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Uncertainty of natural tracer methods for quantifying river–aquifer interaction in a large river

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SUMMARY

The quantification of river–aquifer interaction is critical to the conjunctive management of surface water and groundwater, in particular in the arid and semiarid environment with much higher potential evapotranspiration than precipitation. A variety of natural tracer methods are available to quantify river–aquifer interaction at different scales. These methods however have only been tested in rivers with relatively low flow rates (mostly less than 5 $m^3 s^{-1}$). In this study, several natural tracers including heat, radon-222 and electrical conductivity were measured both on vertical riverbed profiles and on longitudinal river samples to quantify river–aquifer exchange flux at both point and regional scales in the Heihe River (northwest China; flow rate 63 $m^3 s^{-1}$). Results show that the radon-222 profile method can estimate a narrower range of point-scale flux than the temperature profile method. In particular, three vertical radon-222 profiles failed to estimate the upper bounds of plausible flux ranges. Results also show that when quantifying regional-scale river–aquifer exchange flux, the river chemistry method constrained the flux (5.20–10.39 $m^2 d^{-1}$) better than the river temperature method (−100 to 100 $m^2 d^{-1}$). The river chemistry method also identified spatial variability of flux, whereas the river temperature method did not have sufficient resolution. Overall, for quantifying river–aquifer exchange flux in a large river, both the temperature profile method and the radon-222 profile method provide useful complementary information at the point scale to complement each other, whereas the river chemistry method is recommended over the river temperature method at the regional scale.

1. Introduction

Rivers in arid and semiarid regions are of paramount importance to local communities, as they not only provide direct accessible water resources for domestic and agricultural uses but play a central role in maintaining ecosystem health (Bauer et al., 2006; Brunke and Gonser, 1997; Chen, 2007; Lamontagne et al., 2005; Wayne Minshall and Andrews, 1973; Zhou et al., 2013). As a river flows downstream, it exchanges water and solutes with the adjacent aquifer. Quantifying this river–aquifer exchange is critical for the thorough understanding of hydrological processes and the conjunctive management of surface water and groundwater (Fleckenstein et al., 2010; Shanafield and Cook, 2014). Quantification of river–aquifer exchange is also important for managing potential contaminants (e.g., salt, nitrate) in connected river–aquifer systems (e.g., Chapman et al., 2007; Chen, 2007; Lamontagne et al., 2005; McMahon and Böhlke, 1996; Verstraeten et al., 1999).

Numerous methods are available for quantifying river–aquifer exchange flux, often classified into point-scale (e.g., Anibas et al., 2009; Cranswick et al., 2014; Hyun et al., 2011; Libelo and MacIntyre, 1994; McCallum et al., 2014; Shanafield et al., 2010, 2011; Silliman et al., 1995) and regional-scale methods (e.g., Bourke et al., 2014; Cook et al., 2006; Harrington et al., 2014; McCallum et al., 2012; Pinder and Jones, 1969; Simpson and Herczeg, 1991; Unland et al., 2013; Westhoff et al., 2007). Kalbus et al. (2006) thoroughly reviewed different techniques to quantify river–aquifer exchange flux at various scales. More recently, Constantz (2008) specifically summarised the use of heat to estimate river–aquifer exchange flux at point scales, and Cook (2013) reviewed the use of chemical and isotopic tracers for quantifying this flux at reach scales.

The choice of a method at any particular location should dependent on its inherent uncertainty, relative to the uncertainty of other methods. Where exchange flux is directly calculated from

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equations involving only a small number of parameters, it is relatively easy to conduct an uncertainty analysis. Thus, Lautz (2010) examined the uncertainty of the temperature profile method developed by Hatch et al. (2006) to estimate river–aquifer exchange flux using temperature time series. She concluded that the temperature profile method is more robust than the Darcy method, as the inherent uncertainty in estimating the hydraulic conductivity for the Darcy method is usually large. Cranswick et al. (2014) compared results derived from radon-222 residence time and 1D temperature modelling. They found that where flux can be constrained, the uncertainty of flux derived from both methods is typically between plus minus 50% and an order of magnitude of the mean values, and that when flux is high and low, both methods become less accurate. For methods where flux is derived by model calibration rather than direct calculation, estimation of uncertainty is more difficult as there are usually a large number of parameters. McCallum et al. (2012) estimated exchange flux based on river chemistry, and discovered that the predictive error decreased as more tracers were added. More often, though, analysis of the uncertainty of flux derived from natural tracers is limited to simple sensitivity tests on different parameters (e.g., Cook et al., 2006; Harrington et al., 2014; Loheide and Gorelick, 2006). Clearly, a comparison of the uncertainties of different methods in different environments is warranted in order to make recommendations for future studies.

It is also apparent that many methods for estimating river–aquifer exchange flux have mainly been applied to small rivers with relatively low flow rates, partly because it is easier to instrument or sample small rivers. This can bias our understanding of the utility (and uncertainty) of different methods. As river size or flow rate increases, many methods become more difficult to apply due to reduced accessibility, and because river–aquifer exchange flux is usually a smaller proportion of river flow rate in large rivers. The differential flow gauging method is one of the most common methods to estimate reach-scale river–aquifer exchange flux. It has been applied to a wide range of rivers flow rates from $0.001\ m^3\ s^{-1}$ to $400\ m^3\ s^{-1}$ (e.g., Bencala and Walters, 1983; Grapes et al., 2005; Harvey and Fuller, 1998; Konrad, 2006; Langhoff et al., 2006; McCallum et al., 2012; Opsahl et al., 2007; Ruehl et al., 2006; Wondzell, 2006). Although this method can be applied to rivers with large flow rates, in these cases it usually relies on established gauging stations rather than manual flow measurements (Konrad, 2006), and cannot be safely carried out in fast flowing rivers using manual flow meters. The seepage meter method has been applied mostly to streams with flow rates less than $5\ m^3\ s^{-1}$ (e.g., Kennedy et al., 2010; Libelo and MacIntyre, 1994; Lowry et al., 2007; Rosenberry, 2008). The Darcy method including the use of mini-piezometers has been mostly applied to rivers with flow rates from $0.007\ m^3\ s^{-1}$ to $2\ m^3\ s^{-1}$ (e.g., Cey et al., 1998; Harvey et al., 1996; Harvey and Bencala, 1993; Kennedy et al., 2009a, 2009b, 2010). Both methods become difficult to operate in fast flowing rivers. For seepage meters directly measuring exchange flux, another problem is that the uncertainty of exchange flux estimates increases with the increase in river flow rates (Rosenberry, 2008). The tracer dilution test (e.g., Harvey et al., 1996; Ruehl et al., 2006) cannot be easily applied in rivers with large flow rates, because large tracer mass is required to avoid dilution to below detection limit. In comparison, natural tracer methods are not necessarily limited to small rivers, but they are nevertheless mainly applied in rivers with relatively low flow rates or sizes. For example, the temperature profile method have been applied mostly to rivers with flow rates between 0.01 and $2.0\ m^3\ s^{-1}$ (e.g., Anibas et al., 2009, 2011; Cranswick et al., 2014; Constantz et al., 2002). The river temperature method has been mostly applied to rivers with flow rates between $0.0012\ m^3\ s^{-1}$ and $2.4\ m^3\ s^{-1}$ (e.g., Briggs et al., 2012; Loheide and Gorelick, 2006; Westhoff et al., 2007) and the river chemistry method has been mostly applied to rivers with flow rates less than $5.0\ m^3\ s^{-1}$ (e.g., Cook et al., 2006; Harrington et al., 2014; McCallum et al., 2012).

In this study, we apply four natural tracer methods to quantify river–aquifer interaction at both point and regional scales. A 32-km long reach of the Heihe River, northwest China was selected as a study river given its high flow rate ($63.0\ m^3\ s^{-1}$) relative to previous studies. Because of the lack of accurate high resolution flow gauging data, diverse methods including temperature profile, radon profile, river temperature and river chemistry methods were used to provide insights from different perspectives. Uncertainty analyses were conducted to examine the feasibility of different methods in large rivers and to make recommendations for future studies in similar river conditions.

2. Background of the Heihe River basin

The Heihe River is a 800-km long semi-perennial river in arid northwest China (Fig. 1), draining an area of approximately $130{,}000\ km^2$. The upper mountainous part of the catchment has a mean annual precipitation of 200–500 mm, whereas the middle agricultural area receives a mean annual precipitation of 50–150 mm (Chen et al., 2006). The lower reach of the Heihe River traverses the Gobi Desert (mean annual precipitation of less than 50 mm) and terminates at the inland Juyan Lake (Chen et al., 2006). Most of the flow in the river is generated in the upper reach. This river is the critical water supply for supporting surrounding communities. In particular, the continuous flow to the terminal lake is essential to the maintenance of the brittle ecosystem along the downstream losing reach, surrounded by the Gobi desert. This river basin has been used to study hydrological and ecological impacts on water-scarce regions for more than a decade (Chen et al., 2006; Yang et al., 2011; Yao et al., 2014; Hu et al., 2007; Qian et al., 2005; Wu et al., 2004, 2014). Detailed hydrogeological description can be found in Yao et al. (2014).

2.1. Previous surface water–groundwater interaction work

Direct analysis of surface water–groundwater interaction in the Heihe River is limited. Wu et al. (2004) quantified groundwater discharge along the middle reach by sampling radon-222 activities and measuring flow rates at five sites with an average spacing of 30 km during a low flow period. However, the sampling date and time were not provided by Wu et al. (2004). Despite the first attempt to quantify groundwater discharge in the Heihe River, such a large sampling spacing caused large uncertainties of estimates and did not allow for the determination of groundwater discharge hotspots. Moreover, Wu et al. (2004) neglected hyporheic exchange processes which could significantly affect the radon-222 budget (Cook et al., 2006). Qian et al. (2005) also used radon-222 as a tracer to qualitatively analyse the connectivity between the Heihe River and the adjacent groundwater. They reported that a large part of the middle reach received groundwater discharge, although no effort was made to quantitatively estimate the flux.

2.2. Field site description

This study focuses on the Heihe River middle reach. The basin covering the middle reach contains an unconfined aquifer formed by coarse-grained sand and gravel with interbedded low-permeability lens at the mountain front. The thickness of the aquifer is up to 1000 m. Several confined aquifers formed by medium- to fine-grained and silty sand are developed in the