Is River-Aquifer Exchange an Important Control for the Nitrate Export from a Catchment under Monsoonal Climate Conditions?

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Abstract: In landscapes where groundwater and surface waters actively interact, the high concentrations of dissolved constituents in groundwater can have significant implications for surface water quality. In the Haean Catchment in South Korea, which has a strong monsoon type climate, high nitrate concentrations of up to 39.8 mg/L in the groundwater were measured in 2009. It is hypothesized that river-aquifer exchange in the Haean Catchment can significantly affect the nutrient export from the catchment and that the export is variable in time driven by monsoonal events. The identification of nitrate sink and source areas is based on groundwater and river water sampling at sites which reflect the dominant land uses as well as different elevations. Furthermore, we investigated the dynamics of river-aquifer exchange at two sites via piezometer transects at mid and lower elevations within the catchment. Our results suggest that due to river-aquifer exchange the river reaches in the lower part of the catchment have significantly higher nitrate concentrations than reaches at mid and high elevations. Hence, river-aquifer exchange fluxes might be an important control for the nitrate export from the catchment. However, this study also suggests that more research is needed to prove the general significance of this transport pathway.

Keywords: *nitrate export, river-aquifer exchange, agriculture, monsoonal storm events, subcatchment, land use*

1. Introduction

The overall goal of this study is to investigate the nitrate, dissolved organic carbon (DOC) and phosphorous export from the Haean Catchment, South Korea. Clean water from the Haean Catchment is important because it is a subcatchment of the Lake Soyang watershed which serves as a major drinking water supply for Seoul metropolitan area. Several reasons exist why the supply of clean water from the Haean Catchment can be seen as a challenge. The Haean catchment is used intensively for agriculture, where even steep slopes at higher elevations are utilized and cultivated. In addition, Korean fertilizer application rates for the intense agricultural productivity in mountainous regions are very high, relative to other locations throughout the world because during monsoonal extreme precipitation events large losses occur by erosion and/or leaching into the groundwater. In order to cope with this challenge we need to gain a better understanding of source areas (different agricultural land uses) and transport pathways of nutrients from the different compartments of the Haean Catchment into the receiving waters.

Many studies have concentrated on overland flow and surface runoff since this can be seen as one of the primary transport pathways for nutrient transfer from the field site to the receiving waters (Haygarth et al. 2005; McDowell et al. 2004; Heathwaite et al. 2005; Hart et al. 2004). Nutrient export and soil erosion from the Haean Catchment have been investigated with particular focus on phosphorous transport and it's implication on surface water quality (Kim et al. 2009). To date, no significant effort has been undertaken to investigate the compartment "groundwater" in the Haean Catchment and potential exchange fluxes between the rivers and the groundwater.

But in landscapes where groundwater and surface waters actively interact, high concentrations of dissolved constituents in groundwater can have significant implications for surface water quality (e.g. Kalbus et al. 2007).

Preliminary results from 2009 indicate high groundwater nitrate concentrations of up to 39.8 mg/L whereas, the nitrate concentrations in the rivers were found to be in general lower. Therefore, nitrate export from the Haean Catchment might be highly influenced by groundwater discharge into the rivers. It is hypothesized that the export of nitrate from the catchment is dominated by groundwater discharge to the lower reaches of the stream, which is variable in time controlled by monsoonal events. The objectives of this study are (1) to indentify nutrient sink and source areas in relation to dominant land uses in a subcatchment (2) identify locations of potential river-aquifer exchange (3) investigate and quantify these exchange fluxes on the reach-scale, and (4) determine the significance of river-aquifer exchange for nitrate export from the Haean Catchment.

2. Materials and Methods

2.1 Site Description

The investigation area is a subcatchment of the Haean Catchment located in South Korea (a detailed description of the Haean Catchment is given in the appendix by Seo et al. 2011).

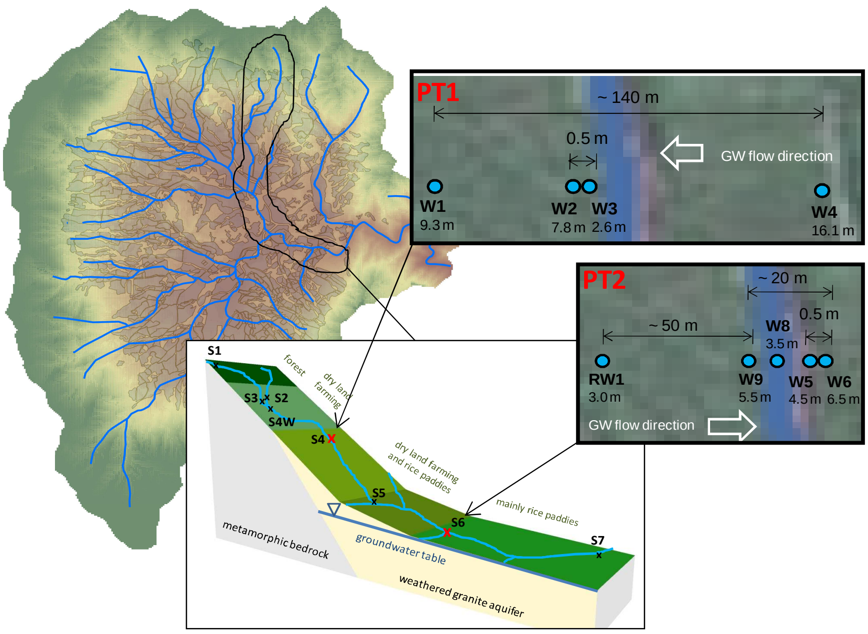

Figure 1. *Haean Catchment and the investigation area with general geologic structure at depth. Dominant land use is provided in relation to the sampling locations. In addition the piezometer transect locations and installations are presented (PT1 and PT2).*

2.2 Identification of Sink and Source Areas of Nutrients

Identification of nitrate sink and source areas is based on river and groundwater sampling at locations, which reflect the dominant land uses and elevation zones of the catchment (see Figure 1). During dry conditions surface water was sampled once per week and during monsoonal precipitation events every two hours at each site, respectively, and analyzed for nitrate. Groundwater was sampled from the wells of the piezometer transects (Figure 1) once a week and before and after precipitation events using a submersible pump. The samples were also analyzed for nitrate. In order to test the effect of rice paddies on nitrate export water from rice paddies was also sampled once a week and analyzed for nitrate. Discharge was measured with two sharp-crested v-notch weirs located at Sites S1 and S4w (Figure 1). In addition, a stage-discharge relationship was determined at six additional locations (Site S2, S3, S4, S5, S6, and S7 (Figure 1)) to estimate continuous discharge rates similar to Clark et al. (2007).

2.3 Characterization of River-Aquifer Interactions

Characterization of river-aquifer interactions is based on monitoring the hydraulic gradient along piezometer transects. Two piezometer transects were installed perpendicular to a second and third order stream, respectively. The first one (PT1) is located in the mid-elevation area of the catchment and dominated by dry land farming whereas, the second piezometer transect (PT2) was installed in the rice paddy dominated lower part of the catchment (Figure 1: PT1 and PT2). PT1 consists of four and PT2 of five 2-inch diameter, PVC wells with 0.5 m screened intervals. At both piezometer transects two nested wells were installed with a distance of approximately 0.5 m to each other and in order to determine the vertical hydraulic gradient at different depths. One well of PT2 (W8) with a length of 3.5 m is located in the center of the river channel. A stilling well, equipped with a pressure transducer, was attached to W8 to monitor the vertical hydraulic gradient between the river and the groundwater. Groundwater levels as well as the river stage were recorded at 15 minute intervals with pressure transducers (Solinst, Canada). Hydraulic conductivity was estimated in each piezometer with falling head slug tests. A known volume of water (500 - 1000 ml) was instantaneously introduced into each of the piezometers and the head drop was measured as a function of time (0.1 sec. interval) until the original water level was reached again.

2.4 Modeling Approaches

River-aquifer exchange fluxes were calculated by setting up a 2D model based on the numerical code HydroGeoSphere (Therrien et al. 2006), which describes fully-integrated surface and subsurface water flow as well as solute and thermal energy transport. The total head data measured at the piezometer transect and in the river were used as time variable boundary conditions whereas; the precipitation data were used as upper boundary fluid source.

3. Results

3.1 Nitrate Concentrations in the Rivers and Groundwater

In general surface water nitrate concentrations decrease with increasing discharges during monsoonal extreme precipitation events. As expected, subcatchment discharges increases with declining elevation (S3<S4w<S5<S6<S7). The highest nitrate concentrations are correlated with the sites S6 and S7, (Figure 2A/B) located in the lower part of the catchment. Figure 2B indicates that the highest nitrate concentration ranges also were found at site S6 and S7.

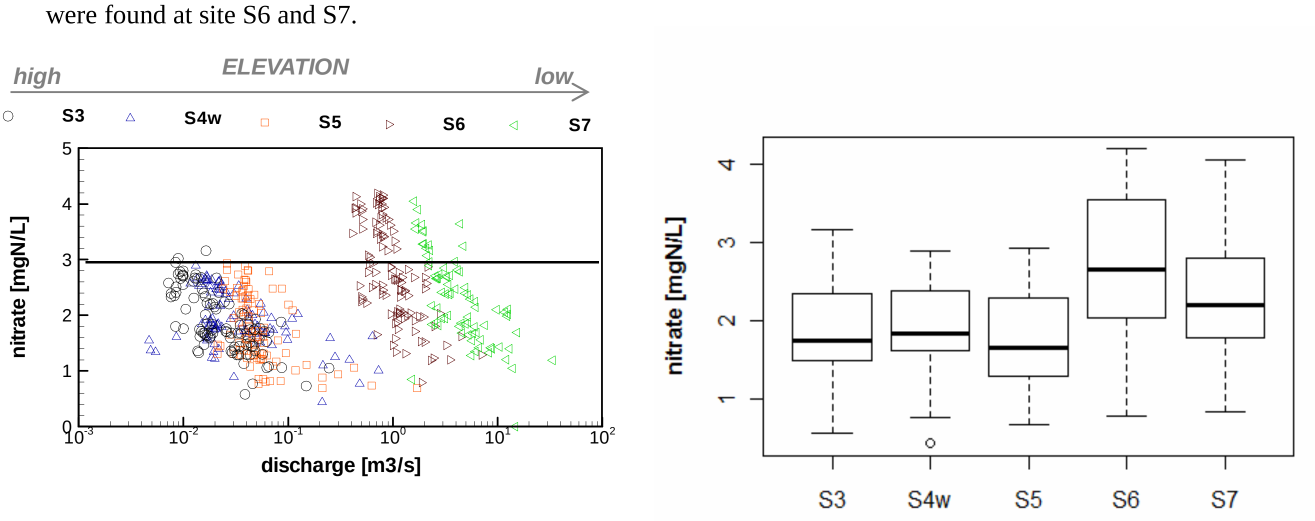

Figure 2. ***A)*** *Discharge versus nitrate concentrations measured at the river sites (S3, S4w, S5, S6 and S7) over the measuring period and* ***B)*** *boxplots of the nitrate concentrations at the sites*

Highest nitrate concentrations were found in the groundwater wells W1, W4, W9 and RW1 (Figure 1) that are either located some distance away from the rivers or are likely not influenced by the rivers due to their position in relation to the general groundwater flow direction.

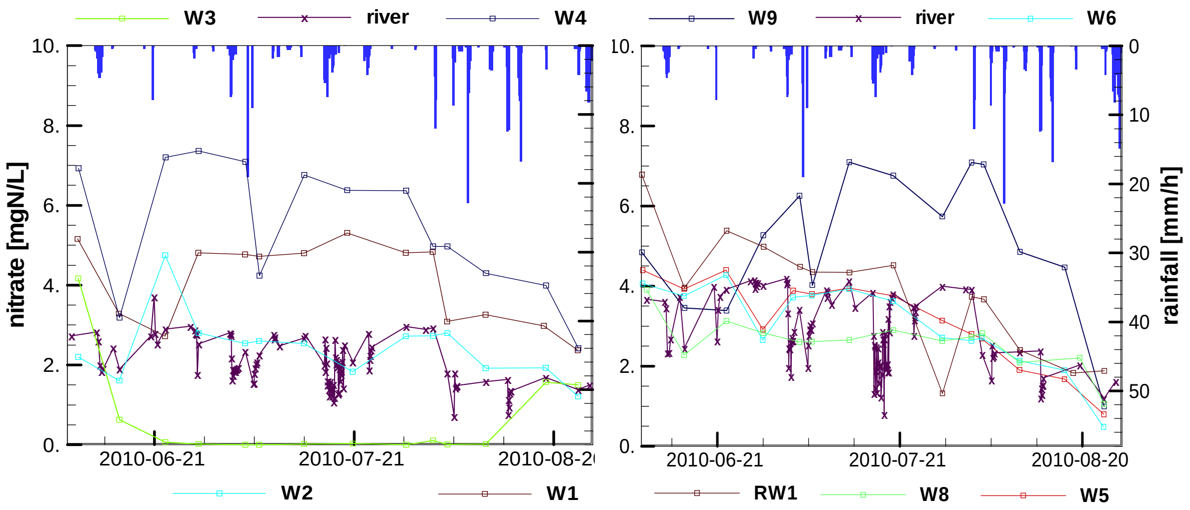

***Figure 3.** Nitrate concentrations measured at **A)** PT1 (mid elevation) **B)** PT2 (low elevation)*

In contrast, wells which are influenced by the rivers (W3, W5 and W6) show nearly the same concentration as measured in the rivers. Exceptions are the wells screened at 2-3 m below the riverbed (W3 and W8, Figure 1). In those riverbed wells the lowest nitrate concentrations were measured (Figure 3). In general the nitrate concentrations of the wells closest to the river, which during high river stage may be influenced by river water infiltration (W5, W6 and W8) are higher at PT2 compared to those (W2 and W3) of PT1.

3.2 Hydraulic Gradients and Exchange Fluxes

Hydraulic gradients at PT1 consistently indicated losing conditions (river water is recharging the groundwater). The total head measured in the shallowest well (W3) close to the river was found to always be at least 0.31 m lower than the river stage. In contrast, the differences in total head between the stream and the wells at PT2 show reversals in the direction and are generally larger than at PT1. The vertical hydraulic gradients between the river stage (measured laterally at the same point as well W8) and well W8 ranged from 0.12 to -0.11 (Figure 4A).

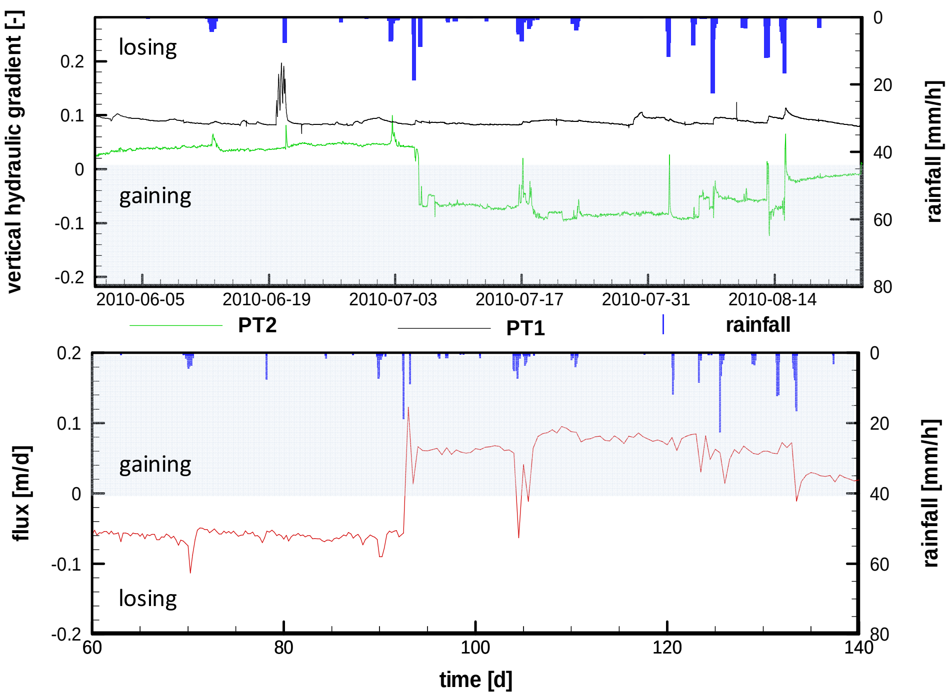

***Figure 4.** A) Vertical hydraulic gradients measured at PT1 (mid elevation) and PT2 (low elevation) as well as B) simulated exchange fluxes at W8 (PT2)*

Hence, losing as well as gaining conditions are evident in this part of the catchment. These results are generally supported by the numerical simulations, which also reflect the gradient reversals and the temporal variability of exchange fluxes. At the beginning of our measuring period losing conditions were evident followed by a gradient reversal and predominantly gaining conditions triggered by a short but very heavy precipitation event the 5th of July.

4. Discussion and Outlook

Nitrate concentrations were typically higher in the river reaches located in the lower parts of the catchment (site S6 and S7). These reaches with higher nitrate concentrations in the river water were investigated for river-aquifer exchange fluxes to quantify the impact of exchange on nitrate transport (Figure 4, 5 and 6). Initial results suggest that, groundwater discharge to the river may be a reason for the elevated nitrate concentrations in river reaches in the lower part of the catchment. During monsoonal extreme precipitation events large amounts of nitrate, mainly from areas of dry land farming (Figure 1), might be leached from agricultural fields around the upper and mid reaches of the river and percolate to deeper groundwater. As in the upper part of the catchment the connectivity between the rivers and groundwater is limited due to the geology (Figure 1) and due to sealing of riverbeds by channelization nitrate inputs via groundwater (baseflow) are negligible and river water quality hence unaffected in these areas. But in the lower parts of the catchment where the river at least temporarily receives baseflow high nitrate concentrations in the groundwater might have a significant impact on instream concentrations and hence the export of nitrate from the catchment. Nitrate concentrations in rice paddy water ranged from 0.01 to 0.91 [mgN/L] suggesting that these systems do not provide a major contribution to nitrate concentrations in the adjacent river. In conclusion, we could show that the river reaches in the lower part of the catchment are influenced by groundwater. We could further demonstrate that nitrate concentrations are generally higher in groundwater than in surface waters except for some wells in the immediate vicinity of the river, which may temporarily be affected by infiltrating river water. This suggests that baseflow contributions to the lower reaches of the river represent an important pathway for nitrate into the receiving waters. To what degree this transport pathway can be seen as a main control for nitrate export from the catchment remains to be seen. Therefore, we will first concentrate on, quantifying the exchange fluxes and their nitrate loadings at the river reach scale and then estimate the extent of exchange fluxes at catchment scale. Furthermore, we need to further investigate the controls of these exchange fluxes especially under complex hydraulic dynamics as they are typical for the monsoon type climate in Korea.

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