



Elucidating temperature effects on seasonal variations of biogeochemical turnover rates during riverbank filtration

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SUMMARY

Riverbank filtration (RBF) is a mechanism by which undesired substances contained in infiltrating surface waters are attenuated during their passage across the riverbed and its underlying aquifer towards production wells. In this study, multi-component reactive transport modeling was used to analyze the biogeochemical processes that occur during subsurface passage at an existing RBF system – the Flehe Waterworks located along the Rhine River in Düsseldorf, Germany. The reactive transport model was established on the base of a conservative solute transport model for which temperature and chloride data served as calibration constraints. The model results showed that seasonal temperature changes superimposed by changes in residence time strongly affected the extent of the redox reactions along the flow path. The observed temporal, especially seasonal, changes in the breakthrough of dissolved oxygen were found to be best reproduced by the model when the temperature dependency of the biogeochemical processes was explicitly considered. High floods in the Rhine drastically reduced the travel time to the RBF well from an average travel time of 25–40 days to less than 8 days. On the other hand, low flow conditions increased the subsurface residence times between the Rhine River and the RBF well to about 60 days. The model results revealed that short term changes in the terminal electron acceptor consumption (biodegradation extent) were solely attributed to fluctuations in residence time, while more gradual changes in biodegradation extent were due to both seasonal variations of the river water temperature and gradual changes in residence time.

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1. Introduction

Riverbank filtration (RBF) is a mechanism by which undesired substances contained in infiltrating surface waters are attenuated during their passage across the riverbed and its underlying aquifer towards collector wells (Ray et al., 2002a). Riverbank filtration wells for public water supply have been widely used in Europe for more than a century (Schubert, 2002) and for more than half a century in the United States (Ray et al., 2002a). Water in the aquifer below or adjacent to the water bodies is typically harvested using vertical or horizontal collector wells. This yields, in general, cleaner water that is more consistent in quality and requires a lesser amount of subsequent treatment and disinfection compared to

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using the surface water as a direct source (Eckert and Irmischer, 2006). The quality of surface water is often affected by agricultural runoff, industrial discharges and municipal outfalls which introduce a large variability of contaminants in the source water. During the subsurface passage the infiltrating water is subjected to a combination of physical, chemical, and biological processes such as filtration, sorption and biodegradation that can significantly improve the raw water quality (Hiscock and Grischek, 2002; Kuehn and Mueller, 2000; Ray et al., 2002a). The quality improvements obtained by bank filtration may allow for significant reductions of turbidity, microbial contaminants, natural organic matter (Wang et al., 2002; Weiss et al., 2004), organic trace pollutants (Grünheid et al., 2005) such as pesticides (Ray et al., 2002b) and pharmaceutical residues (Massmann et al., 2008; Petrovic et al., 2009). On the other hand, hydrogeological or geochemical factors such as long flow paths and high sedimentary organic matter (SOM) concentrations or high dissolved organic carbon (DOC) concentrations in the raw, i.e., in the river water can cause adverse redox reactions that

deteriorate the water quality by inducing the reductive dissolution of minerals and the associated increase of, for example, manganese and iron (Bourg et al., 2002) as well as trace metal concentrations in the infiltrated water.

During RBF the pumping-induced infiltration of surface waters typically affects the redox conditions in the hyporheic zone, resulting from DOC/SOM being degraded while sequentially consuming the terminal electron acceptors (TEAP) dissolved oxygen, nitrate, manganese and iron(hydr)oxides and sulfate. (Barry et al., 2002; Champ et al., 1979). This sequential consumption of electron acceptors along the flow path of infiltrating river water and the development of distinct redox zones towards more reducing conditions in downstream direction has been documented for many cases. Bourg and Bertin (1993) used groundwater mixing and degradation of organic matter to explain the observed reducing zones in an aquifer adjacent to the Lot River (France). More recently Kedziorek et al. (2008) confirmed through geochemical modeling for the same site the occurrence of redox reactions and also showed that they affected groundwater quality away from the river bank.

Where hydrochemical monitoring covered longer time periods it was shown, in many cases, that redox gradients and zonation undergo strong temporal variations. Jacobs et al. (1988), for example, documented significant seasonal water quality changes along a saturated river-groundwater infiltration flow path. Similar to an RBF situation, a spatially and temporally varying redox zonation was also found below an artificial pond near Lake Tegel, Germany (Greskowiak et al., 2005a). For that site it was demonstrated that the redox zonation and its changes were driven by seasonally varying, temperature-dependent organic matter degradation. A complete removal of the PhAC phenazone was shown to occur when the aquifer remained aerobic during colder months. It was substantially more persistent during the warmer months when anaerobic conditions dominated (Greskowiak et al., 2006; Massmann et al., 2006). Similarly, temperature dependent reactions of the key reductants were shown to be crucial for successfully modeling the redox zonation created by the injection of oxic surface water into a deep pyritic aquifer (Prommer and Stuyfzand, 2005). In their case, the consideration of heat transport that accounted for strong seasonal temperature variations was also shown to be highly valuable for an improved calibration of redox changes. Other cases also showed the use of temperature measurements to aid groundwater flow modeling (Anderson, 2005) and in modeling groundwater surface water interactions (Blaschke et al., 2003; Constantz, 2008; Doppler et al., 2007; Doussan et al., 1994; Stonestrom and Constantz, 2003).

Despite a continuously increasing interest in surface water/groundwater interactions, to date no detailed, model-based quantitative analysis of the temporal biogeochemical dynamics of RBF systems has been undertaken, linking dynamic flow processes with the effects of varying temperature, reaction kinetics and the resulting overall biogeochemical turnover rates at the river groundwater interface. The objective of the present paper is to fill this gap and to identify and quantify the interactive, dynamic physical and chemical processes impacting water quality changes within the hyporheic zone and the extraction wells in an RBF system under seasonally changing hydrological and raw/river water hydrochemical conditions. We use data from a well-documented field site in the lower Rhine Valley near Düsseldorf (Germany) to develop and test a process-based reactive transport model.

2. Study site

The RBF site used for our modeling study is the Flehe Waterworks well field, situated on the Eastern bank of the Rhine River (see Fig 1) on the outer side of the river bend between river kilome-

ters 730.7 and 732.5 (Eckert et al., 2005; Schubert, 2002; Sontheimer, 1980). At the site the Rhine River is 400 m wide, has a median discharge of 2100 m³/s, a hydraulic gradient of 0.2 m/km and a flow velocity of 1–1.4 m/s. The data analyzed by our study were collected between January 2003 and May 2004. During this period the highest recorded flood level was 36.35 m (above mean sea level) and the lowest observed level was 27.44 m. The median flow occurs at river levels of approximately 29.8 m.

The RBF system consists of a gallery of wells located 60 m from the bank. The wells are typically 0.60 m in diameter, 22 to 28 m deep with 15 m screen lengths and interconnected by siphon pipes. The design capacity of the well field is 44,000 m³/d, but the actual pumpage during the period of our study varied between 34 and 1480 m³/h (816–35,520 m³/d) including a number of short shut off periods. In total, 50 wells are located linearly in a reach of 1400 m parallel to the river on the North-East bank.

In the river water, the temperature fluctuates seasonally between a minimum of 3 °C and a maximum of 27 °C and between 7 °C and 21 °C in the infiltrated water (see Fig 3). A distinct lag is apparent between the river temperature extremes of the river and the infiltrated water.

2.1. Hydrogeology

The aquifer targeted by the RBF system consists of sandy gravelly Pleistocene sediments with an underlying confining layer of very fine Tertiary sands. The thickness of the aquifer at the Flehe site varies between 15 and 25 m (Schubert, 2002) as shown in Fig 2. The aquifer is exposed and hydraulically connected to the Rhine River. The average hydraulic conductivity of the aquifer is reported to range between 4×10^{-3} m/s and 2×10^{-2} m/s (Schubert, 2002). The riverbed at the site was previously reported to contain zones affected by riverbed clogging (Eckert and Irmischer, 2006; Schubert,

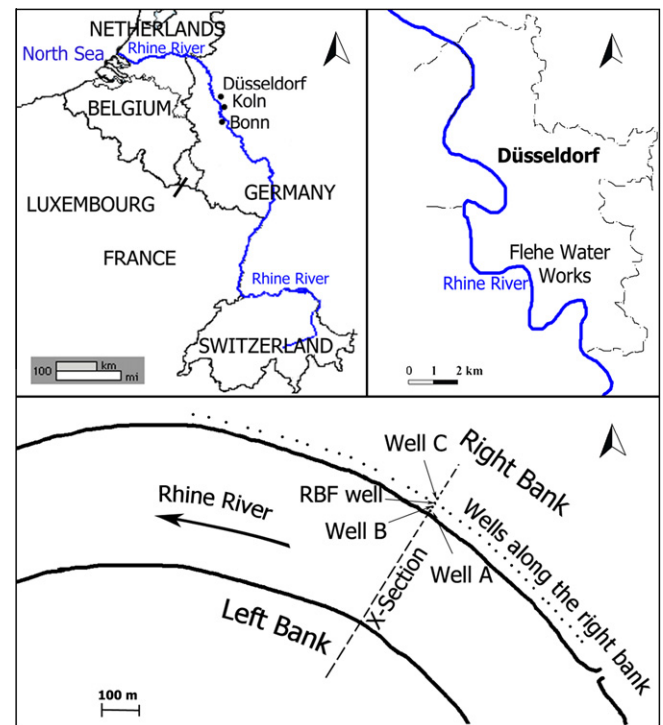


Fig. 1. Location of the Flehe water works along Rhine River in Düsseldorf, Germany. The modeled x-section of the Rhine River, the observation wells and RBF well are shown. The alignment of other wells along the Rhine in the right bank is also shown by black dots, the position of the dots are only indicative and do not represent actual wells.

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