Thermograph analysis for estimating vertical hydraulic conductivity and near streambed fluxes : Cockburn River, NSW, Australia

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Abstract

The dynamic nature of streambed vertical hydraulic conductivity (VHC) was studied at two sites in the Cockburn River, near Tamworth, New South Wales, Australia. Near streambed fluxes were estimated using the USGS heat transport model, VS2DHI, based on thermal data. For modelling purposes, the entire period of observation, extending from July 2008 to April 2011, was split into fifteen segments. In this paper we analyse a segment thermograph, which represents the two flood events that occurred in late 2008. This illustrates the hydrologic regime prior to the flood events, the effect of floods on the temporal development of de-clogging process and low flow event. During this period, at the pool site, near the Kootingal Bridge the VHC varied from $8*10^{-5}$ to 10^{-3} m/s and the corresponding fluxes ranged from $1.6*10^{-5}$ to $4*10^{-4}$m. In contrast, in an armoured zone, near the Ballantines Bridge, the VHC varied from $8*10^{-5}$ to $2*10^{-3}$m/s, with stream leakage ranged from $9*10^{-5}$ to $2*10^{-4}$. At both locations, a maximum VHC was simulated after flood events, probably induced by increase in stream temperature and break up of the clogging layer by the increase in stream velocity. Available hydrological information suggests that low flow hydrologic regime create a favourable environment for clogging of coarse streambed sediments and disintegration takes place during high and flood events.

Introduction

Vertical Hydraulic Conductivity (VHC) is an important hydrologic parameter that regulates near streambed water fluxes. Due to physical, biological and chemical factors, VHC is highly variable both in space and time. Thus, the exchange processes between surface water and groundwater vary both in time and space (Brunke and Gonser, 1977; Huggenberger et al., 1996; Woessner, 2000). Temporal fluctuations may be caused both variations in focus and distributed recharge, whereas spatial variations are caused by streambed heterogeneity and associated hydraulic conductivity (Fleckenstein et al., 2006; Huggenberger et al., 1996; Kalbus et al., 2009, Vogt et al., 2009).

Commonly used simulation models such as MODFLOW (McDonald and Harbaugh 1988) treat groundwater/surface water fluxes through a streambed as being vertical. While in reality, both horizontal and vertical fluxes can occur and the directions are a complex function of many hydrogeologic variables (Harvey and Bencala 1993; Woessner 2000). This paper will also concentrate on VHC. In most mechanistic models, the exchange of water between an aquifer system and a stream/creek is expressed by:

$$q = \frac{(VHC) * LW}{M} * (H_{aq} - H_{ck}) \qquad (1)$$

Where q is flux between the aquifer and the stream, VHC is the vertical hydraulic conductivity of the stream/creek bottom sediments, L is the stream width, W is the width of the stream, M is the stream bed thickness, H_{aq} is the hydraulic head in the aquifer and H_{ck} the water level (stage) in the creek.

From this it can be observed that the water fluxes between surface water and groundwater systems are a function of the difference between river stage and aquifer head. Down-welling will occur whenever the river stage exceeds the groundwater head, but the rate depends on the magnitude of the difference, the conductivity of riverbed deposits, and the saturated area of the channel.

In natural system, however, settling and straining of suspended and bed load sediment at the riverbed may cause a substantial reduction of the conductivity of the outermost layer. These processes are usually referred to as clogging (Lisle, 1989; Joppen et al., 1992; Schälchli, 1996). One of the hydraulic properties of a clogged layer is expressed in terms of streambed conductance, which is defined as VHC divided by thickness of the layer (VHC/M). This important parameter is difficult to estimate due to a lack of knowledge of VHC and thickness of the clogging layer (Dahl *et al.* 1999).

Another major assumption made in regional groundwater models is that a linear relationship between flux and Δh exist. This is often too simplistic and does not take into account the decreased resistance to the passage of water as the stream volume and velocity increases (Rushton and Tomlinson, 1979, Groenendijk and van den Eertwegh, 2004), due to de-clogging of the upper streambed layer. Bedload movement, which occurs during high runoff and flood events, facilitates the de-clogging process. In addition, stream reaches with upwelling 'groundwater', tend to maintain hydraulic connectivity between streambed and groundwater, due to upward hydraulic forces reducing siltation (Schalchili, 1993, Hatch 2010).

During the last decade, due to the availability of cheap and reliable thermistors, several investigators have successfully used heat as an environmental tracer for estimating near streambed fluxes and VHC (Bartolino and Niswonger, 1999; Constantz and Stonestrom, 2003; Anderson, 2005; Cox et al., 2007; Schmidt et al., 2007; Mututi and Levy, 2010, Hatch et al., 2010). Most of these studies covered a short time frame. In addition, few of these investigators, targeted the dynamic nature of VHC explicitly. In this study, we have used extensive hydrological data collected over 30 months, to understand the spatial and temporal variability of VHC in the Cockburn Valley. The data collected covers a range of hydrologic regimes covering both low flow and flood events.

We hypothesize that the dynamic nature of VHC is linked to the hydrologic regime of the river. During low flow hydrologic regimes the critical tractive force responsible for mobilizing river bed sediments is low. Consequently, there is a tendency for the reaches to deposit rather than transporting sediments. In contrast, during high river flow the transport of sediments may be prevalent.

The main objectives of this paper are to: 1) study the variability of vertical hydraulic conductivity in space and time; 2) quantify the magnitude of fluxes in contrasting bedforms; 3) infer dry spells or disconnection of streams using streambed temperature measurements at different depths and 4) delineate 'gaining' and 'losing' reaches.

Study site

The Cockburn River joins the Peel River southeast of Tamworth. In the catchment, the alluvial aquifer of the valley is restricted to a narrow zone between Nemingha and Ballantines Bridge, a length of approximately 15 km of varying width between 1-3 km and a gradient of 40 m in 15 km (Calaitzis and Leitch, 1994). Generally the top 6 metres of the alluvium consist of finer sediments and the main water bearing zones occur below this depth. There are a large number of shallow wells and bores in the alluvium which are generally used for irrigation. The fractured rock aquifer systems are represented by Carboniferous meta-sediments and granites of the New England Batolith.

The average annual rainfall decreases with decreasing altitude from the highest point in the Great Dividing Range (1440 m) to Tamworth (280 m). Rainfall ranges from 800 to 650 mm. Tamworth has an annual rainfall of about 670 mm (Donaldson, 1999).

The study area is an ideal location to study surface groundwater connectivity because of the relatively high density of gauging stations and hydrogeomorphological factors. Three permanent (419016, 419056, 419099) and two temporary gauging stations (TGS) are operated by the NSW Office of Water. The gauging station at Mulla Mulla Crossing has operated since 1936 (Figure 3). At this particular gauging station, the catchment area is about 900 km^2 and elevation is 441 mAHD.

In addition, there are 7 NSW Office of Water (NOW) monitoring bores (GW93036-40). These bores are equipped with loggers, which measure groundwater levels and temperature at an hourly interval. Two additional wells were equipped with loggers as part of this study.

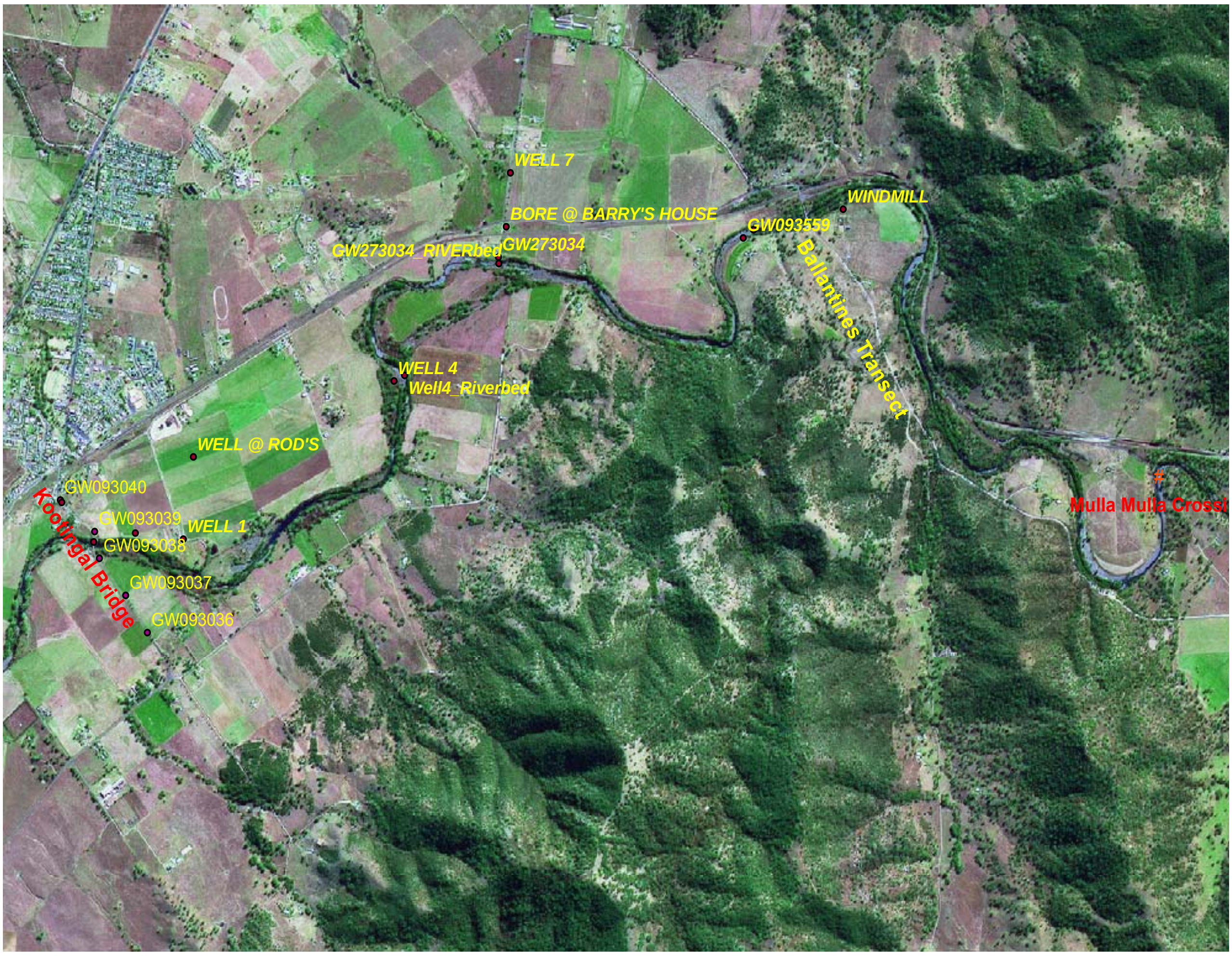

Figure 1. Locations of the monitoring bores in the Upper Cockburn Valley transect

Methods

At selected reaches of the Cockburn River (Well 4, Ballantines and Kootingal transect, Figure 1), 37 mm diameter galvanized pipes were hand driven to 1m depth below streambed elevation. The Kootingal transect is a representative of a pool zone and the Ballantines transect is a representative a riffle cross-section/armoured zone.

HOBO® Temperature/Light Data Loggers (at 25°C, accuracy: ±0.47°C; resolution:0.1°C) were suspended on a string and inserted below the riverbed to the required depths inside the piezometers. As the river bed sediments predominantly consist of gravels, cobbles and boulders, construction of in-stream piezometers of 30 mm diameter by hand was extremely difficult.

In the context of this report, a river system is considered to be a groundwater dominated or effluent, when it receives water from groundwater systems (local, intermediate and regional). In regions where water tables are depressed, due to high evapotranspiration rate, the lateral contributions of regional, intermediate and local groundwater flow systems to river systems are insignificant. In fact, some of these systems are probably dominated by small scale exchanges which take place in a longitudinal and lateral direction.

During the first phase of the instrumentation the designated transects in the Cockburn Valley were oriented in a cross-sectional direction. As this setup was not considered an ideal configuration to capture small scale hydrological processes (upwelling and down welling) occurring in a longitudinal direction, it was modified in November 2009 by construction of ten additional in-stream piezometers installed in a longitudinal direction along a 20m reach of a riffle-pool transect at the Ballantines (Figure 2).

Figure 2. Location of in-stream piezometers used to delineate upwelling/downwelling process at the Ballantines transect. The picture was taken during a dry spell of 2009**.**

Spot streambed temperature survey along the Ballantines and Kootingal transects were carried out using a 'Temperature T bar'. It consists of a T shaped handle at the top and a spear point at the bottom, with 5 temperature sensors spaced at distance of 20cm between the spear point and a T bar. The 5 temperature sensors are connected to a DaqPRO 5300 (a 16-bit, high-resolution, eight-channel data logger that offers the pros graphic displays and analysis functions for measuring voltage, current and temperature in real-time). At each site streambed temperatures are measured simultaneously at 5 depths (0, 20, 40, 60, 80, 100cm depth below channel elevation).

Modeling

After review of available heat transport models, the USGS heat energy and water flow model VS2DH (Healy and Ronan, 1996) and its graphical user interface VS2DI (Hsieh et al., 2000) were considered to be suitable for the hydrogeomorphological environment of the study area for the following main reasons:

- the package has been tested extensively for arid and semi-arid environments in the US. A number of investigators have used VS2DI to estimate near streambed water fluxes (e.g ., Ronan et al.,1998; Stonestrom and Constantz,2003; Constantz et al., 2003; Su et al.,2004;
- it solves heat and water transport in unsaturated and saturated model domains;
- is a public domain package and user friendly.

Given the limited soil and groundwater temperature data available for the study area, the instrumented sites in the Cockburn valley were modelled in one dimension using 1 column and several rows of different grid spacing. The total domain length was 15 m, representing the maximum thickness of the alluvial deposit in the Valley and grid spacing varied from 0.1 at surface to 0.25 m at depth.

Stream stage and temperature data for the Mulla Mulla and Kootingal gauging stations are available since April 2008 and this data set represented the upper boundary of the model domain. The specified head condition allows a flux of water (recharge or discharge) to cross the water table during modelling.

No-flow conditions were assigned to the lateral boundaries.

Table 1. Summary of hydrothermic properties used in VS2DHI simulations

Parameter	**Value**	**Source**
Hydraulic conductivity (k_z)	Calculated	Site specific
Porosity	0.37-377 (m^3/m^3)	Site specific
Heat capacity of dry solids (C_s)	$1.2*10^6$-$2.18*10^6$ ($J/m^{3\,0}C$)	Niswonger & Prudic (2003)
Heat capacity of water (C_w)	$4.18*10^6$ $J/(m^{3\,0}C)$	Su et al.(2004)
Thermal conductivity (k_t)	1 $W/(m^{3\,0}C)$	Su et al.(2004)
Longitudinal thermal dispersivity (a_l)	0.5	Niswonger & Prudic (2003)
Traverse thermal dispersivity (a_t)	0.01 to 0.1 (m)	Niswonger & Prudic (2003
Anisotropy ratio (K_v/K_h)	1	Site specific

As field data is not available for estimating hydrothermic parameters listed in the above table, these properties were derived from literature.

Results and analysis

River reaches

Based on a geomorphological survey of the Namoi Valley, Thomas (1998) has identified seven bedforms or river reach types (constrained, pool, armoured/riffle, mobile, meander anabranch and distributary, Figure 2). The first type of river zone occurs in the upper reaches of the sub-catchments, including the Cockburn Valley. The location of the zones reflects the variable control of the discharge of water and sediment in relation to catchment size and geological influences on the nature of the valley. Similarly, the extent of each zone varies according to the overall geomorphology of the region.

Streambed sediments in the upper part of the study area consist predominantly of boulders, cobbles, gravels and silt. Bed armouring was observed in the riffle sections between the Ballantines and Well 4 transects.

In the lower part of the study area, the sediment size decreases, the beds consist of poorly sorted cobbles, gravels, with variable amounts of clay and silt material. Due to streambed metamorphosis, the hydraulic properties at streambed scale are highly variable both in space and time.

In the context of this paper, human induced changes play a role in surface and connectivity study. For instance, sand and gravel extraction on the river has contributed significantly to the degradation of the river. As reported by Legasse and Simons (1976), “the removal of gravel from the river can seriously impact river morphology and stability by removing significant quantities of the coarser sediments from the river. This coarser fraction, particular gravel, has a tendency through hydraulic sorting to armour the riverbed, thereby retarding and arresting excessive scour, stabilising banks and bars, and preventing excessive sediment movement. Gravel armoured sandbars serve as semi-permanent controls that define river form. Removal of the gravel armour can lead to erosion and loss of this control.” For example, wooden supports for the old Kootingal Bridge, which were originally cut off at riverbed level, are now up to a metre above the riverbed.

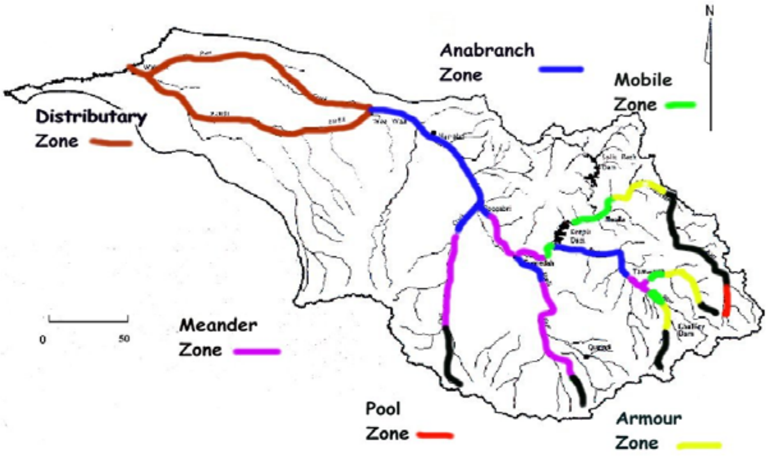

Figure 2. River zones in the Namoi Valley catchment (after Thomas, 1988)

In the Cockburn River, the excessive mining in the past has caused bed lowering and degradation. The lowered baseline of the riverbed caused by degradation increased the slope of the mouth of the tributaries along the reach. This increased slope results in upstream progressing degradation of the tributaries.

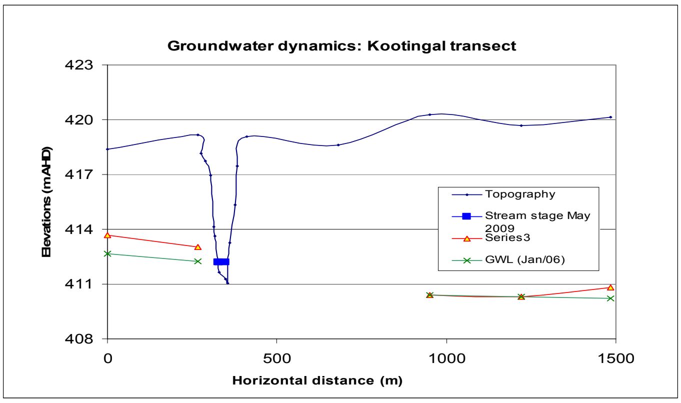

Figure 3. Groundwater dynamics at the Kootingal transect

Reach I: Water hole/ Pool Zone at the Kootingal transect

Pool zones in the study area are characterized by long pools separated by short channel constrictions. The pools form upstream of these channels constrictions and are the dominant morphological feature in the zones. Channel constrictions are generally associated with major bedrock bars that extended across the channel or substantial localized gravel deposits that act as a riffle area (Thomas, 1988). The Kootingal pool is the largest pool system in the Cockburn River; this system is partly fed through flow system. It dries up only during extreme drought events.

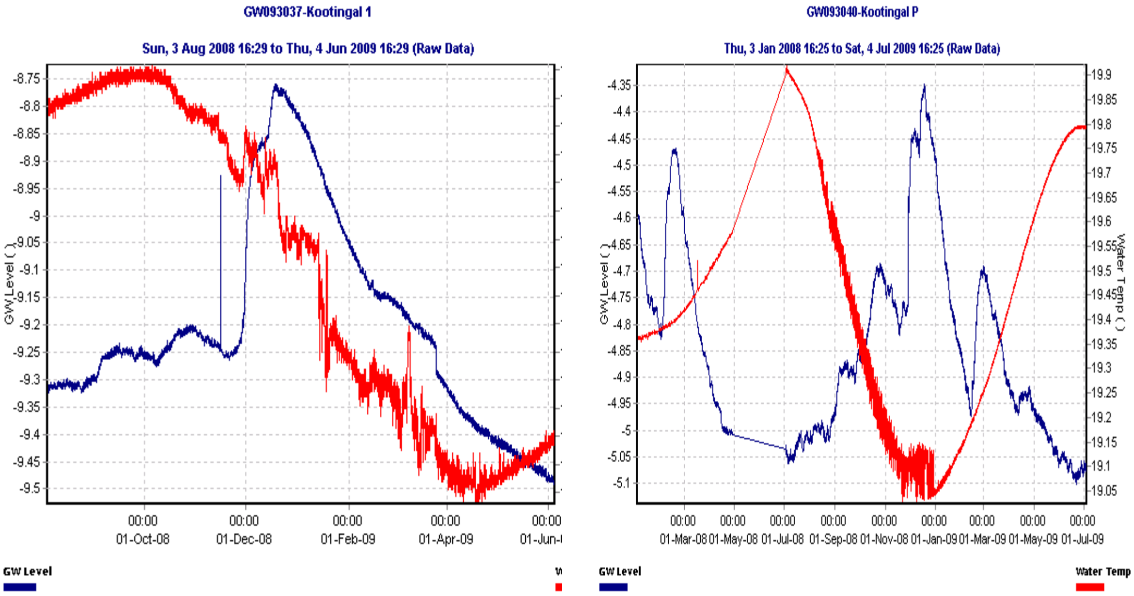

Figure 4: Contrasting groundwater temperature responses in losing (GW93037) and gaining sections (GW93040)

Groundwater thermographs for bores (GW93036, GW93039, GW93040, GW93037) screened in gravels at different depths (8.5-11.5, 12.5-15.5,13.5-16.5,17.5-20.5 mbgl) respectively and different horizontal distances from the bank of the Cockburn River were decomposed into Fourier components, to determine the phase and amplitude of the annual frequency components for bores with long term data (Berhane et al, 2008). The average groundwater temperatures ranged from 18.9 ^{o}C to 19.6 ^{o}C. The surface temperature propagates with decreasing amplitude into the groundwater. The highest amplitude of fluctuation was observed in GW93040 and lowest in GW93036.

Interestingly, this particular transect gains water on the right hand side of the bank and loses water on the left hand side of the bank. The available data suggest that the groundwater table is far below the channel level for GW93036-38, indicating a losing stream condition. In contrast, water levels in bore GW93040 are higher than the streambed elevation for some flow periods, indicating the groundwater system may be contributing to stream discharge after runoff and flood events. However, the in-stream piezometer located at the RHS didn't suggest the stream is gaining at this transect. Probably, the groundwater seepage is insignificant when compared to stream discharge.

The conceptual model shown in Figure 3 was corroborated by groundwater temperature measurements in piezometers (GW93036-40). During flood events, a slowly changing groundwater temperature was disrupted by an advective heat transport mechanism, which is very noisy compared with the slowly changing temperature trend in the gaining section of the groundwater temperature profile (Figure 4).

The monitoring period extended for more than two years. During that time we were able to capture multiple stream flow events consisting of single, multiple and complex events. For the overall analysis the hydrograph and thermograph for the entire period of observation was divided into fifteen segments, which are considered to be representative of hydrologic environments. In this paper, a more detailed analysis was carried out for the third segment, extending from 19/11/08 to 3/02/2009 (Figure 5). This particular segment represents two consecutive flood events that occurred after heavy rainfall over the Cockburn Valley in November and December 2008. These events have resulted in scouring up to 1m depth upstream of the Kootingal Bridge. As a result of first flood event, two of the three in-stream piezometers, located on the left hand side and middle part of the transect were washed away.

Simulation results

At this particular site, the groundwater flow direction is perpendicular to river direction and construction of a 2D model was not deemed to be appropriate. Having this in mind, the modelling effort was kept as simple as possible and a one dimensional model was constructed to estimate VHC and fluxes.

Due to numerical oscillation and numerical dispersion, the clogging layer was not modelled explicitly. Instead, the stratified profile was considered as one homogenous layer with total thickness of 10 m, overlain by a clogging layer of thickness of 0.25m. Having this information, the VHC of the clogging layer was inferred from the depth-weight hydraulic conductivity equation of the form (Bouwer, 1978):

$$k_z = \frac{z}{\sum_{i=1}^{n} \frac{d_i}{k_i}} \tag{2}$$

Where K_z= vertical average hydraulic conductivity (VHC) (m/s);

K_i = vertical hydraulic conductivity of layer i

Z = total thickness of the alluvium (m)

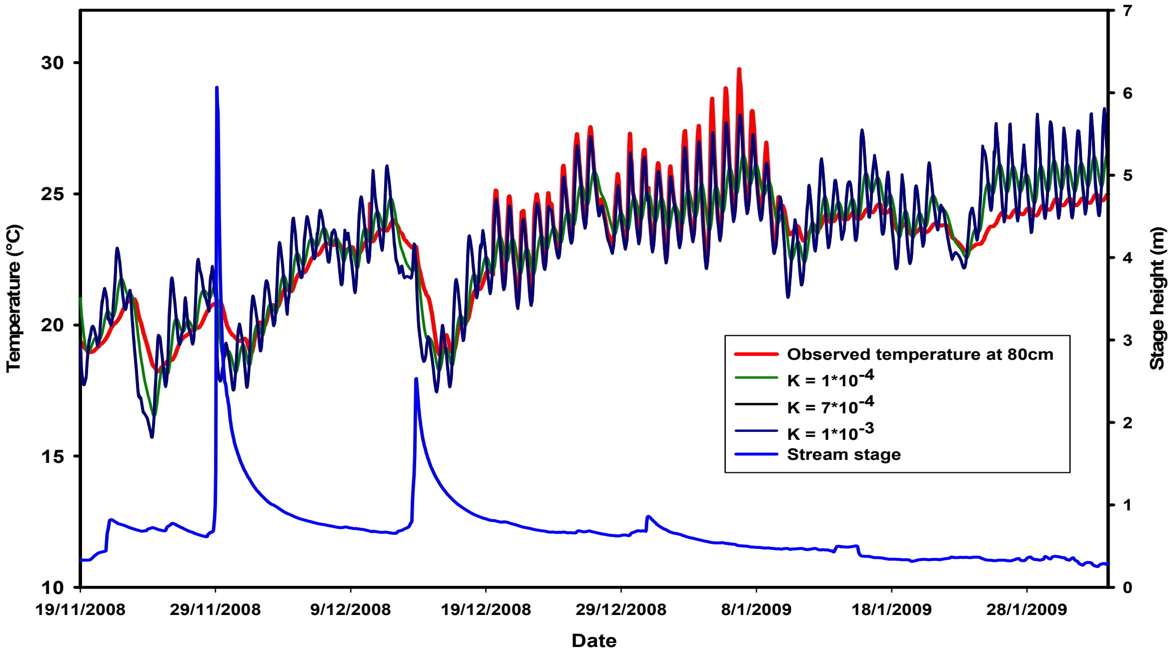

Figure. 5. Dynamic nature of streambed hydraulic conductivity estimated from heat transport modelling.

For example, for a 2 layer model with thicknesses of 0.25 and 9.75 meters, a model simulated composite VHC of $3.5*10^{-6}$ m/s, generates a VHC of 10^{-7} m/s for an upper clogging layer.

The VHC values were adjusted by trial and error to minimise differences between simulated and measured streambed temperatures over selected segment of the thermograph. None of the hydraulic conductivities provided a good fit over the entire period of the third segment, extending from 19/11/08 to 3/02/2009. Different sub-segments of the thermograph were fit with different values of VHC, which varied from $8*10^{-5}$ to 10^{-3} m/s respectively. The best fit value of VHC in the middle part of the segment was 10^{-3} m/s.

Besides studying the dynamic nature of VHC, we have also gained in-sight on the magnitude of fluxes during these extreme events. During the consecutive flood events of 2008/09, the maximum recorded stream stages were 6.1 and 3.2 m, with a corresponding infiltration rate of $4*10^{-4}$ and $2.8*10^{-4}$ m/s respectively. The magnitude of stream leakage is mainly regulated by head difference between stream stage and groundwater heads. In addition, de-clogging of the stream bed at the Kootingal site after flood events may have contributed to focused groundwater recharge.

Reach II : An armoured zone (Pool/Riffle junction), Ballantines transect

At the Ballantines transect, the valley floor is about 2 km wide and forms the upper limit of the alluvial aquifer system. The in-channel environment consists of well developed riffle-pool sequences. However, immediately downstream of Ballantines Bridge the river channel is very shallow and the gravel sediment has been completely removed, exposing bedrock material. There are signs of active channel erosion at this site that are associated with sand and gravel extraction (Thomas, 1998).

In order to ascertain magnitude and direction of fluxes, the stream bed elevations at the Ballantines transect were surveyed in detail. In the survey, GW93559, located on the left hand side of the bank and two privately owned wells on the right hand side of the bank were included. The available data suggest that the groundwater is far below the channel level for GW93038, indicating a potentially losing stream condition.

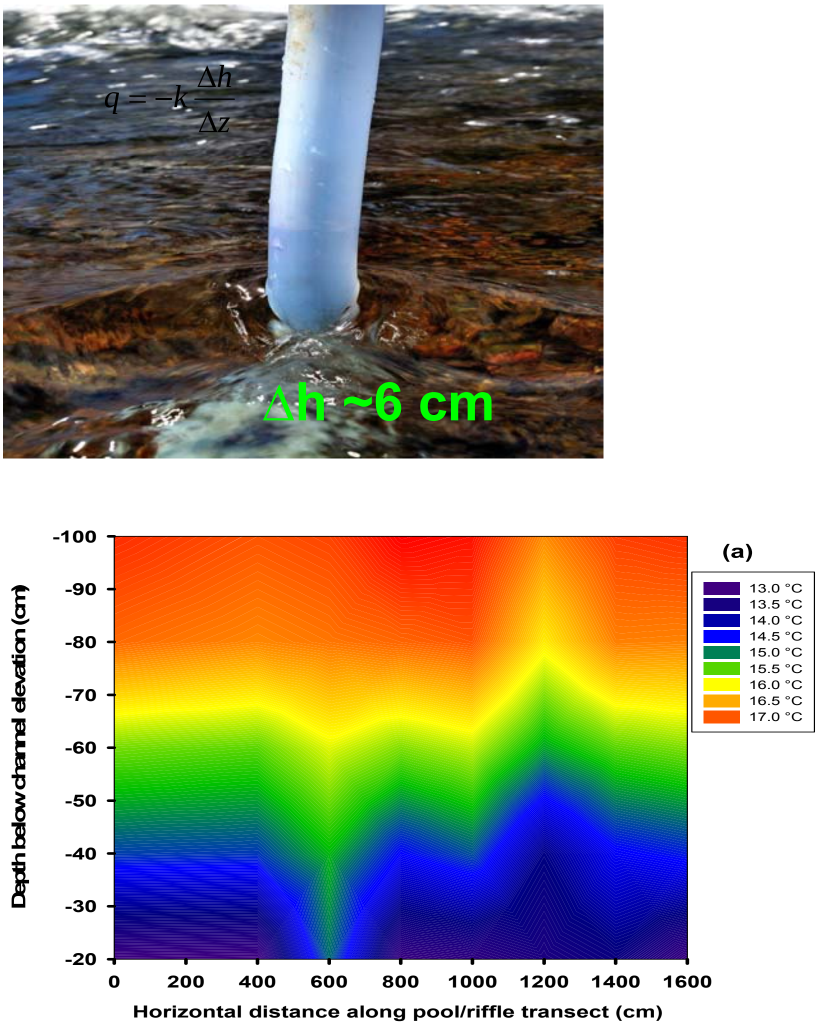

Figure 6. (a) Occurrence of a positive head of 6 cm at a tail of riffle; (b) Streambed isotherms along the Ballantines transect showing upwelling at 600cm and downwelling at 1200cm

Although the unravelling/delineation of multi-scale interactions is problematic in this study, near streambed exchanges occurred simultaneously on various scales (Brunke and Gonser, 1997; Boulton et al., 1998). Channel features such as riffles may establish longitudinal “hyporheic’ flow and temperature patterns as demonstrated by flume experiments (Vaux 1968; Savant et al., 1987; Thibodeaux and Boyle, 1987). Only limited data appear in the literature on depth penetration of streamwater measured by temperature patterns (Hartman and Leahy 1983). An upwelling component at a riffle junction of the Ballantine transect was captured during the spring runoff event of 2010, where, a relatively colder surface water enters the subsurface sediments at the upstream end of a riffle (a shallow, fast flowing section of a stream) and upwelling of relatively warmer streambed water occurred at 600 cm. The observed streambed isotherms confirm with Vaux's model (Figure 2).

In the armoured zone near the Ballantines, we have used VS2DHI to estimate the VHC and fluxes. During the two consequtive flood events of 2009, the VHC varied from $8*10^{-5}$ to $2*10^{-3}$m/s, with stream leakage ranged from $9*10^{-5}$ to $2*10^{-4}$.

Discussion

Thermograph trends as a surrogate indicator of a dry spell

In ephemeral and intermittent streams, quantification of exchange of water between the stream and groundwater is problematic. In most of the cases the creek beds are dry and disconnected from the water-bearing formations. In the absence of stream flow data, temperature was used as a surrogate indicator of dryness in a channel in a qualitative fashion.

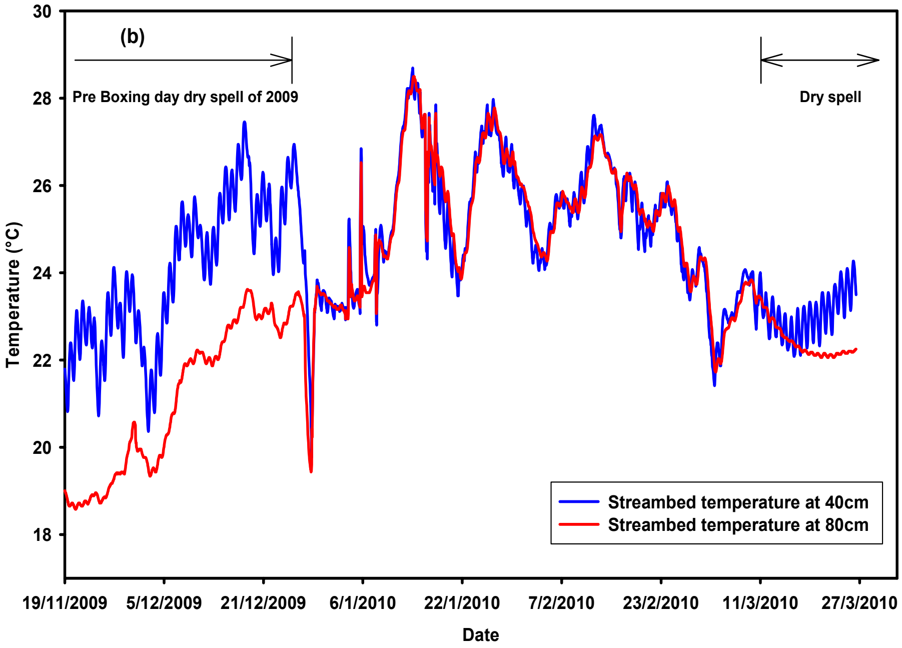

Figure 7. Beginning and end of a dry spell, inferred by comparing temperature measurements at two depths at the Ballantines transect.

Based on streambed thermograph trends at two levels (40 and 80 cm below the channel elevation), one could infer on the degree of connection between surface water and the phreatic groundwater system. For example, during runoff events, streambed temperatures at the two measurement points, oscillated in a synchronized fashion, suggesting that both advective and conductive heat transport mechanisms occur. In contrast, during a dry spell, the thermographs at the two levels show different patterns of oscillations (the Cockburn River ceased to flow in November and Dec 2009; the dry spell that persisted in the valley was broken on 27/12/09 by a rare/episodic cyclonic event. Therefore, based on the thermographs patterns at two levels, one could infer the onset, duration and termination of a dry spell for a highly connected, intermittent stream as the Cockburn River. When heat transfer is dominated by both water and vapor flux, VS2DH is not an appropriate tool to use.

Effects of stream velocity on hydraulic conductivity

There are several factors that affect the magnitude of the streambed conductance. These are: physical, chemical and biological parameters. The physical factors include stream water temperature and velocity of stream flow.

Lyons (1996) developed average tractive stress duration curves for different bedforms in the Cockburn Valley. In this particular study, it was reported that armoured riffles have a critical stress of approximately 34 N/m^2; the probability of occurrence is low and exceeded only 2% of the time during the period of record. Only during extreme hydrologic events would the armoured riffle material be transported as bed load. This confirms our observations that occurred during the last two consecutive flood events of 2008/09, that the in-stream piezometers located on an armoured transect, survived the effect of flooding, erosion and scouring. In contrast, in the pool dominated reaches, the critical tractive stress is approximately $7N/m^2$ this level of stress was exceeded 26% of the time. Therefore, the bed material in the pool sites of the study area can be expected to be transported as active bedload 26% of the time.

Effects of gravel mining of the past on hydraulic regime and fluxes

In the context of the Cockburn Valley, an important data set for surface and groundwater interactions, is the unstable nature of streambed elevation in the valley. Elevation surveys conducted at bridges along the river have shown that streambed of the river has been lowered 0.9 m at Ballantines Bridge since 1965, and up to 2.4 m at Kootingal Bridge since 1939. In order to arrest erosion and streambed lowering, seven weirs (rock ramps) have been constructed on the lower Cockburn Valley (Donaldson, 1999).

Despite the contradictory postulates of the past, the effects of bed lowering on water exchange between surface and groundwater are still unclear. However, two scenarios are postulated. For gaining and groundwater-dominated reaches, the lowering of riverbed elevation is expected to increase ‘baseflow’ and underflow, based on a simple Darcy equation. In contrast, for losing reaches, stream leakage values generally reach a constant rate when the water table depth is greater than twice the stream width because flow is generally controlled by gravity at these depths (Bouwer and Maddock, 1997). In addition, some of other factors that influence on hydraulic conductivity are listed below:

Conclusions/Recommendations

- The thermal method is a robust and affordable method for estimating infiltration/discharge and assessing the onset and termination of dryspells;
- The thermal data indicated that a low flow hydrologic regime creates a favourable environment for clogging of the coarse streambed sediments and the breakup of the sediments takes place during high and flood events;
- The thermal data and hydrological data indicated that near streambed exchanges occur simultaneously on various scales. At a basic unit scale, exchange of water

between the stream and streambed occurs across riffle-pool sequences longitudinally down the stream.

- In order to increase the level of certainty, we recommend that recharge/discharge estimates should be used in conjunction with other methods such as chemical and isotopic tracers.
- Local effects differed from reach behavior in both space and time. Coupled with:
    - the complexity of geomorphological and geological units,
    - scale dependence of parameters used in the models,
    - incomplete knowledge of the hydrological systems

  upscaling from point scale as in this study to sub-catchment and catchment scale is a challenge that needs to be investigated.

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