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Estimating groundwater-ephemeral stream exchange in hyper-arid environments: Field experiments and numerical simulations

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ABSTRACT

Surface water infiltration from ephemeral dryland streams is particularly important in hyporheic exchange and biogeochemical processes in arid and semi-arid regions. However, streamflow transmission losses can vary significantly, partly due to spatiotemporal variations in streambed permeability. To extend our understanding of changes in streambed hydraulic properties, field investigations of streambed hydraulic conductivity were conducted in an ephemeral dryland stream in north-western China during high and low streamflow periods. Additionally, streamflow transmission losses were numerically estimated using combined stream and groundwater hydraulic head data and stream and streambed temperature data. An analysis of slug test data at two different river flow stages (one test was performed at a low river stage with clean water and the other at a high river stage with muddy water) suggested that sedimentation from fine-grained particles, i.e., physical clogging processes, likely led to a reduction in streambed hydraulic properties. To account for the effects of streambed clogging on changes in hydraulic properties, an iteratively increasing total hydraulic resistance during the slug test was considered to correct the estimation of streambed hydraulic conductivity. The stream and streambed temperature can also greatly influence the hydraulic properties of the streambed. One-dimensional coupled water and heat flux modelling with HYDRUS-1D was used to quantify the effects of seasonal changes in stream and streambed temperature on streamflow losses. During the period from 6 August 2014 to 4 June 2015, the total infiltration estimated using temperature-dependent hydraulic conductivity accounted for approximately 88% of that using temperature-independent hydraulic conductivity. Streambed clogging processes associated with fine particle settling/wash up cycles during flow events, and seasonal changes in streamflow temperature are two considerable factors that affect water infiltration in ephemeral dryland streams. Our results show that time series measurements of stream and sediment temperature and surface and groundwater head can be used to effectively determine the seasonal dynamics of streambed water exchange. Such combined heat and head monitoring at field sites is useful for calibrating regional surface-groundwater models. The results of this study may provide insights into hyporheic exchange in ephemeral dryland streams.

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1. Introduction

Surface water infiltration from intermittent or ephemeral dryland streams is considered to be a predominant process for groundwater recharge in many arid and semi-arid areas (de Vries and Simmers, 2002, 1997; Villeneuve et al., 2015). Streambed water fluxes typically exhibit significant temporal and spatial variability, which is mainly determined by the state of connection between a river and aquifer (Brunner et al., 2009; Desilets et al., 2008) and the heterogeneity of the streambed hydraulic conductivity (K) (e.g., Chen et al., 2010; Leek et al., 2009; Tang et al., 2017). For losing streams with significant diurnal or seasonal variations in streamflow temperature, streambed water exchange is expected to exhibit large temporal variations due to the temperature sensitivity of the streambed hydraulic conductivity (Anderson, 2005; Constantz, 1998, 2008).

Currently, the most common approach for estimating and forecasting stream-aquifer interactions in combined surface-groundwater systems (Filimonova and Baldenkov, 2015) at both the basin and sub-basin scales involves using a groundwater model

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connected to a surface water model (e.g., Arnold et al., 1993; Brunner et al., 2017; Frei et al., 2009; Gunduz and Aral, 2005). Even relatively simple physically based stream routing modules, such as the MODFLOW SFR1 package (Prudic et al., 2004) require characterization and parameterization of the hydrological relationship between the surface flow and groundwater (Brunner et al., 2010; Miracapillo and Morel-Seytoux, 2014). For ephemeral dryland streams, exchange between the stream and aquifer depends on the hydraulic connectivity between the river and aquifer (Tang et al., 2017), the stream stage, a complex relationship between stream depth and width, and the streambed hydraulic resistance, which also varies with depth and can be subject to spatiotemporal changes (Cuthbert et al., 2016; Dogramaci et al., 2015; Irvine et al., 2012). Successful calibration of the surface-groundwater interaction parameters in such environments relies on a reliable network of surface flow and groundwater level monitoring (Kalbus et al., 2006; Wang et al., 2015). Such monitoring data can be used together in a objective calibration function (Brunner et al., 2012). It is possible to compensate for a lack of surface flow or groundwater level measurements with direct investigations of stream-aquifer interactions using different field techniques (Cook, 2015; Kalbus et al., 2006).

Given that streambeds act as the interface between a river and groundwater (Brunner et al., 2017; Constantz, 2016), the hydraulic properties of streambeds control river-aquifer interactions. Quantifying the exchange flux between a river and an aquifer requires constraining the mean and the variance of streambed hydraulic conductivity (Tang et al., 2017). Thus, one of the most widely used methods for assessing streambed water exchange involves taking direct measurements of streambed hydraulic properties at pilot points along a stream network during point-scale field investigations (Kalbus et al., 2006; Landon et al., 2001). Differential gauging and tracer injection experiments are also effective field techniques for estimating average losses or gains at the scale of a reach (Cook, 2015; McCallum et al., 2014; Shanafield and Cook, 2014). Additionally, an optimal monitoring network designed to continuously measure hydraulic gradients between a stream and nearby groundwater (Wang et al., 2015) can be directly applied to determine stream-aquifer flow exchanges using Darcy's Law (Cook, 2015). In addition to the aforementioned approaches, there is a broad range of field methods for quantifying recharge in ephemeral and intermittent streams and determining the temporal and spatial scales of recharge (e.g., Dogramaci et al., 2015; Keery et al., 2007; McCallum et al., 2014). As noted by Hatch et al. (2006) and Shanafield and Cook (2014), each field method has limitations related to its characteristic spatial and temporal scales, assumptions, and uncertainties. The key to successfully estimating streambed water exchange lies in the use of a variety of independent methods (McCallum et al., 2014).

Recently, substantial improvements in automatic temperature measurements have created the opportunity to use heat as a naturally occurring, nonreactive and robust tracer to examine the interactions between a stream and the underlying aquifer (Anderson, 2005; Constantz, 2008). Time series measurements of sediment temperature and water temperature can supplement head measurements; they can even be considered surrogates of head to quantitatively analyse the downward flux through the streambed (Anderson, 2005; Stonestrom and Constantz, 2003). Accordingly, analytical solutions using diel streambed thermal records (e.g., Caissie and Luce, 2017; Hatch et al., 2006; McCallum et al., 2012) have been developed to understand the gain versus loss relationship between steams and aquifers. Another important approach for investigating water flow in streambeds is through the application of modelling techniques, which can simulate combined flow exchange with heat transport within stream-aquifer systems (e.g., Healy, 2008; Koch et al., 2016; Roshan et al., 2012; Schneidewind et al., 2016; Šimůnek and Bradford, 2008).

In ephemeral dryland river systems, water temperature fluctuations and the suspended sediment load carried by the flow exert an important control on the infiltration of river water by changing the hydraulic properties of the streambed (Dunkerley, 2008). Surface water-groundwater exchange plays a significant role in the deposition of fine sediment, which in turn modifies the hydraulic properties of the streambed (Partington et al., 2017). This study examines the characteristics of streambed hydraulic properties and the associated river-aquifer flux in the lower Heihe River, an ephemeral river in hyper-arid north-western China. This region experienced significant environmental degradation at the end of the twentieth century (e.g., regional groundwater level decline and associated vegetation die-off in the riparian area), which was caused by decreased surface flow from the Heihe River (Wang et al., 2011b). Since 2000, surface water has been delivered to the lower Heihe River each year to restore the natural ecosystems (Wang et al., 2011a). Therefore, a quantitative assessment of river water infiltration into the shallow aquifer is essential for the sustainable improvement of riparian ecosystems in this region (Wang et al., 2011b).

Field observations have shown that the lower Heihe River exhibited intermittent flows and significant temporal variations in water temperature (Wang et al., 2014a). Based on continuous measurements of river-aquifer hydraulic head and streambed temperatures with depth, heat was used as a natural tracer to quantify water fluxes through the streambed. Additionally, in situ standpipe tests were conducted to estimate streambed hydraulic conductivities during the high and low stages of river flow, which are associated with different concentrations of suspended sediments carried by the flow. The objectives of this study are as follows: 1) to estimate the local spatial and temporal variability in streambed hydraulic properties and identify the major processes that control these variations; 2) to quantify daily streambed water fluxes by considering coupled flow and temperature fields in the streambed sediments and the effective streambed hydraulic parameters for regional-scale surface-subsurface flow simulation; and 3) to assess the effects of temperature-dependent streambed hydraulic conductivity on annual river losses to groundwater.

2. Study area

The study area is located in the lower Heihe River in north-western China (Fig. 1), which is characterized by a hyper-arid environment with extremely hot summers and severely cold winters. Meteorological observations from the Ejina Weather Station (Fig. 1) show that the mean annual air temperature was 9.09 °C from 1961 to 2015, with a maximum monthly mean air temperature of 27.05 °C in July and a minimum of −11.23 °C in January. Annual precipitation was extremely low (averaging 35 mm per year between 1961 and 2015), while the average annual potential evapotranspiration was estimated to be approximately 1450–1550 mm (Du et al., 2016; Liu et al., 2016).

The Heihe River, which originates from snowmelt and rainfall in the Qilian Mountains (Fig. 1), branches into two losing streams at Langxinshan (the Donghe and Xihe Rivers) and then flows through the Gobi Desert before entering terminal lakes (the East and West Juyan Lakes). According to observations at the Langxinshan Hydrological Station (Fig. 1), the average annual runoff volume was estimated to be approximately 5.88×10^8 m^3 during the period from 1988 to 2015. Approximately 71% of the total runoff was allocated to the Donghe River for maintaining the Juyan Oasis in the lower reaches of the river and transporting river water to East Juyan Lake. The streambed is composed of fine to medium sand without an obvious and continuous clogging layer. Due to relatively high vertical hydraulic conductivity (Min et al., 2013), river water is the

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