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River-aquifer exchange fluxes under monsoonal climate conditions

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SUMMARY

An important prerequisite to better understand the transport of nutrients and contaminants across the river-aquifer interface and possible implications for biogeochemical transformations is to accurately characterize and asses the exchange fluxes. In this study we investigate how monsoonal precipitation events and the resulting variability in river discharge affect the dynamics of river-aquifer exchange and the corresponding flux rates. We evaluate potential impacts of the investigated exchange fluxes on local water quality. Hydraulic gradients along a piezometer transect were monitored at a river reach in a small catchment in South Korea, where the hydrologic dynamics are driven by the East-Asian Monsoon. We used heat as a tracer to constrain river-aquifer exchange fluxes in a two-dimensional flow and heat transport model implemented in the numerical code HydroGeoSphere, which was calibrated to the measured temperature and total head data. To elucidate potential effects of river-aquifer exchange dynamics on biogeochemical transformations at the river-aquifer interface, river water and groundwater samples were collected and analyzed for dissolved organic carbon (DOC), nitrate (NO_3) and dissolved oxygen saturation (DO_{sat}). Our results illustrate highly variable hydrologic conditions during the monsoon season characterized by temporal and spatial variability in river-aquifer exchange fluxes with frequent flow reversals (changes between gaining and losing conditions). Intense monsoonal precipitation events and the associated rapid changes in river stage are the dominant driver for the observed riverbed flow reversals. The chemical data suggest that the flow reversals, when river water high in DOC is pushed into the nitrate-rich groundwater below the stream and subsequently returns to the stream may facilitate and enhance the natural attenuation of nitrate in the shallow groundwater.

1. Introduction

The dynamic exchange of water, energy and solutes across the river-aquifer interface affects the ecology of river systems (Brunke and Gonser, 1997), pathways of nutrient cycling (Krause et al., 2009) as well as the transformation and attenuation of nutrients and contaminants (Smith et al., 2009; Zarnetske et al., 2011a,b). Across scientific disciplines interest in the dynamics of river-aquifer exchange and the transition zone between ground- and surface water where differences in chemical, biological and physical properties of the two adjoining compartments result in steep biogeochemical gradients has steadily grown in recent years (Fleckenstein et al., 2010; Krause et al., 2013). River-aquifer interactions were found to have positive as well as negative effects on groundwater and stream water quality (Grasby and Betcher, 2002; Schmidt et al., 2011). High concentrations of contaminants in groundwater can significantly impact surface water quality and vice versa (Kalbus et al., 2007). Groundwater ecosystems often depend on infiltrating surface water that is rich in organic matter as an energy source (Madsen et al., 1991) for biogeochemical reactions.

An important prerequisite to understand the transport of nutrients and contaminants across the river-aquifer interface and the resulting biogeochemical processes in the transition zone is to accurately characterize and asses the exchange fluxes at the river-aquifer interface (Conant, 2004; Greenberg et al., 2002). A broad range of methods exists to quantify groundwater–surface water exchange fluxes (Kalbus et al., 2006). However, the extreme variability of hydrologic conditions in monsoonal systems can make the use of many of them quite challenging. For example direct

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measurements of exchange fluxes by conventional seepage meters. (Landon et al., 2001; Rosenberry, 2008) are highly impractical under monsoonal conditions. During extreme precipitation events, river discharge can rapidly rise by up to 2 orders of magnitude relative to the discharge under dry conditions making in-stream installations difficult to employ. Additionally extreme flows may result in sediment scour and associated stream bed elevation changes, which further complicates the direct quantification of river aquifer-exchange fluxes in the field.

A commonly accepted conventional method for investigating river aquifer-exchange fluxes is based on monitoring of hydraulic gradients along piezometer transects (Eddy-Miller et al., 2009). The advantage of this method is that in-stream installations are not imperative. However, the head gradients between a piezometer in the riverbed, river bank, riparian zone and the stream alone is often only a weak indicator for the general direction of exchange (Kaeser et al., 2009) and spatial patterns of exchange fluxes are typically much more variable (Schornberg et al., 2010; Lewandowski et al., 2011; Angermann et al., 2012). Scanlon et al. (2002) therefore suggested the application of multiple methods for an accurate assessment of river-aquifer exchange fluxes. An increasing number of studies have combined hydraulic head measurements with the use of heat as a natural tracer and inverse numerical modeling (Eddy-Miller et al., 2009; Anibas et al., 2009; Schmidt et al., 2007; Constantz, 2008; Essaid et al., 2008).

Using heat as a tracer is based on natural temperature differences between ground- and surface water, which result in temperature distributions in the transition zone that are indicative of conductive and advective heat transport processes between the two compartments. Most surface waters show diurnal temperature fluctuations, whereas groundwater temperatures are relatively constant over time. Heat is transported by advection (with the moving water) and conduction (heat exchange due to temperature gradients) through the riverbed sediments (Constantz, 2008). In river reaches where surface water is infiltrating into the aquifer (losing conditions) the diurnal temperature signal from the surface water propagates downward by advective and conductive, heat transport (Graf, 2005). In contrast, in gaining reaches the temperature signal, which is conductively transported downwards, is attenuated by upward advection of groundwater with steady temperature, which dampens the diurnal temperature variation originating from the surface water (Eddy-Miller et al., 2009). Combining both, temperature and head data in the calibration of numerical models of groundwater–surface water interactions can provide more reliable estimates of exchange fluxes as opposed to using head data alone (Anderson, 2005).

In this study, we use head and temperature data from a river-aquifer system in South Korea that is driven by the East-Asian Monsoon to constrain a numerical model of the river-aquifer exchange dynamics. The main objective was to investigate how monsoonal precipitation events and the resulting variability in river discharge affect the dynamics of river-aquifer exchange and the corresponding flux rates. Hydraulic gradients between the river and the aquifer were monitored in a piezometer transect across a typical river reach in the catchment. Temperatures at different depth in the aquifer below the stream were measured in the central piezometer in the Thalweg of the stream. The 2D-model, based on the code HydroGeoSphere, was calibrated to the measured temperature and total head data. To elucidate potential effects of the observed and simulated river-aquifer exchange dynamics on biogeochemical transformations at the groundwater–surface water interface, river and groundwater samples were collected and analyzed for dissolved organic carbon (DOC), nitrate (NO_3) and dissolved oxygen saturation (DO_{sat}).

2. Materials and methods

2.1. Study area and site

The study area is the Haean-myun Catchment (longitude 128°5′ to 128°11′E and latitude 38°13′ to 38°20′N) located in Yanggu County, Gangwon Province, South Korea. With an agricultural area of 42% of the entire basin area (62.7 km^2), the Haean Catchment is one of the major agricultural areas in the region. It contributes significant amounts of agricultural nutrients (nitrogen, phosphorus) to the downstream receiving waters (Kim et al., 2006), which eventually feed into Lake Soyang an important drinking water reservoir for the metropolitan area of Seoul. Surface elevation within this bowl-shaped mountainous catchment ranges from a minimum of 340 m above sea level (masl) near the catchment outlet to a maximum of 1320 masl along the surrounding mountain ridges. At the bottom of the basin, the bedrock consists of highly weathered Jurassic biotite granite, surrounded by Precambrian metamorphic rocks forming the mountain ridges (Kwon et al., 1990; Jo and Park, 2010). The land use pattern in the Haean basin roughly follows the elevation gradient. Forest land use is typically associated with higher elevation and steep slopes, followed by dryland crops on lower elevation and moderate slopes and predominately rice paddies in the lowland area. The study site is located in the lower elevation, central part of the basin (Fig. 1), where rice paddy cultivation is the dominant land use.

The climate of the Haean Catchment is strongly influenced by the East-Asian Monsoon, with hot and humid summers and cold and dry winters. Seventy percent of the annual precipitation falls during intense rain events in June, July and August. Nearly 90% occurs within the cropping season from April to October (Kettering et al., 2012). The annual average air temperature (1999–2009) and the annual average precipitation amount (1999–2009) in the catchment are 8.5 °C and approximately 1577 mm, respectively (Kettering et al., 2012).

2.2. Field instrumentation and data collection

2.2.1. Piezometer installation and head measurements

A piezometer transect was installed across the main stem of the Mandae River (a third-order stream) in the lower part of the Haean Catchment that is dominated by rice paddies (Fig. 1B). The piezometer transect consists of four 2-in. diameter, polyvinyl chloride (PVC) piezometers (wells) with 0.5 m screened intervals at their lower end. At the left river bank a piezometer nest was installed with two piezometers placed about 50 cm apart from each other, one to a depth of 6.00 m below ground (W6) and the other to a depth of 4.00 m. In the center of the river channel, we installed a piezometer (W8) to a depth of 3.0 m, which was capped and sealed to prevent surface water from entering during high river stages. Piezometer W9 on the right bank was installed to a depth of 5.00 m. All piezometers were equipped with absolute pressure transducers (M10 Levelogger, Model 3001, Solinst Ltd., Canada, ±0.01 m), which recorded total head and temperature at 15 min intervals over the period from March to December 2010. A stilling well, equipped with an additional M10 pressure transducer, was attached to W8 to monitor river stage and from that the vertical hydraulic gradient between the river and the groundwater at 2.75 m below the streambed (center of the screened interval of W8). River stage was recorded every 15 min. Water level readings recorded by leveloggers were corrected for atmospheric pressure variations by using the atmospheric pressure readings of a Barologger (Barologger, Model 3001, Solinst Ltd., Canada), attached to the outer top of piezometer W5.