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title: **Investigation of surface water-groundwater interactions and temporal variability of streambed hydraulic conductivity using streambed temperature data**

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INTRODUCTION

Water resource management is increasingly moving towards a conjunctive approach for surface water and groundwater. For this to be successful the possible interactions between surface water and groundwater needs to be understood and quantified. However, quantifying this interaction is notoriously difficult. Often groundwater management decisions are based on numerical models of a groundwater aquifer system where the connection to surface water is poorly conceptualised. This has implications for the usefulness of such models as predictive tools. For example, the impact of groundwater abstraction on the river-aquifer exchange will not be properly quantified if the model does not capture this process appropriately. In part, this difficulty has arisen due to a scarcity of field based studies into river-aquifer interactions. In this context, a study of the interaction between a major river and underlying aquifer in a semi-arid region, the Maules Creek Catchment located in north-western New South Wales, Australia, was carried out (Figure 1).

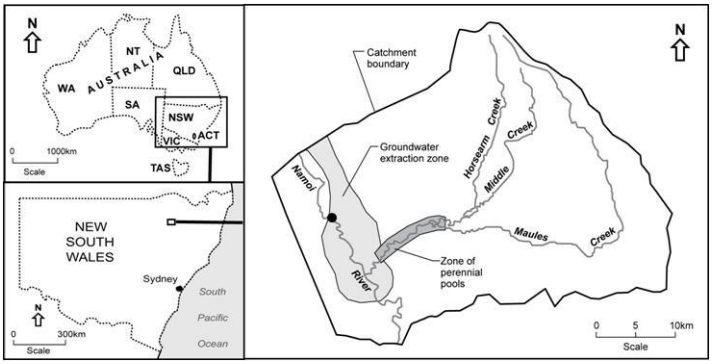

Figure 1. Maules Creek Catchment with location of the study area shown as a black marker (Source: McCallum et al., 2009).

METHODOLOGY

A thermal approach using arrays with temperature loggers was employed to investigate the river-aquifer interaction. Four arrays, each consisting of three loggers mounted in a PVC pipe, were installed vertically into the riverbed, with loggers located at 0, 15 and 30 cm depth. The arrays were deployed in a single pool within the Namoi River (Figure 2). The loggers were set to record every 15 mins (from November 2007 to April 2008). In addition, pressure transducers were installed to log the river stage and groundwater level in a nearby borehole (approximately 40 m from river) every 15 mins.

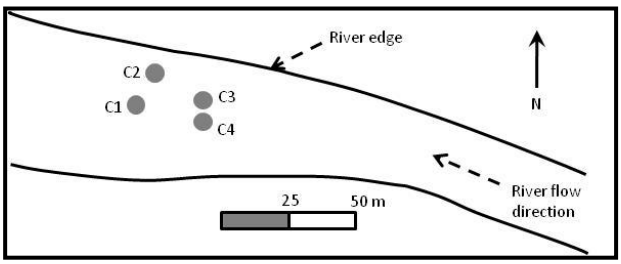

Figure 2. Location of temperature probes within the Namoi River.

Streambed water fluxes were calculated on the basis of the 1D convection-conduction heat transport differential equation for fully saturated conditions:

$$\frac{\partial T}{\partial t} = \kappa_e \frac{\partial^2 T}{\partial z^2} - \frac{n v_f \rho_f c_f}{\rho c} \frac{\partial T}{\partial z}$$

where T is temperature, which varies with time (t) and depth (z); κ_e is effective thermal diffusivity; n is porosity; v_f is vertical fluid velocity; ρ_f and c_f are density and heat capacity of the fluid; and ρ and c are density and heat capacity of the saturated sediment-fluid system.

Hatch et al. (2006) presents a solution to this equation in which two values of vertical flux can be independently calculated by comparing the diurnal amplitude damping and phase shift of temperature time series at different depths. The recorded temperature time series were filtered to isolate the diurnal variations. The amplitude ratio and phase shift for the upper and lower loggers were then computed and used to derive river-aquifer fluxes. For more details as well as thermal parameters used see also Rau et al. (2010).

RESULTS AND DISCUSSION

The river stage data shows that during the period of investigation there were four main flow events (Figure 2a, solid line). Two were large (~ 3–4 m stage increase) events caused by rainfall periods each of which were preceded by a smaller (~1 m stage increase) event caused by dam releases up river. The groundwater levels responded in a damped fashion to each of the flow events (Figure 2a, dashed line). Also evident in the groundwater levels were rapid events of drawdown (~1 m) caused by near-by groundwater abstraction. The difference between the river stage and groundwater level is the driving force for river-aquifer interactions (Figure 2b).

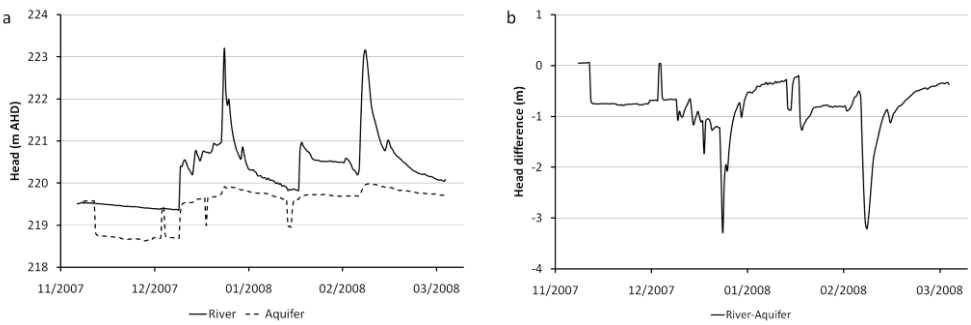

Figure 2. a) Head time series in river and aquifer; b). River-aquifer head difference (negative value indicates potentially losing conditions).

The measured temperature time series show strong diurnal heat patterns as well as longer-term heat trends and noise (Figure 3a) while the filtered time series more clearly reveals a damping of amplitude and shift of phase with depth at each location (Figure 3b).

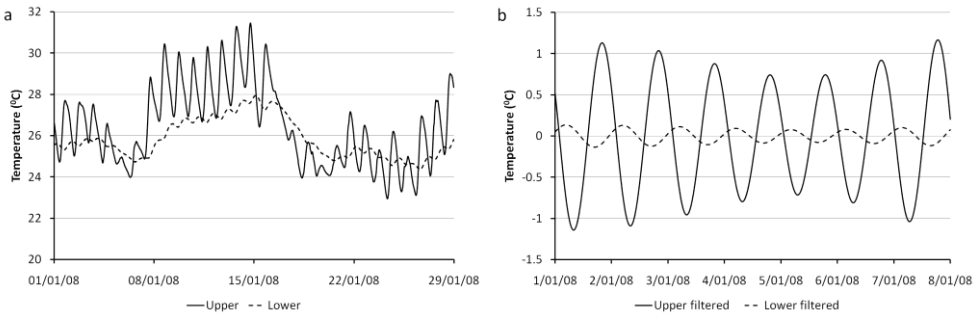

Figure 3. a) A portion of unprocessed temperature data from temperature array C1. The solid line is the surface water temperature at the streambed and the dashed line is at 30 cm into the streambed; b) Example of 7 days of filtered temperature data from the same sensors in array C1.

Interestingly, the fluxes derived from the phase shifts were consistently greater than those calculated from the amplitude ratios. This is possibly due to violation of the 1D flow assumption inherent in the analysis (Rau et al., 2010). Regardless of this discrepancy, both sets of results showed the same overall patterns. Results discussed below are those derived from using the amplitude ratio, which have been found more robust (Lautz, 2010).

At all locations the computed long-term river-aquifer fluxes were approximately 0.1 m/day downwards, indicating losing river conditions, which is consistent with the negative gradient in Fig. 2b. There was little apparent spatial variability in flux rates between arrays (Table 1). This was somewhat surprising as it was anticipated that the heterogeneity of the streambed would have led to strong spatial trends. This result, however, gives confidence in the possibility of up-scaling these point measurement to larger spatial scales.

Table 1 Statistics of flux results (m/day).

	C1	C2	C3	C4
Mean	–0.107	–0.101	–0.144	–0.095
Median	–0.087	–0.084	–0.138	–0.084
Variance	0.003	0.002	0.001	0.001
Std deviation	0.055	0.046	0.032	0.031
Minimum	–0.295	–0.245	–0.245	–0.190
Maximum	0.280	0.201	0.027	–0.036

The time series of calculated velocities revealed a number of interesting features (Fig. 4a). First, for short periods of time, following the initial high river stage related to a flow event, an upwards flux was observed. The cause of this is presently unknown but could possibly reflect a return of bank-storage to the river. Second, the pattern of the temperature-derived flux follows a similar pattern to the river-aquifer head difference (compare Fig. 4a with Fig. 2b). The correlation coefficient between these two variables during the flood events varies from 0.77 to 0.98. This indicates that there is a clear relationship between river stage and river loss. Third, the fluxes were constant for long periods but changed temporarily during flood events as indicated by the change in slope of the cumulated river-aquifer fluxes in Fig. 4b.

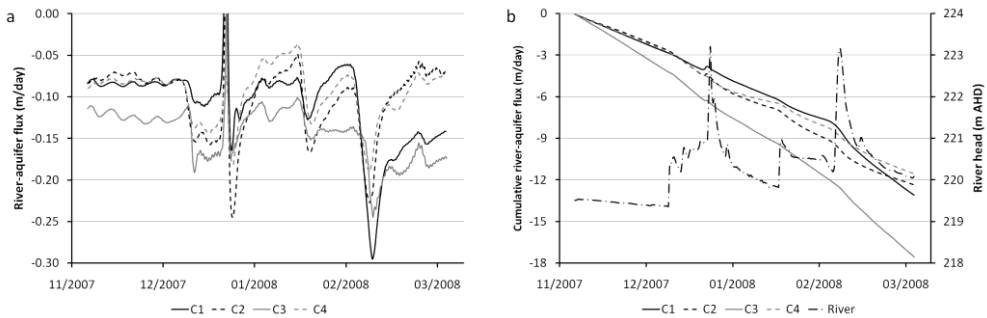

Figure 4. a) River-aquifer flux calculated from the temperature data. A negative flux indicates losing conditions; b) The river-aquifer fluxes as in a. but cumulated over time.

It is hypothesised that these field observations can be interpreted using a simple conceptual model of how the riverbed hydraulic conductivity changes over time (Figure 5).

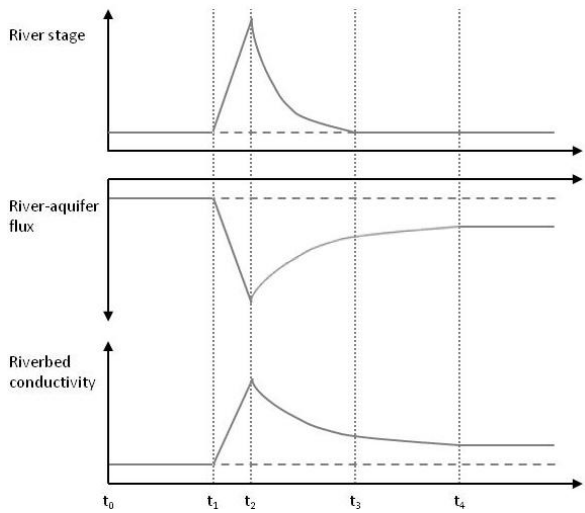

Figure 5. Conceptual understanding of riverbed conductivity changes through time and relationship to river stage and river-aquifer flux.

Between t_0 and t_1 the system is in a steady state. From t_1 to t_2 a flood increases the river stage. Corresponding to this increase in an increase in river-aquifer flux (more negative since the river is already losing) according to Darcy's law. Importantly, also corresponding to this increase in river stage is an increase in riverbed conductivity due to scouring of lower permeability material in the riverbed by the flow event. As the river stage declines between t_2 and t_3 the river-aquifer flux decreases, again according to Darcy's law. However, at t_3 where the river stage is back at the level at t_1 the exchange flux is still larger than at t_1. This is due to the increased riverbed conductivity. Between t_3 and t_4 the river-aquifer flux slowly reduces, although the river stage remains constant, as the riverbed conductivity declines due to deposition and colmation of the riverbed. At t_4 a new steady state is reached. The observed change in riverbed conductivity and consequently in the exchange flux related to flood events is an important finding since most numerical models simulating stream aquifer exchanges assumes the streambed hydraulic

conductivity is constant over time. The data presented here suggest that it is important not only to understand the spatial variability of the hydraulic conductivity but that the temporal variability must be assessed as well.

CONCLUSIONS

This study demonstrates how surface water groundwater interactions can be understood and quantified using thermal investigations. Further work is still required to make the interpretation more robust, especially unravelling the discrepancy between results derived using amplitude damping and phase shift of temperature time series. Nevertheless, the method can be used to better constrain the river-aquifer interaction in groundwater models, in particular riverbed changes through time.

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