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A novel method to evaluate the effect of a stream restoration on the spatial pattern of hydraulic connection of stream and groundwater

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SUMMARY

Stream restoration aims at an enhancement of ecological habitats, an increase of water retention within a landscape and sometimes even at an improvement of biogeochemical functions of lotic ecosystems. For the latter, good exchange between groundwater and stream water is often considered to be of major importance. In this study hydraulic connectivity between river and aquifer was investigated for a four years period, covering the restoration of an old oxbow after the second year. The oxbow became reconnected to the stream and the clogging layer in the oxbow was excavated. We expected increasing hydraulic connectivity between oxbow and aquifer after restoration of the stream, and decreasing hydraulic connectivity for the former shortcut due to increased clogging. To test that hypothesis, the spatial and temporal characteristics of the coupled groundwater-stream water system before and after the restoration were analysed by principal component analyses of time series of groundwater heads and stream water levels. The first component depicted between 53% and 70% of the total variance in the dataset for the different years. It captured the propagation of the pressure signal induced by stream water level fluctuations throughout the adjacent aquifer. Thus it could be used as a measure of hydraulic connectivity between stream and aquifer. During the first year, the impact of stream water level fluctuations decreased with distance from the regulated river (shortcut), whereas the hydraulic connection of the oxbow to the adjacent aquifer was very low. After restoration of the stream we observed a slight but not significant increase of hydraulic connectivity in the oxbow in the second year after restoration, but no change for the former shortcut. There is some evidence that the pattern of hydraulic connectivity at the study site is by far more determined by the natural heterogeneity of hydraulic conductivities of the floodplain sediments and the initial construction of the shortcut rather than by the clogging layer in the oxbow.

1. Introduction

In the past decades there has been an increasing effort on research and practice according to the restoration of rivers and their floodplains. The main reasons for that are the valuation of river ecosystems as place for species conservation and habitat diversity, recreational and aesthetic purposes, flood protection, enhancing the potential of contaminant deposition and nutrient degradation (Bernhardt et al., 2007; Kondolf et al., 2007; Hester and Gooseff, 2010; Pander and Geist, 2013; Schirmer et al., 2013). This is also reflected in a growing body of legislative directives (Pander and Geist, 2013; Schirmer et al., 2013), e.g. the EU Water Framework Directive demands a good chemical and ecological status of groundwater and surface water (European Commission, 2000). The chemical and ecological status of surface waters is impacted by the adjacent connected aquifer and vice versa. Hence both waters have to be considered when assessing water qualities of either of them. Nevertheless, in river restoration practice the measures most often focus solely on surface waters, whereas the connection of the river and the groundwater below the river bed and the adjacent floodplain is often neglected (Boulton, 2007; Boulton et al., 2010; Hester and Gooseff, 2010).

Previous studies identified the transition zone between stream water and groundwater, the hyporheic zone, as highly relevant for mass exchange, residence time of water and substances in the stream or in the sediment, the chemical and metabolic turnover

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and in general as crucial for water quality (Brunke and Gonser, 1997; Sophocleous, 2002; Boulton, 2007). The spatial extent of the hyporheic zone is mainly determined by two drivers, the hydraulic gradient between the river and the groundwater and the sediment structure (Kasahara et al., 2009), especially the permeability of the stream bed and aquifer sediments (Woessner, 2000; Kalbus et al., 2009). Therefore, clogging of the stream bed, i.e. the sealing of the stream bed with sediments of very low hydraulic conductivity, has been identified as major problem for exchange of surface water and groundwater and the related ecological functions of the hyporheic zone (Sophocleous et al., 1995; Brunke and Gonser, 1997; Sophocleous, 2002).

Fluxes are spatially and temporally heterogeneous due to the spatial heterogeneity of hydraulic conductivity of the sediments and spatial and temporal variability of hydraulic gradients (Woessner, 2000; Malard et al., 2002; Krause et al., 2011; Binley et al., 2013). Different methods are available to estimate fluxes across the interface in a river-groundwater system (Kalbus et al., 2006). Selective approaches, such as vertical temperature profiles (e.g. Schmidt et al., 2006; Anibas et al., 2009), heat pulse sensors (e.g. Lewandowski et al., 2011), hydraulic gradients (e.g. Krause et al., 2012) or seepage meters (e.g. Rosenberry and LaBaugh, 2008) are able to monitor the flux over time for a specific point, but it is not possible to draw conclusions for a whole river section. A method to capture larger areas is distributed temperature sensing (DTS) (e.g. Selker et al., 2006a,b; Krause and Blume, 2013), which is able to detect spots with intense groundwater ex- and infiltration. Another option is to use natural or artificial tracers to determine the degree of interactions (e.g. Négrel et al., 2003; Cox et al., 2007). Beside the different measuring techniques, numerical modelling was often used to examine groundwater-surface water interactions (e.g. Nützmann et al., 2013). One advantage of the latter method is that it does not have to be restricted on the hyporheic zone itself and can include the adjacent floodplain. All methods have in common the large temporal and monetary effort and in most case the restriction to certain areas or certain seasons. Furthermore, most approaches rely on information about hydraulic conductivity or related parameters, which are hard to estimate and result in uncertainties.

Another method which directly estimates the spatial distribution of the hydraulic properties of the sediments is hydraulic tomography (e.g. Yeh and Liu, 2000; Zhu and Yeh, 2005). In a network of spatially distributed wells the response to an artificial pressure signal induced by a pump at one well is recorded at all other wells. The procedure is repeated by sequentially circulating the pump through the other wells. With packers each well can be segregated in different depth intervals and by circulating the pump through the depth intervals at all wells the depth integrated estimation of hydraulic properties can be enhanced to a 3D-tomography (Yeh and Liu, 2000; Cardiff and Barrash, 2011). With an inverse model the spatial distribution of the hydraulic properties of the aquifer is estimated from the interplay of all the observed hydraulic head series. Up to now most of the non-numerical hydraulic tomography studies aimed to map the small scale variability of the hydraulic properties of the sediments on the lab to plot scale and used artificial pressure pulses (Yeh et al., 2009; Cardiff and Barrash, 2011). Recently there were attempts to extend hydraulic tomography to the groundwater basin scale and to use natural pressure signals, e.g. river stage fluctuations as signal (Yeh et al., 2009).

Similarly we use in the present study river stage fluctuations as natural pressure signals and study their propagation in the aquifer before and after a stream restoration measure to study groundwater-stream water interactions. Time series of hydraulic head reflect effects of different causes, like river stage fluctuations, groundwater recharge, precipitation, evapotranspiration, measurement errors, etc. (Yeh et al., 2009). In contrast to the aforementioned approaches we decomposed the hydraulic head series into independent components using a principal component analysis in order to disentangling the different effects.

The study was conducted at a section of the river Spree and its floodplain in the east of Berlin. Here an island is formed by an artificial stream channel (shortcut) and an oxbow. As restoration measure the shortcut was detached from the river at its upstream end, the former oxbow was reconnected to the stream and its clogging layer was excavated. The site was equipped with 15 groundwater observation wells, 2 river stages and 2 hyporheic wells, where data loggers measured every hour two years before and after the restoration. Please note that in our study we do not focus on the small scale heterogeneity of the hydraulic properties of the sediments as it would be important e.g. for estimations of the flowpaths of contaminants or the study of biogeochemical processes in the hyporheic zone. Instead we investigated the effect of the removal of the clogging layer and the change of the river course on the hydraulic connection of stream and groundwater.

Our analysis is based only on hydraulic head data and does not require any additional information. Please note that therefore our analysis is restricted to the transmission of pressure waves. We use the term "hydraulic connectivity" in contrast to the broader concept of "hydrologic connectivity" which is defined by Pringle (2001) as "water-mediated transfer of matter, energy, and/or organisms within or between elements of the hydrologic cycle" to account for that. The presented approach does not allow direct conclusions on related mass fluxes, flowpaths and water exchange rates (Lewandowski et al., 2009; Page et al., 2012). Instead the permeability for pressure signals is a necessary prerequisite for the exchange of mass fluxes. Thus, the hydraulic connectivity between the observation wells can be used as proxy for the relative differences in effective hydraulic conductivity of the floodplain sediments between the observation wells. With this integrative measure the problem of measuring the small scale variability of hydraulic conductivity in the floodplain is avoided.

To that end, we followed the approach presented by Lewandowski et al. (2009) for a time period where the river section was not restored and applied a principal component analysis on time series of groundwater heads and stream water levels. Based on the findings of Lewandowski et al. (2009) we hypothesized that (1) due to the restoration the hydraulic connectivity between the oxbow and the nearby groundwater will increase and that (2) in the shortcut the river bed will be clogged due to the reduced stream velocity, resulting in decreasing hydraulic connectivity between the shortcut and the adjacent groundwater.

2. Methods

2.1. Study Site

The Freienbrink site is situated in the floodplain of the lowland river Spree about 30 km east of the centre of Berlin (52°22′06″N, 13°48′25″E). The discharge of the river Spree is regulated by the Weir Grosse Tränke located 10 km upstream and varies usually between 5 and 20 $m^3 s^{-1}$ (Nützmann et al., 2013). At the site, a straight, artificial channel (shortcut) and an old meander (oxbow) form an artificial island. The shortcut was constructed in the 1960s to increase the flow velocity within the river and lower the surrounding groundwater table for agricultural purposes. In the first two years of the monitoring period, the shortcut served as the main stream channel and the oxbow was nearly completely blocked at its upstream end with a dam (Fig. 1). Some pipes inside the dam that connected the oxbow to the main stream were blocked with fine sediments. Therefore, the flow velocity in the