

3.4 Confined aquifer

Hydrographs showing potentiometric head within the confined aquifer are given in Figure 8 and Figure 9 and in Appendix A. Figures A1 and A3 plot confined aquifer hydrographs for winter flooding periods in 2003-4 and 2004-5 respectively. Figures A5 to A18 plot hydrographs for each site from December 2002 to early 2005; confined aquifers are indicated by black lines.

The confined aquifer responds very rapidly to changes in the Bremer's water level (Figure 8 and Figure 9). The magnitude and timing of the water-level response at a well depends on (1) the distance between the well and the river, (2) the distance from the well to the lake, (3) the furthest downstream location reached by the water in the river and (4) whether the aquitard is present at the site.

At sites adjacent to the Bremer river, the head in the confined aquifer rises by up to 2 m in a few days, following increases in Bremer water level at Hartley of 0.8 - 2.9 m. Water levels at sites further from the river (e.g. at site C that is east of the Bremer and north-west of Mosquito Creek and at site K to the west of the Bremer) start to rise within (? number) hours of when they rise beside the river at site J.

Site L is located furthest downstream of all the soil moisture logger sites. In September 2003, the confined aquifer well water levels at site L rose about 40 hours after rises at site J (Figure 8). In August 2004 water levels rose at both J and L at approximately the same time, with the level at L rising more slowly (Figure 9). In 2003, if the River Bremer waters took a long time to flow as far downstream as site L, this might explain the 40 hour delay between the responses at J and L.

Confined aquifer water levels rise higher and more rapidly close to the Bremer than further away. When the rise beside the Bremer was 2 m (e.g. at site J), the rise 2 km away at, e.g. site O, was about 0.5m (winter 2003) or 0 m (winter 2004).

Where the aquitard exists, the amplitude of the water level rise in the confined aquifer remains constant as distance downstream along the Bremer increases, e.g. at wells J and K.

Note that a rise in the confined aquifer level is seen in the third week of May 2003, *before* water levels rise in the Bremer. One possible explanation is that this is due to River Murray water that was pumped into the aquifer as part of local Aquifer Storage and Recharge schemes. Eleven ASR sites lie within the ABPWA (Figure 1).

About 1km from the Angas, at each of sites P and N, the water levels in the confined aquifer did not change when the water levels changed in the Bremer.

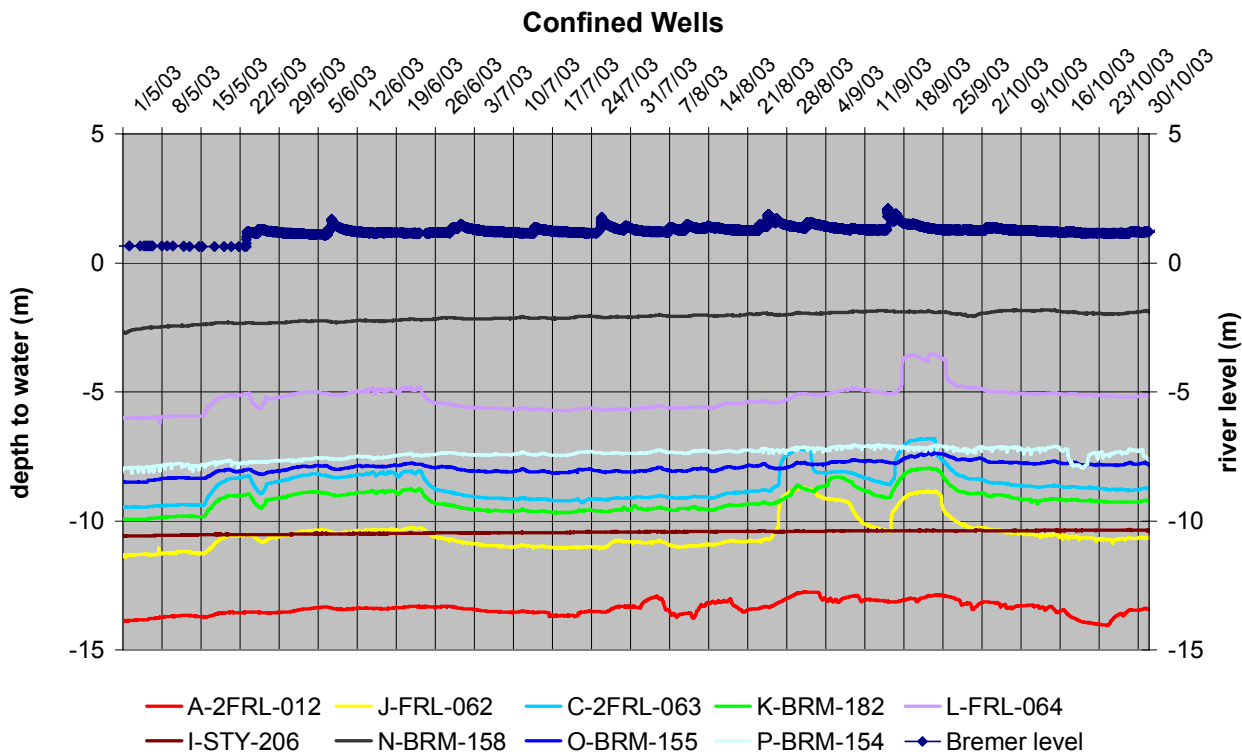


Figure 8: Confined aquifer levels and Bremer River level, May-November, 2003.

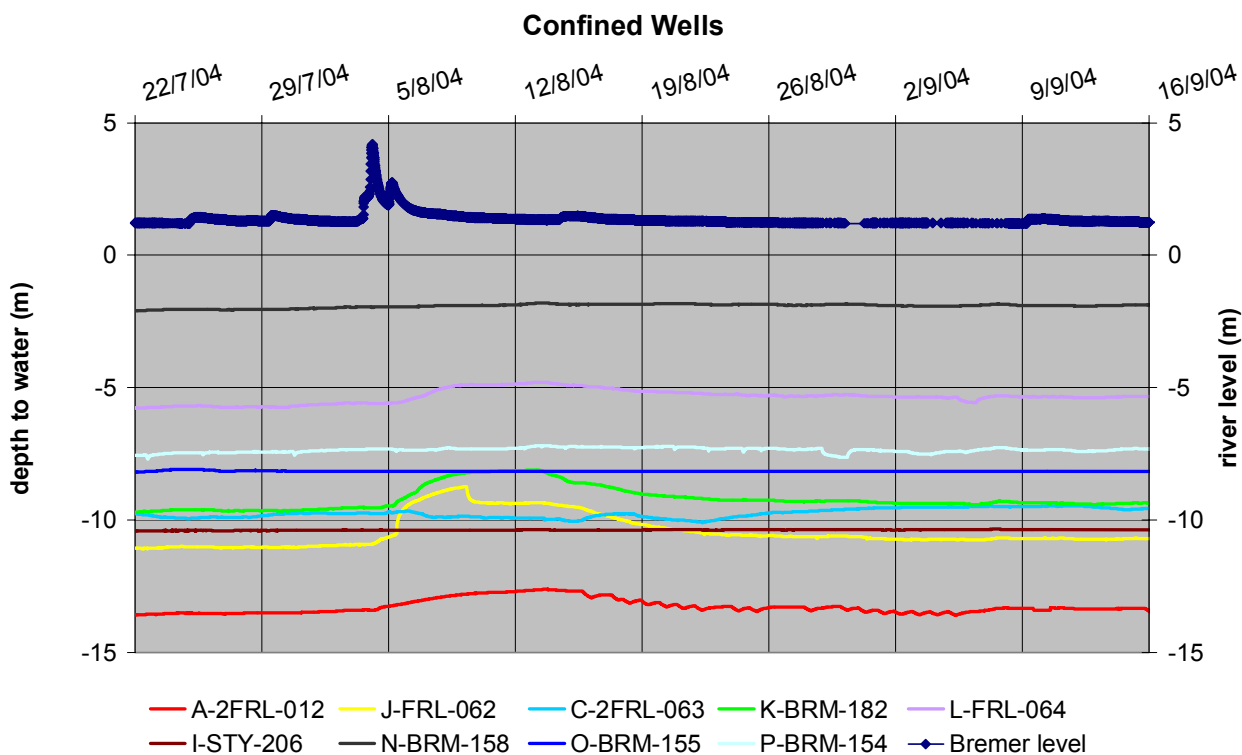


Figure 9: Confined aquifer levels and Bremer River level, August, 2004.

3.5 Unconfined aquifer

Hydrographs showing water levels within the unconfined aquifer are given in Figure 10 and Figure 11 and in Appendix A. Figures A2 and A4 plot unconfined aquifer hydrographs for winter flooding periods in 2003-4 and 2004-5 respectively. Figures A5 to A18 plot hydrographs by site from December 2002 to early 2005; unconfined aquifers are indicated by white lines.

A step pattern of watertable levels is seen at sites C, D, E, F, G and J, i.e. all wells adjacent to the Bremer excepting L (Figure 10 and Figure 11). Sites further away from the Bremer show slower, smoother and lower watertable responses. Along the Bremer, when comparing downstream site L with upstream site J, the unconfined aquifer starts to rise later at L (36 - 44 hrs), rises by a smaller amount (0.4 m less than at J) and rises at a slower rate (5-10 mm/hr at L compared with 12-30 mm/hr at J).

The watertable surface then falls by about one metre over the next month and by a total of 2.5 m (in 2003-4) or 5 m (2004-5) over 12 months (see Figures in Appendix A).

Hydrograph data was available for longer time periods at some sites (not plotted). It could be seen that in years when there is no flow in the Bremer, the surface of the unconfined aquifer falls by about one metre over 12 months. The large flood of December 1992 raised the level of the unconfined by 4 m and the level of the unconfined stayed high for 35 months after the 1992 flood. In 1992, the confined aquifer rose by about 5 m and has remained at or above that higher level ever since.

Recharge to the aquifers from the Bremer causes a mound in the water table. The height of the mound decreases almost linearly with distance from the River Bremer (or River Angas), and extends over a zone 1 600 m wide (Figure 12). The amplitude of the water level rise in the unconfined aquifer peaks beside the Bremer at 5.0 m in 2003-4 and at 3.0 m in 2004-5 and the height decreases with increasing distance from the Bremer. About 800 m to the west of the Bremer, the rise in the unconfined level has reduced to zero. This linear relationship does not hold for site C2, where the change in head is higher than expected. This is due to the fact that C2 lies close to Mosquito Creek in which the creek water levels are linked to and hence they respond quickly to changes in Bremer water levels.

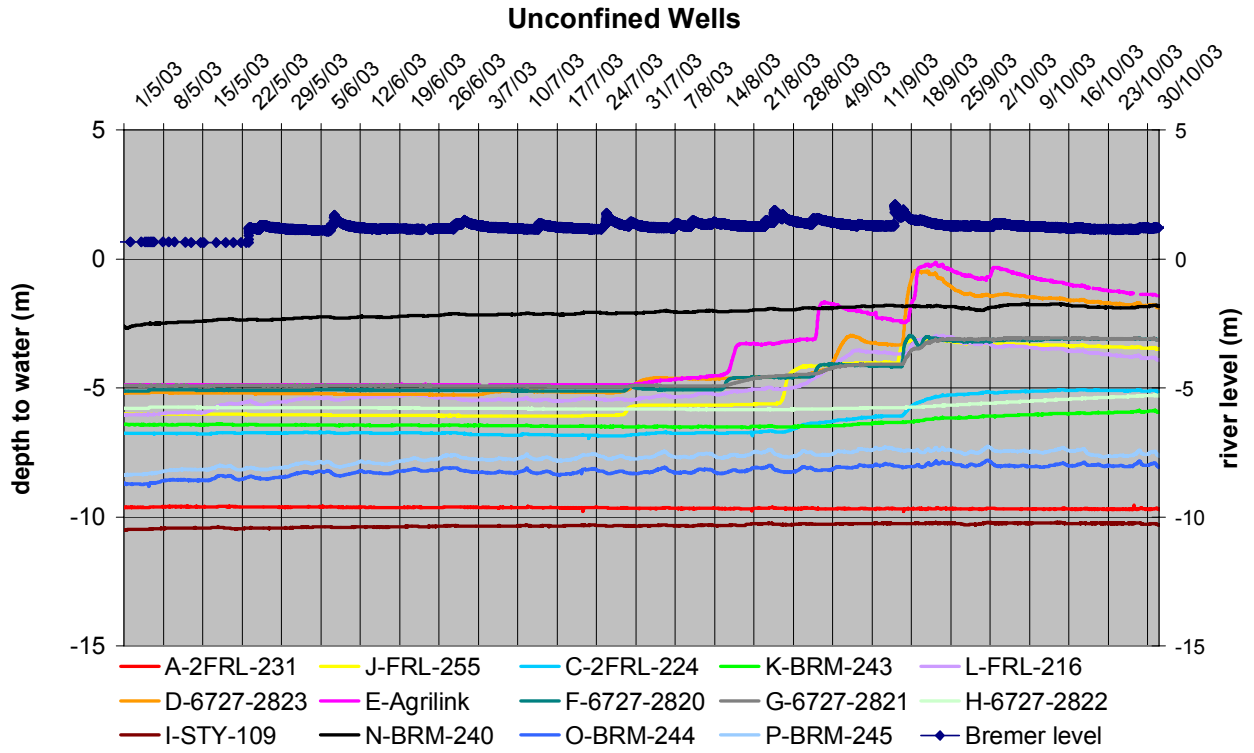


Figure 10: Unconfined aquifer levels and Bremer River level, May–November, 2003.

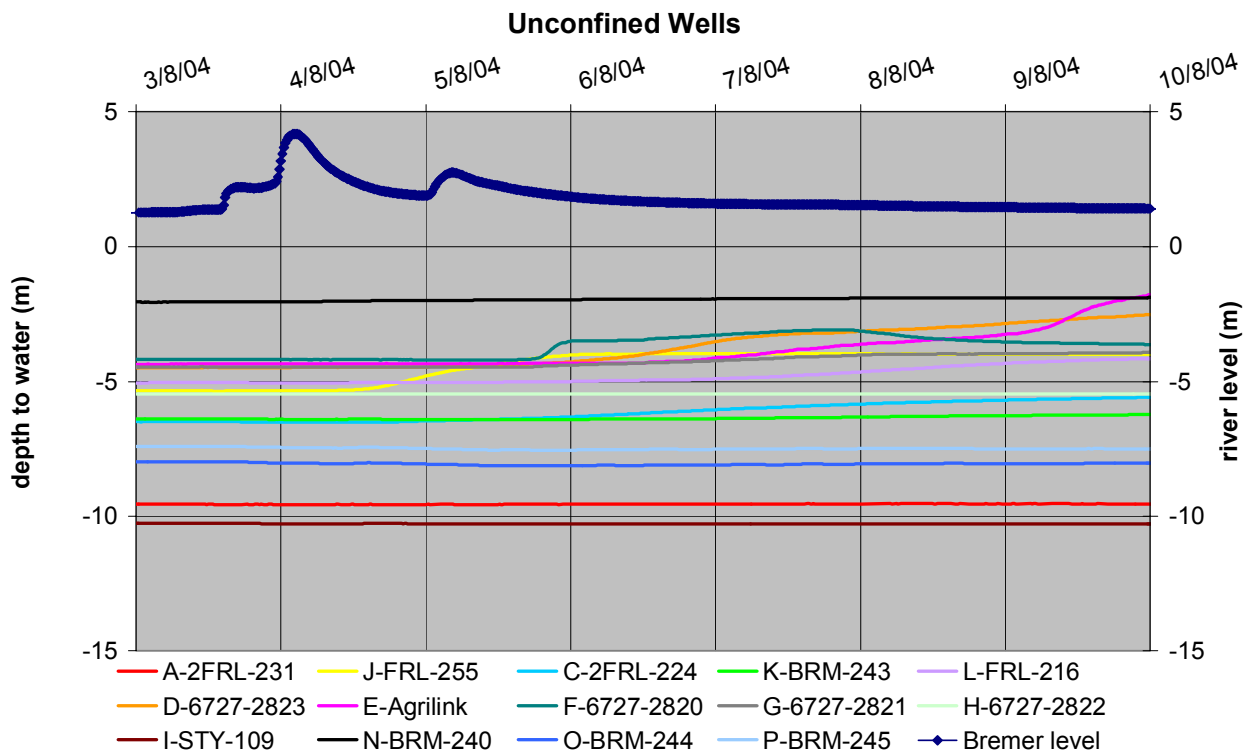


Figure 11: Unconfined aquifer levels and Bremer River level, August, 2004.

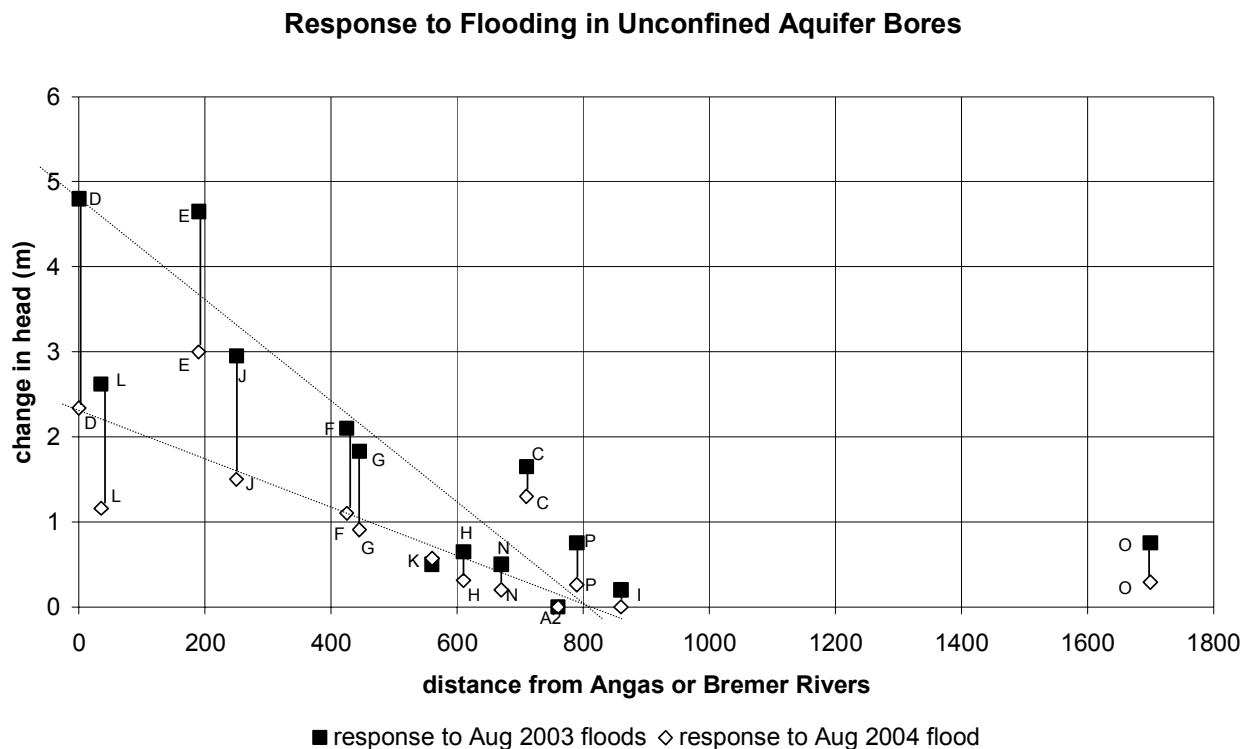


Figure 12: Unconfined aquifer head rise plotted against distance to watercourse.

3.6 Comparison between confined and unconfined aquifers

Plots comparing heads in the unconfined and confined aquifers at each site are given in Appendix A. Figures A1 and A2 show the response of all wells during the 2003 irrigation period; Figures A3 and A4 show the response of all wells during the 2004 irrigation period. Figures A5 to A18 plot well water levels by site from December 2002 to early 2005 (white lines are used for wells in the unconfined aquifer while black lines are used for wells in the confined aquifer).

It can be seen from Figures A1 to A4 that when the Bremer water level rises, water levels rise in the confined aquifer first and then in the unconfined aquifer. At sites where the water level in the unconfined aquifer increases, the rise starts between 2 and 300 hours after the water level starts to rise in the confined aquifer. As the water level in the Bremer falls, the head in the confined aquifer falls quickly (e.g. there is a fall of 1.5m over a week at sites J, K, C) but the level in the unconfined aquifer falls more slowly, gradually returning to its initial level over the following 12 months (a fall of up to 5m).

Close to the Bremer, the amplitude of the water level rise in the unconfined aquifer (3 or 5 m, depending on the year) is larger than the rise in the confined aquifer (2 m).

Based purely on comparisons of head in matched pairs of confined and unconfined observation bores, the aquitard layer separating the two aquifers appears to be present at sites A, C, J and K but not at sites I, N, O or P. Site L on the Bremer and site M on the Angas suggest weak separation between the aquifers at these locations.

At locations where there is presumably no aquitard separating the unconfined aquifer from the confined aquifer (i.e. Sites I, N, O or P), the unconfined level rises and falls almost identically with the confined levels.

At locations where the aquitard separates the unconfined aquifer from the confined aquifer (i.e. Sites A, C, J and K), water levels in the unconfined aquifer move between the same high and the same low levels. Over the 25 years for which we have records, the water level of the unconfined aquifer has not trended either upward or downward (not plotted).

3.7 Soil moisture

Plots of soil moisture at each site are given in Appendix B. The pattern of soil wetting differs in 2003-4 from 2004-5. In 2003-4, rainfall, Bremer flow, rises in the unconfined aquifer level and deep soil wetting occur over several months in a series of steps, primarily in August and September 2003. In 2004-5, watertable rises and deep soil wetting occur only once, starting with a sharp rise in Bremer River levels on 3 August 2004.

Agrilink data from site A shows that soil wetting occurs both from above, through soil infiltration, and from below, as the water level in the unconfined aquifer rises. Wetting from below is seen most clearly at M on the River Angas, where the water table reached the surface in August 2004 (Figure A16 in Appendix A).

Figure 13 and Figure 14 show the date and time when the soil moisture starts to increase at each depth and site, for the key periods of July-August 2003 and August 2004. Increases in soil moisture occur after the level rises in the Bremer at Hartley; the exception to this is at Site A in August 2004, which was irrigated using River Murray water before Bremer levels rose.

Information from Bruce Allnut (Table 2) indicates that soil wetting often occurs *before* controlled winter flooding takes place at a site. As soil wetting at most sites usually begins within the same few days, regardless of when controlled flooding begins, this indicates that the timing of soil wetting may not be due to flooding. It may instead be due to sprinkler irrigation, as many properties draw water from the Bremer for sprinklers when the river levels first rise (Rob Giles, pers. comm.).

Infiltration rates at each of the soil moisture logger sites were calculated using the estimated time of the first increase in moisture at 0.5 m and at 3.0 m and these are shown in Figure 15. The 0.2 m records were not used because the soil often wets at 0.2 m without the water seeping below afterwards. Rates at each site vary from year to year, either due to difficulties in estimation or to the soil's response to different conditions, such as flood ponding depth and the initial level of soil moisture. Estimates range between 0.21 to 2.89 m/d (excepting two outliers of 0 and 30 m/d). The outliers are Site A in 2003-4, as no increase in soil moisture was recorded at the 3m sensor, and Site M on the Angas in 2004-5, as the watertable rapidly rose to wet the soil from below. Loggers failed at site B in 2003-4 and at site L for both study years.

These rates represent averages through the total depth of each site’s soil profile, which should be more representative than rates derived for narrow layers. However, calculations of soil moisture movement from sensor to sensor provide an indication of how particular soil types affect infiltration rates. A presumed clay layer from 3-4m below the surface at Site A slows infiltration to 0.08 m/d in August 2004, while the greatest rate between sensors was recorded in August 2004 at Site C: 48 m/d in sandy loam from 1.5-2.0 m depth. Not all of the calculated rates agreed well with the available soil profile descriptions, as some of the faster rates recorded took place in clay layers. Further studies are needed to establish ways of estimating infiltration rate based on soil profile.

The maximum time for which an area should be flooded will be less than the time taken for water to infiltrate to the bottom of the root zone. Floodwaters ponded for longer than this will recharge the aquifer but be unobtainable to the plant. The maximum time will also depend on the soil type and on the initial water content of the root zone. For a root zone depth of 3m, and conditions as observed in 2003-4 and 2004-5, the time ranges from 1 to 14 days, as shown in Table 3. It is suggested that the higher river levels seen in the Bremer during 2004-5 are more typical and that the 2004-5 times should inform best practice until they can be refined by further work.

	2003-4		2004-5	
<i>Site</i>	<i>first flooding</i>	<i>first wetting at 0.5 m depth</i>	<i>first flooding</i>	<i>first wetting at 0.5 m depth</i>
A-Agrilink	17/07/2003	13/08/2003	4/08/2004	28/04/2004
B	5/09/2003		8/08/2004	5/08/2004
C1	28/07/2003	15/08/2003	4/08/2004	4/08/2004
E	23/8/03*	13/08/2003	8/08/2004	3/08/2004
J	25/08/2003	13/08/2003	4/08/2004	3/08/2004
K	17/09/2003	27/07/2003	7/08/2004	3/08/2004
L	29/08/2003		6/08/2004	3/08/2004
M	none		5/08/2004	3/08/2004

Table 2: Comparison of dates of controlled winter flooding and initial soil wetting

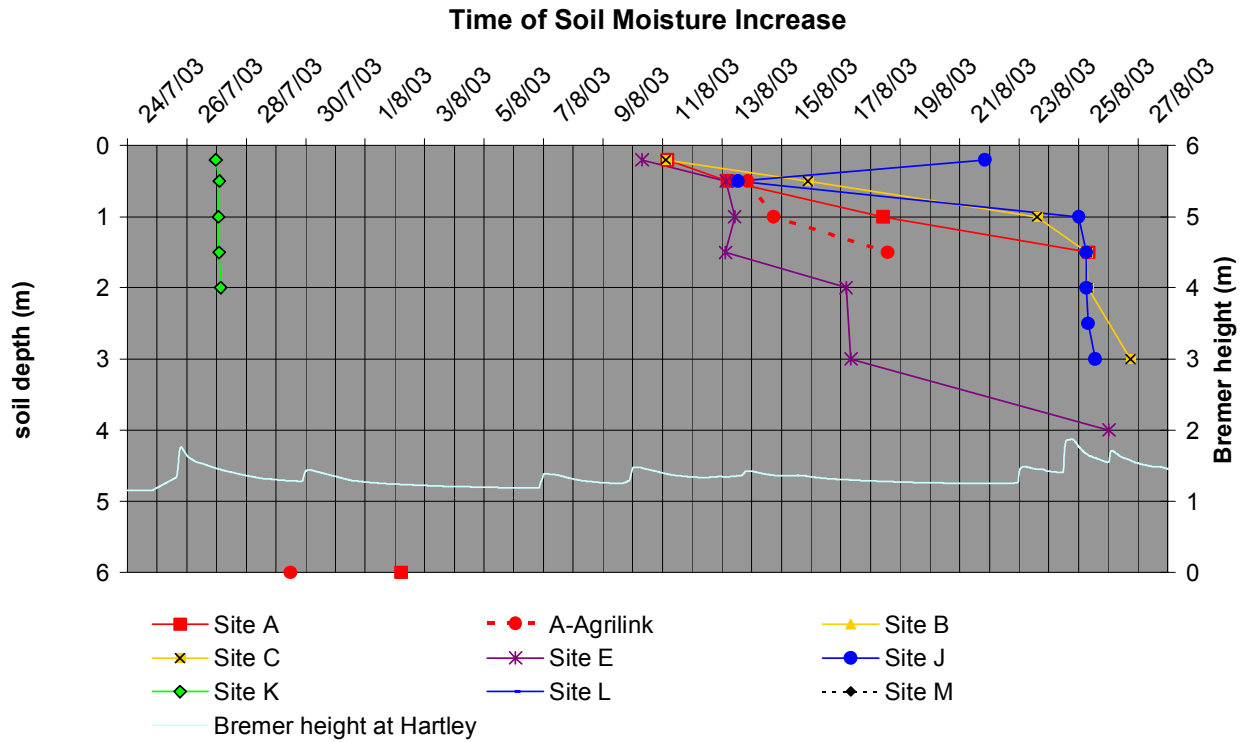


Figure 13: Time of soil moisture increase versus depth, July-August 2003.

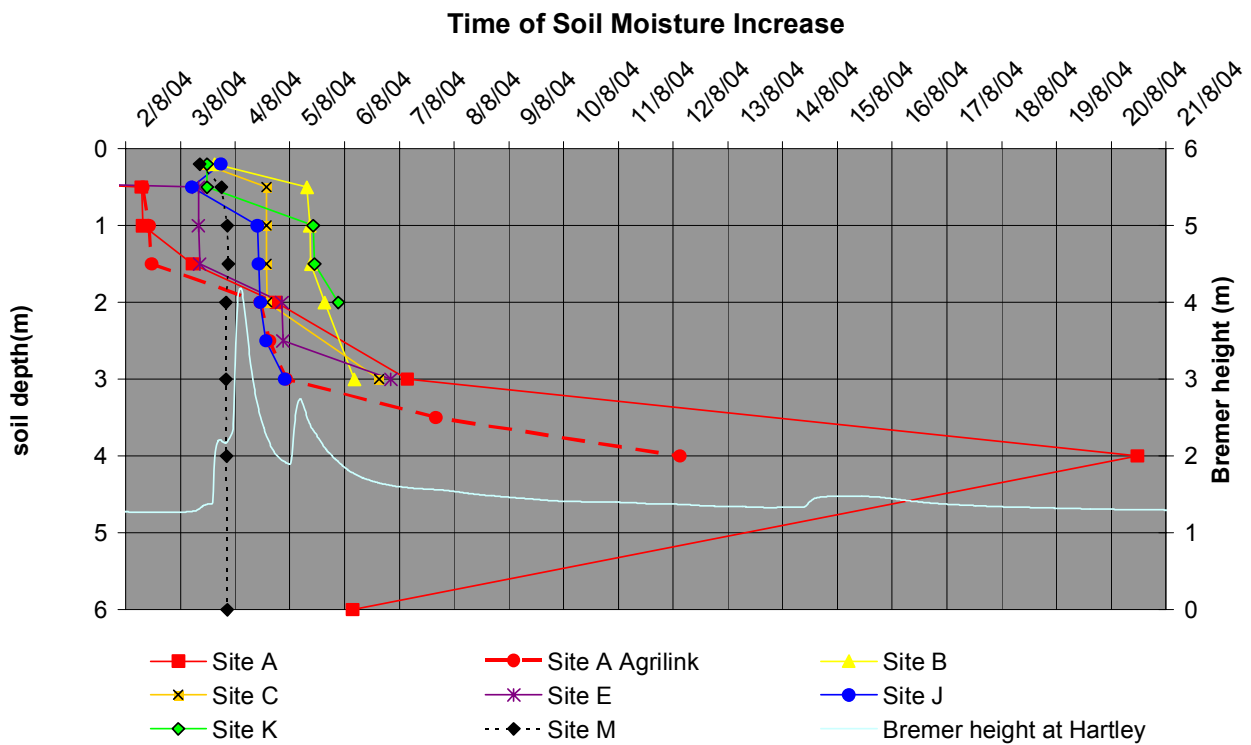


Figure 14: Time of soil moisture increase versus depth, August 2004.

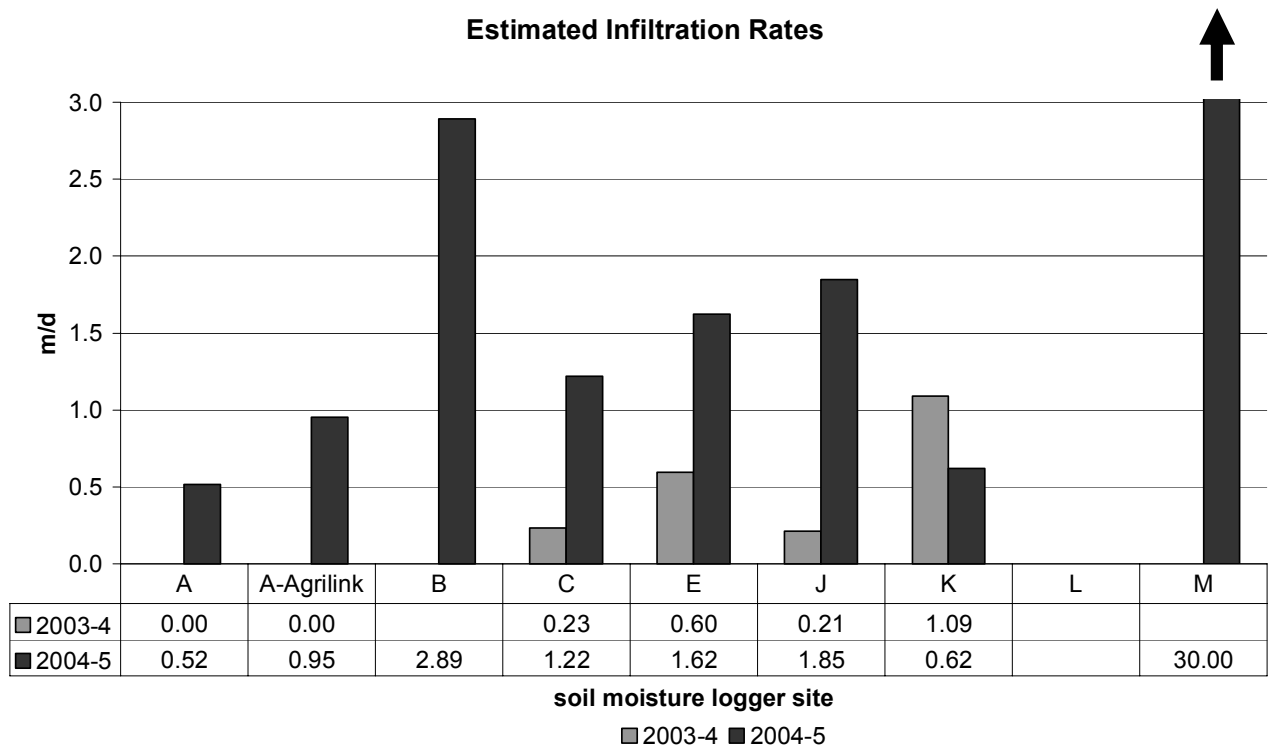


Figure 15: Speed of wetting front from 0.5-3.0m by site and year.

Site	Days until soil moisture increases at 3 m depth	
	2003-4 conditions	2004-5 conditions
A	no increase observed	5.83
A-Agrilink	no increase observed	3.16
B	no data	1.04
C	13.02	2.46
E	5.04	1.85
J	14.14	1.62
K	2.75	4.86
L	no data	no data
M	no data	wet from below

Table 3: Maximum time for ponding of floodwater.

4. Infiltration volume estimation

The calculation of the *total volume of water that reaches the unconfined aquifer due to infiltration below flooded land* relies on estimates of three key parameters, given in Table 4. The tabulated parameters are values that have been rounded from measured extremes. The infiltration rate is estimated using the data given in Figure 15. The effective porosity and the soil retention fraction are derived from studies made at sites A, B and C as reported in Hignett (2003). Effective porosity is taken to be the difference in water cc/cc between suctions of 1 kPa and 10 kPa. Soil retention fraction is the difference in water cc/cc between suctions of 10 kPa and 1 000 kPa.

The calculated infiltration volume is the product of the infiltration rate (m/day), the effective porosity (dimensionless) and the total number of flood hectare-days (Ha-days). The estimated values for the years 1997/8 to 2003/4 are plotted in Figure 16; they vary from 0.02 to 26.89 GL, depending on the assumptions made and the number of flooding hectare-days.

Property	Unit	Low infiltration case	Most likely infiltration case	High infiltration case
Infiltration rate	m/d	0.20	1.10	3.00
Effective porosity	--	0.05	0.10	0.15
Soil retention fraction	--	0.20	0.12	0.05

Table 4: Estimated properties used for infiltration volume estimation.

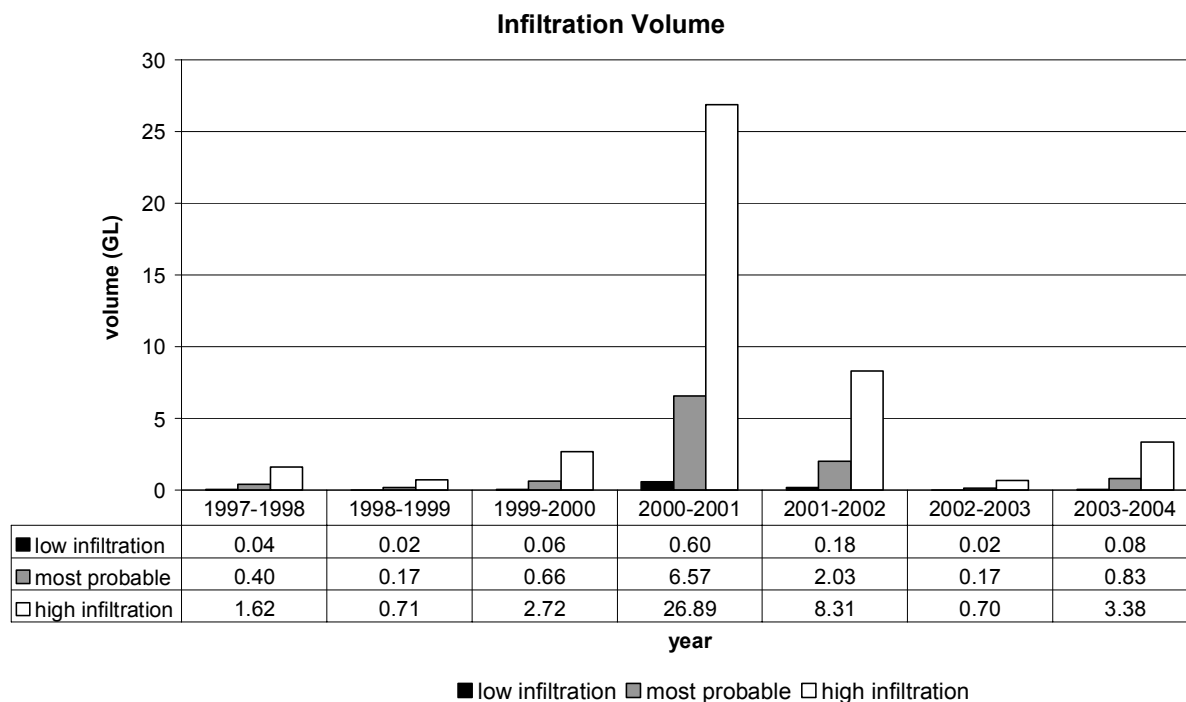


Figure 16: Infiltration volume

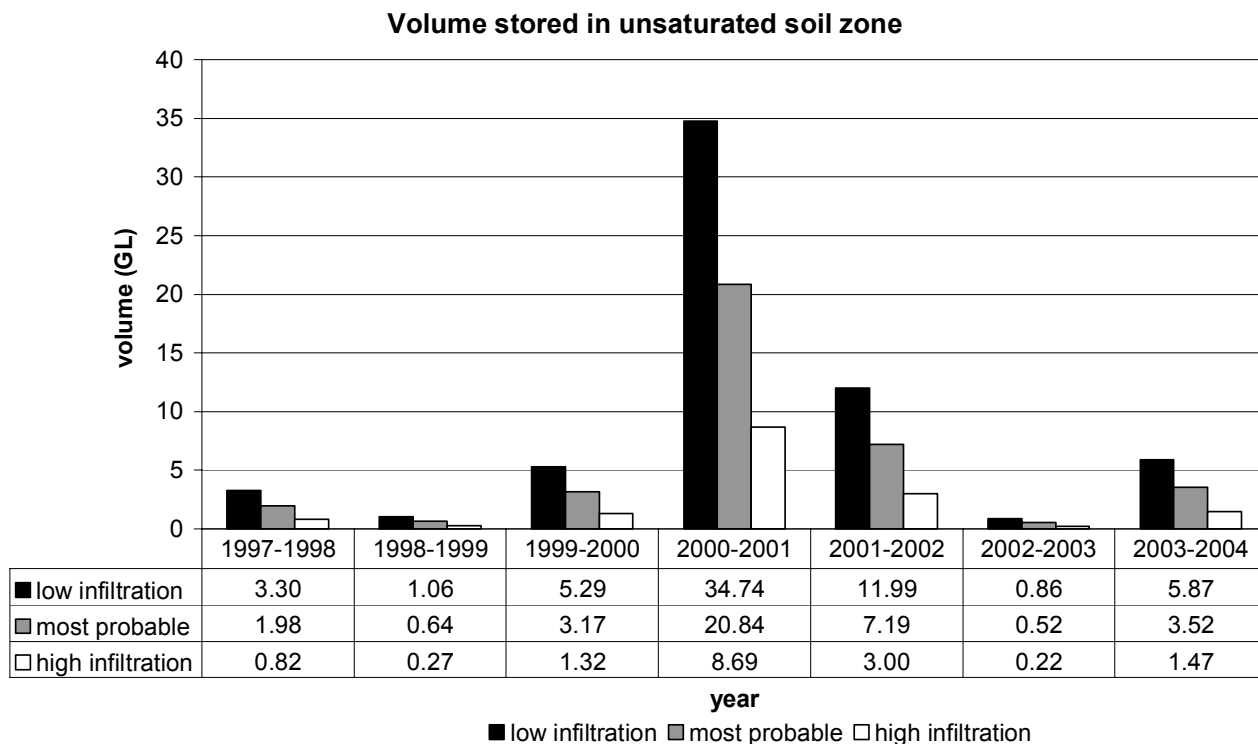


Figure 17: Maximum volume stored in the unsaturated zone of the soil.

The *maximum volume that can be stored below flooded areas and above the watertable in the unsaturated zone soils* is also estimated. This storage volume is the product of the soil retention fraction, an assumed depth to water of 5 m, and the total number of flooded hectares. The storage volume is plotted in Figure 17 and ranges from 0.22 to 34.74 GL depending upon the assumptions and the year.

Water can also move into the unconfined aquifer laterally from the flooding rivers, as well as vertically as infiltration below the flooded land. The combined, total impact of both lateral and vertical recharge processes can be estimated by calculating *the additional volume observed in the unconfined aquifer after a flood*. As seen in Figure 12, the rise in head at the river during 2003-4 was approximately 4.8 m and this decreased almost linearly with distance in a region 800 m to each side of the Bremer. Assuming that this rise is observed over the roughly 4 km stretch where controlled winter flooding is recorded, the additional volume is then 0.5 x 1600 m x 4.8 m x 4000m x effective porosity, where the effective porosity is assumed to range from 0.05 to 0.15. This yields a total volume increase in that area of 0.77 to 2.3 GL, depending on the porosity chosen. (Flooding at the Angas River is not included as most of the controlled winter flooding occurs on the Bremer.)

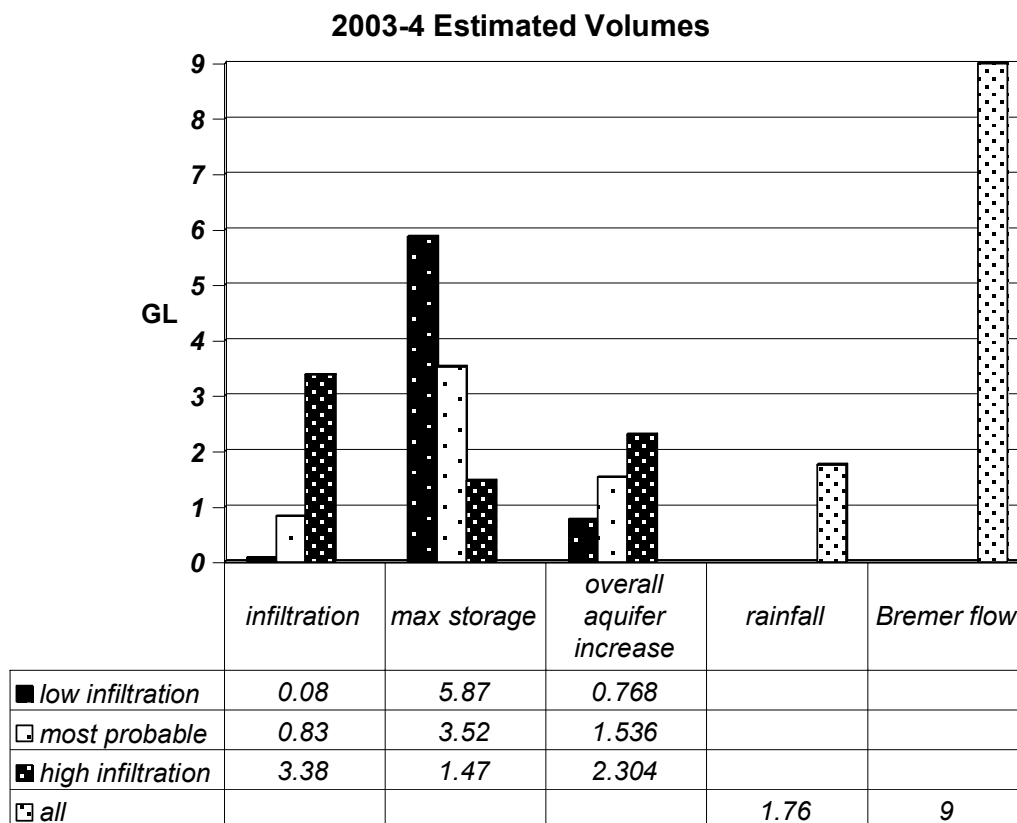


Figure 18: Estimated volumes for 2003-4 for the 4 x 1.6 km region of controlled winter flooding adjacent to the River Bremer.

The various volume estimates for 2003-4 in this 4 km x 1.6 km region are plotted in Figure 18 along with cumulative flow in the Bremer and an estimate of rainfall. The low-infiltration case suggests that vertical infiltration through the floodplain (0.1 GL) is an eighth of the total increase in aquifer volume (0.8 GL); i.e. that most of the aquifer recharge occurs through lateral movement from the Bremer. The “most probable” case suggests that vertical infiltration (0.8 GL) accounts for slightly more than half the overall increase in aquifer volume (1.5 GL). The high-infiltration case may over-estimate the vertical infiltration volume (3.3 GL) as it is greater than the estimated total increase in aquifer volume (2.3 GL). All volume estimates are less than the total flow in the Bremer, as would be expected.

5. Conclusions

Based on analysis of the available data as detailed in this report, the following conclusions can be made:

- The area of land covered by the floods during the period 1998/99 to 2003/04 varied enormously from 86 ha in 2002/03 to 3 474 ha in 2000/01. The area flooded is generally determined by the volume of flow in the Bremer River, and presumably the Angas River.
- The area flooded (ha) multiplied by the days of flooding on each property is summed over all properties to provide a unit (ha.days) for analysis of this data. This parameter ranges from 155 ha.days for the 2002/03 flood to 5 976 ha.days for the 2000/01 flood.
- Based on the soil moisture logger data and on the number of flooded hectares, estimates of the infiltration (or recharge) volume to the unconfined aquifer during the 2003/04 flood range from 0.08 GL to 3.38 GL, depending on the parameter values assumed for infiltration rate and for porosity. Average parameter values result in an estimate of 0.83 GL.
- An alternative method of calculating the flood recharge volume to the unconfined aquifer is through analysis of the locations and magnitudes of unconfined aquifer hydrograph responses. This method provides an estimated recharge volume from the 2003/04 flood of 0.77 GL to 2.30 GL, depending on assumed aquifer porosity.
- The above supports the conclusion that a flood recharge volume of 1 to 2 GL occurs under the conditions seen in 2003/04, although it is expected that this value will vary greatly depending on the number of ha.days, on the flood characteristics and on the assumed porosity values for both the unsaturated zone and the unconfined aquifer.
- the fraction of the flood-recharge that infiltrates down through the soil that is directly below the flooded land is estimated to be 10 to 54% of the total flood recharge.
- Additional monitoring during future flood events is required to determine the relationship between flood characteristics and estimated recharge volume.
- Estimates have been made of the maximum time for which flood water should be ponded on an area (defined as the time taken for water to infiltrate to the bottom of the root zone) and this will depend on the soil type and initial water content of the root zone. For a root zone depth of 3m, and the conditions as observed in 2002-3 and 2003-4, the ponding time ranges from 1 to 14 days.

6. References

Australian Water Environments (2005). *Angas Bremer Prescribed Wells Area Hydrogeological Review and Investigations – Phase II*. Report for River Murray Catchment Water Management Board, 2005.

Hignett, Cliff (2003). *Soil Physics of the Angas-Bremer Catchment*. Soil Water Solutions, April 2003.