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Recharge Mechanisms in an Arid Zone River: Effects of Channelisation

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Abstract: Arid zone, ephemeral rivers typically experience very high transmission losses. Most international studies have identified infiltration into stream sediments and subsequent percolation to the unconfined alluvial aquifer as the major cause of transmission losses. There is relatively little data regarding mechanisms and stores controlling transmission loss processes in Australian arid zone streams, particularly in regards recharge to the unconfined aquifer. This study reports on a field study of recharge mechanisms occurring in the Neales River of the Lake Eyre Basin (northern South Australia). Piezometric monitoring, numerical and analytical modelling were used to identify and quantify recharge to the unconfined aquifer during streamflow events in 2004-2005. Significant recharge only occurred in channelised reaches and rates of recharge did not show a clear relationship with stage but tended to be higher for flow events occurring after longer periods of no flow. Reaches lacking a single, well-defined channel are common in the anastomosing rivers of the Lake Eyre Basin. Piezometers monitoring the alluvial sediments at two locations lacking well-defined channels did not measure any development of a saturated zone in the alluvial aquifer following flow events. The data suggests that most percolation and recharge occurs through the bank, rather than the floodplain and this needs to be taken into account when estimating transmission losses for these river systems.

Keywords: arid zone, groundwater mounds, analytical modelling.

1. INTRODUCTION

Recharge rates to shallow groundwater during streamflow events are a poorly constrained part of the water balance of rivers in arid zone catchments. Considerable research has examined transmission losses and recharge rates of ephemeral streams with predominantly coarse grained channel sediments [Walters 1990] but far less is known of corresponding recharge rates from rivers with finer grained channel and floodplain sediments that are more typical of much of the Australian arid zone. Arid zone catchments typically occur in regions of high potential evapotranspiration and so flux rates of groundwater recharge are difficult to separate from the large loss term of evapotranspiration. The rivers are also characterized by a scarcity, or complete absence in some catchments, of streamflow gauging stations.

An estimation of the rates of varying recharge to unconfined, alluvial groundwater systems during and after flow events provides important information to constrain this loss process in streamflow models of arid zone rivers. Recharge fluxes and pathways to the alluvial groundwater aquifer also provide critical information toward understanding salinity processes [Lamontagne et al. 2005] and riparian vegetation water use [Akeroyd et al. 1998] in arid and semi-arid rivers.

The large arid zone rivers of the Lake Eyre Basin (LEB) of Australia generally transport clay-sized particles and have floodplains dominated by cracking clay sediments [Nanson et al. 1988]. Transmission losses for two of the major river systems in the LEB (Cooper Creek and Diamantina River) result in approximately a 75-80% decrease in streamflow in their middle reaches [Knighton and Nanson 1994; Costelloe et al. 2006]. The proportion of these losses that are made up of recharge to alluvial aquifers has not been previously studied. Results from field monitoring and modelling of groundwater responses to flow events in the Neales River catchment of the LEB are presented in this paper.

1.1 Study catchment

The Neales River is an ungauged, unregulated, ephemeral river system in the arid Lake Eyre Basin (LEB) of central Australia. The headwaters of the catchment develop on the stony tablelands forming the western rim of the Lake Eyre Basin, at an altitude of 300-370 m, and the river has a course of 430 km before reaching its terminus at approximately sea level in Lake Eyre North (Figure 1). The catchment has an area of 34,000 km^2 and occurs in the arid core of the LEB, with a median annual rainfall of 140 mm and a mean annual pan evaporation loss of 3800 mm.

The Neales River generally has an anastomosing channel morphology with a number of poorly incised channels occurring within river/floodplain widths up to 3 km. However, in some reaches, a primary channel and associated floodplain morphology occur. The alluvial sediments are typified by sands and gravels overlain by sands, silts and clay. The modern deposits of the river are dominated by clay and silt.

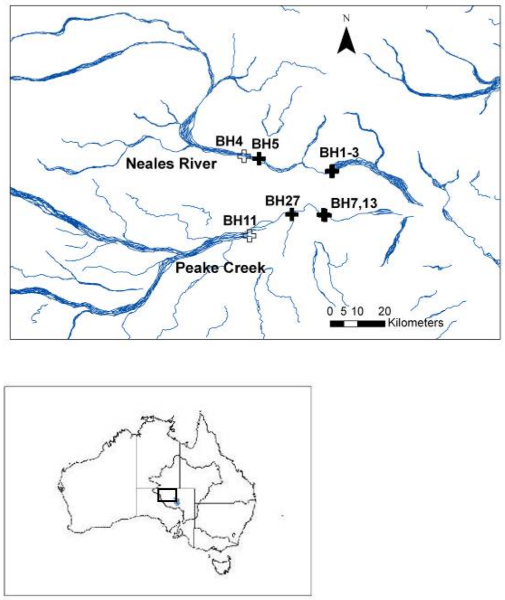

Figure 1. Location diagram showing position of Neales catchment and piezometers (unsaturated aquifer shown as hollow cross, saturated aquifer shown as solid cross). The major river networks of the Neales catchment are dominated by an anastomosing channel morphology without a primary channel, as indicated by the thickness of the river network.

2. METHODS

Piezometric monitoring, numerical and analytical modelling were used to identify and quantify recharge to the unconfined aquifer during streamflow events in 2004-2006. The piezometer network contained nine piezometers installed into the alluvial sediments of the Neales River and major tributaries (Figure 1) and instrumented with water level loggers. Surface flows were also monitored by water level loggers at the BH1-3 sites (Neales River) and BH7,13 sites (Peake Creek). Soil profiles were cored and soil water measured for chloride concentration at selected sites.

Two modelling methods were used in the estimation of recharge rates from streamflow events. In the two reaches with reliable streamflow stage data (BH1-3 and BH7, 13) the MODFLOW numerical modelling program was used. Recharge was simulated using a constant leakage factor for flow through the base of the channel and driven by head differences between channel stage and the groundwater level. The advantage of using MODFLOW was that the overall width of the groundwater system did not need to be estimated and recharge, hydraulic conductivity and specific yield values could be determined through calibration. The disadvantage of this approach was that MODFLOW used a constant leakage factor and did not allow for reduced recharge following peak inundation due to sediment clogging and crack closure.

An analytical modelling technique [Rai and Singh 1995] derived from a solution of a linearised Boussinesq equation was also used to simulate the growth and decay of groundwater mounds beneath the Neales River following flow events. The method models recharge beneath a strip basin using a finite Fourier sine transform that allows for time varying recharge (see equations below) but does not account for return flow to the channel. The model geometry is shown in Figure 2. In (1), h is the height of the groundwater mound at position X, m is the wave number, K is the hydraulic conductivity and a is the product of the hydraulic conductivity and the mean water table level divided by the specific yield.

$$h^2 = h_0^2 + \frac{8a}{K\pi} \sum_{m=1}^{\infty} \left(\frac{1}{m}\right) \sin\left[\frac{m\pi(X_2 + X_1)}{2A}\right] \sin\left[\frac{m\pi(X_2 - X_1)}{2A}\right] \sin\left(\frac{m\pi X}{A}\right) \left[R_1 \frac{1-\exp(-am^2\pi^2 t/A^2}{am^2\pi^2/A^2} + R_0 \frac{\exp(-\alpha t) - \exp(-am^2\pi^2 t/A^2}{am^2\pi^2/A^2) - \alpha} \right] \quad (1)$$

The recharge rate from the strip basin is given by (2) where $R(t)$ is the transient recharge, R_1 is the transient final discharge, $R_0 + R_1$ is the initial rate of transient discharge and α is a decay constant.

$$R(t) = R_1 + R_0 \exp(-\alpha t) \quad (2)$$

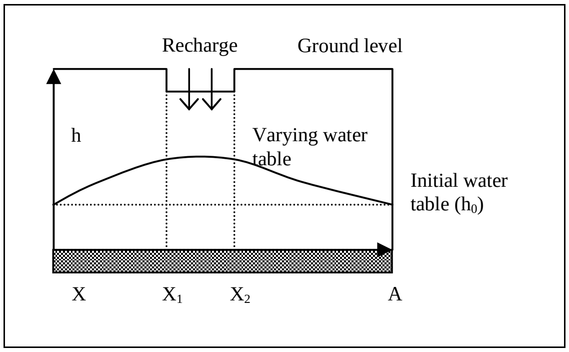

Figure 2. Vertical cross-section of the flow system showing model geometry [after Rai et al. 2001].

The saturated hydraulic conductivity was calculated from rising head tests in selected piezometers and specific yield values were estimated during model calibration. In general, the data from the drilling of the piezometers were insufficient for fully defining the geometry of the groundwater body, particularly the overall width of the aquifer. The latter was estimated during calibration of the analytical model and tested by sensitivity analysis.

The analytical model was used to produce optimal fits between observed and modelled changes in head using the Solver module of Microsoft Excel, allowing the three parameters (R_0, R_1, α) of (2) to vary. In reaches with no available streamflow stage data to use in numerical modelling, the parameter values of hydraulic conductivity and specific yield were also optimised during model calibration.

3. RESULTS

3.1 Field data

During the monitoring period (April 2004 – December 2005) five flow events occurred. Of the nine monitoring piezometers, the two most upstream piezometers did not measure any development of a saturated zone in the alluvial sediments following flow events. The other seven piezometers measured responses to up to four of the five flow events, depending on location and instrument operation. The two upstream piezometers were installed in channel reaches lacking well-developed primary channels (bankfull depths <1.3 m) while the other seven piezometers were installed within 250 m of the primary channel (bankfull depths of 1.9 – 7.4 m).

At most measured sections the piezometric level of the alluvial groundwater was close to the base of the stream in dry channels (e.g. Figure 3), and above the base of the stream at Algebuckina Waterhole (Figure 4). The maximum piezometric response to the flow events is shown in Table 1. Groundwater head responses to flow events were generally modest (range of 0.05 – 0.61 m, mean of 0.20 m). The groundwater was saline to hypersaline.

Table 1. Maximum stage of surface flow events and corresponding maximum groundwater response ($^{+}$possibly higher, nm=not measured).

Event	**Jun 04**	**Oct 04**	**Jul05**	**Oct 05**
Stage	2.68	2.04	2.84	3.33
BH1	0.189	0.094^{+}	0.113	0.081^{+}
BH3	0.211	0.046	0.168	nm
BH5	0.095	0.048	0.089^{+}	nm
Stage	0.78	1.20	nm	nm
BH13	0.186	nm	nm	nm
BH27	nm	nm	0.614	0.511

The movement of streamflow into the alluvial groundwater system can be illustrated for two sites on the Neales River using piezometric and soil water data. The upper Neales (BH5) site contains hypersaline groundwater but three weeks after a streamflow event, the standing surface pool was fresh (560 mgL^{-1} Cl), the groundwater close to the bank (BH62) was less saline than the groundwater further out (BH5) and the zones of near saturated soil water close to the bank (BH62) had low salinity (<2500 mgL^{-1} Cl, Figure 3). The near saturated soil water zones coincided with gravel lenses in the alluvial sediments that were also observed outcropping in the channel bank. These observations suggest that lateral movement of streamflow into the gravel layers results in recharge to the alluvial aquifer.

The lower Neales site (BH1-3, Algebuckina Waterhole) contains saline groundwater. During November 2005, soil core profiles (BH64) found low salinity soil water in the upper one metre and then high salinity (26,000 – 34,000 mgL^{-1} Cl) soil water below this to a depth of 3.75 m. Soil cores could not be obtained below this depth due to the presence of coarse gravels. The water table occurred at a depth of 4.9 m at this time and had a salinity of only 7020 mgL^{-1} Cl. Further out on the floodplain (210 m from channel), the salinity of the groundwater rises to 15,500 mgL^{-1} Cl.

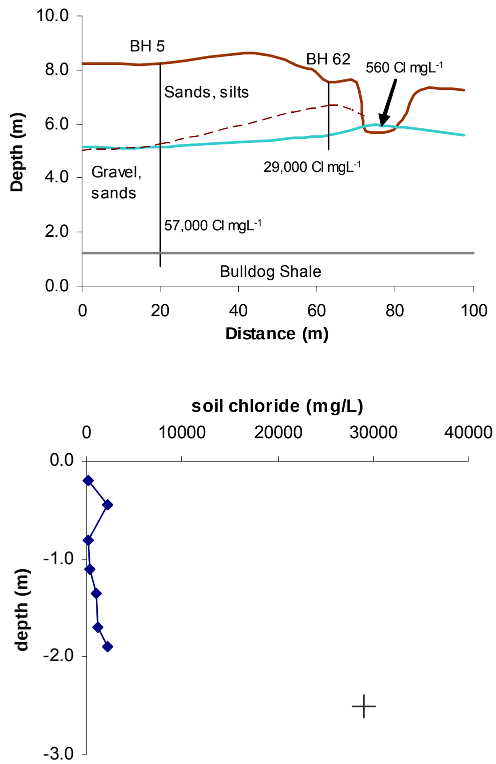

Figure 3. Top panel shows cross-section at BH5 at November 2005, showing position of BH5 and BH62. Bottom panel shows soil chloride profile for BH62, with chloride concentration of groundwater (at BH62) shown as a cross.

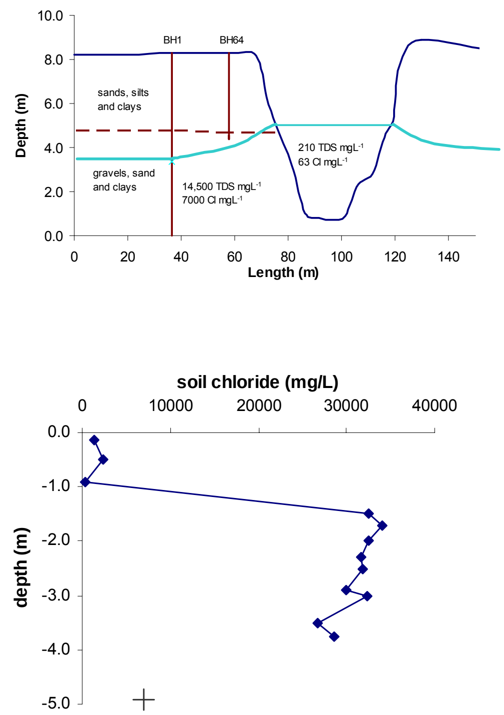

Figure 4. Top panel shows cross-section at BH1 at November 2005, showing position of BH1 and BH64. Bottom panel shows soil chloride profile for BH64, with chloride concentration of groundwater (at BH1) shown as a cross.

The low salinity upper zone of BH64 is interpreted as representing a zone of surface leaching due to rainfall or occasional floodplain inundation. The high salinity zone below this suggests that vertical recharge to the water table is limited but that near-horizontal recharge from bank sediments (or bypass recharge along cracks/macropores) best explains the moderate salinity of the groundwater. The alluvial sediments at the sites on the Neales River contain varying amounts of gravels, with the gravel content increasing down the profile. At the BH1 site, interbedded sands, silts and clays overlie interbedded gravels, sands and lesser clays (Figure 4). The highly saline soil water intersected in BH64 occurs within the upper, finer-grained part of the profile and approximately horizontal flow paths through saturated gravels are the most likely conduit for surface waters into the subsurface. The gravel layers do not outcrop in the banks at Algebuckina Waterhole but cracks in the clay-rich bank sediments or root macropores are likely to provide pathways for surface waters into the gravel layers.

3.2 Numerical modelling results

At reaches containing waterholes (BH1-3, BH7,13) MODFLOW's automatic calibration procedure was not able to achieve reasonable fits with long periods of the observed piezometric data. This is illustrated with data from the BH3 site (Figure 5) where a small flow event in October 2004 has an undue effect on the optimised modelled response. This is probably a result of that event maintaining high water levels in the waterhole that result in high recharge rates using the head driven leakage algorithm of MODFLOW.

Improved fits were achieved by calibrating the numerical model with groundwater responses to individual flow events, particularly with the rising stage of the groundwater response (see Figure 6 for example). The optimised hydraulic conductivity and specific yield values determined for these events are shown in Table 2. The mean optimised hydraulic conductivities for BH3 showed good agreement with that determined using a rising head test (Table 2).

The BH1 and BH3 parameter values were then used in the analytical modelling for this site.

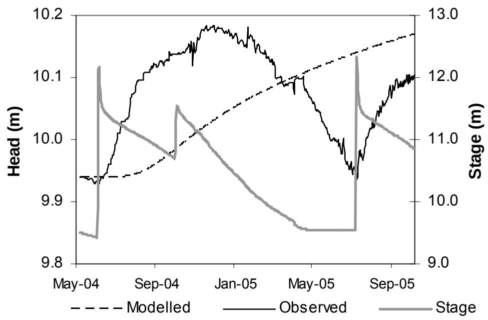

Figure 5. Optimised modelled response using MODFLOW at BH3 site. Also shown are the observed groundwater response and the streamflow stage for the same period.

The numerical modelling was not able to achieve reasonable fits at the BH13 site (Peake Creek). In this case, the modelled peak groundwater rise was approximately half that of the observed rise and the optimised parameters resulted in unfeasibly high recharge rates. A nearby piezometer (BH7) showed unusual recharge patterns indicating very rapid rises and falls in the groundwater level that suggest aquifer complexities (e.g. macropores or preferred flow paths) not addressed using the simple model structures of this study.

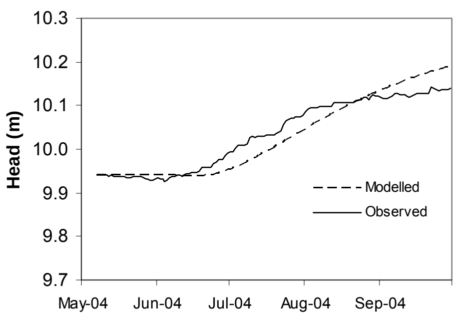

Figure 6. Observed groundwater response and optimised modelled response using MODFLOW at BH3 site for June 2004 flow event.

Table 2. Parameters calibrated in numerical modelling (K_{cal} – calibrated hydraulic conductivity, S – calibrated specific yield, K_{meas} – hydraulic conductivity measured in rising head test).

	K_{meas}	K_{cal}	S
BH1	-	0.0503	0.1021
BH3	0.0717	0.0826	0.0267
BH13	0.0778	0.2755	0.0063

3.2 Analytical modelling results

The hydraulic conductivity and specific yield values derived from the numerical modelling were used in the analytical modelling for the BH1 and BH3 sites. The parameter values for the width of the aquifer and the recharge equation were calibrated using the analytical model. In general, the observed groundwater piezometric responses were well-fitted using the exponentially decaying recharge equation of the analytical model. However, the small number of piezometers at each reach placed considerable uncertainty on the parameter estimation and so the optimised solutions were non-unique and a wide range of parameter values could be fitted. The most poorly constrained parameters were the specific yield and the total width of the floodplain aquifer.

At the BH1-3 site, the optimised width of the alluvial aquifer (1600 - 2300 m) was approximately that of the alluvial sediments (2000 m). As a result, the width of the alluvial sediments at each reach was measured from Landsat TM satellite images and used as the aquifer width input for the analytical modelling. The final set of modelled recharge totals for each observed flow event is shown in Table 3 (as depth of recharge across the channel width per unit length of channel). Narrower aquifer widths lead to generally higher estimates of total recharge as did higher values of specific yield. Therefore, the results shown in Table 3 are likely to represent minimum estimates of recharge given the high uncertainty in parameter values. The results used measured or calibrated saturated hydraulic conductivities that were within expected ranges for the aquifer sediments. However, the calibrated specific yields were often lower than expected for these sediments and may reflect the thin, interbedded nature of the alluvial sediments that ranges from clays and silts through to gravels.

Table 3. Modelled total recharge (m) across channel width per unit length of channel for each flow event.

	Chan. width (m)	Jun 04	Oct 04	Jul 05	Oct 05
BH1	50	0.788	-	0.538	-
BH3	50	1.308	0.091	0.555	-
BH5	17	0.461	0.182	-	-
BH13	50	3.982	-	-	-
BH27	55	-	-	1.387	1.163

4 DISCUSSION

The infiltration in the poorly channelised, anastomosing reaches is sufficient to maintain relatively dense riparian vegetation. During ‘sub-bankfull’ events, streamflow in these reaches is restricted to a small number of shallow anastomosing flow paths that also support the highest density of riparian trees. The lack of a saturated zone in the alluvial aquifer of the two upstream sites suggests that the long-term transpiration rates of the riparian vegetation are likely to be in equilibrium with the rainfall and streamflow infiltration at the site (assuming no lateral flow). Transpiration rates have not been measured for riparian vegetation of the Lake Eyre Basin. However, transpiration rates measured for riparian Eucalyptus species in the semi-arid Murray-Darling Basin indicate that annual rates per unit area of <0.12 m can be expected [Akeroyd et al. 1998]. Given the mean annual rainfall in the catchment is 0.18 my^{-1} (only part of which will infiltrate into the soil profile) then the infiltration due to streamflow is likely to be <0.1 myr^{-1} across the flow paths within the poorly channelised, anastomosing reaches.

During the six-year period with available streamflow stage data (2000-2005), 12 flow events (four involving substantial floodplain inundation) occurred in the Neales River and 14 flow events (three involving substantial floodplain inundation) occurred in the Peake River. Therefore the number of flow events within the study period (2-3 per year) is relatively typical for this river. The flow events during the study period were sub-bankfull in the reaches with primary channels and were restricted to the shallow anastomosing channels of the poorly channelised reaches. Despite the uncertainty in parameter values, the modelling indicates that the recharge across the channel width (generally 15-50 m) from sub-bankfull streamflow events at channelised reaches is likely to be in the range of 0.1 – 1.4 m per event. Given an average of two flow events per year, these results indicate that recharge rates are significantly higher in reaches with primary channels than in poorly channelised anastomosing reaches.

5 CONCLUSIONS

The results of this study suggest that most recharge from sub-bankfull flows occurs through the bank of the primary channel, rather than in shallow anastomosing channels on the floodplain of poorly channelised reaches that are typical of many rivers in the Lake Eyre Basin. This has implications for estimating, or modelling, transmission losses for reaches of these arid zone rivers, in addition to understanding the role of recharge from streamflow on the distribution of riparian vegetation.

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