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Evaluating recharge to an ephemeral dryland stream using a hydraulic model and water, chloride and isotope mass balance

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SUMMARY

Dewatering associated with mining below water table to achieve dry mining conditions may exert significant pressure on water balance in terms of lowering the water table and change in the dynamics of interactions between surface water and groundwater. The discharge of surplus mine water into ephemeral streams may also affect the water balance, by elevating groundwater levels and altering the exchange rate between streams and underlying aquifers. However, it is unclear whether volumes and recharge processes are within the range of natural variability. Here, we present a case study of an ephemeral creek in the semi-arid Hamersley Basin of northwest Australia that has received continuous mine discharge for more than six years. We used a numerical model coupled with repeated measurements of water levels, chloride concentrations and the hydrogen and oxygen stable isotope composition (δ^2H and δ^{18}O) to estimate longitudinal evapotranspiration and recharge rates along a 27 km length of Weeli Wolli Creek. We found that chloride increased from 73 to 120 mg/L across this length, while δ^{18}O increased from −8.2‰ to −7.00‰. Groundwater is directly connected to the creek for the first 13 km and recharge rates are negligible. Below this point, the creek flows over a highly permeable aquifer and water loss by recharge increases to a maximum rate of 4.4 mm/d, which accounts for ~65% of the total water discharged to the creek. Evapotranspiration losses account for the remaining ~35%. The calculated recharge from continuous flow due to surplus water discharge is similar to that measured for rainfall-driven flood events along the creek. Groundwater under the disconnected section of the creek is characterised by a much lower Cl concentration and more depleted δ^{18}O value than mining discharge water but is similar to flood water generated by large episodic rainfall events. Our results suggest that the impact of recharge from continuous flow on the water balance of the creek has not extended beyond 27 km from the discharge point. Our approach using a combination of hydrochemical and isotope methods coupled with classical surface flow hydraulic modelling allowed evaluation of components of the water budget otherwise not possible in a highly dynamic system that is mainly driven by infrequent but large episodic floods.

1. Introduction

Accurate quantification of recharge rates and dynamics, as well as understanding of the key processes that determine surface–groundwater interactions, underpins optimal management and protection of water resources, particularly in more arid (dryland) regions. The recharge into ephemeral and intermittent streams in dryland regions are often complex owing to a high degree of natural variability in hydrological conditions, significant evaporative loss and often diverse geological landscapes (Morrice et al., 1997; Wroblicky et al., 1998; Andersen and Acworth, 2009; Skrzypek et al., 2013). For example, rivers and creeks in the subtropical, semi-arid Hamersley Basin of northwest Australia are characterised by episodic flows that occur in response to intense rainfall events associated with cyclones or tropical lows, coupled with dissected terrain and a largely impermeable geology, particularly at the stream headwaters (Dogramaci et al., 2012). Peak surface flow rates generated from some of these ephemeral rivers and creeks can reach thousands of cubic metres per second after such events, which then decline over weeks to months depending on patterns of supplementary rainfall and the nature of the catchment in terms of

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size, recharge through the regolith and topography (Ruprecht and Ivanescu, 2000). Mean annual rainfall deficits based on pan evaporation across the basin also often exceed 2500 mm/yr (Charles et al., 2013). These factors contribute to high spatial and temporal heterogeneity of recharge–discharge mechanisms across any one catchment, which in turn presents considerable challenges for estimating rates and volumes of recharge.

In general, the magnitude of recharge from ephemeral streams to groundwater aquifers is dependent on the amount of water infiltrating into the streambed as a flood wave from an episodic rainfall event progresses in the downstream direction (Vazquez-Sune et al., 2007; Noorduijn et al., 2014). The rate of recharge depends on a number of factors including hydraulic properties of stream sediments and the underlying aquifer as well as topography, hydraulic gradient, temporal variation in precipitation, local groundwater flow patterns and climate (Cey et al., 1998; Oxtobee and Novakowski, 2002; Kumar et al., 2009; Jiménez-Martínez et al., 2013). The hydraulic connection between surface water and underlying aquifers also has a direct effect on the rate of recharge (Brunner et al., 2011). Given these complexities and the highly unpredictable nature of stream flow in arid and semi-arid environments, the infiltration-recharge process for ephemeral streams has generally been calculated using a combination of approaches, including a range of analytical and numerical models (e.g., Abdulrazzak and Sorman, 1983; Morel-Seytoux et al., 1990; Lamontagne et al., 2014). However, numerical models on their own are of limited usefulness because multiple scenarios can be considered from the same input data (Moore and Doherty, 2006). Alternatively, a combination of hydrochemical tracers and isotope water mass balance approaches may provide greater insight into recharge processes and have been applied extensively to quantify the rates of groundwater inflow to rivers (Cook et al., 2003); distinguish sources of groundwater recharge (Blasch and Bryson, 2007); and calibrate numerical models (Taniguchi et al., 1999).

Major dissolved ions, particularly chloride, and stable isotopes of water, can be used to constrain numerical models, thus helping to develop a more realistic understanding of the study system. Chloride is a conservative tracer as it is primarily derived from rainfall, is very soluble and does not precipitate out of solution unless in very high concentrations (>300 g/L; Hem, 1985), which means it is an ideal indicator of evaporation and evapotranspiration in surface and groundwater (Skrzypek et al., 2013). The $\delta^{18}O$ and $\delta^{2}H$ signatures of water also become progressively more enriched with increasing evaporation (Clark and Fritz, 1997). Transpiration losses have generally been assumed to have relatively little influence on the stable isotope composition of the water sources taken up by plants as uptake and transport within most plants occurs without isotope fractionation (Flanagan et al., 1991; Farquhar et al., 1993). While recent direct measurements of transpired $\delta^{18}O$ have demonstrated that transpired water is often not in an isotopic steady-state, especially under highly variable environmental conditions (Song et al., 2013), this is mainly of concern to partitioning ecosystem water fluxes over short time intervals. Over longer timeframes, the relative contribution of evaporation versus transpirational losses may theoretically be resolved from observing the variation in chloride and isotope composition of the source waters (Herczeg et al., 2001; Cartwright et al., 2012). The usefulness of conservative tracers in hydrology also relies on the assumption that they move at the same speed as the water body and their concentration fluctuations are dependent only on evaporation and mixing (Drever, 1988; Kirchner et al., 2010).

Groundwater sustains agriculture, industry and domestic needs in many parts of the world, particularly in dryland regions where surface water is limited. Consequently, most studies of recharge to groundwater in arid environments have focused on reducing the risks of declining groundwater levels associated with abstraction. However, there have been fewer studies of how ephemeral systems may respond to artificial recharge and potential rising groundwater levels. Here, we investigate the influence of continuous discharge of surplus mining water on the overall water budget of Weeli Wolli Creek, a naturally ephemeral, losing stream in the Hamersley Basin of northwest Australia. Continuous discharge into Weeli Wolli Creek since 2007 has created permanent pools in areas that previously held water only for brief periods of time, with likely increased recharge to surrounding groundwater systems. We sought to estimate evaporation and transpiration losses from Weeli Wolli Creek and ultimately recharge to the underlying aquifer as a basis for understanding stream-aquifer interactions and assessing potential impacts on the water balance of the underlying groundwater.

2. Catchment characteristics

2.1. Climate

The climate of the region is hot and semi-arid, with a loosely bimodal rainfall distribution. Most rainfall occurs in the austral summer between December and March, with occasional winter rainfall. The average long-term rainfall at the site (1937–2013) is 250 mm, although rainfall varies considerably from the average from year to year. The largest recorded single rainfall event associated with a cyclone resulted in >500 mm of rainfall in 24 h at Newman weather station (December 2002, www.bom.gov.au). In the summer months (December to March) the average maximum temperature is often over 40 °C, while during the winter months it falls to about 25 °C.

2.2. Physiography

The Weeli Wolli Creek catchment covers an area of approximately 4000 km^2. The upper catchment is characterised by relatively wide, flat plains, surrounded by rugged hills of outcropping Banded Iron Formation (BIF). Weeli Wolli Creek and its tributaries drain in a northeast direction, converging at a narrow valley system approximately 30 km down gradient from the headwaters (Fig. 1). The lower catchment downstream of this valley joins with Marillana Creek to the west and drains on to a wide alluvial floodplain (20 to 60 km wide), with a meandering channel that can alter its course following large flood events (Fig. 1).

Upper Weeli Wolli Creek (Section A; Fig. 2) is underlain by the relatively impermeable Weeli Wolli Formation for 12 km extending from the upper outlets of the mine water discharge (discharge area 1-DP1) to the lower discharge point (discharge area 2-DP2). The impermeable nature of the formation has been established from prior drilling, which also demonstrated a K value two orders of magnitude less than the CID aquifer (Kirkpatrick and Dogramaci, 2010). This upper Section A contrasts to the lower part of the creek (Section B, Fig. 2), which is underlain by a Palaeochannel Iron Deposit (CID) aquifer that is characterised by a relatively high hydraulic conductivity ($K \sim 10$ m/d; Kirkpatrick and Dogramaci, 2010). The narrow ~500 m wide and 100 m thick) CID aquifer is hosted within the impermeable Weeli Wolli Formation for most its length. The Brockman Iron Formation ($K \approx 5$ m/d) underlies the lower part of Section B, before the creek leaves the Hamersley Ranges and drains into the Fortescue Valley. In general, the creek alluvium is comprised of inter-bedded layers of clays to sands and gravels to cobbles. The coarse alluvium of the creek bed is highly conductive ($K \approx 1000$ m/d), resulting in rapid recharge to the underlying alluvium during creek flows (Peck and Associates, 1995). However, the volume of the creek bank storage is relatively