Recharge Rates to Shallow Groundwater from Streamflow in Arid Zone Catchments

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EXTENDED ABSTRACT

Recharge rates to shallow groundwater that occur during streamflow events are a poorly constrained part of the water balance of large rivers in arid zone catchments. Considerable research has examined transmission losses and recharge rates of ephemeral streams with predominantly coarse grained channel sediments but far less in known of corresponding recharge rates from rivers with fine grained channel and floodplain sediments that are more typical of many Australian arid zone rivers. The arid zone catchments generally occur in regions of high potential evapotranspiration and flux rates from groundwater recharge are difficult to separate from the large loss term of evapotranspiration. An estimation of the rates of varying recharge to alluvial groundwater systems during and after flow events provides important information to constrain this loss process in streamflow models of these arid zone rivers. A field project collected data on flow events and the piezometric level of shallow groundwater at a number of floodplain sites within arid zone rivers of the Lake Eyre Basin of Australia.

An analytical modelling technique was used to simulate the growth and decay of groundwater mounds beneath river systems and lake bodies following flow events in 2004. The technique was developed for modelling recharge from a strip basin or channel with groundwater flow moving laterally away from channel. The geometry and boundary flow conditions of some of the reaches under study did not meet the criteria of the analytical model. In these reaches, the model was generally able to simulate the growth of the groundwater mounds but not the rate of decay. An example of the model results for simulating recharge from a sub-bankfull flow event is shown in Figure 1.

The initial recharge rates modelled from the rivers of the Lake Eyre Basin range from 0.01-0.03 md^{-1} (500–1300 m^3km^{-1}) for rivers with floodplains comprised of interbedded sediments, or dominated by cracking clays, and 0.13-0.5 md^{-1} for sand dominated floodplains (5200–20,000 m^3km^{-1}). The June 2004 flow event in the Neales River had an estimated peak discharge of 300,000-400,000 m^3d^{-1} (i.e. 300-400 MLd^{-1}) implying the initial recharge was 0.3%, or less, of the peak discharge. The 2004 flood in the lower Diamantina reach had an estimated peak discharge of approximately 30,000,000 m^3d^{-1} implying that the initial recharge for this reach was <0.1% of the peak discharge.

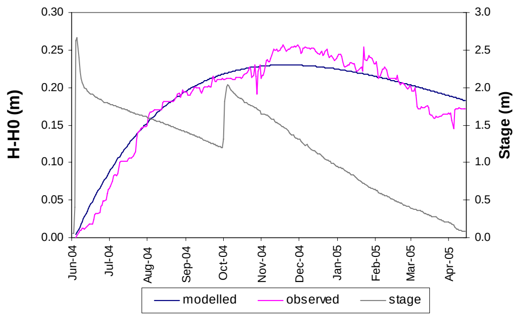

Figure 1. Modelled versus observed groundwater response to a flow event in the Neales River (Algebuckina Waterhole) during June 2004. Note that the groundwater response to the small flow event of October 2004 has not been modelled.

Two of the lake bodies inundated from a dry state were best modelled with an initial recharge rate of 0.015 md^{-1} which corresponds to an initial areal recharge rate of 15,000 m^3km^{-2}, which is approximately 1% of the lake full volume.

These initial recharge rates are small compared to the peak discharge of the flow events but can be considerable given the long channel lengths and extensive floodplains of many of these arid zone rivers. The recharge rates to unconfined aquifers vary considerably among three river reaches of the Lake Eyre Basin and are highest during the rising and peak flow periods. The recharge rates are best modelled using an exponentially decaying function or pulses of constant recharge during the peak of the flow event.

1. INTRODUCTION

Recharge rates to shallow groundwater that occur during streamflow events are a poorly constrained part of the water balance of large 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, Shentsis *et al*. 1999) but far less is known of corresponding recharge rates from rivers with fine grained channel and floodplain sediments that are more typical of much of the Australian arid zone. The arid zone catchments generally occur in regions of high potential evapotranspiration and so flux rates from 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 these arid zone 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 have previously been studied for two river systems in the Lake Eyre Basin. Losses during flow events account for approximately 75-80% of streamflow in the middle reaches of Cooper Creek (Knighton and Nanson 1994) and the Diamantina River (Costelloe *et al*. 2003). The proportion of these losses that are made up of percolation to alluvial aquifers has not been previously studied. Results from field monitoring of groundwater responses to flow events in three river systems of the LEB and preliminary modelling of recharge processes are presented in this paper.

2. METHODS

A field project collected data on flow events and the piezometric level of shallow groundwater at a number of floodplain sites within three arid zone rivers of the Lake Eyre Basin of Australia; Neales River, Diamantina River and Cooper Creek (Figure 2). A total of 28 piezometers were installed in April and November 2004 and monitored groundwater responses to flow events, ranging from small, sub-bankfull events in the Neales River to large regional floods with extensive overbank discharge in the Diamantina River and Cooper Creek.

In general, the piezometer network was sparse and monitored large areas. As a result, the information available for modelling the recharge from flow events was limited. The initial modelling has used a relatively parsimonious analytical technique for modelling recharge rates to the water table rather than numerical modelling of unsaturated zone processes.

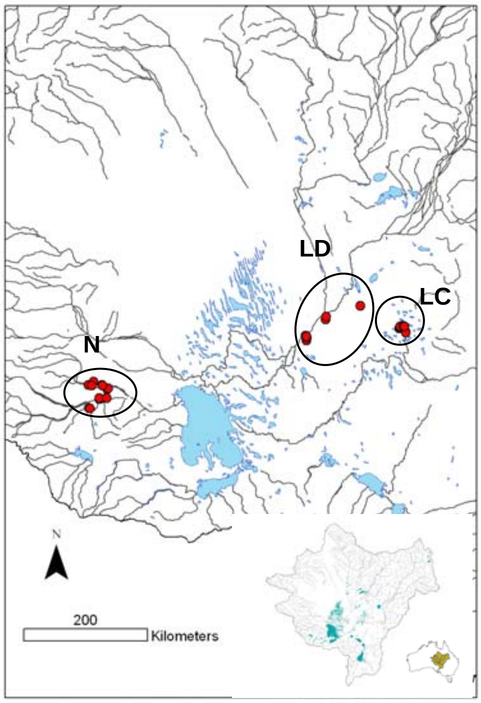

Figure 2. Location of piezometers and field areas in the Lake Eyre Basin (LC-lower Cooper, LD-lower Diamatina, N-Neales).

An analytical modelling technique (Rai and Singh 1995, Rai *et al*. 2001) derived from a solution of a linearised Boussinesq equation was used to simulate the growth and decay of groundwater mounds beneath river systems following flow events in 2004. The method models recharge beneath a strip basin using a finite Fourier sine transform that allows for time varying recharge (see equations below). The model geometry is shown in Figure 3. In (1), h is the height of the groundwater mound above 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.

$$h^2 = h_0^2 + \frac{8a}{K\pi}\sum_{m=1}^{\infty}\left(\frac{1}{m}\right)\sin\left[\frac{m\pi(X_2+X_1)}{2A}\right]$$

$$\sin\left[\frac{m\pi(X_2-X_1)}{2A}\right]\sin\left(\frac{m\pi X}{A}\right) \qquad (1)$$

$$\left[\begin{array}{l} R_1 \dfrac{1-\exp(-am^2\pi^2 t/A^2)}{am^2\pi^2/A^2} \\ + R_0 \dfrac{\exp(-\alpha t)-\exp(-am^2\pi^2 t/A^2)}{am^2\pi^2/A^2)-\alpha} \end{array}\right]$$

The recharge rate from the strip basin is given by (2).

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

where $R(t)$ is the transient recharge, R_1 is the transient final discharge, $R_1 + R_0$ is the initial rate of transient discharge and α is a decay constant. In some cases a constant rate of recharge was used for a period of time coinciding with the passage of a flow event. This has been termed as a 'pulse' of constant recharge in contrast to the exponentially decaying recharge. The form of the algorithm for the constant recharge is contained in Rai *et al.* (2001).

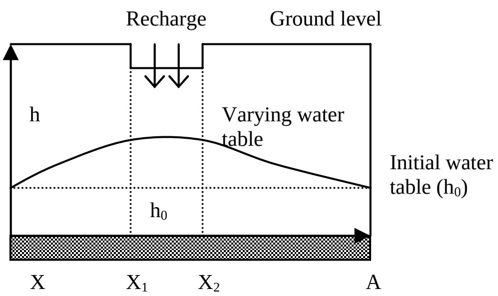

Figure 3. Vertical cross-section of the flow system showing model geometry (after Rai *et al.* 2001).

The saturated hydraulic conductivity was calculated from rising head tests in available piezometers and specific yield values were taken from the literature. In general, the data from the drilling of the piezometers were insufficient for fully defining the geometry of the groundwater body. Best estimates were used in the modelling and their validity tested by sensitivity analysis.

The algorithm 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_1, R_0, α) of (2) to vary.

3. RESULTS

3.1. Field data

Flow events in all three reaches resulted in measurable increases in groundwater level within the alluvial aquifers.

Two small sub-bankfull flows during 2004 in the Neales catchment ranged in stage from 0.8 to 2.6 m and produced groundwater rises of up to 0.47 m (Table 1). These rises occurred in unconfined alluvial aquifers with depths to groundwater of 2.6 – 5.2 m below ground level. The rate of rise was gradual in most cases but did show a sharp rise in the piezometer with the highest rise in groundwater level. The bank and floodplain sediments of the Neales catchment were comprised of interbedded layers of clays, silts, sands and thin gravel lenses. Many of the layers showed upward fining patterns. Surficial deposits from recent flood events comprised mud drapes.

The piezometers on the lower Diamantina floodplain were installed after the passage of a large flood in February-March 2004 and only measured a fall in groundwater level following that flood, except for the most downstream piezometer (BH29, see Figure 4). This reach is characterized by having floodplains and banks mostly comprised of fine-grained sands on the eastern side of the river and cracking clay sediments overlying the fine grained sands on the western side (Figure 4). The floodplains of most of the major LEB rivers having cracking clay dominated floodplains. Substantial discharge of bank/floodplain storage back into the river channel has been observed over the period 2000-2004 (Costelloe *et al.* 2005). It has been assumed that the fall in groundwater level observed in the piezometer data for this reach reflects the decay of the groundwater mound that grew in response to the flood event of early 2004. The largest falls in piezometric level (1.06-1.35 m) occurred in piezometers close to the channel (<40 m) but with smaller changes further away from the channel (Figure 4, Table 2). During May 2004, the depth to the water table was between 2.6-4.0 m below ground surface and the gradient of the water table was away from the channel but was towards the channel by November 2004. The most downstream piezometer (BH29, Figure 4) measured a small rise in the groundwater level from November 2004 (installation date) to January 2005 and then stabilized. These changes suggest that groundwater movement was complex with observed discharge into the channel, movement downstream and probable movement laterally away from the channel during the peak of the groundwater mound formation. In addition to recharge from the channel, there was also considerable floodplain inundation during February-March 2004 which would have also contributed to the recharge to the unconfined aquifer.

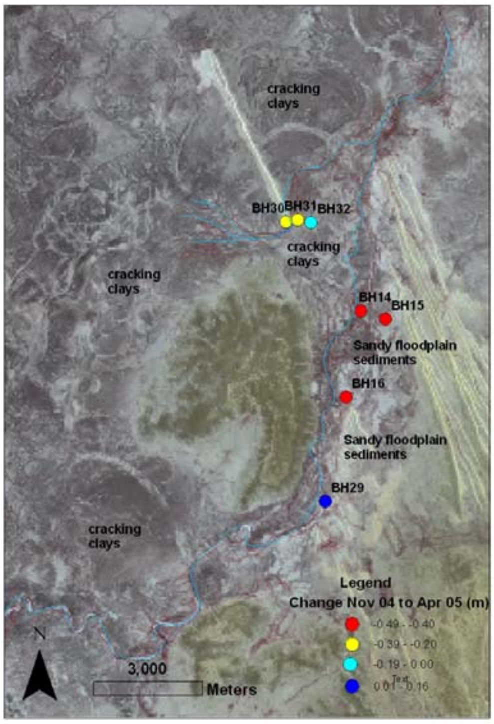

Figure 4. Change in groundwater level in lower Diamantina reach between November 2004 and April 2005. A Landsat TM image shows the lower Diamantina River (blue line) and areas of floodplain with differing composition are shown. The direction of surface water flow is from top-right to lower-left of the image.

Substantial rises and then falls in groundwater level of between 0.36-1.01 m were also observed at the margins of three lakes in the lower Cooper reach that were filled by the large 2004 flood from a previously dry state (Table 3). The depth to the water table was initially between 2.9-4.0 m below the ground surface. The lake sediments are comprised of clays and fine-grained clayey sands and characteristically exhibit deep cracks when dry and are typical of floodplain sediments through much of the lower Diamantina and lower Cooper catchments.

3.2. Analytical modelling results

The results for the Neales catchment found that the observed growth and decay in groundwater mounds in response to sub-bankfull flow events were well fitted by modelled exponentially decaying patterns of recharge over time, except for one piezometer. The observed groundwater level rises and peak streamflow stage rises for a flow event in June 2004 are shown in Table 1 along with the modelled initial rate of recharge and total volume of recharge per kilometer of stream length. The reach length with greatest concentration of piezometers occurs on the Neales River at Algebuckina Waterhole. Here, a triangular pattern of piezometers was installed with two piezometers located close to the bank and another piezometer occurring further out on the floodplain. Both the piezometers close to the bank recorded broadly similar observed and modelled recharge patterns to the flow events of 2004. The floodplain piezometer recorded only negligible observed and modelled responses to the sub-bankfull flow events. A typical modelled curve for the growth and decay of a groundwater mound is shown in Figure 5.

Table 1. Stage, groundwater rise, modelled initial rate of recharge and total volume of recharge for a flow event in June 2004, Neales River. Stage was not measured at BH5 location.

Bore	Stage (m)	GW rise (m)	Initial (md^{-1})	Total (m^3km^{-1})
BH1	2.618	0.185	0.026	23,050
BH2	2.618	Neglible	-	-
BH3	2.618	0.231	0.010	47,300
BH5	-	0.095	0.034	27,948
BH7	0.776	0.469	0.300	>48,000
BH13	0.776	0.186	0.013	29,800

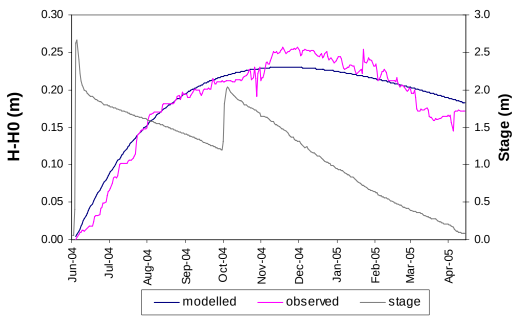

Figure 5. Modelled versus observed groundwater response to a flow event in the Neales River (Algebuckina Waterhole) during June 2004. Note that the groundwater response to the small flow event of October 2004 has not been modelled.

One piezometer that showed sharp rises in immediate response to flow events was best modelled using pulses of constant recharge (Figure 6). High recharge rates were modelled during flow events and then a low constant recharge rate during the period of no flow. Another piezometer on the same reach and only 640 m downstream displayed a more typical exponentially decaying recharge pattern. The atypical 'pulse' pattern may be a result of direct flow through macropores or sands in the bank. The total modelled recharge was larger than the peak stage of the event and this is mostly due to the low constant recharge rates following the flow event required to maintain the observed water level. This suggests that lateral flow may be constrained resulting in erroneously high modelled total recharge.

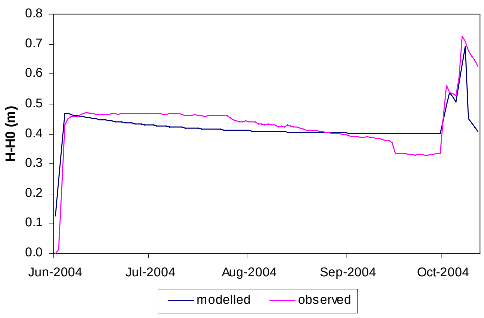

Figure 6. Modelled versus observed groundwater responses to flow events in the Peake River (Neales River catchment) during June and October 2004. Periods of constant recharge were used to model the groundwater response.

Sensitivity analyses shows that for the Rai algorithm, the parameters estimating the initial rate of recharge (R_1 and R_0) are sensitive to changes in the specific yield, with increases in the specific yield resulting in increased rates of initial recharge. In contrast, increases in the hydraulic conductivity result in small increases in the rate of initial recharge and a more significant decrease in the decay constant (α). Increases in the estimated depth of the equilibrated water table (i.e. h_0 of Figure 3) result in negligible increases in the initial recharge rate and moderate decreases in the decay constant. Increases in the width of the groundwater system result in significant increases in both the initial recharge rate and decay constant.

The analytical modelling approach was not able to simulate the relatively rapid declines in the piezometric level of the lower Diamantina reach during 2004 (Table 2). The best solution involved a pulse of constant recharge during the rising and peak stage of the flow event followed by zero recharge during the falling stage (see Figure 7). The discharge of groundwater back into the channel system is the most likely explanation for this rapid fall and this contravenes the geometrical assumptions of the algorithm of Rai *et al.* (2001), which assumes that the groundwater level remains below the level of the strip basin and the groundwater movement is away from the recharging basin. The best fit modelling solutions using constant recharge resulted in recharge rates of between 0.10-0.50 m and total recharge of approximately 2.7-10.5 m (108,000-420,000 m^3km^{-1}) through the river channel (Table 2). Some recharge was also likely to have occurred through the floodplain and so the total recharge amounts from the channel are probably overestimated.

Two piezometers (BH31 and BH32) were installed on the western floodplain of the Diamantina River (see Figure 4) where the floodplain is composed of a cracking clay layer overlying the fine-grained sand unit. Here, falls in the groundwater level were substantially less than observed in the eastern piezometers (Table 2) suggesting that recharge rates through the cracking clay were less than observed in the sand unit.

Table 2. Changes in piezometric level in lower Diamantina reach, May 2004 to April 2005. Note that BH29 to BH31 were only installed in November 2004.

Piezometer	Change May04-Apr05 (m)	Change Nov04-Apri05 (m)	Recharge Rate (md^{-1})
BH14	-1.02	-0.53	0.13
BH15	-0.68	-0.40	0.18
BH16	-1.35	-0.49	0.50
BH29	-	0.16	-
BH30	-	-0.26	-
BH31	-	-0.24	-
BH32	-	0.00	-

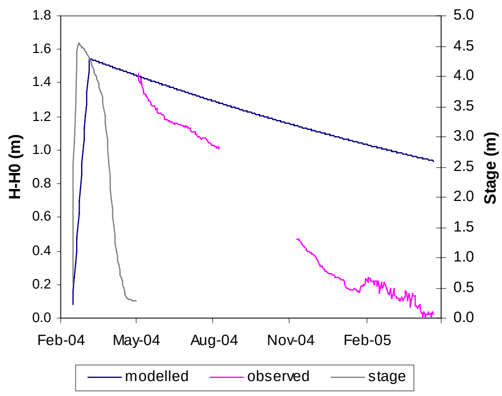

Figure 7. Modelled versus observed groundwater response to a flow event in the lower Diamantina reach between November 2004 and April 2005. Data from piezometer BH16 (Figure 4).

Only one of the lakes (Lake Apanburra, next to BH21 in Figure 8) of the lower Cooper reach satisfied the approximate geometry of a strip basin used by the modelling algorithm. In this case, the piezometer was installed approximately 30 m from the bank of the inflow channel of the lake and within 50 m of the edge of the lake (Figure 8). The Lake Apanburra location was modelled using the geometry of the inflow channel as the strip basin and then using the width of the lake to represent the strip basin (Figure 9). Both model structures simulated the rising stage reasonably well but could not satisfactorily model the falling stage. The model using the narrower inflow channel geometry performed the better of the two geometries. The relatively rapid rate of decrease in the piezometric level implies that more complex flow patterns occur other than lateral flow away from the waterbody.

Table 3. Maximum increases in groundwater level and maximum depth of lakes during 2004-2005. Note that BH20 was not modelled.

Piezo.	Max. Change May04-Apr05 (m)	Estimated maximum depth of lake (m)	Modelled initial recharge rate (md^{-1})
BH20	1.01	2.05	-
BH21	0.69	0.80	0.015
BH22	0.36	2.21	0.015

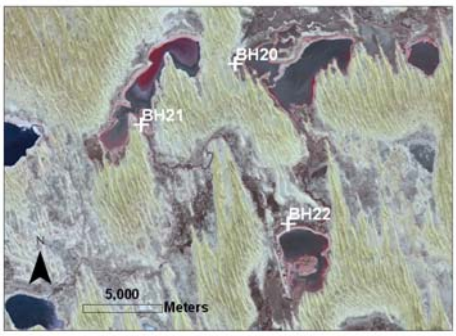

Figure 8. Position of piezometers (cross) around lake margins in the lower Cooper reach.

Assuming symmetry of recharge along the axis of the strip basin, half of the width of the basin contributes to recharge per unit perimeter length using the Rai algorithm. For circular bodies, using a similar logic, the contributing width to the recharge per unit perimeter is the area divided by the perimeter (i.e. half the radius). This approach was used to model the recharge rate for the most regularly shaped of the three monitored lakes (Toontoowaranie, next to BH22 in Figure 8) in the lower Cooper reach (Figure 10). The model was able to simulate the rising groundwater level but was less successful in simulating the decay of the groundwater mound. Increasing the hydraulic conductivity by an order of magnitude (from 0.026 to 0.26 md^{-1}) resulted in higher rate of decay of the groundwater mound.

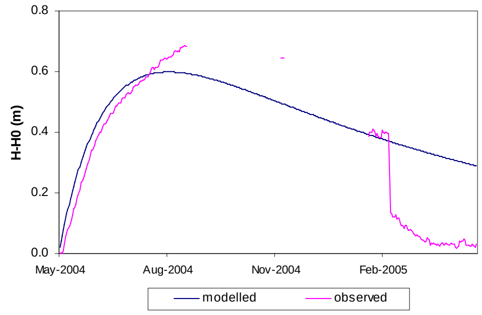

Figure 9. Modelled versus observed groundwater response to a flow event in the lower Cooper reach between May 2004 and April 2005. Data from piezometer BH21 (Figure 8).

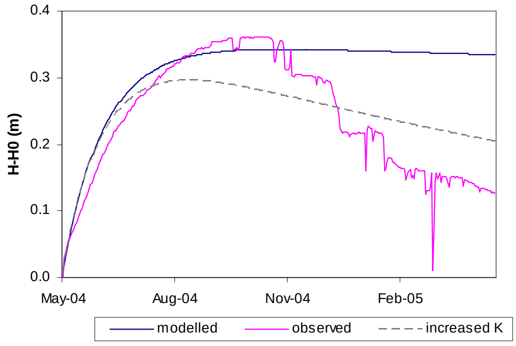

Figure 10. Modelled versus observed groundwater response to a flow event in the lower Cooper reach between May 2004 and April 2005. Data from piezometer BH22 (Figure 8).

4. DISCUSSION

The initial recharge rates modelled from the rivers of the Lake Eyre Basin range from 0.01-0.03 md^{-1} (500–1300 m^3km^{-1}) for rivers with floodplains comprised of interbedded sediments, or dominated by cracking clays and 0.13-0.5 md^{-1} for sand dominated floodplains (5200–20,000 m^3km^{-1}). The June 2004 flow event in the Neales River had an estimated peak discharge of 300,000-400,000 m^3d^{-1} (i.e. 300-400 MLd^{-1}) implying the initial recharge was 0.3%, or less, of the peak discharge. The 2004 flood in the lower Diamantina reach had an estimated peak discharge of approximately 30,000,000 m^3d^{-1} implying that the initial recharge for this reach was <0.1% of the peak discharge.

Two of the lake bodies inundated from a dry state were best modelled with an initial recharge rate of 0.015 md^{-1} which corresponds to an initial areal recharge rate of 15,000 m^3km^{-2}, which is approximately 1% of the lake full volume.

Other studies have reported recharge rates generally between 7000 m^3km^{-1} to 62,000 m^3km^{-1} for arid zone streams in North America, Middle East and India (Knighton and Nanson 1997, Gheith and Sultan 2002). These international examples were from streams with relatively coarse sediments. The results reported in this study with channel and floodplains dominated by fine sands are within the typical range of recharge rates from international studies. However, the recharge rates from this study for channels and floodplains with high clay contents are an order of magnitude less than for streams with coarser sediments. The results from the lakes of the lower Cooper reach indicate that even these relatively low initial recharge rates can be significant when large areas and long river reaches are inundated, as can occur over the extensive floodplains of the major rivers of the Lake Eyre Basin.

Further modelling of the reaches, particularly the lower Cooper and lower Diamantina reaches, requires more flexible analytical or numerical approaches to allow for different boundary conditions, such as groundwater discharge into the river channel and differing model geometries.

5. CONCLUSIONS

These initial recharge rates are small compared to the peak discharge of the flow events but can be considerable given the long channel lengths and extensive floodplains of many of these arid zone rivers. The recharge rates to unconfined aquifers vary considerably among three river reaches of the Lake Eyre Basin and are highest during the rising and peak flow periods. The recharge rates are best modelled using an exponentially decaying function or pulses of constant recharge during the peak of the flow event.

6. ACKNOWLEDGMENTS

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