temporally and spatially variable. For the representation of the upper boundary condition, the infiltration/uptake of nitrate from/into the root zone, simulation results from the model SWIM (Krysanova *et al.*, 2000; Habeck *et al.*, 2005) for the same region were used. The nitrate leakage rates from the root zone simulated by SWIM are redistributed on a daily time step on the basis of the vertical groundwater recharge dynamics based on the IWAN simulations. A detailed description of the model routines and parameterisation, model calibration and validation, as well as limitations of the model, can be found in Krause & Bronstert, 2007.

For the simulations in this study, the IWAN model was applied with a daily time step for the period 1 January 1988–31 December 1999 for the simulation of the water balance and groundwater dynamics. Due to limited nitrate observations, the nitrate dynamics in groundwater was simulated with a daily time step for the period 1 January 1994–31 December 1999 only. The spatial resolution of the model was a 250 m raster grid.

RESULTS AND DISCUSSION

Experimental investigations

Comparisons of time series of observed water-level fluctuations at surface water gauges and groundwater boreholes showed that the mean annual water level fluctuation of the Havel River is about 1.5 m, and thus is generally greater than the groundwater level fluctuation at 0.2–1.3 m (Fig. 4). A greater similarity of observed surface water stages and groundwater level dynamics could be observed for those groundwater gauges which are located a short distance from the river and thus are assumed to be well-connected with the surface water (Fig. 4). The great similarity of groundwater stage dynamics and surface water level fluctuations is related to exchange

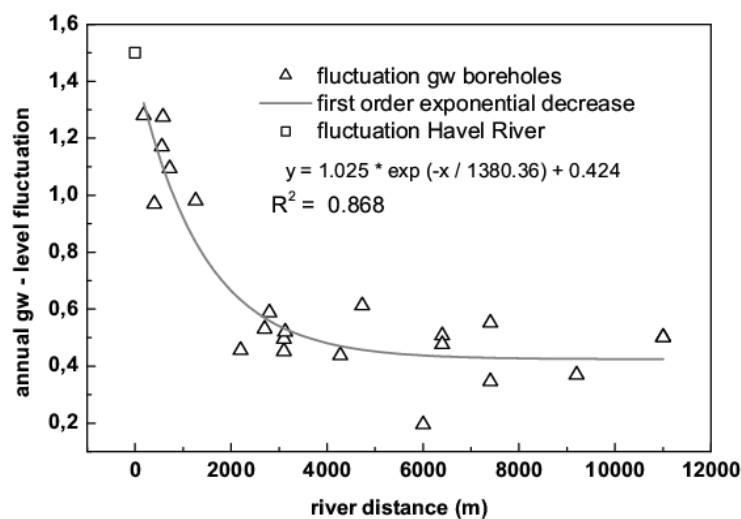


Fig. 4 Observed annual groundwater fluctuation in relation to borehole–river distance for the 22 observation boreholes.

fluxes across the groundwater–surface water interface. Furthermore, Fig. 4 shows that, within a distance of approx. 2 km from the surface water, the annual groundwater level fluctuation rates decline significantly from approx. 1.3 m to approx. 0.5 m. Considering that the groundwater is subject to vertical recharge and uptake from the root zone, as well as to lateral movement and exchange with the surface water, it is assumed that this effect indicates the decrease of the impact of groundwater–surface water exchange fluxes. Thus, an annual water level change of approx. 0.5 m represents the sole result of vertical processes such as percolation, root water uptake and evapotranspiration losses. It is furthermore assumed that the zone alongside the stream, which is characterised by higher annual groundwater fluctuation, represents the part of the flood plain where groundwater and surface water interact intensively.

Water balance simulations

Simulations of the water balance and groundwater dynamics with the model system presented in this study indicate substantial exchange fluxes across the groundwater–surface water interface of the riparian flood plain (Fig. 5). Exchange fluxes occur in both directions—from the groundwater towards the river as well as infiltration of the surface water into the groundwater. The fluxes depicted in Fig. 5 represent the net exchange rates across the groundwater–surface water interface. These values represent the spatial integral of all fluxes in both possible directions that may occur simultaneously at different locations in the riparian flood plain (Krause & Bronstert, 2007). Characteristic seasonal patterns of net exchange fluxes can be observed with dominant groundwater fluxes towards the river from summer to autumn, and surface water infiltration into the riparian flood plain during typical flood conditions in late winter and spring (Fig. 5). The simulated balance integrated over the simulation period and the entire area indicates an overall net contribution of groundwater into the river.

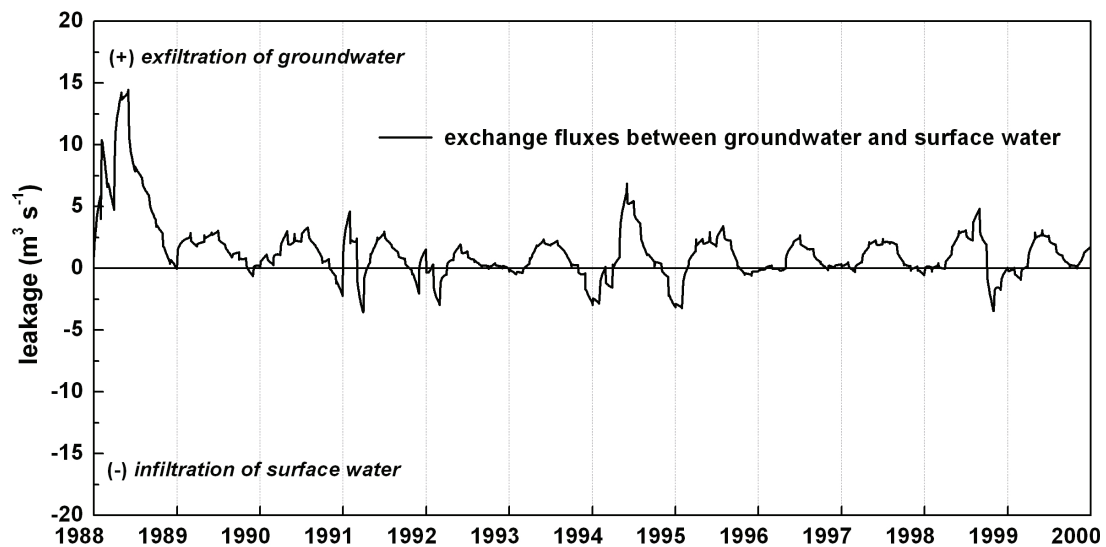


Fig. 5 Simulated exchange fluxes across the groundwater–surface water interface of the Direct Catchment of the Havel River.

Simulation of nitrate dynamics

Simulations of the nitrate dynamics within the riparian flood plain detect substantial attenuation of nitrate within the groundwater due to microbial denitrification. Nitrate retention of approx. 70% of the diffusive nitrate inputs leaching from the top soil into the anaerobic groundwater zone is simulated. Clearly, the water transport across the groundwater–surface water interface also affects the nitrate exchange between riparian groundwater and river. As Fig. 6 indicates, nitrate exchanges between groundwater and surface water occur in two directions, i.e. from the groundwater into the river, as well as from the river into the groundwater. As in the case of water fluxes, seasonal dynamics in the exchanged nitrate loads can be observed (Fig. 6). Hence, on average, groundwater-borne nitrate drains into the river and therefore increases the river nitrate loads from summer to the end of winter. Nitrate from the river is transported into the riparian groundwater mainly during late spring–early summer (Fig. 6). The offset of maximum groundwater–surface water exchanges and of the simulated nitrate transport across the groundwater surface water interface is caused by nitrate leaching from the root zone in late summer and autumn, which results in higher nitrate concentrations in the groundwater and, therefore, even small groundwater drainage to the surface water can contribute substantial nitrate loads.

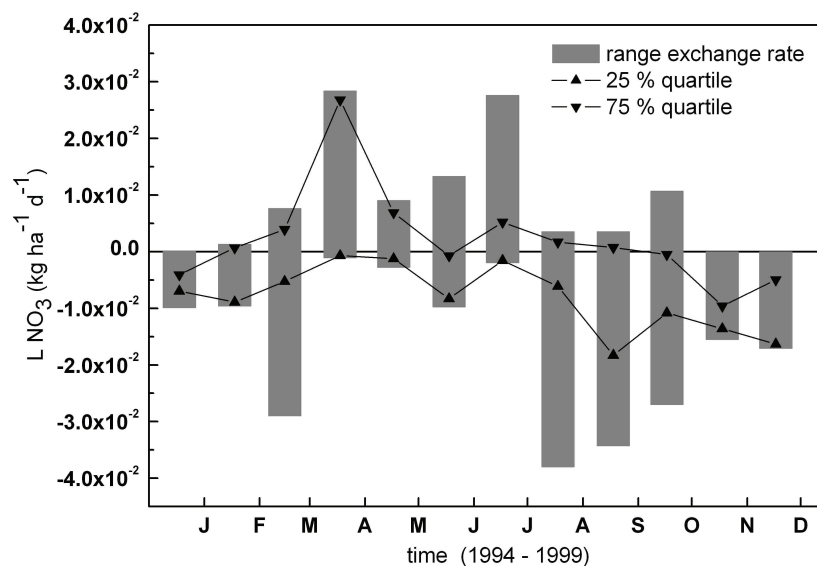


Fig. 6 Annual dynamics of simulated nitrate exchange rates between riparian groundwater and the Havel River. Negative values indicate groundwater-borne nitrate discharging into the river and positive values show retention of river-based nitrate.

Impact of exchange fluxes on water balance and nitrate dynamics

Comparative analyses of the simulated water exchange fluxes across the groundwater–surface water interface with observed discharges of the Havel River at the Havelberg gauge indicate that groundwater contributions of the riparian flood plain represent only a minor proportion on the whole river discharge (Fig. 7). In addition, seasonal variations in the relative impact of groundwater contributions to the river discharge are

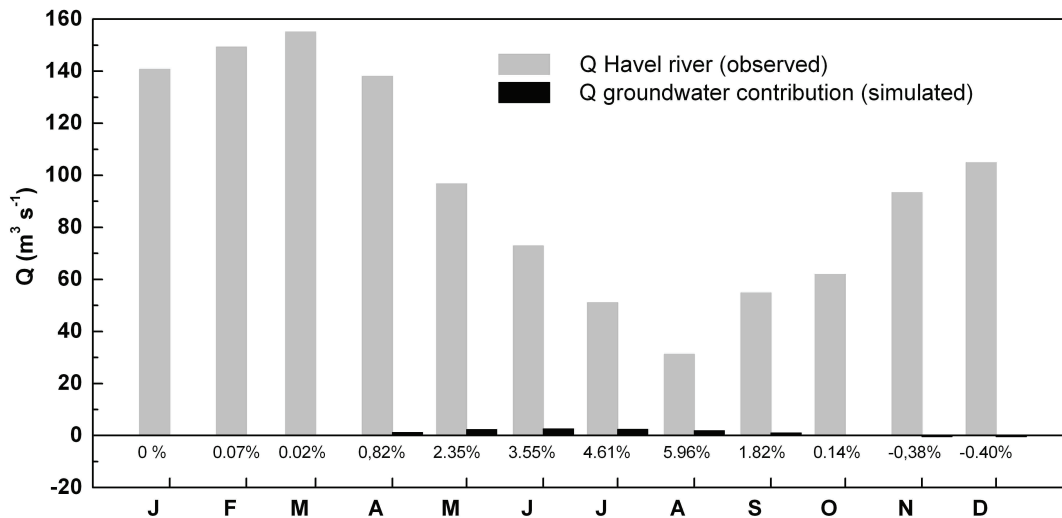


Fig. 7 Proportion of simulated groundwater contributions to the observed discharges of the Havel River at the Havelberg gauge.

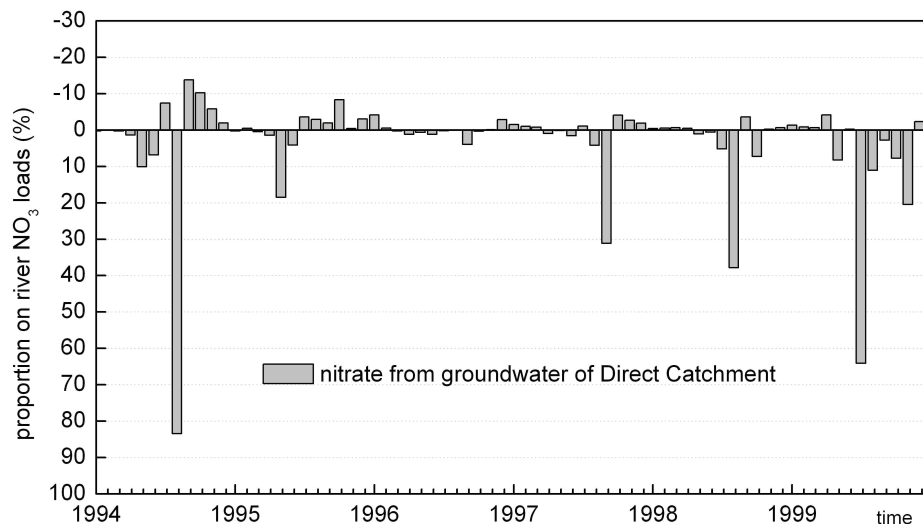


Fig. 8 Percentage fraction of the simulated groundwater-borne nitrate contributions to the observed nitrate loads within the Havel River at the Havelberg gauge for the period 1 January 1994–31 December 1999.

significant. The average annual proportion of riparian groundwater contributions from the research area (which represents 3.8% of the Havel catchment) to the total discharge is approx. 1% (Fig. 7). During high discharges and flood conditions in winter and autumn, groundwater contributions are lower. Furthermore, it is common for the net exchange fluxes even to indicate retention of surface water in the riparian flood plain (Fig. 7). However, during the low-flow conditions in summer, groundwater contributions from the Direct Catchment represent up to 6% of the total observed discharges in the river (Fig. 7), which is significantly higher, by approximately two-fold, than its spatial proportion of the total catchment size.

A comparison of simulated nitrate net exchange rates between the groundwater and the river with the observed nitrate loads in the Havel River indicate a similar

seasonal dynamic as was the case for the water exchange fluxes (Fig. 8). During late summer, groundwater contributions from the Direct Catchment represent regularly more than 5% of the observed river loads (Fig. 8). Occasionally the fraction of groundwater contributions is even higher (>10%). However, during flood conditions in spring, when surface water infiltrates into the flood plain, nitrate from the Havel River is regularly attenuated within the groundwater of the riparian zone (Fig. 8).

CONCLUSIONS

The experimental and model-based investigations give evidence for the impact that temporally and spatially variable interactions between groundwater and surface water have on the water balance and groundwater dynamics in the riparian flood plain. However, significant contributions of groundwater on the river discharge are limited to the low-flow season in summer. As simulation results of the riparian nitrate dynamics indicate, nitrate is transported in both directions across the groundwater–surface water interface. Hence the riparian flood plain acts as a source as well as a sink for nitrate during the simulation period. The amount of nitrate drained from the groundwater into the surface water exceeds the nitrate loads transported from the river into the flood plain, so that overall the riparian groundwater represents a nitrate source. However, approximately 70% of the incoming nitrate (river and root zone) gets denitrified within the groundwater, which again highlights the significant attenuation of nitrate within the riparian flood plain. The passage through the riparian zone significantly buffers diffusive nitrate pollution from agriculture and prevents higher contributions to the river load.

The proportion of groundwater-borne nitrate contributing to the total river load is temporally very variable. Thus, during summer the nitrate contributions from the groundwater represent regularly more than 10% of the total loads of nitrate in the river. Considering the ecological sensitivity of the summer period, the importance of these contributions and the significance of management measures altering this source become apparent. The results of this research clearly indicate the strong necessity of a seasonally variable evaluation of the impact of nitrate attenuation in the investigated riparian flood plain and its temporally dynamic impact on the river quality.

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