




The Use of Natural Heat as a Tracer to Quantify Surface Water and Groundwater Interactions: Maules Creek, New South Wales, Australia

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1. Introduction

Surface water and groundwater are intimately connected. Surface water includes rivers, streams, creeks, ponds, lakes, etc. Groundwater is water that fills the voids between sediment grains in the subsurface. Effective water management must consider surface water and groundwater as a single water resource.

The Water Research Laboratory is currently undertaking a major research project within the Maules Creek Catchment of the Namoi River, funded by the Cotton Catchment Community CRC, to investigate the issue of how surface water and groundwater are connected (see Figure 1).

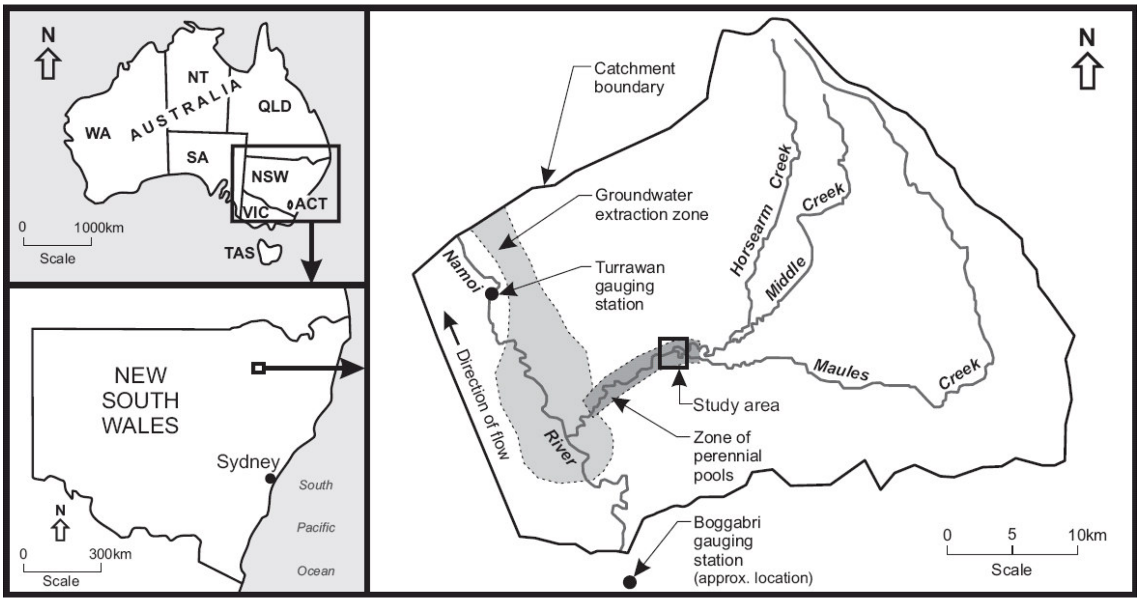

Figure 1: Map of Australia, New South Wales and Maules Creek Catchment (enlarged).

There are four possible scenarios of surface water and groundwater interaction as shown in Figure 2.

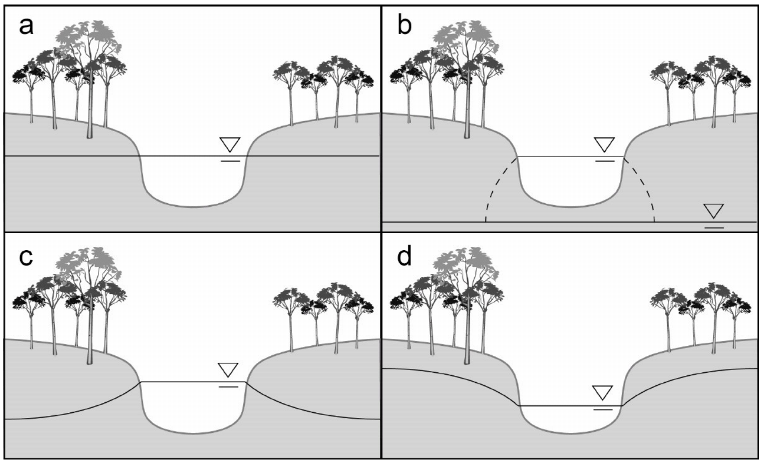

Figure 2: Schematic illustration of the interaction between surface water and groundwater: (a) neutral reach, (b) disconnected reach, (c) losing reach and (d) gaining reach (modified from Winter et al, 1998).

The connectivity can be seen in records of river flow through time (i.e. stream hydrographs). For example, as shown in Figures 3 and 4, more water passes the Namoi River at Boggabri than downstream at Turrawan. This is largely due to this section of the river being a losing reach (i.e. type 'c' in Figure 2).

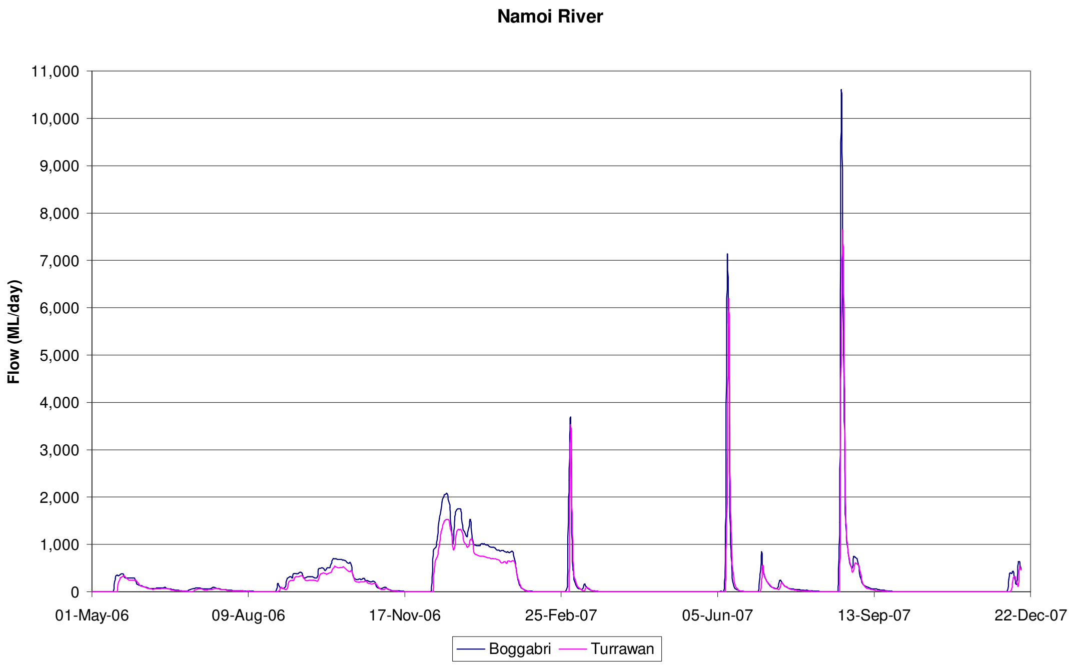

Figure 3: Stream Hydrographs for Boggabri and Turrawan Gauging stations (see Figure 1). The graph shows three occasions of water release from Lake Keepit dam between May 06 and Dec 06, and three flow events generated by storm events from Feb 07 to Sept 07, followed by the start of a fourth dam release in Dec 07.

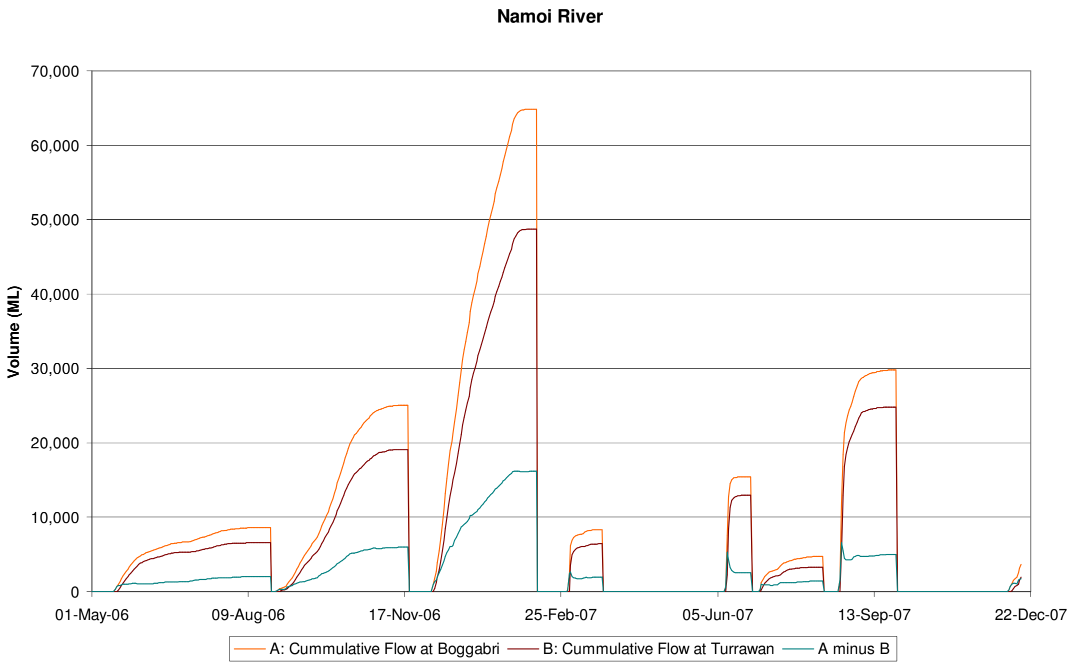

Figure 4: Summation of water flowing through Boggabri and Turrawan. Blue line represents quantity of water removed from river system between these two gauging stations, indicating a losing reach.

As surface water and groundwater are a single resource, it is important to estimate the fluxes between them. This is commonly carried out using the Darcy method. This method uses a water level gradient combined with a hydraulic conductivity of the subsurface to give an estimate of the flux. The hydraulic conductivity, however, is very sensitive to variations in grain size and sorting. Consequently, sparse knowledge of the distribution of the hydraulic conductivity may lead to erroneous or uncertain fluxes.

This research project investigates the use of natural heat as a tracer of water movement as an alternative method to the traditional Darcy method.

2. Theory

In a porous medium, such as streambed sediments, heat is transported by both conduction and convection, as shown in Figure 5. Heat conduction occurs through the bulk medium while convection is caused by fluid moving in the voids between sediment grains. Both processes can be superimposed.

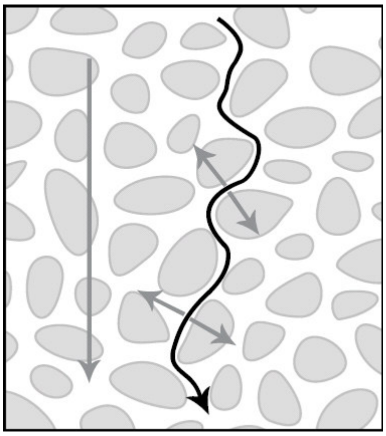

Figure 5: Illustration of the travel path of heat by conduction (grey) and convection (black) in a porous medium.

These processes can be mathematically described using the conduction-convection equation:

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

In this equation 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 bulk density and heat capacity of the fluid, and ρ and c are density and heat capacity of the saturated sediment-fluid system.

The atmospheric temperature fluctuates due to daily, seasonal and annual changes in solar radiation. These fluctuations also affect the temperature of shallow surface waters which are then transferred into the subsurface by conduction and convection.

The temperature fluctuations can be used to derive fluxes between surface water and groundwater using two different approaches.

Approach One – Forward Modelling

If the temperature signal at the surface of the sediments is recorded, it is possible to predict the temperature signal at any depth within the sediments, using (Silliman et al, 1995):

$$T_s^n(z,t) = T_0(z) + \sum_{i=1}^{n} \Delta T_s^{i,i-1}(z,\tau) \quad \text{with } \tau = t - t_i$$

where:

$$\Delta T_s^{i,i-1}(z,\tau) = \frac{\Delta T_w^{i,i-1}}{2}\left[erfc\left(\frac{z-C\tau}{2\sqrt{D\tau}}\right) + \exp\left(\frac{Cz}{D}\right)\cdot erfc\left(\frac{z+C\tau}{2\sqrt{D\tau}}\right)\right]$$

where:

$$C = \frac{\rho_f c_f}{\rho c} nv \text{ and } D = \frac{\kappa_e}{\rho c}$$

In the equations above $\Delta T_s^{i,i-1}(z,\tau)$ is the temperature at any depth (z) and time (t), T_0 is the temperature at depth z when t=0, $\Delta T_w^{i,i-1}$ is the change in temperature at depth z=0.

The forward modelling approach involves comparing the predicted temperature signal against a recorded temperature signal at some depth, and adjusting the flux until both signals are the same, thereby deriving the flux. The field setup used for this approach is shown in Figure 6.

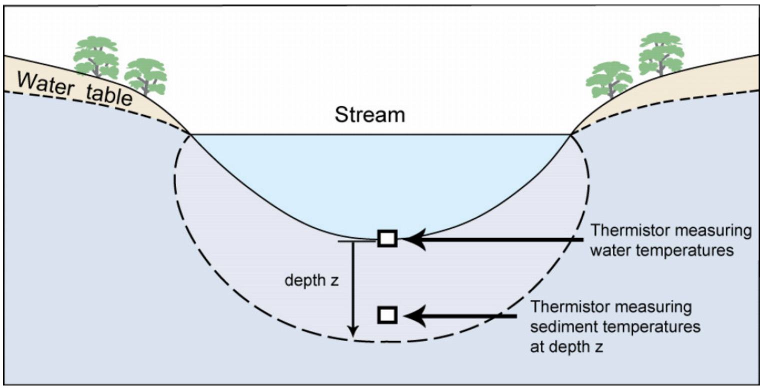

Figure 6: Cross section of stream-aquifer showing the locations of thermistors for recording temperature variations.

Approach Two – Transient Modelling

A second approach is to record one temperature signal at the surface of the sediments and another at some depth within the sediments. The temperature signal at depth will display an amplitude drop and phase shift, as shown in Figure 7.

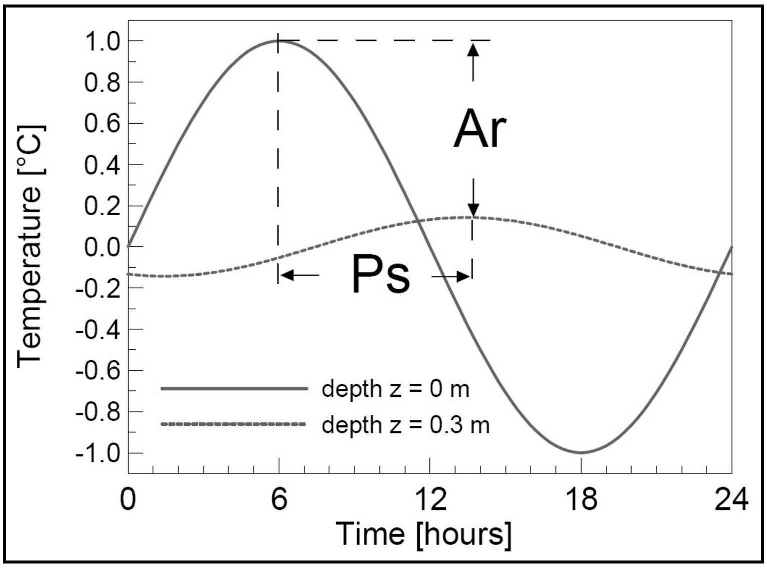

Figure 7: Two hypothetical temperature signals showing how a signal at 0.3 m depth will have an amplitude drop and phase shift compared to a signal at 0 m depth (i.e. just above the sediments) (modified from Hatch et al, 2006).

These phenomena can then be used to derive the flux using (Hatch et al, 2006):

$$v = \frac{2\kappa_e}{\Delta z}\ln(A_r) + \sqrt{\frac{\alpha_i + v^2}{2}}$$

and:

$$v = \sqrt{\alpha_i - \left(\frac{\Delta\phi 4\pi\kappa_e}{P\Delta z}\right)^2}$$

where:

$$\alpha_i = \sqrt{v^4 + \left(\frac{8\pi\kappa_e}{P}\right)^2}$$

where:

$$v = v_f \frac{\rho_f c_f}{\rho c}$$

In the equations above Δz is the spacing between temperature signals, A_r is the amplitude difference between temperature signals, $\Delta\phi$ is the phase difference between temperature signals, P is the period of the temperature fluctuation.

3. Field Application

The field site is located within the Maules Creek catchment (see Figure 1, above). The Maules Creek area is composed of Tertiary alluvial sediments with medium to heavy clays and lenses of sand and gravel overlain by sands, gravels and cobbles to a depth of approximately 10 m (see Figure 8). Recent investigations by Andersen and Acworth (2007) suggest that that groundwater is discharging slightly upstream of the confluence of Maules Creek and Horsearm Creek. The water then flows through a series of perennial pools and in a shallow unconfined sand and gravel aquifer of approximately 200 m width. Closer to the Namoi River, surface flow in Maules Creek stops when it crosses a large subsurface paleochannel.

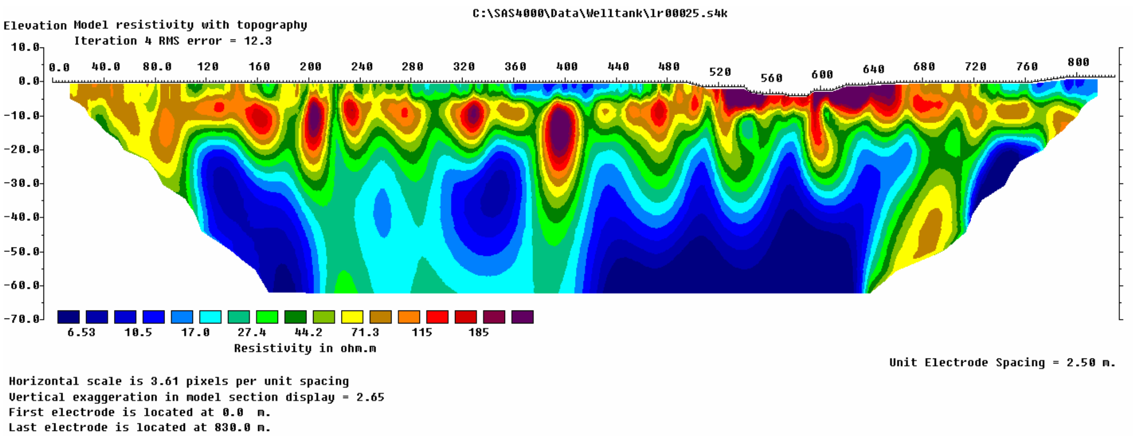

Figure 8: Resistivity Image across Maules Creek (LHS is North, RHS is South). The high resistivity (70–1000 Ω·m) material overlying low resistivity material (2–70 Ω·m) probably corresponds to an upper zone of variably saturated sands, gravels and cobbles overlying more clayey lithology (after Andersen and Acworth, 2007).

Three sites were selected on Maules Creek for investigation. These locations are shown on the aerial photograph (Figure 9).

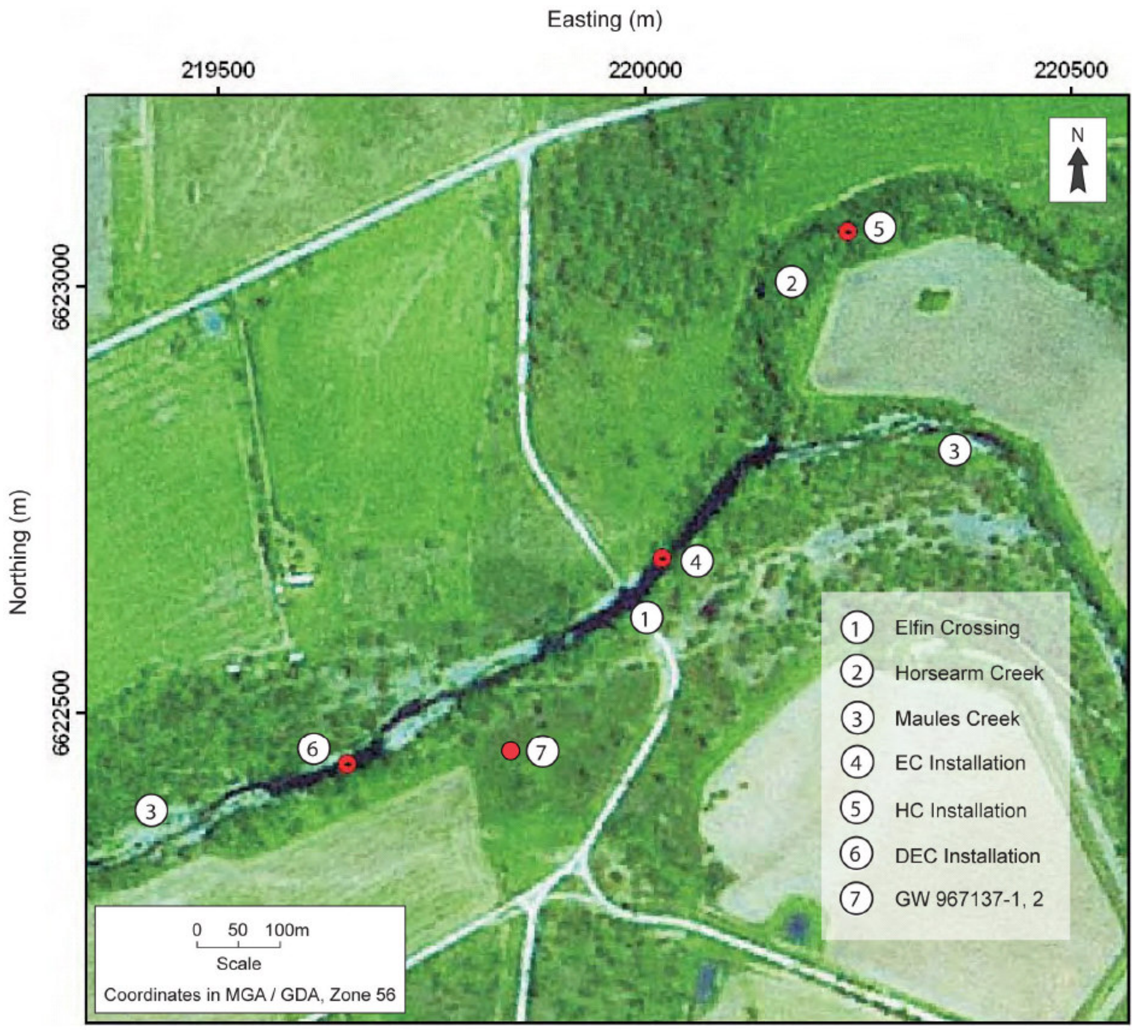

Figure 9: Location of investigation sites: at Elfin crossing (EC), upstream on Horsearm Creek (HC) and downstream on Maules Creek (DEC).

For each site a temperature array was designed, constructed and installed (see Figure 10). The array consisted of five temperature probes separated by insulators. The arrays were installed in the streambed with the uppermost probe at the surface of the sediments. This allowed for the collection of temperature signals at five different depths. The probes logged temperature data every 15 minutes.

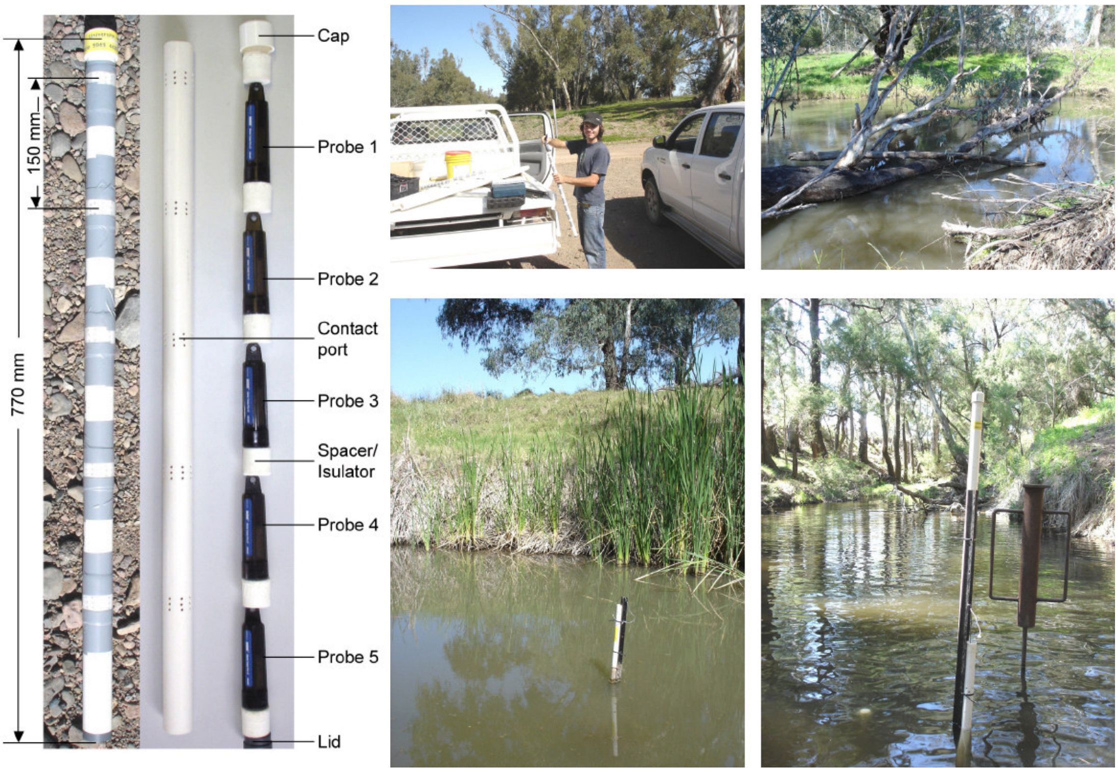

Figure 10: A temperature array (left) and photos from installation in the field (right).

4. Results and Discussion

One set of results are shown in Figure 11. The upper graph shows two temperature signals: one from 0 m depth and the other from 0.6 m depth. The lower graph shows the same data but transformed by a filtering process from true temperatures to relative temperatures. This filtering process allows the daily fluctuations in temperature to be more clearly observed and analysed.

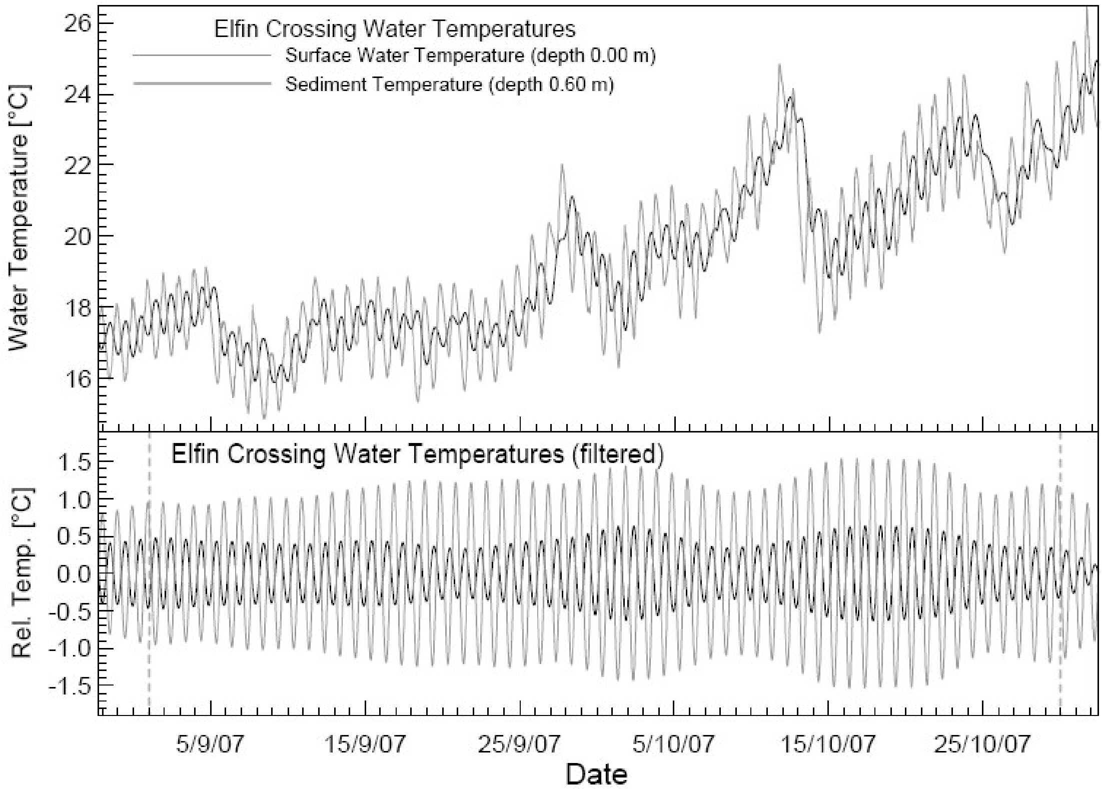

Figure 11: Temperature data from Elfin Crossing (see Figure 9 for location).

Using the data shown in the upper graph in Figure 11 it was possible to apply *Approach One – Forward Modelling* to derive a flux (see Figure 12). For this location at Elfin crossing the calculated velocity was approximately 0.6 m/day downwards into the streambed.

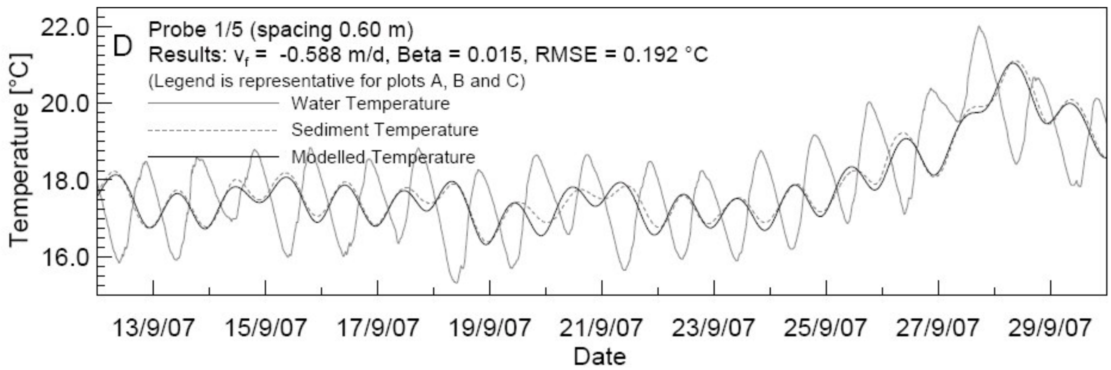

Figure 12: Results of applying *Approach One – Forward Modelling* to data from Figure 11.

Approach Two – Transient Modelling was then applied to the data shown in the lower graph in Figure 11 to derive a flux (see Figure 13). This method showed that although the flux was approximately 0.6 m/day downwards, it varied over time.

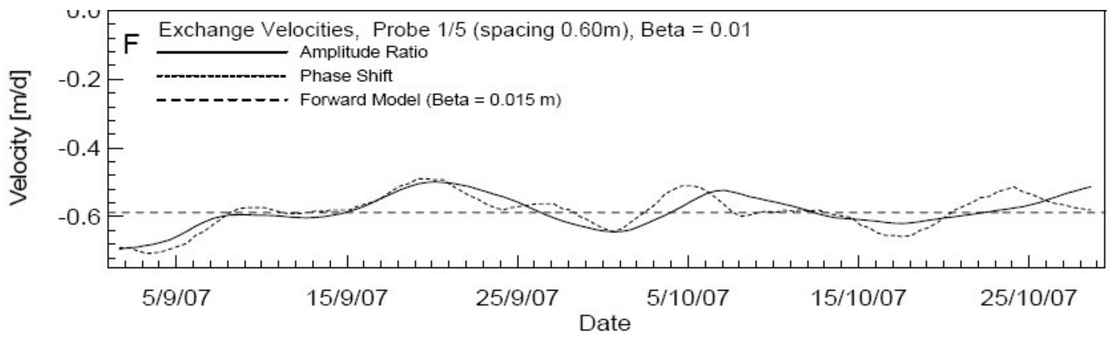

Figure 13: Results of applying *Approach Two – Transient Modelling* to data from Figure 11.

These results show clearly that during the time of the experiment, water was moving downward from the pool into the aquifer at Elfin Crossing. To achieve a total volume flux, a number of measurements would need to be made at different locations in the pool and integrated.

5. Conclusion

Surface water and groundwater interactions are important to understand from the perspective of water resource management. One method to calculate the fluxes is the Darcy method, but a lack of knowledge of the hydraulic conductivity distribution makes this difficult to use in practice with any accuracy. A complimentary method, that does not have the same limitations as the Darcy method, is to use natural heat as a tracer of water movement.

This research project has investigated the use of two different mathematical approaches to derive values for the exchange fluxes. The two approaches gave very similar results. At Elfin Crossing (Figure 14) it appears that the water is percolating downwards from the stream into the streambed, at a rate of approximately 0.6 m/day (Figure 14).

Figure 14: View of Elfin Crossing where the initial results indicate that water is moving from the pool into the aquifer at a rate of 0.6m/day

The results from this study show that the use of natural heat as a tracer of water movement could become a reliable standard method for estimating fluxes between surface water and groundwater. Significant scope exists for the method to be further developed to account for unsaturated sediments and two or three dimensional water movement.

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