Connectivity of stream water and alluvial groundwater around restoration works in an incised sand-bed stream

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Abstract

The drainage of Australian streams since European settlement has resulted in widespread incision, with catastrophic widening leading to increases in sediment yield. This has left many thousands of kilometres of streams isolated from their floodplains, resulting in the loss of in-stream geomorphic complexity and associated changes to stream health and water flows. Widden Brook, a right bank tributary of the Goulburn River in the Hunter Valley, NSW, is an active sand-bed channel characterised by low to moderate specific mean annual flood and high to very high flood variability. On Widden Brook, floods have caused substantial bank erosion with the whole floodplain being reworked since first European settlement, but rapid channel contraction is now occurring. In this study, strong hydrological linkages existed between stream water and alluvial groundwater table depths. However, the effect of an in-stream structure on the stream water - groundwater exchange zone was localised despite changes in geomorphic complexity and water quality. The implications of the de-coupling of streams from their floodplains are only now beginning to be understood, with significant impacts on hydrological connectivity.

Keywords

Hyporheic zone, riparian function, floodplain processes, hydrological exchange, water chemistry

Introduction

The hydrological connections between stream flows and alluvial groundwaters, and between main channels and floodplains, are critical factors in sustaining many river landscapes (Boulton, 1993), particularly small streams during drought (Boulton, 2003; Lake, 2003). Sedimentation and the loss of geomorphic complexity have reduced hydrological exchange between the channel and floodplain by smoothing out the longitudinal profile of the stream bed (Brooks *et al.*, 2006), primarily due to the impact of human activities (Boulton, Sheldon, Thoms, & Stanley, 2000; Hancock, 2002). The key benefit of restoring hydrological connectivity of stream flows with alluvial groundwaters of the floodplain is increased groundwater storage, leading to increased stream base flow in dry seasons and enhanced ecological function of the hyporheic zone (Boulton, 1999). The hyporheic zone is the saturated sediments below and adjacent to river channels, and in many streams it directly links surface water to permeable alluvial aquifers underlying the riparian zones and deeper regional groundwater (Brooks *et al.*, 2006). Hence, this distinct zone between surface water and groundwater has fundamental ecological significance for surface ecosystem processes such as stream health and riparian function (Boulton, Findlay, Marmonier, Stanley, & Valett, 1998), with a role in the alteration of water chemistry. Both hyporheic function and floodplain processes are significant for an understanding of stream water and groundwater interactions in hydrological and biogeochemical models, particularly associated with changes to channel morphology.

Study area
The study area consisted of pastoral land in the riparian corridor of Widden Brook, which is a southern tributary of the Goulburn River in the upper Hunter Valley, NSW, Australia. *Casuarina cunninghamiana* is the dominant tree species in the riparian corridor, including the river bed, bars, benches and floodplain. The site investigated had a catchment area of 630 km^2 and consisted of a 700 m long reach of slightly sinuous, sand-bed channel, discontinuously flanked by bars, benches and floodplains. The channel has contracted significantly since the large flood of February 1955 by floodplain and bench accretion into the flood-widened channel, as shown by sequential vertical air photographs. Detailed radiocarbon and optical dating has

demonstrated that the whole floodplain has been reworked since first European settlement, reflecting substantial channel shifting, widening and subsequent contraction. The Widden catchment is located in part of the Permo-Triassic Sydney Basin, which is a thick sequence of predominantly sedimentary rocks, such as conglomerate, sandstone and siltstone. The Sydney Basin rocks are overlain by Tertiary olivine basalt in the headwaters and on the higher parts of the drainage divides downstream of the headwaters (Wellman & McDougall, 1974), located in the deep bedrock valleys of the pristine Wollemi National Park. Erosion has exposed the Narrabeen Group to form the steep escarpments and higher hills which dominate the valley-fill landscape. Underlying the Triassic conglomerates and sandstones are the interbedded Permian shales, sandstones and coals of the Wollombi and Wittingham Coal Measures (Beckett, 1988). These alternating shallow marine and continental Triassic and Permian sediments store significant deposits of salinity. Unconsolidated alluvial sediments were deposited along the Hunter and Goulburn Rivers and their tributaries during the Holocene, which form the large alluvial aquifer system in the Hunter Valley (Kellett, Williams, & Ward, 1989).

Erskine (1994) found that the three largest recorded floods on the Goulburn River occurred in 1955, 1971 and 1977 and exhibited flood peak discharges between 15.0 and 43.4 times greater than the mean annual flood. Each flood caused substantial bank erosion, with the mobilised sand being temporarily stored in the stream bed as sand slugs which were rapidly reworked into in-channel benches. A similar geomorphic response to the recorded floods of 1955 and 1971 was evident on Widden Brook. Erskine & Warner (1988) defined alternating wet and dry periods, known as flood- and drought-dominated regimes, respectively and documented substantial channel widening by bank erosion during the flood-dominated regimes. With a trend since 2000 to lower annual rainfall, as found at Denman (Station No. 61016) and elsewhere in NSW, flushing flows and decreasing flood frequency during this current dry period has limited the opportunity for this method to restore hydrological linkages, as suggested by Hancock & Boulton (2005). This study examines those hydrological linkages between stream water and alluvial groundwater to determine the effect of an in-stream structure on the interaction between an incised sand-bed channel and its floodplain.

Methods

Floodplain transects

A number of transects were established from the channel across the floodplain and piezometers were located at intervals corresponding to topographic changes. The piezometers were constructed from 100 mm ID PVC slotted along the lower 0.50 to 1.50 m and installed to a depth up to 4 m in the alluvial sediments. The floodplain cross-sections consisted of a general fining upwards sequence from coarse sand and pebble gravel (channel deposits) to medium sand (bar top deposits and sand splays) to fine sand and fine sandy loams (overbank deposits). An in-stream bed control structure was installed by the landholder as a road crossing, constricting flow and channel width to the diameter of a single box culvert with height to midslope of the stream bank. The structure was located in the middle of the study reach, with piezometer transects at upstream and downstream locations (Figure 1).

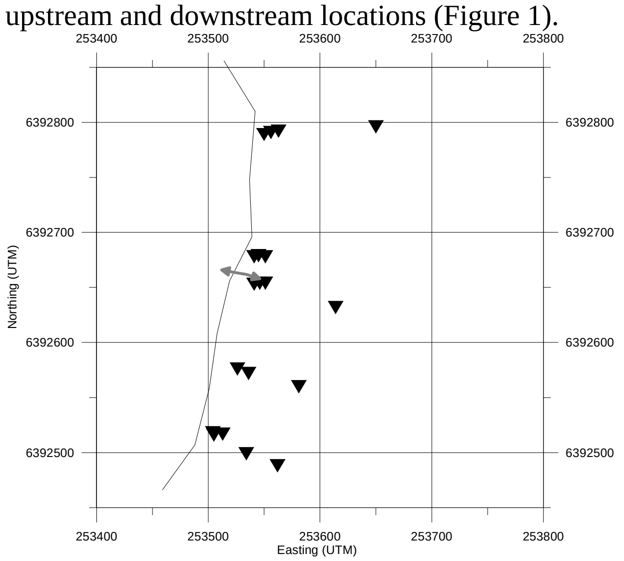

Figure 1. Location of in-stream structure and piezometers in transects from channel to floodplain for measured stream water and alluvial groundwater.

Sampling techniques
Groundwater was collected from piezometers for chemical analysis following water table and quality measurements and pumping to dryness or flushing for several water volumes. Field pH, EC, DO, redox and temperature were measured using a calibrated TPS 90-FLMV meter. Samples were immediately filtered with a 0.45µm membrane and one subsample collected for major anions and one subsample acidified to pH<2 using analytical grade HNO_3 for major cations and concentrations analysed using FIA and ICP-OES, respectively. The period of study spanned from May 2005 to July 2006. Nine sampling trips were made during this period, covering different flow conditions. However, no sampling period coincided with peak flow conditions. Rainfall was recorded at well below historical average, resulting in low to base flow conditions. Water level and quality measurements of piezometer networks were conducted every field trip.

Results

General water quality parameters
A wide variety of geochemical environments existed across the floodplain but some general trends emerged between the alluvial groundwater and the stream water, as represented on a catchment-wide scale from open wells and surface waters (Table 1). Groundwater from the alluvial aquifer tended to be suboxic to anoxic, whereas stream water was well oxygenated. A wide range in salinity (as represented by EC or Cl^- concentration) was found in both types of water. However, alluvial groundwater (0.17-3.01 dS/m) and stream water (0.05-1.29 dS/m) ranged from fresh to occasionally brackish, with the alluvial aquifer tending to be more saline. In both water types, pH was circumneutral to alkaline (5.9 to 8.8). Na dominated the soluble ion complex, even greater than the combined concentrations of Ca and Mg, with some large Na concentrations (>100 mg/L) in the alluvial groundwater possibly indicating salt stores associated with underlying sedimentary features. Nutrient concentrations (N, P, and Si) were generally higher in groundwater than in stream water. For nitrogen, mineral forms (NO_3^- and NH_3^-) were important, particularly in groundwater. Soluble Fe was present in appreciable concentrations in both stream water and groundwater.

Table 1. Mean and standard error in water quality parameters from alluvial groundwater and stream water in the Widden catchment for all sampling trips. The true range may be larger for stream water because not all flow conditions were sampled during the study. Data in mg/L unless otherwise noted.

	Alluvial groundwater	Stream water		Alluvial groundwater	Stream water
Temp (°C)	16.8 ± 1.7	15.9 ± 4.7	Na^+	138 ± 112	34.9 ± 25.4
Field pH	7.4 ± 0.4	7.5 ± 0.4	Cl^-	114 ± 60	45.1 ± 29.7
DO	2.4 ± 2.0	7.7 ± 2.3	SO_4^{2-}	20.6 ± 13.7	8.3 ± 8.9
Redox (mV)	280 ± 70	307 ± 77	NO_3^-	0.72 ± 0.74	0.04 ± 0.05
EC (dS/m)	1.04 ± 0.62	0.27 ± 0.18	NH_3^-	1.65 ± 1.98	0.31 ± 0.42
Ca^{2+}	25.1 ± 10.8	7.4 ± 5.6	PO_4^{2-}	0.17 ± 0.18	0.01 ± 0.00
K^+	11.7 ± 9.4	2.7 ± 1.5	Si	10.3 ± 2.8	5.35 ± 1.38
Mg^{2+}	28.3 ± 15.2	10.5 ± 8.4	Fe	1.42 ± 1.63	1.32 ± 1.30

When comparing these values (Table 1) to water quality parameters determined in the piezometer network at the study site, there was no observed difference apart from greater soluble Fe concentrations in the alluvial groundwater sampled from the piezometers. The presence of soluble Fe in groundwater samples indicated that the alluvial aquifer was suboxic to anoxic. This can be attributed to the closed piezometers limiting water table evaporation, rainfall inputs and atmospheric exchange.

Spatial trends across the floodplain
Water table and quality trends in cross-section from channel to floodplain are shown in Figures 1 and 2 to ascertain lateral hydrological exchange. Groundwater table depths and EC were most variable in the alluvial sediments of the stream bank when compared with those of the levee and floodplain (Figure 2). However, EC values were significantly larger across the alluvial sequence than those measured in the stream waters. Similarly, larger soluble Na concentrations were evident, with alluvial groundwater dominated by Na and Fe particularly in the stream bank and levee (Figure 3). Groundwater table depths were generally horizontal and reflect the lateral connectivity through transmissive pebbly sands of the underlying channel deposits to the stream. Ferruginous segregations were evident in these channel deposits as concretions, soft segregations, veins and laminae in the water table. The groundwater mound generated by EC and soluble ions in this zone of the alluvial aquifer is considerably greater than the stream water (Figures 2 and 3).

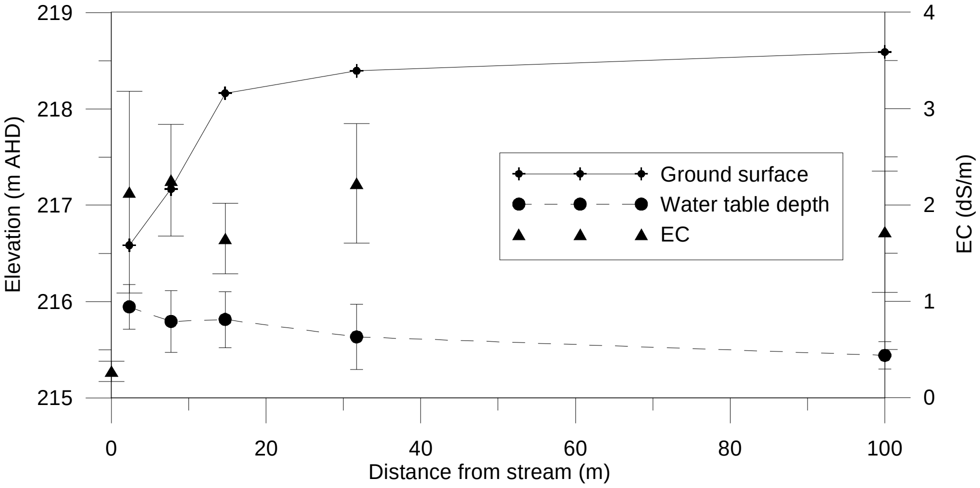

Figure 2. Surface elevation, mean water table depth and electrical conductivity (dS/m) in alluvial groundwater in cross-section from channel to floodplain. Vertical bars represent standard error of the mean for piezometers in a selected transect.

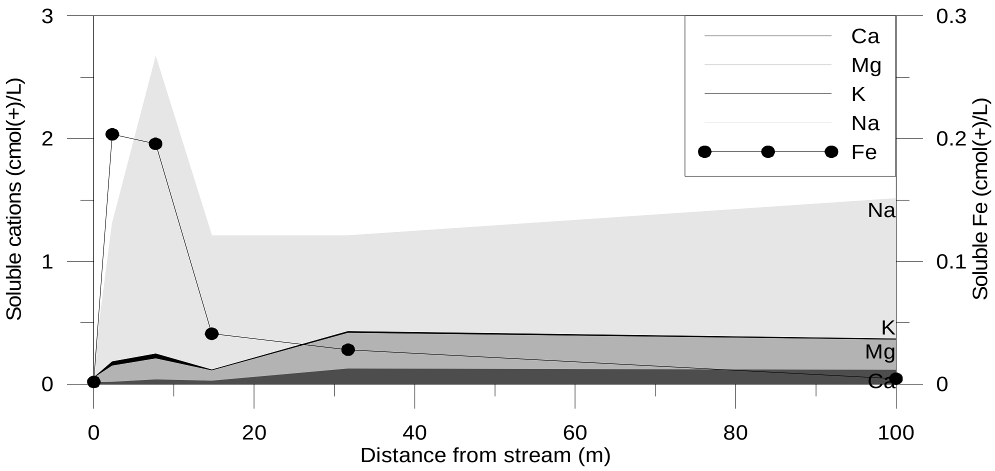

Figure 3. Stacked soluble salts and iron concentrations (cmol(+)/L) in alluvial groundwater in cross-section from channel to floodplain. Data presented from one sampling period under base flow conditions for piezometers in a selected transect.

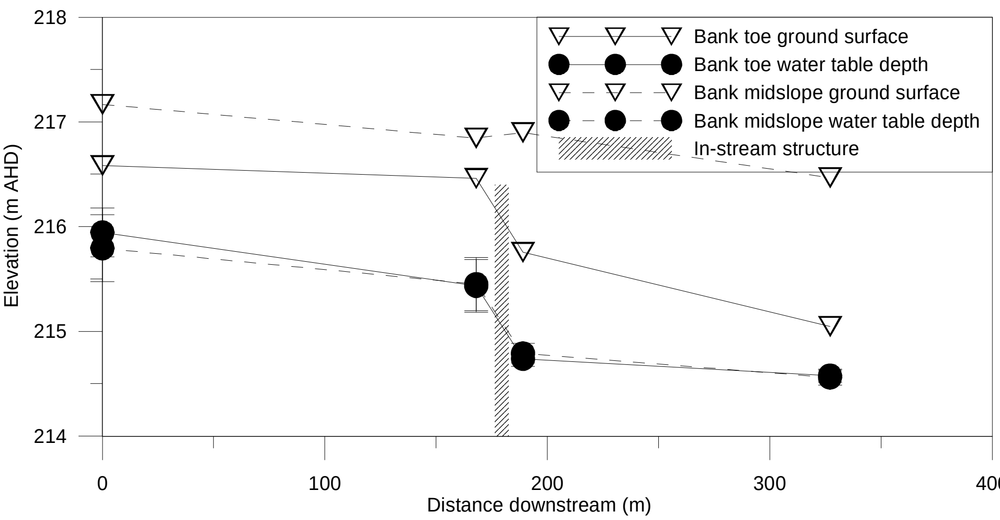

Figure 4. Surface elevation and mean water table depth of alluvial groundwater in longitudinal profile. Vertical bars represent standard error of the mean for piezometers in a selected transect.

Spatial trends associated with in-stream structures

The water table depth in the alluvial aquifer has been shown to be a reflection of stream level and, in a longitudinal channel profile, groundwater levels in the stream bank were almost identical despite surface elevation changes in the stream bank downstream from the structure (Figure 4). This could possibly result from the upstream effects of the structure. However, water chemistry was quite dissimilar between stream water and groundwater in longitudinal profile (Figure 5). The EC of groundwater stored in the alluvial aquifer tended to be greater at increasing distance away from the structure. This suggests that the structure itself may be reducing EC values between the stream water and groundwater by promoting localised hydrological exchange.

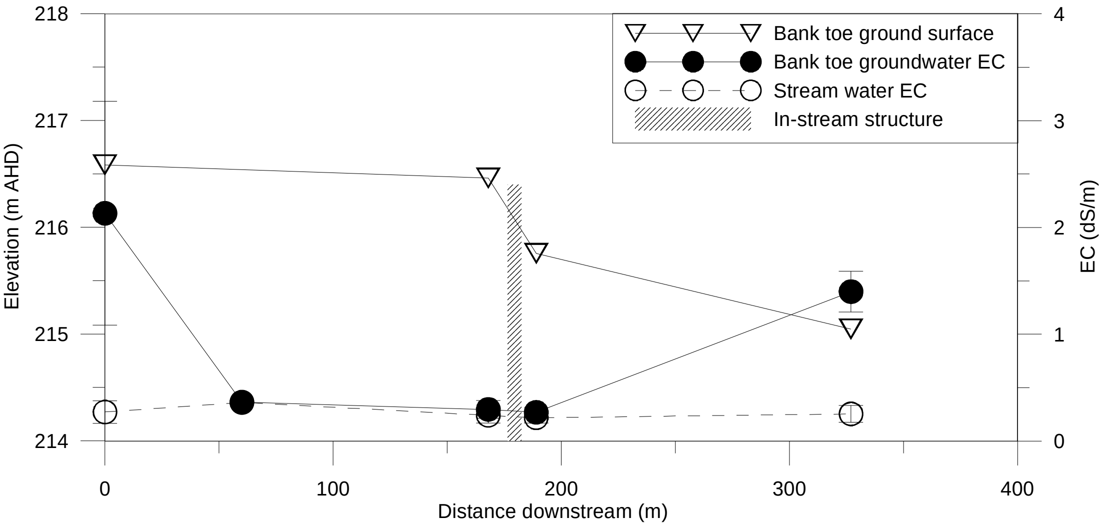

Figure 5. Surface elevation and mean electrical conductivity (dS/m) of alluvial groundwater and stream water in longitudinal profile. Vertical bars represent standard error of the mean for piezometers in a selected transect.

This trend in EC values in longitudinal profile was reflected by soluble Fe concentrations in the groundwater. Small Fe amounts were measured immediately around the structure and increasing Fe amounts away from the structure. Small concentrations of Fe were also found in the stream water, possibly derived from hyporheic exchange with channel sediments or from the discharge of alluvial groundwater.

Discussion

The post-European condition of Widden Brook has been heavily impacted by erosion, with widespread channel incision and the deposition of numerous sand slugs. Sedimentation is usually associated with a loss of geomorphic complexity and lower water quality (Brooks *et al.*, 2006). However, less frequent inundation and flood disturbance has allowed vegetation colonisation and mud deposition, contributing to rapid channel recovery by promoting oblique accretion and stabilising in-channel features. With changes in patterns of sediment deposition enhancing geomorphic complexity, water quality in Widden Brook was generally excellent.

During flow events, water levels in the alluvial aquifer adjusted quickly to changes in stream level, indicating an instantaneous hydraulic response in groundwaters. These levels dissipate as the flow subsided and base flow conditions dominated. This dissipation of the groundwater following flow events appeared to be an important component of the base flow. Results showed that although water levels were laterally connected from channel to floodplain, alluvial groundwater chemistry was independent of stream water. Considerably larger values of EC, Na and Fe were present in the anoxic groundwaters. In longitudinal channel profile, the hydrological exchange between the hyporheic zone and channel in response to the geomorphic complexity of the in-stream structure was localised. Brooks *et al.* (2006) demonstrated that log sill bed controls are capable of inducing localised downwelling and upwelling of stream water in the hyporheic zone. Stream waters may have percolated through the sand-bed and altered the groundwater chemistry of the hyporheic zone in a localised region around the in-stream structure. Outside the effects of the in-stream structure, results indicated that alluvial groundwater discharge from the stream bank to the channel was occurring with increases in salinity and dissolved iron. This suggested a positive hydraulic gradient toward the channel from the hyporheic zone under base flow conditions.

Conclusion

The hydrological connectivity of stream water and alluvial groundwater around the introduced geomorphic complexity of an in-stream structure in an incised sand-bed channel (Widden Brook, NSW) was studied over time using networks of piezometers and stream water profiles at a representative site with defined geomorphic properties. Several key findings emerged from the study:

- Stream water and groundwater levels reflected strong hydrological linkages in coarse channel deposits.
- The alluvial groundwater storage of the floodplain was important for maintaining base flow conditions.
- The redox status, ionic concentration and salinity of the alluvial aquifer appeared unrelated to the water table depths in the floodplain.
- The effect on the hyporheic zone from the in-stream structure was localised.
- Alluvial groundwater discharge from the hyporheic zone to the channel occurred under base flow conditions.

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