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Evaluation of infiltration from losing-disconnected rivers using a geophysical characterisation of the riverbed and a simplified infiltration model

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SUMMARY

Despite their significance to alluvial aquifer water balances, there are few field-derived estimates of infiltration from losing-disconnected rivers. Infiltration was estimated over a 2 km section of Billabong Creek (Murray-Darling Basin, Australia) using a combination of field measurements and modelling techniques. A method was developed whereby in-river and riverbank electrical resistivity surveys were used to map the spatial coverage and thickness of the riverbed clay layer, thought to be the key control on infiltration in this environment. Inverted resistivity measurements were used to generate a surrogate for a spatial map of clay layer thickness, with constraint provided by coring the riverbed at selected high and low resistivity locations to independently determine the thickness of the clay. The survey showed that the clay layer was continuous across the study reach but varied in thickness (~1 m to >4 m). A simple infiltration model was developed for infiltration through a clay layer and shown to be accurate under steady state conditions when compared to estimates obtained using a variable saturation numerical model for idealised riverbed cross-sections. Infiltration rates across the study reach were estimated to range between 1700 and 7800 m^3 km^{-1} year^{-1}, with an average of 3400 m^3 km^{-1} year^{-1}. A sensitivity analysis showed that infiltration rates were most sensitive to clay hydraulic conductivity, not clay layer thickness. However, it is anticipated that when applied at a larger scale (10–100 km), infiltration rates will be more sensitive to the presence or absence of a clay layer in the riverbed. The proposed methodology can provide independent estimates of infiltration in losing-disconnected rivers at a scale suitable for the calibration of regional groundwater models.

1. Introduction

In many semi-arid areas, losing-disconnected streams and rivers are a major source of recharge for alluvial aquifers and support agriculture, urban supplies and groundwater-dependent ecosystems (CSIRO, 2008). Infiltration from losing-disconnected water bodies occurs through a vadose zone (Fox and Durnford, 2003; Brunner et al., 2009a). For all practical purposes, a necessary (but not sufficient) condition for a vadose zone to develop below a riverbed is the presence of a clogging layer with a lower hydraulic conductivity than the aquifer material below (Brunner et al., 2009a). However, it is theoretically possible for a vadose zone to develop without a clogging layer (Wang et al., 2011) but this has not been observed in a field situation. Although there have been many field studies that have estimated recharge from losing-connected rivers (Beyerle et al., 1999; Barlow et al., 2000; Constantz et al., 2003; Kalbus et al., 2006; Ruehl et al., 2006; Kennedy et al., 2007) these same techniques have not been successful in losing-disconnected rivers (Lamontagne et al., 2011a). There are few field measurements of infiltration from losing-disconnected rivers (e.g. Dahan et al., 2007) in part because identifying this condition in the field at a regional scale is difficult (Brunner et al., 2011; Shanafield et al., 2012; Lamontagne et al., 2013). This is the case for the Murray-Darling Basin (Australia), where over a thousand kilometres of river channel may be losing-disconnected in the vicinity of exploited alluvial aquifers (CSIRO, 2008).

In the absence of direct measurements of infiltration from losing-disconnected riverbeds, modelling is often used to estimate groundwater recharge from rivers. Earlier work focused on stream depletion through pumping using both numerical (e.g. Su et al. (2007)) and analytical models (e.g. Spalding and Khaleel (1991)) at a local scale. River models often treat losses to groundwater as an unallocated loss which is lumped in with other errors, such as with IQQM (Simons et al., 1996) and REALM (Perera et al., 2005). More recent river models provide some simple capability for esti-

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mating losses to groundwater but they are not widely used yet (Rassam, 2011; Welsh et al., 2013). Groundwater models often treat rivers very simply and the recharge rate is usually obtained via calibration to groundwater levels (e.g. MODFLOW; Harbaugh and McDonald, 1996), which may yield large errors (Brunner et al., 2010). Models do exist that are capable of modelling the vadose zone below a river, such as HydroGeoSphere (Therrien et al., 2006), MODHMS (HydroGeoLogic, 2006) and HYDRUS (Šimůnek et al., 2008, 2011), but these are computationally very intensive and not always suitable for regional applications. As these models estimate the infiltration without observational constraints, there is clearly a need to estimate infiltration from losing-disconnected rivers with simple methods that can be applied at the regional scale.

The objective of this study was to develop a field technique to estimate infiltration rates in losing-disconnected rivers and use it to evaluate infiltration along a 2 km reach of the regulated Billabong Creek (Murray-Darling Basin, New South Wales). The study had two broad components: (1) use of in-river vertical resistivity soundings (VES) to map the presence and thickness of riverbed clay layers and (2) development and evaluation of a simple model of infiltration through a clay-lined riverbed. The rationale for using VES was that the clogging layer in this environment usually takes the form of a clay layer overlying a sand aquifer (Lamontagne et al., 2012). A saturated clay layer overlying unsaturated sand should provide a strong contrast in electrical resistivity (Wildenschild et al., 2000). Particular care was taken to validate the in-river VES results through coring of the riverbed at high and low resistivity locations and by complementary riverbank-based VES over smaller sections of the study reach.

In the following, a summary of the VES surveys is provided, along with the development and evaluation of the simplified infiltration model. The variations in infiltration rate are estimated along the Billabong Creek study reach and the uncertainty on the infiltration rates evaluated with a sensitivity analysis. A detailed description of the VES surveys and of the inversion procedures to estimate riverbed clogging layer thickness will be made elsewhere (see also Lamontagne et al., 2012). A detailed account of the VES surveys is not necessary here as it will be shown that the infiltration estimates were insensitive to the thickness of the clay layer at the study reach.

The novelty of the proposed approach is neither in the modelling or the field measurements themselves but in the potential to combine them to produce estimates of infiltration at the reach-scale (10's of km). This is the scale of interest for the calibration of regional groundwater models where there are currently no practical methods for estimating infiltration from losing-disconnected rivers.

2. Methods

2.1. Field site

The field site chosen for this study was a 2 km section of Billabong Creek (35.35°S, 145.49°E), downstream of Jerilderie in south-eastern Australia (Lamontagne et al., 2011a; Fig. 1). This is a semi-arid region with an annual average rainfall of 400 mm year^{-1} and an average annual potential evapotranspiration of 1340 mm year^{-1} (Allen et al., 1998). Billabong Creek is a regulated river (there are large dams supplying water from upstream and a series of weirs in the lower reaches to hold the water) used to supply irrigation water for the rice and dairy industries. Due to the regulated nature of the river, the stage does not vary as much as a natural system. Over a 28 year period, the gauge at Jerilderie has shown a range of less than 2 m and the annual average stage has only varied over less than 0.6 m (Fig. 2). Losing-disconnected conditions had been previously demonstrated at this site by the water table being 7.2 m below the riverbed in a piezometer adjacent to the river and also through the presence of an unsaturated zone below the river (Lamontagne et al., 2013). Previous work had shown a well-developed clogging layer in the riverbed in the form of a clay or silty-clay layer 0.5 m to >2 m in thickness overlying a sand aquifer (Lamontagne et al., 2011a, 2013).

2.2. Mapping of riverbed clay thickness

The complete procedure to map the thickness of riverbed clogging layer is described in brief here (more information can be obtained from Lamontagne et al., 2012). Essentially, vertical profiles of riverbed resistivity were measured with two different VES techniques (towed in-river array and riverbank fixed array) and calibrated to riverbed core profiles taken at six sites with contrasting resistivity. The in-river VES survey was made in 2008; at a time when the river was relatively low (0.2 m at the Jerilderie gauge) due to a regional drought (van Dijk et al., 2013). All other measurements were made in November 2011, when the river levels were slightly higher (0.8 m at the Jerilderie gauge).

2.2.1. Vertical electrical soundings

The in-river VES were acquired using a floating resistivity array which was attached to an Argo 6 × 6 Frontier 580 amphibious vehicle. The array, specifically designed for in-river resistivity surveys, was 100 m long and consisted of a modified inverse Schlumberger array, using two current (transmit) electrodes and eight pairs of receiver electrodes distributed equally either side of the transmitters. The sampling depth of each quadrupole is determined by the combination of transmitter-electrode to receiver-electrode spacing. The inverse Schlumberger electrode spacing separations were chosen to ensure that high-resolution shallow data (~1 m) recorded together with good quality data at greater depths (up to 20 m), given the relatively weak transmitter currents (Roy and Apparao, 1971; Allen and Merrick, 2006).

For riverbank VES, three longitudinal transects (150–250 m in length) were established at locations with high or low resistivity based on the in-river VES survey. Surface resistivity at the river edge was undertaken using a GF Instruments Automatic Resistivity System (ARES) using 48 electrodes deployed at 2.5 m intervals. The sounding depth achieved with this configuration was about 20 m.

2.2.2. Riverbed profiles

Changes in the thickness of the riverbed surface clay layer along the 2 km study reach were evaluated to help constrain the geophysical measurements. Firstly, the in-river VES soundings were examined to identify regions with high and low resistivity. Six locations were chosen, covering the range in riverbed resistivity observed. At each location, a profile of the riverbed was collected by hand augering. For each profile, an outer casing (9 cm dia. PVC pipe) was first inserted to ~50 cm depth into the riverbed. The inside of the casing was dewatered using a small bilge pump and observed to determine if a proper seal with the sediments was maintained. Following dewatering, sediment profiles were augered by 20 cm increments using sand or clay augers with extensions. The sediment samples were collected and doubly-bagged in well-marked zip-lock bags. Augering proceeded as far as practical, which was either the physical extent of the auger (4.5 m), or until very dry sediments were encountered. The purpose of these profiles was twofold: firstly, to identify the vertical variations in riverbed texture and, secondly, to collect samples for laboratory measurements of the vertical variations in matric potential, gravimetric water content, and electrical conductivity (EC) (see measurement details in Lamontagne et al. (2012)).