TIME-SERIES MEASUREMENTS OF STREAM AND SEDIMENT TEMPERATURE FOR UNDERSTANDING RIVER-GROUNDWATER INTERACTIONS: BORDER RIVERS AND LOWER RICHMOND CATCHMENTS, AUSTRALIA

S. **Baskaran**[1], R.S. **Brodie**[1,2], T. **Ransley**[1] and P. **Baker**[1]
[1] Bureau of Rural Sciences
[2] Centre for Resource and Environmental Studies, Australian National University

GPO Box 858 Canberra ACT 2601 Australia
Baskaran.Sundaram@brs.gov.au
ph 02 62725767, fax 02 62725827

Abstract: Monitoring of temperature in the stream sediment (0.25 – 1.2 m depth) as well as the stream itself was used to investigate groundwater-surface water interactions in two different Australian catchments (Border Rivers and Lower Richmond). When interpreted with hydrographic and hydraulic conductivity data, the temperature monitoring provided useful insights into the spatial and temporal variability of stream-aquifer connectivity. At one site, sediment temperatures fluctuated with the diurnal temperature variation of the stream, reflecting river leakage. No diurnal signal was detected in the sediment temperatures at other sites, which is a typical indicator of gaining conditions. However, with water level measurements indicating negative gradients and the stream sediments dominated by clay at these sites, this lack of sediment temperature variability is interpreted to reflect very low rates of downward seepage. At one site, a transition from gaining to losing conditions was observed through time. In the field trials, operational issues such as timing the monitoring to coincide with reasonable diurnal variations of stream temperature, the requirement of understanding the shallow stratigraphy of the stream bed, and separating out localised effects (such as from weirs) were highlighted. The trials also highlighted that interpretation of the temperature data can be ambiguous when viewed in isolation. Results indicated that time-series measurements of sediment and stream temperatures can be a useful screening tool for identifying gaining and losing reaches and for identifying temporal variations in seepage flux. It is suggested that temperature loggers can be readily and cheaply incorporated into existing hydrographic networks to provide greater understanding of stream-aquifer connectivity. It is also recommended that existing temperature logging (such as with pressure transducers) be upgraded to sufficient accuracy for seepage studies. Temperature monitoring would be particularly useful in estimating seepage from Australian ephemeral streams. This data also has relevance to the investigation and management of aquatic ecosystems, notably within the hyporheic zone.

Key Words: groundwater-river interactions, seepage flux, sediment temperature, Border Rivers, Lower Richmond, Australia.

INTRODUCTION

Groundwater and surface water systems are hydraulically connected in many landscapes and the extraction of groundwater can alter river hydrology. The contribution of groundwater discharge in maintaining stream flow for consumptive users and for aquatic ecosystems is increasingly being recognised as an important aspect of water allocation policy in Australia. Water issues such as over-allocation, environmental flows and river salinity are all influenced by the degree and nature of the connectivity between rivers and aquifers.

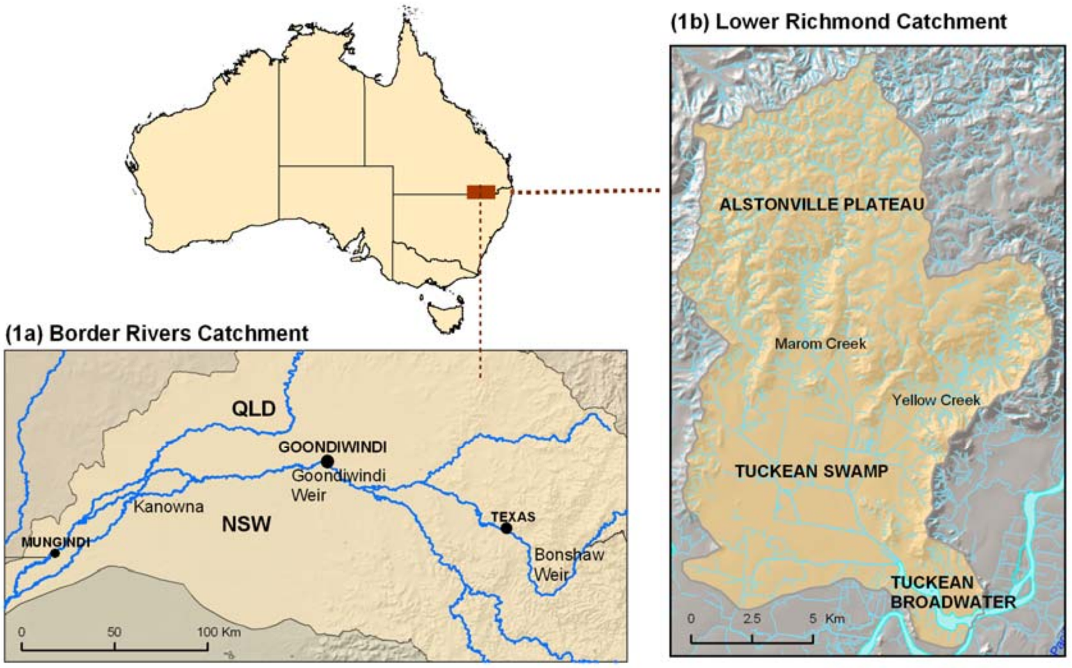
In a connected system, the exchange of water between the stream and shallow aquifer plays a key role in influencing temperature not only in streams, but also in their underlying sediments. As a result, analysis of subsurface temperature patterns can provide information about seepage flux. Studies, notably in North America, have used temperature monitoring in the stream and underlying sediments as a screening tool for identifying gaining and losing reaches (Silliman and Booth 1993; Stonestrom and Constanz 2003). Recently, heat as a tracer has been demonstrated to be a robust method for quantifying surface water-groundwater exchanges in a range of environments, from perennial streams in humid regions (Lapham 1989; Silliman and Booth 1993) to ephemeral channels in arid locations (Stonestrom and Constanz 2003).

This paper discusses the results of time-series temperature monitoring for defining seepage flux in two different catchments in Australia, one in the Murray-Darling Basin (Border Rivers) and the other a New South Wales coastal example (Lower Richmond), refer Figure 1. The catchments were selected due to contrasts in climate, hydrogeology, land use and water management, to trial different methods of assessing groundwater-surface water interactions (Baskaran *et al*, 2005; Brodie *et a*l, 2005)

STUDY AREAS

The Border Rivers catchment is located in southern Queensland and northern New South Wales on the western side of the Great Dividing Range. The two major rivers in the catchment, the Dumaresq and the MacIntyre, define the border between the two States. The prevailing climate is dry winters with sporadic and unreliable rainfall and warm to hot summers with moderate to heavy rainfall. Annual median rainfall decreases from the east (>800 mm) to the west (500 mm). Agriculture is the dominant activity in the region. Along the Dumaresq River, lucerne and other fodder crops are irrigated by groundwater whereas cotton is the main irrigated crop along the MacIntyre River. Surface water is the main source for the predominately flood irrigation of cotton. The major regulated rivers have narrow alluvial valley fill in their upper reaches, broadening out to an extensive alluvial plain down stream. Water allocation and salinity are the main water issues in the catchment.

The Lower Richmond catchment is located in the far North Coast region of New South Wales, about 700 km north of Sydney. The catchment consists of three components: (i) the southern half of the Alstonville Plateau, which is a dissected upland basalt plateau whose streams drain into; (ii) the Tuckean Swamp, a large estuarine back swamp on the coastal plain connected to; (iii) the Tuckean Broadwater, which is an arm of the Richmond River estuary. The catchment experiences relatively mild temperatures and high rainfall (~1600 mm/yr) with a distinctly wetter season during the summer and autumn. The plateau is an important tropical horticultural area, dominated by macadamias, avocadoes and commercial nurseries. The plateau streams are unregulated and groundwater fed, and allocation is the major water management issue. Downstream, the hydrology of the Tuckean Swamp has been highly modified by drains and a tidal barrage. This has allowed the shallow watertable to decline in the pyritic estuarine sediments, causing acid sulfate soils. In the Tuckean, the generation and export of acid waters is the management focus.



(1a) Border Rivers Catchment

(1b) Lower Richmond Catchment

Figure 1: Location of the field trial sites in the (1a) Border Rivers and (1b) Lower Richmond catchment

THE HEAT TRACER METHOD

Heat has been used as a tracer of water movement to estimate groundwater velocity and aquifer hydraulic properties, and to identify areas of recharge and discharge (eg. Bouyoucos 1915; Suzuki 1960; Lee 1985; Lapham 1989; Silliman and Booth 1993; Brewster Conant Jr, 2004). One way of using heat tracing in stream-aquifer studies is to compare the temporal patterns in stream and shallow sediment temperature. Stream temperatures have a characteristic diurnal pattern overprinting seasonal trends, being influenced by changes in solar radiation, air and ground temperature, rainfall and stream inflows that include groundwater discharge (Sinokrat and Stefan, 1993). In contrast, the temperature of regional groundwater tends to be relatively constant at the daily scale. The movement of heat between surface water and groundwater systems is both advective (associated with fluid movement) and conductive (through the static solid/liquid phase). Ignoring the effect of insitu sources of thermal energy (such as from biological activity or exothermic reactions), the temperature pattern in the shallow stream sediment profile can be used to evaluate seepage flux.

The temperature signatures for three potential forms of stream-aquifer connectivity (gaining, losing and neutral) have been hypothesised (Silliman and Booth 1993). In gaining stream reaches, the hydraulic gradient is upward and although the stream has a large diurnal temperature variation, the shallow sediment has only a slight or no diurnal variation. The downward propagation of any surface temperature effects is moderated by water that is flowing up from depths where temperatures are constant at the daily time scale. In losing stream reaches, the hydraulic gradient is downward and the downward flow of water transports heat from the stream into the sediments. This downward advection of heat results in deeper propagation of diurnal temperature fluctuations into the sediment profile. Losing streams also tend to have larger daily temperature fluctuations than gaining reaches, due to the absence of any moderating effect due to groundwater inflow (Constanz 1998). In neutral reaches of the stream, thermal conduction will control stream sediment temperatures. This means that sediment temperature can vary due to changes in surface water temperatures, and will have an average that is between that of the surface water and groundwater. The distinct temperature signal of episodic infiltration associated with ephemeral streams has also been characterised (Ronan *et al*, 1998; Constanz *et al*, 2002).

Estimating the water exchange between the stream and shallow aquifer requires knowledge of the hydraulic and thermal conductivity of the material and the hydraulic gradient as defined by the stream stage and groundwater level. Numerical models of heat flow, such as VS2DH (Healy and Ronan 1996) and SUTRA (Voss 1984) can be used to quantify seepage fluxes. These can supplement and help calibrate more traditional groundwater flow models. In particular, temperature modelling can help constrain estimates of hydraulic conductivity which can vary over several orders of magnitude, as the thermal conductivity of sediments has a much smaller range of potential values. Stream sediments composed of sand and gravel can have a hydraulic conductivity six orders of magnitude higher than clay. In contrast, the thermal conductivity of porous materials depends upon the composition and arrangement of the solid phase with the potential range in thermal conductivity between coarse grained sand (2.2 W/m ^{o}C) and clay (1.4 W/m ^{o}C) being much smaller than that for hydraulic conductivity (Stonestrom and Constantz 2003). The work of Bravo *et al* (2002) is a recent example of using temperature data to constrain estimates of boundary fluxes and hydraulic conductivity in a groundwater flow model for a wetland system.

Fluctuations in temperature can also directly influence seepage rates due to its influence on water density. The hydraulic conductivity of the stream bed is both a function of the porous medium and the water itself, the latter in terms of density and dynamic viscosity. Hence, transmission rates through the sediment bed can increase with increased water temperature. This process was used to explain diurnal variations in seepage flux in losing reaches of a small alpine stream (Constanz 1998).

FIELD METHOD

At different sites in the Border Rivers and Lower Richmond catchments, Odyssey® submersible temperature recorders were installed at various depths (0.25-1.2 m) within the bed of the stream as well as the stream itself (Table 1). The Odyssey logger was chosen due to its low cost, compact waterproof design and memory capacity (64K), however there are many temperature recorders commercially available. The loggers have a capacity to be deployed for extended periods, depending on the frequency of measurement (Table 2). Figure 2 outlines the procedure for installing the loggers into the sediment. A 1.5-m length of galvanised pipe of 50-mm outside diameter with a loosely fitted end cap was driven into the stream bed to the desired depth using a sledge hammer. A metal rod was then inserted down the pipe and lightly tapped to detach the end cap from the pipe. A temperature recorder was connected to a length of wire cable and activated to commence logging at a 30-minute interval. The logger was then lowered down the galvanised pipe with the wire cable fed through a length of 25-mm OD electrical conduit. The conduit was used to keep the recorder at the required depth during installation. The galvanised pipe was then removed with the conduit held down to keep the recorder in position, before the conduit was also removed. The hole was then backfilled with sediment and manually tamped down. The cable from the recorder was attached to a star picket on the stream bank, to allow the recorder to be located and recovered. Typically temperature data was collected for a 7-10 day period before the recorders were removed. Some loggers were left employed at sites in the Border Rivers, to provide data over a four month period to define seasonal changes in seepage flux.

Minipiezometers and stilling wells were also constructed at the same sites (refer Table 1) to measure the shallow watertable and stream stage respectively. The minipiezometers were 1-2 m lengths of 25mm OD electrical conduit stoppered at the base with a series of 2-mm holes drilled to form a 15cm long perforated inlet. These were installed into the stream bed using an outer steel casing and driver mechanism (Figure 3). Once driven to the appropriate depth, the steel casing was removed and the sediment allowed to collapse around the conduit. Granulated bentonite was used to seal the annulus above the perforated inlet when required. The minipiezometers were developed by moving a length of solid steel rod up and down within the conduit, to dislodge any smeared clay and ensure hydraulic connection at the inlet. A length of 50mm PVC casing was attached to a star picket and used as a stilling well to stabilise stream water levels. Once established, stream stage and the shallow groundwater level were monitored at different time intervals. This was either done manually or involved the temporary installation of water level loggers. In some cases, sites were located at stream gauging stations to enable comparison with established stream level monitoring.

Table 1: Details of stream and streambed temperature monitoring sites in the Border Rivers and Lower Richmond Catchments

Catchment	Site	Logging Depth (m)	Streambed sediments
Border Rivers	Bonshaw Weir	0 (surface water)	
		0.5	Coarse sand and gravel
	Goondiwindi Weir	0 (surface water)	
		0.25	Sand/sandy loam
		0.5	Clay loam
	Kanowna	0 (surface water)	
		0.25	Clay loam/clay
		0.7	Clay
Lower Richmond	Yellow Creek	0 (surface water)	Clay
		0.5	Clay
		1.2	Clay
	Marom Creek	0 (surface water)	
		0.4	Clay/Silt
		0.9	Clay
		1.1	Clay

Table 2: Some features of the Odyssey temperature recorder

Dimensions	39mm diameter and 160mm long
Resolution	0.02^{o}C
Power Source	2x3.6 volt lithium batteries
Readings	Up to 16350 readings with interval set between 10 seconds and 8 hours
Data Format	Text file (.PRN) for import into Excel

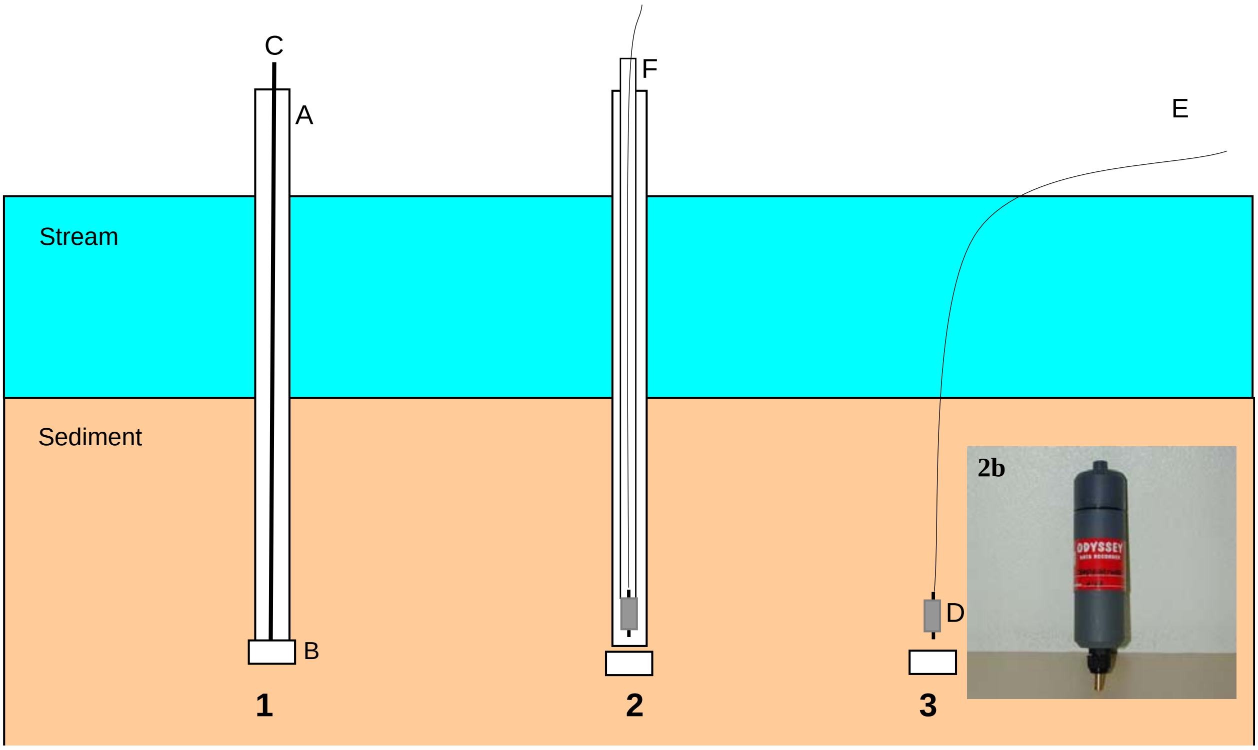


Figure 2: Installation of temperature loggers in the stream sediment, using (A) length of 50-mm OD galvanised pipe with (B) galvanised end-cap fitting, (C) length of metal rod (D) Odyssey® temperature recorder, attached to (E) wire or cable and (F) 25-mm OD electrical conduit.
(2b) Temperature logger used in field trials

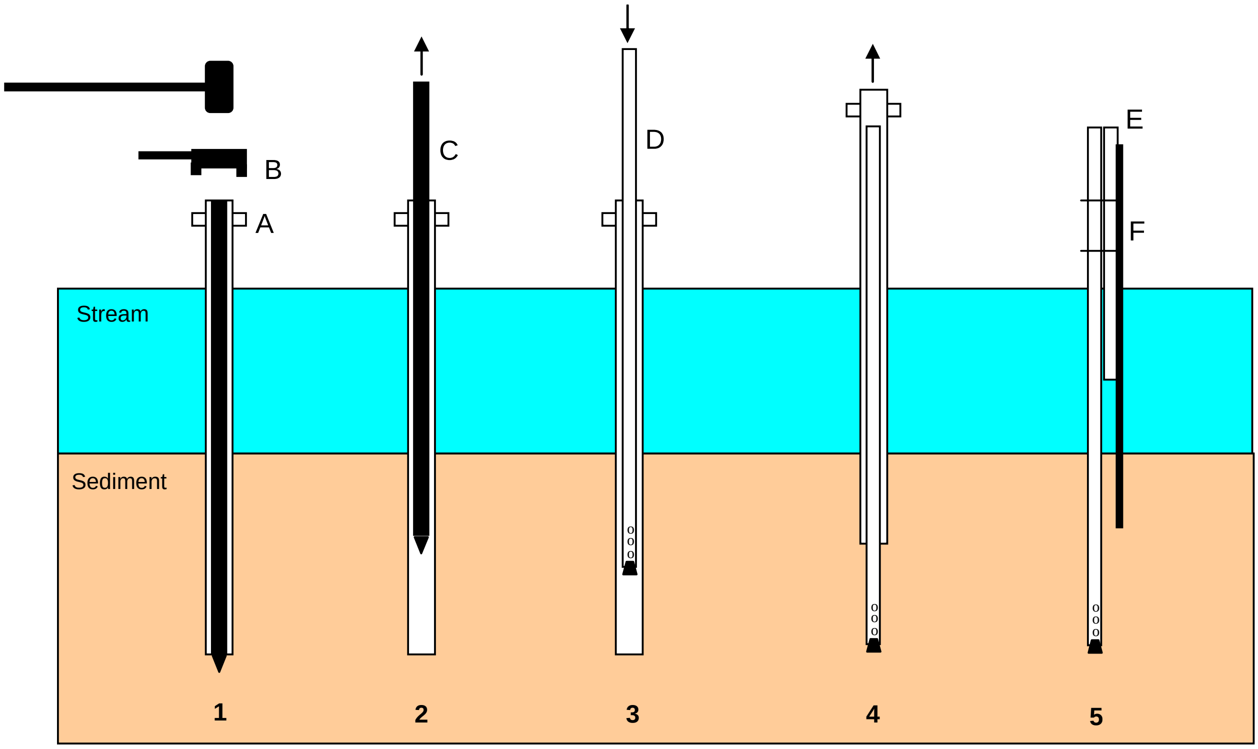


Figure 3: Stages in the installation of minipiezometer and stilling well for hydrometric investigations of seepage flux (modified from Baxter *et al*, 2003)

(1) Driver mechanism consisting of solid steel driver rod (C) and steel outer casing with flange (A) hammered into sediment to suitable depth using a cap fitting (B)
(2) Driver rod (C) removed with the steel outer casing retained
(3) Minipiezometer inserted into the outer steel casing
(4) Outer steel casing removed with minipiezometer held in position and sediment manually tamped around the minipiezometer. Bentonite clay can also be used to seal the annulus between minipiezometer and hole, above the inlet.
(5) Stilling well fitted and secured using a star picket

RESULTS

The time-series temperature monitoring from three sites in the Border Rivers catchment (Bonshaw, Goondiwindi and Kanowna) as well as from the two sites in the Lower Richmond catchment (Yellow Creek and Marom Creek) are shown in Figures 4-7.

Bonshaw site

Figure 4 shows the stream and sediment temperature recorded during high flow (summer) and low flow (winter) seasons in the Dumaresq River downstream of Bonshaw Weir. The stream temperature during high flow (November-December) shows relatively large diurnal variation over a range of 26.1-35.9^{o}C (Figure 4a). Over the same time period, no diurnal variation is evident in the sediment temperature, showing a gradual rising trend from 25 to 26.1^{o}C. The sediment temperature was generally cooler than the stream and is about the same as that of the shallow groundwater temperature (24.5^{o}C) measured in the region. The time-series temperature data in Figure 4a provides evidence of shallow groundwater input to the stream (gaining reach) at this site at this time. This may be due to rainfall received during November 2004 (101.8 mm) raising the shallow watertable to above the stream stage. It may also be a local effect, as the temperature monitoring was undertaken immediately downstream of the weir. The gaining conditions may be due to local shallow groundwater flow originating from the upstream weir pool.

During the low flow season (July 2005) there is significantly less diurnal variation in stream temperature, in the order of 0.7-2.2 ^{o}C (Figure 4b). Regardless, the sediment temperature record has very slight fluctuations that relate to the diurnal stream pattern, with a lag of about 3-4 hours. Sediment temperature was generally warmer than the stream and decreases during the winter season. The temperature data indicates that the stream is losing water to the groundwater at this time. Groundwater and stream level measurements taken at this site during July 2005 showed that groundwater levels are generally below the stream level, which confirms losing conditions. Overall, the temperature data indicate that the Dumaresq River immediately downstream of Bonshaw Weir can gain groundwater during the high rainfall periods coinciding with the high flow (Nov. – Feb.) season but loses water to the groundwater system during the low flow season.

Goondiwindi site

Stream and sediment temperatures recorded at the Goondiwindi site during high flow (summer) and low flow (winter) seasons are depicted in Figure 5. The sediment temperature shows regular fluctuations that relate to the diurnal temperature pattern of the stream, during both the high flow and low flow seasons. Such fluctuations are evident at different depths in the sediment during the November 2004 high flow conditions (Figure 5a). The sediment temperature measured at shallow depth (0.25 m) recorded a diurnal signal varying between 24.3-25.8^{o}C, with the peaks lagging by 4 hours from the corresponding maxima in daily stream temperature. The dramatic change in shallow sediment temperatures after 13/11/05 was due to premature removal of the logger from the stream bed, thereafter effectively measuring the stream temperature. The diurnal pattern deeper in the profile (0.5m) is more subtle in amplitude with a time lag of about 6 hours. This reflects the time taken to transfer heat by both conduction and advection downwards through the sediments.

It should be noted that the diurnal variation in sediment temperature (0.5 m depth) is significantly greater during high flow than in the low flow season. This might be due to the fact that the stream temperature diurnal fluctuation was high (6-7^{o}C) during the high flow summer but very low (0.5-2^{o}C) during the low flow winter. Sediment temperature was generally warmer than the stream and decrease with time during July 2005. Temperature fluctuations evident in the sediment profile indicate that the stream is losing water to the groundwater system during both the high flow and low flow seasons. Subsequent stream and groundwater level measurements taken at this site showed a negative head difference (of 2.6-3cm), confirming a potential downward hydraulic gradient.

Kanowna site

Figure 6 shows the stream and sediment temperatures measured at the Kanowna site during high flow (summer) and low flow (winter) seasons. Sediment temperatures showed only subtle changes during the day. In general, sediment temperature fluctuations observed at Kanowna are relatively small compared to other sites because of the low hydraulic conductivity of the heavy self-mulching clay profile at this site. In contrast, the stream temperature shows relatively large diurnal variation (~6^{o}C) during high flow (summer) but much smaller variation (~1^{o}C) during low flow (winter). The very low diurnal fluctuations of stream temperature as well as low seepage bought about by the low hydraulic conductivity would have contributed to low diurnal fluctuations of sediment temperature. Although the sediment temperature fluctuations are small, the river-groundwater interactions are characterised as a disconnected losing system based on very low seepage. The groundwater levels measured from minipiezometers at this site were lower than the stream level, indicating the potential for losing rather than gaining conditions.

Lower Richmond Sites

Figure 7 summarises the temperature data for the Yellow Creek and Marom Creek sites in the Lower Richmond catchment. The characteristic diurnal variation in surface water temperature is clearly evident, with the Yellow Creek site depicting greater daily temperature differences (Figure 7a). In contrast, no diurnal variation was evident in any of the recorders set at depth into the stream bed. This relatively static trend in all of the temperature monitoring of the stream bed would normally suggest gaining conditions at both of these sites. Limited diurnal temperature variations, particularly at shallow depths within the stream bed, are typically inferred to be due to upwelling of groundwater with a relative constant temperature. However, this interpretation of gaining conditions is not consistent with the other field tests undertaken at these sites. The groundwater levels measured from minipiezometers were lower than the stream level at the time, indicating the potential for losing rather than gaining conditions. Water balances from stream flow surveys suggest that these particular reaches also seem to lose water to the shallow aquifer. On this basis, the temperature data is interpreted to represent losing conditions but at a very low rate of flux reflected in the equilibration of subsurface temperatures. Such a low seepage rate is confirmed by estimates of hydraulic conductivity of the streambed sediments derived from slug tests on the minipiezometers installed at these sites. At the Yellow Creek site, the stream bed consists of competent highly plastic clay with very low hydraulic conductivity (0.004 m/d). The sediments underlying the Marom Creek site were soft, clayey and had similar estimates of hydraulic conductivity from slug tests.

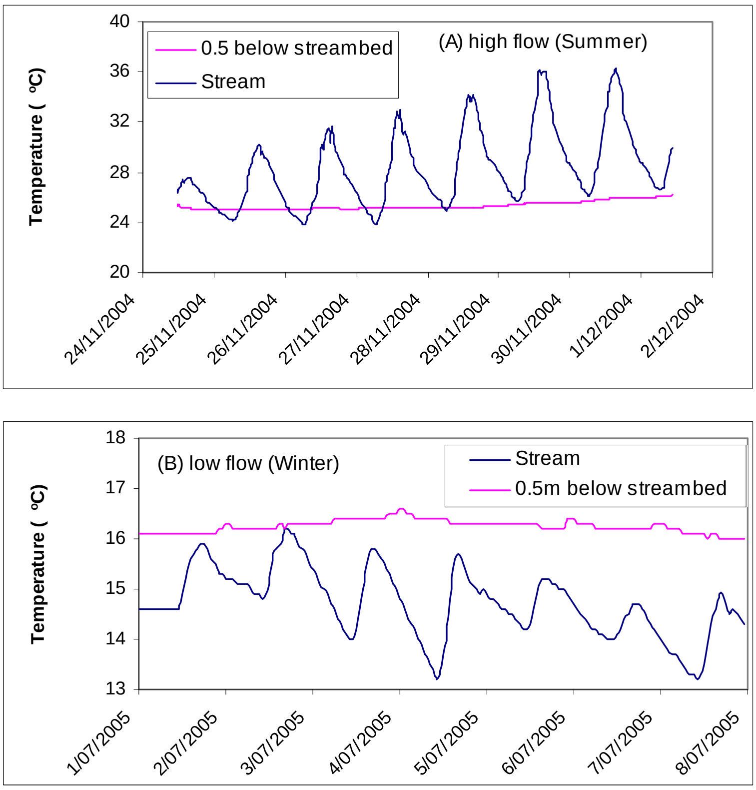


Figure 4: Observed stream and sediment temperatures downstream of Bonshaw Weir during high flow (A) and low flow (B) seasons

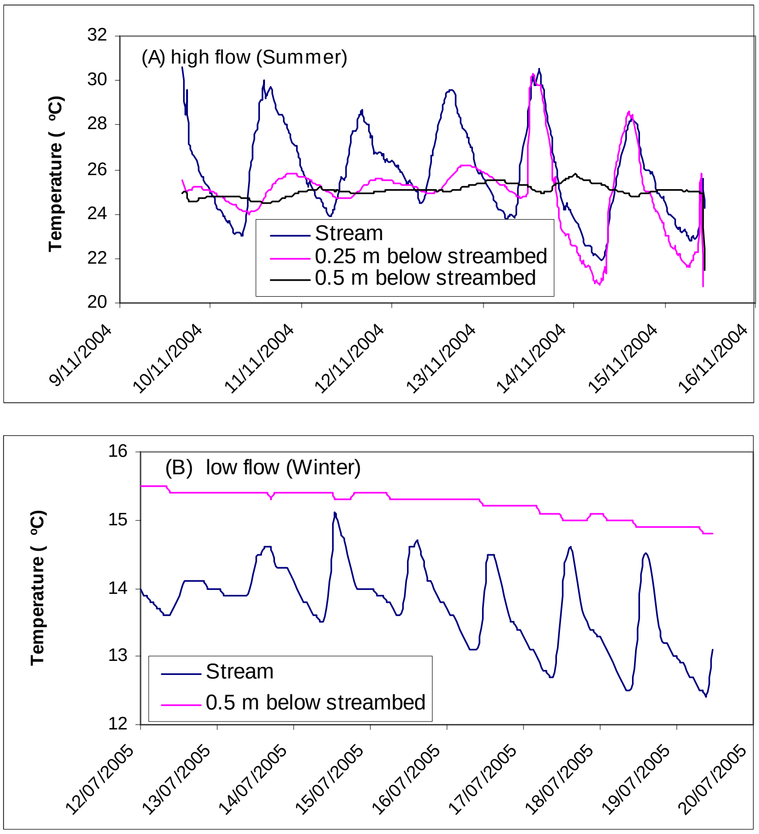


Figure 5: Observed stream and sediment temperatures downstream of Goondiwindi Weir during high flow (A) and low flow (B) seasons

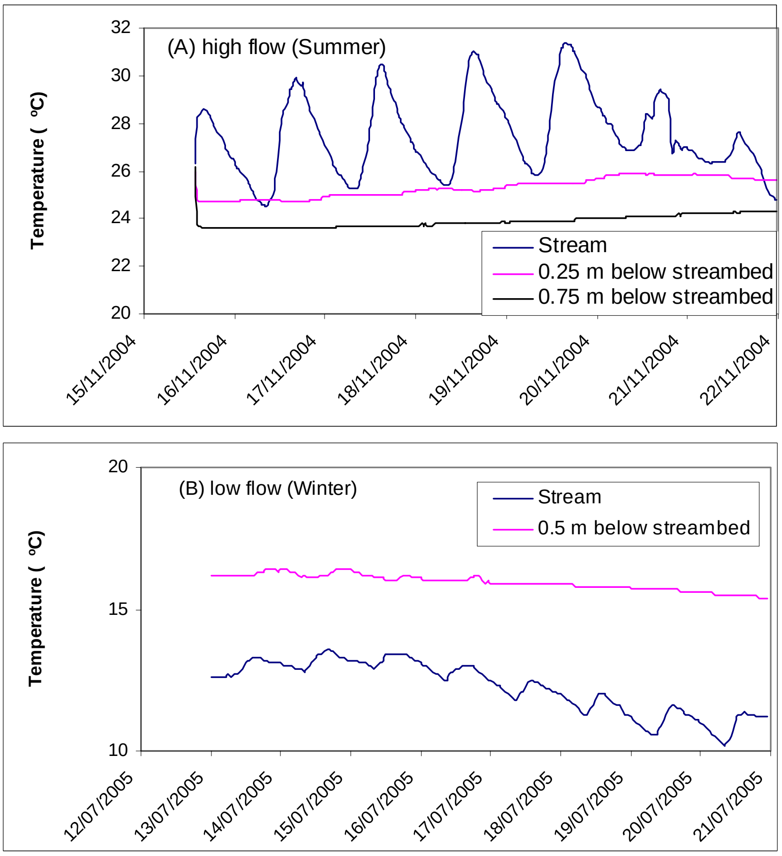


Figure 6: Observed stream and sediment temperatures at Kanowna during high flow (A) and low flow (B) seasons

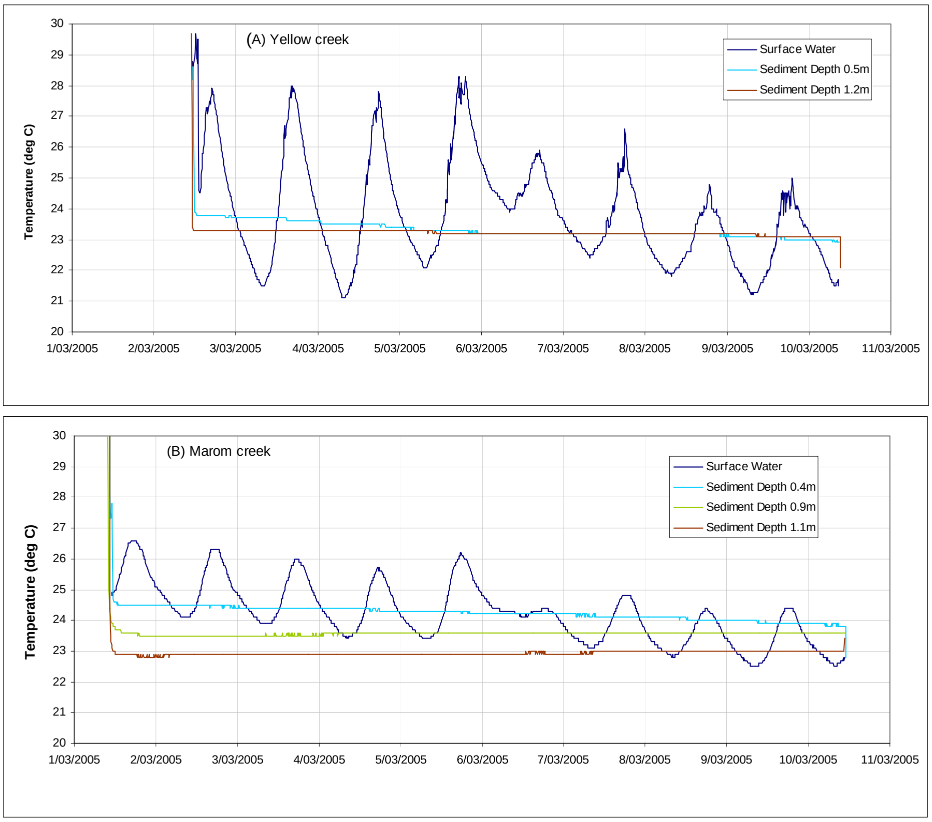


Figure 7: Observed stream and sediment temperatures at (A) Yellow Creek and (B) Marom Creek in the Lower Richmond catchment

DISCUSSION AND CONCLUSIONS

In this study, information about the texture and hydraulic conductivity of the sediment profile, as well as the hydraulic gradient between stream and aquifer was used to interpret the temperature monitoring. The difference in sediment type, and therefore hydraulic conductivity, has a major influence on differences in seepage fluxes (and ultimately heat transport) between the field sites. In the Border Rivers catchment, the temperature data suggests that the Dumaresq River immediately downstream of Bonshaw Weir is gaining groundwater during the high flow (high rainfall) season but losing water to the groundwater system during the low flow season. Seepage was interpreted to be relatively high at this site as sand and gravel dominates the streambed profile (refer Table 1). However, at the Goondiwindi and Kanowna sites, temperature fluctuations in the sediment indicate that the stream is losing water to the groundwater system during both high flow and low flow seasons. At Goondiwindi, the seepage was relatively high at shallow depth (0-30 cm) and very low at depths exceeding 30 cm. This is because the streambed at shallow depths consists of alluvial sand whereas heavy clay is dominant at depth. At the Kanowna site downward seepage is inferred to be low due to the dominance of heavy clay in the profile. At the Marom Creek and Yellow Creek sites in the Lower Richmond, no diurnal variation was evident in any of the recorders set at depth into the stream bed. This normally indicates gaining conditions but a very low downward seepage flux is inferred due to the combination of a downward hydraulic gradient measured from minipiezometers and the very low hydraulic conductivity of the heavy clay profile measured by slug tests.

In addition to variations in streambed materials at these sites, the magnitude of the daily stream temperature fluctuations is a significant factor in the transport of heat to sediments. In the Border Rivers sites, the diurnal stream temperature fluctuations are large (5-7^{o}C) during the high flow (summer) season whereas less variation (1-2^{o}C) in stream temperature was observed during the low flow (winter) season. This smaller variation in stream temperature during July 2005 would have resulted in less streambed variation. Overall, the streambed texture, the hydraulic gradient and the magnitude of the diurnal fluctuations are the main factors controlling the propagation of stream temperature changes into the stream bed.

The results of this study show that heat tracing techniques are a useful screening tool for identifying gaining and losing reaches of streams and for identifying temporal changes in seepage flux. However, our field work suggests that interpretation of the temperature data can be ambiguous when viewed in isolation. It is recommended that this method be used in conjunction with other methods such as minipiezometers, seepage meters or hydrographic analysis when interpreting stream-aquifer connectivity. Also, the temperature measurement is at a point in space and many measurements may be required to obtain information on spatial variability. It can be difficult to separate out localised effects (such as associated with weirs or shallow throughflow) from the broader seepage domain. Despite these issues, heat tracing has several advantages over other field methods to assess groundwater-surface water interaction. Temperature logging devices are robust, simple and relatively inexpensive and available for various scales of measurement. The temperature signal arrives naturally and data are immediately available for inspection and interpretation. Once installed, loggers can provide useful time-series data that can provide information on seasonal changes in seepage flux. Temperature studies are particularly useful in defining small-scale flow paths, such as associated with stream banks or sand bars (Stonestrom and Constanz 2003).

Numerical models have been developed that solve the equations governing the flow of water and heat through sediments. These models can be one-dimensional (1D) that incorporate vertical flow through the streambed or two-dimensional (2D) that incorporate both lateral and vertical flow through the streambed. VS2DH (Healy and Ronan 1996) is a commonly used model when using heat as a tracer and can be downloaded from the USGS website. Modelling of the temperature data from the Border Rivers and Lower Richmond sites is the next logical step in this study.

It is suggested that temperature loggers can be readily and cheaply incorporated into existing hydrographic networks to provide a supplementary dataset for understanding stream-aquifer connectivity. This is because the water level data can indicate the potential seepage direction and the temperature data can help estimate the magnitude of the seepage. It is also recommended that existing temperature logging (such as with pressure transducers) be upgraded to sufficient accuracy for heat transfer studies. An accuracy of at least a decimal degree is suggested. Temperature monitoring would be particularly useful in estimating infiltration rates in Australian ephemeral streams, where conventional water level recording and hydrographic analysis is problematic. Routine recording of temperature data also has relevance to the investigation and management of aquatic ecosystems, notably within the hyporheic zone.

ACKNOWLEDGEMENTS

The heat tracer studies described in this paper are part of an evaluation of methods to assess groundwater-surface water interactions undertaken within the *Managing Connected Water Resources Project*. This project is collaborative between the Bureau of Rural Sciences, ABARE, the Australian National University, NSW Department of Infrastructure Planning and Natural Resources and Queensland Department of Natural Resources and Mines, and funded by the Natural Heritage Trust and the Australian Research Council. Information about the project is available at http://www.brs.gov.au/connectedwater

REFERENCES

Baskaran S, Ransley T and Brodie RS (2005) Tools for assessing groundwater- surface water interactions: a case study in the Border Rivers catchment, Murray-Darling Basin. Bureau of Rural Sciences, Canberra.

Bouyocous G (1915) Effects of temperature on some of the most important physical processes in soils. Michigan College of Agriculture Technical Bulletin 24, 63p.

Bravo HR, Feng J and Hunt RJ (2002) Using groundwater temperature data to constrain parameter estimation in a groundwater flow model of a wetland system. Water Resources Research 38(8): 1153.

Brodie RS, Baskaran S and Hostetler S (2005) Tools for assessing groundwater-surface water interactions: a case study in the Lower Richmond catchment, NSW. Bureau of Rural Sciences, Canberra.

Constanz J (1998) Interaction between stream temperature, streamflow and groundwater exchanges in alpine streams. Water Resources Research 34: 1609-1616.

Constanz J, Stewart AE, Niswonger R, Sarma L (2002) Analysis of temperature profiles for investigating stream losses beneath ephemeral channels. Water Resources Research 38(12): 1316.

Healy RW and Ronan AD (1996) Documentation of the computer program VS2DH for simulation of energy transport in variably saturated porous media – Modification of the US Geological Survey's computer program VS2DT. US Geological Survey Water Resources Investigation Report 96-4230, 36p.

Lapham WW (1989) Use of temperature profiles beneath streams to determine rates of vertical ground-water flow and vertical hydraulic conductivity. US Geological Survey Water Supply Paper 2337.

Lee DR (1985) Method for locating sediment anomalies in lakebeds that can be caused by groundwater inflow. Journal of Hydrology 79:187-193.

Ronan AD, Prudic DE, Thodal CE, Constanz J (1998) Field study and simulation of diurnal temperature effects on infiltration and variably saturated flow beneath an ephemeral stream. Water Resources Research 34:2137-2153.

Silliman SE and Booth DF (1993) Analysis of time-series measurements of sediment temperature for identification of gaining vs. losing portions of Juday Creek, Indiana. Journal of Hydrology 146, 131-148.

Sinokrat BA and Stefan HG (1993). Stream temperature dynamics: Measuring and modelling. Water Resources Research 29(7): 2299-2312.

Stonestrom DA and Constanz J (2003) Heat as a tool for studying the movement of ground water near streams. Circular 1260. US Geological Survey.

Suzuki S (1960) Percolation measurements based on heat flow through soil with special reference to paddy fields. Journal of Geophysical Research 65(9): 2883-2885.

Voss CI (1984) A finite-element simulation model for saturated-unsaturated, fluid density-dependent ground-water flow with energy transport or chemically-reactive single species solute transport. US Geological Survey Water Resource Investigations Report 84-4369, 409p.