Appraisal of the effect of a stream reinstatement of hydraulic connection of stream of Mahi River

RASHMIKANT G. SHAH
Ph.D. Scholar, Madhav University, Sirohi, Rajasthan

DR.NANAK PAMNANI
Department of Civil Engineering, Madhav University, Sirohi, Rajasthan

Abstract:
Stream reinstatement 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 second, 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 couple of years. We expected increasing hydraulic connectivity between river meander and aquifer after reinstatement of the stream, and decreasing hydraulic connectivity for the previous point due to increased clogging. At first year water level fluctuation were not observed much significant as the distances increases however the hydraulic connection of the neighboring aquifer was very competitive. After reinstatement of the stream, a slight but not significant increase of hydraulic connectivity in the river meander is observed.

Keywords: *Reinstatement, Hydraulic, aquifer, river meander*

1. Introduction

In the past decades there has been number of research carried out for the reinstatement of rivers and their floodplains. The river ecosystems as place for species conservation has always remain on priority. The flood protection, enhancement the potential of contaminant deposition and nutrient degradation has always attracted [1; 2, 3, 4, 5**]**. This is also reflected in a growing body of legislative directives [4, 5]. 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 reinstatement 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 [3, 7, 8].

Different methods are available to estimate fluxes across the interface in a river-groundwater system [9]. Selective approaches, such as vertical temperature profiles [10, 11], heat pulse sensors [12], and hydraulic gradients [13] 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) [14, 15], 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 [16]. Beside the different measuring techniques, numerical modelling was often used to examine groundwater-surface water interactions [17]. 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.

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 reinstatement 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. [19]. In contrast to the afore mentioned 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 Vadodara. Here an island is formed by an artificial stream channel (shortcut) and a river meander. As reinstatement measure the shortcut was detached from the river at its upstream end, the former river meander 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 reinstatement.

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. To that end, we followed the approach presented by Lewandowski s 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 reinstatement 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

The Mahmadpura site is situated in the floodplain of the lowland river Spree about 25 km east of the center of Vadodara (22°17'07.2"N 72°56'09.7"E). In the two years of the monitoring period, the organic silt layer had a hydraulic conductivity between 10^{-6} and 10^{-5} ms $^{-1}$ and an effective porosity of 0.5. Compared to the surrounding aquifer with of 10^{-4} to 5 ⁄ 10^{-5} and 0.15–0.2, the organic layer can be ascribed as a clogging layer.

Most of the time groundwater is pull-back into the stream. A mean groundwater pull-back rate of 233 L $m^{-2}d^{-1}$ with a groundwater flow velocity between 10^{-7} and 10^{-6} ms $^{-1}$ wasesti mated. Maximum lateral infiltration of river water into the aquifer is less than 4 m [20]. Velocity of pressure wave propagation from the stream into the aquifer was found to be about 1550 md^{-1}, thereby three to four orders of magnitude higher than the velocity of groundwater mass flux. For a general elaboration on velocity of pressure waves (celerity) vs. velocity of water particles (mass fluxes) in hydrology[22].

Stream water levels at 2 river stages were measured at hourly intervals with data loggers (Aquatek). Measurements were conducted from 1st June 2016 to 31st May of 2017. Furthermore, at both ends of the first point surface water level was measured. Adjacent to the stream water gauges two hyporheic wells no. 1 and 2 were installed that screened at 0.5 to 1.5 m below the riverbed.

Water bodies were showing adequate hydraulic connectivity as they were having very close linear correlation (r = 0.97). The anomalies could be ascribed to different factors that influencing different sites to different grades. The pressure signals were influenced by the river water level fluctuations and recharge which were subjected to on flora and the soil properties [20]. Thus each water level points can be considered to be the result of different overlaying effects.

Firstly, the deviation from the mean of groundwater heads and river water level was calculated for each time step. Afterwards, each of these residual time series was normalized to zero mean and unit variance to ensure equal weighting. Then, a principal component analysis (PCA) was applied to the prepared data. PCA performs an eigenvalue decomposition of a data matrix, yielding a series of independent components.

In order to analyse for long-term shifts PCA was performed for single hydrologic years separately (June to May) yielding 8760 readings at each observation well and 8784 readings in the second year, respectively).

Loadings on a component are the expression of a component at the different sites. They were calculated as Pearson correlation coefficients of the z-normalized residuals of the water level series and the values (scores) of the component [20]. The stability of the loadings in each observation year was estimated with the mean of the loadings of the 4 quartiles of the hydrologic year and their corresponding confidence intervals. All the statistics and calculations were done with the free soft ware package R, version 3.0.1[21].

3. Results and Discussion

For the data set of the first point the first principal component depicted 70% of the total variance in the first year and 70%, 65% and 63% in the subsequent years (Fig. 2). Please note, that the range of loadings on the first component describes the relative differences in the correlations of the first component with the original water level series at the observation wells because the PCA was applied on the z-normalized residuals of the water level series. Hence, we refer to loadings close to one as high loadings and loadings close to minus one as low loadings.

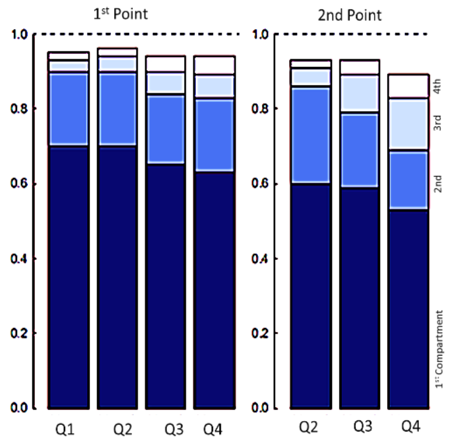

Fig. 2. Ratio of overall variance for the data set of the first point (left) and of the PCA of the joint data set from both point (right).

At the stream water gauges no. 1 in the shortcut and no. 9A in the river meander loadings were very high on the first component throughout the observation period with the exception of lower loadings for no. 9A in the third year (Fig. 3). The hyporheic well no. 1 below the stream bed depicted substantial lower loadings than observation wells no. 2 to 4 in the second year, and slightly lower loadings in the first and fourth year (Fig. 3). Only in the third year loadings at observation well no. 2 were slightly lower than loadings at hyporheic well no. 1.

Groundwater wells next to the river meander showed very low loadings with slightly increasing loadings on the last meter to the river meander from observation well no. 7 to 9 (Fig. 3). Only in the fourth year loadings were substantially higher at observation wells no. 8 and 9 than in the years before. Observation well no. 12 was on the same level as the gauges next to the river meander. Observation wells no. 5, 6 and 11 in the middle part of the island showed decreasing loadings along the first transect from the shortcut to the river meander. The loadings in this middle part showed the highest variability between the years and also within their quartiles. From the first to the second year all loadings in the middle part increased and decreased thereafter until the fourth year.

Thus, the first component explains almost 100% of the deviation of the stream gauges from the mean behavior of all observation wells. This implies that processes that impact the groundwater head in the wells could hardly have any additional effect on the stream water level gauges. Thus, the loadings on the first component can be used as a quantitative measure for the hydraulic connectivity between river and groundwater.

High positive loadings on the first component imply that the respective time series of the groundwater head deviates from the spatial mean in the same way as the stream water level gauges. That allows the conclusion that groundwater head at the respective site is strongly affected by the stream water level fluctuations. In contrast, high negative loadings point to a weak impact relative to the other observation wells, and zero loadings to intermediate effects. Our prior assumption was that the observed water level dynamics at the single sites are a mixture of different superimposing effects. In fact the first component explains only 53–70% of the spatial variance, indicating that other factors have substantial effects on the observed groundwater heads as well. To investigate in particular the hydraulic connection of the river and the groundwater by analyzing the original time series, e.g. using cross-correlation, would therefore not have been satisfactory.

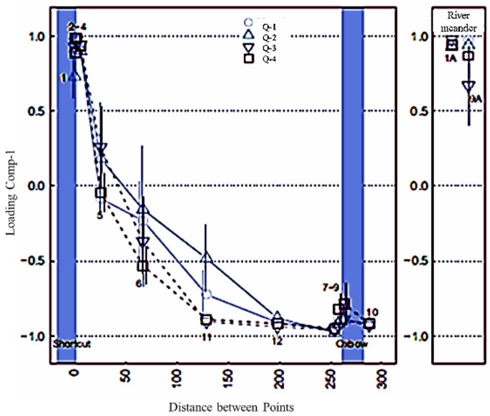

Fig. 3. Loadings of the groundwater observation wells of the first transect on the first principal component vs. distance between points (left) and of the stream water gauges (right).

For the joint data set (water level data from both transects) the first principal component depicted 60% in the second quarter and 59% and 53% in the third and fourth quarter (Fig. 2). The main pattern in the first point with high loadings next to the shortcut, and decreasing loadings to the east was similar to that of the separate analysis based on the first transect. The loadings of the two variants were correlating in the three common years with an r^2 of at least 0.97.

In the northern part of the second point well no. 13 was loading constantly low and well no. 14 constantly loading high on the first principal component over the entire observation period (Fig. 4). In the other part of the second point wells no. 11, 15, 16 and 17 were jointly shifting from slightly positive loadings in the second year towards negative (Fig. 4).

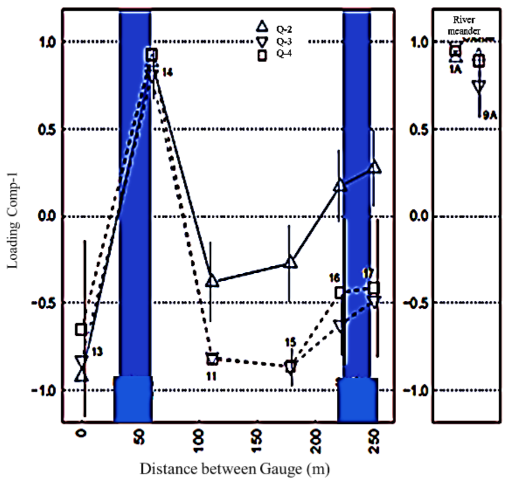

Fig 4: Loadings of the wells of the first principal component of the second point vs. distance to the end of the point (left) and of the stream water gauges (right).

Inter-annual variability was prominent in the second year for wells no. 11, 15, 16 and 17 and in the last year for wells no. 13, 16 and 17 (Fig. 4). There was no regular seasonal the observation period (Figs. 3–4).

The analysis was performed for single years separately in order to capture changes of connectivity. Loadings of the stream gauges were constantly close to one as it is mandatory for the interpretation of the first component as influence of river level fluctuations on groundwater levels. The lower loading at stream gauge no. 9A in the third year (Fig. 3) could be ascribed to the reconnection of the river meander and the construction of the new dam in the shortcut.

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Loadings of observation wells close to the Spree river at the western end of the first transect, and of groundwater well no. 14 close to the river meander in its northern reach were close to one in all years of our study, pointing to a constant high connectivity between river and aquifer. Clogging of the stream bed in the short cut due to the reduced stream velocity was not detected during the two years after the reinstatement. We assume that the first clogging sediments that settled throughout the first year have been removed due to the intense floods in the fourth year. Nonetheless we expect clogging of the shortcut in successive years.

In the central and south-easterly part of the island wells no. 5, 6, 11, 15, 16 and 17 exhibit substantial shifts between single years, although the general spatial pattern remains approximately the same (Figs. 3 and 4). There the loadings are highest for the second year and smallest in the fourth year, whereas those of the third year are similar to those of the fourth year. We did not find an unequivocal explanation for that temporal shift. Such systematic shift can hardly be explained by artefacts of the measurements. In addition, a corresponding change of the properties of the aquifer can be excluded. All of these wells are located close to the same former river bed, although this had not been intended. The associated inter-bedding of different substrates such as gravel, silt, former clogging layers and peat might still affect groundwater flow-paths and lead to a closely coupled.

Wells no. 8 and 9 close to the north-easterly reach of the river meander exhibit almost no shift in time. Loadings are close to minus one for the first three years, indicating low hydraulic contact with the river meander. This suggests that the clogging layer is not the only reason for the lower hydraulic connectivity of the hyporheic well no. 9 below the river meander compared to the hyporheic well no. 1 below the shortcut. This can be attributed to the construction of the shortcut. The shortcut itself and the surroundings are situated in sandy sediments, which were dislocated artificially. In contrast, the sediments around the river meander are characterized by inclined lay ers of sand and organic material of the recent and former point bars. On the other hand the loadings at well no. 14 are close to one for the whole observation period of the second transect, suggesting a strong impact of natural spatial heterogeneity of effective hydraulic conductivity of the floodplain sediments (Fig 4).

Only in the fourth year loadings at wells no. 8 and 9 are slightly higher (but not significantly higher), pointing to increased, although still fairly low connectivity (Fig. 3). Likewise a minor increase of loadings between the third and fourth year is observed at wells no. 13, 16 and 17 close to the river meander (Fig. 4). This is consistent with our prior assumptions of increasing connectivity due to stream channel reinstatement. However, this is more a little piece of evidence rather than a proof and the development has to be checked in the following years. Anyhow, the effect is much weaker than assumed.

Conclusions

The data driven PCA approach used in this study is easy to apply and requires only time series of hydraulic heads in the aquifer and in the stream. It splits up the water table dynamics into independent components which represent different drivers of the hydraulic head dynamics in the system and the spatial expression of those drivers can be analyzed. In the present study, the first component captures the propagation of river stage fluctuations into the aquifer. Areas of relative low and high hydraulic connectivity could be identified, although it is not possible to quantify mass fluxes and water exchange rates.

The hydraulic head data are usually measured with relative high temporal resolution of minutes to hours and stored with data loggers.

The presented approach can be used to optimize the monitoring network and monitor further developments of the stream water system. The suggested set of influencing factors exemplifies that reinstatement of connectivity of groundwater and surface water is a process that might last for several years after the initial reinstatement of the sur face water, while on the surface the reinstatement might appear already successfully completed.

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