Assessment of salinity management options for the Brymaroo catchment, South-eastern Queensland

Chris Smitt, John Doherty, Warrick Dawes, Glen Walker
Assessment of salinity management options for the Brymaroo catchment, South-eastern Queensland

Chris Smitt, John Doherty, Warrick Dawes, Glen Walker
Acknowledgements

This work was funded under the Murray-Darling Basin Commission funded Strategic Investigations and Education projects (Si&E) Grant Number D9004: ‘Catchment characterisation and hydrogeological modelling to assess salinisation risk and effectiveness of management options’. Special thanks to the members of the Project Steering Committee for advice and feedback.

The authors acknowledge the advice and assistance of Dave Free, Ian Gordon, Bruce Pearce, Michael Jamieson, Ed Power and Adrian McKay, all from the Queensland Department of Natural Resources (QDNR), and Queensland Department of Primary Industries (QDPI).

Special thanks to Bob Schuster from CSIRO Land and Water for his work on the figures presented in this report. We also acknowledge Ray Evans, Salient Solutions Australia Pty Ltd, and Ian Gordon, QDPI, for their time taken to review this report. Editorial support was provided by Pauline English and Mat Gilfedder (CSIRO Land and Water).
Executive summary

Introduction

This study of the hydrogeological factors influencing salinity in the Brymaroo catchment in south-eastern Queensland, Australia, was undertaken to:

1. clarify the hydrogeological processes operating within the catchment and thereby understand the causes of salinisation in the lower catchment
2. quantify the relationship between these processes by incorporating them into a groundwater model of the catchment
3. use this model to test the efficacy of different salinity management strategies
4. establish the suitability of this catchment to act as a benchmark for other catchments within the same classification.

Figure (i): Location of Local Groundwater Flow Systems in Basaltic Fractured Rock in the Murray-Darling Basin.
Site description

Brymaroo catchment is located approximately 50 km north-west of Toowoomba in south-eastern Queensland. It covers an area of 14 km² of which approximately four per cent appears to be salinised. There are minor drainage lines within the catchment with the majority of these occurring in the northern half. Rainfall appears to be evenly distributed across the months with only slightly more rainfall occurring in the warmer months, between November and March. The mean annual rainfall is approximately 670 mm. The dominant land use within the catchment is grain cropping.

Groundwater system

The Brymaroo catchment falls within the ‘Tertiary Rocks’ hydrogeological province, and has been identified as having local flow systems in basaltic fractured rock aquifers. The main groundwater system of interest within the Brymaroo catchment is the transmissive Tertiary basalt aquifer that underlies the majority of the catchment. Land salinisation results when groundwater passes through these rocks and is impeded by a bedrock high, at 1-10 m below the ground surface, of less permeable Walloon Coal Measures. Groundwater pressures rise at this point and discharge to the surface occurs as a consequence.

Groundwater flow directions indicate that the Brymaroo catchment is a self-contained groundwater catchment independent from regional groundwater flow systems to the south. Groundwater in the Brymaroo catchment flows in a northerly direction, originating from the elevated areas of basalt in the south and moving towards Cain Creek in the north. Most of the discharge occurs in the northern half of the catchment, in the topographically low area approaching Cain Creek, where the influence of evapotranspiration processes is particularly intense.

Groundwater modelling

The FLOWTUBE model, a simple groundwater model based on Darcy’s Law, was used to simulate the effect of variation in groundwater recharge on the groundwater flow system. The modelling results suggest that, under native vegetation, areas of shallow watertable existed in the middle portion of the catchment while parts of the aquifer in the upland catchment had no permanent groundwater. These results are similar to those modelled by Jamieson (pers. comm. 2001) where a MODFLOW model was designed for a Queensland Department of Natural Resources (QDNR) investigation in the area. Under present land use there is a significant spread of groundwater discharge in the centre of the catchment, which agrees closely with the currently mapped outbreaks of salinity.

The model was used to simulate watertable levels 20 years into the future, based on two scenarios of recharge reduction. The first, a 50% reduction in recharge showed minor changes in the watertable within the vicinity of the salt affected area and a much more substantial impact is made from a 90% reduction in recharge.

Portability of conceptual model, tools and results

For the Brymaroo catchment—and analogous catchments—the response time for the groundwater system to initially respond to a change in land use is likely to be fairly rapid since highly transmissive basalts characterise this area. This understanding is likely to be valid across a wide range of catchments of this geological and geomorphological type although the bedrock high of Walloon sediments influencing the Brymaroo catchment is a distinctive feature in this particular catchment.

The FLOWTUBE catchment-scale groundwater model proved to be suited to this catchment type and it is expected to perform well in other catchments of the same type, provided that a minimum quality data set is available. This includes groundwater parameters such as watertable elevation, aquifer thickness, hydraulic conductivity and the areal extent of the groundwater system.

The groundwater modelling results indicate that the Brymaroo catchment’s groundwater system is full and that biological intervention will be needed for salinity control. Catchments with similar topography, geology,
Conclusions

Brymaroo catchment is relatively responsive to changes in the water balance, and the expansion of secondary salinity as a result of clearing of the catchment has largely approached an equilibrium state. Further spread of salinisation is expected to be minimal if current land use is maintained.

Decreases in the area of salinised land within ten to 30 years can be expected in response to decreases in recharge.

- For a 50% recharge reduction, the simulation predicts that in the upper parts of the catchment, groundwater levels may fall by up to 5 m after 20 years, therefore slightly reducing the amount of salinised land within the discharge zone.

- For a 90% recharge reduction, the simulation predicts the watertable to fall by as much as 7 m in the upper parts of the catchment after 20 years. However, the amount of water discharging would only be slightly less than the amount discharging from the 50% recharge reduction simulation. Reintroducing woody vegetation over the majority of the catchment would probably bring about a recharge reduction of this magnitude.

However, it must be noted that because of the geological nature of Brymaroo catchment, saline discharge may never be completely attenuated as it is possible that there was a small area of natural saline discharge in the catchment prior to clearing taking place. Reductions in recharge will only help decrease the pooling of water (and hence the area of salinised land) behind the basement high of Walloon Coal Measures.
# Table of contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acknowledgements</td>
<td>i</td>
</tr>
<tr>
<td>Executive summary</td>
<td>ii</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Background</td>
<td>2</td>
</tr>
<tr>
<td>1.2 Aims</td>
<td>2</td>
</tr>
<tr>
<td>2. Site description</td>
<td>3</td>
</tr>
<tr>
<td>2.1 General</td>
<td>3</td>
</tr>
<tr>
<td>2.2 Climate</td>
<td>3</td>
</tr>
<tr>
<td>2.3 Geology</td>
<td>4</td>
</tr>
<tr>
<td>2.4 Hydrogeology</td>
<td>7</td>
</tr>
<tr>
<td>2.5 Soils</td>
<td>8</td>
</tr>
<tr>
<td>2.6 Land use</td>
<td>9</td>
</tr>
<tr>
<td>2.7 Salinity extent</td>
<td>9</td>
</tr>
<tr>
<td>2.8 Geomagnetic profiles</td>
<td>10</td>
</tr>
<tr>
<td>2.9 Piezometric levels</td>
<td>11</td>
</tr>
<tr>
<td>2.10 Groundwater geochemistry</td>
<td>14</td>
</tr>
<tr>
<td>3. Conceptual model</td>
<td>15</td>
</tr>
<tr>
<td>3.1 Hydrogeology</td>
<td>15</td>
</tr>
<tr>
<td>3.2 Recharge</td>
<td>16</td>
</tr>
<tr>
<td>4. Groundwater modelling</td>
<td>16</td>
</tr>
<tr>
<td>4.1 Description of the model</td>
<td>16</td>
</tr>
<tr>
<td>4.2 Catchment and aquifer description</td>
<td>17</td>
</tr>
<tr>
<td>4.3 Calibration and parameterisation of the model</td>
<td>17</td>
</tr>
<tr>
<td>4.4 Groundwater modelling simulation and results</td>
<td>18</td>
</tr>
<tr>
<td>5. Discussion</td>
<td>21</td>
</tr>
<tr>
<td>5.1 Assessment of salinity management options</td>
<td>21</td>
</tr>
<tr>
<td>5.2 Portability of conceptual model, tools and results</td>
<td>22</td>
</tr>
<tr>
<td>6. Conclusions</td>
<td>24</td>
</tr>
<tr>
<td>7. References</td>
<td>25</td>
</tr>
<tr>
<td>8. Appendix 1</td>
<td>27</td>
</tr>
</tbody>
</table>
1. Introduction

1.1 Background

Dryland salinisation has been increasingly recognised as one of the main degradation issues in southern Australia (MDBMC 1999, PMSEIC 1999). While the magnitude of the problem has been widely accepted, the way to manage the problem has not. This is in part due to the wide range of processes leading to salinisation and in part to the economics of dryland salinity which has not been well linked to biophysical studies. The ways to best target funding and skills for salinity management will depend on the attractiveness of various options. These will vary nationally with the geology, agricultural systems, climate and intrinsic environmental and water resource values (Coram et al. 2000). Clearly there is a need to compare options for various catchments in an objective fashion to determine how and where to focus efforts.

The National Land and Water Resources Audit (the Audit) has the goal of providing nationwide assessments of Australia's land, vegetation and water resources, to support sustainable development now and in the future, with an emphasis on rural and remote Australia. The Audit's Strategic Plan aggregates these natural resource issues into seven themes, each with its own work plan. The Dryland Salinity Theme of the Audit (Theme 2) is comprised of five distinct projects that address the current extent and predicted future risk of dryland salinity, the impact of land use practices on dryland salinity, and possible land management options.

Within Project 3 of the Dryland Salinity Theme, a basis for evaluating land use changes and land management options for salinity reduction in key Australian landscapes was developed. This was achieved by:

- developing a consistent analytical framework for evaluating costs, benefits and recharge and salinisation response at the catchment scale for a range of land use and management options
- testing this framework for selected representative catchments
- proposing methods for extrapolating the results to develop an understanding of the implications of broad-scale land use change and land management changes. This includes the need for interventions and the development of resource protection policies.

An important component of the cross-sectional approach used in Project 3 was the choice of case studies representative of key Australian landscapes prone to secondary salinisation. The choice was made on the basis of the Australian Groundwater Flow Systems framework (an extension of the National Catchment Classification) developed for salinity management (Coram et al. 2000). This hydrogeological framework aggregates catchments with similar groundwater processes and for which management options are expected to be similar. The framework is based on geology, geomorphology, spatial extent of flow system (local, intermediate, and regional) and other factors that are known to influence salinity occurrence. In total, seven case studies were chosen to provide a national cross-section of the 11 Groundwater Flow Systems identified by this framework. Four of these catchments (one case study each from four states, New South Wales, Victoria, South Australia and Western Australia) were studied within the Audit and the three remaining catchments are being studied within the Murray-Darling Basin Commission (MDBC) Catchment Characterisation project.

The selected four catchments for the Audit case studies were: Upper Billabong Creek, New South Wales (Baker et al. 2001), Kamarooka, Victoria (Hekmeijer et al. 2000), Lake Warden, Western Australia (Short et al. 2000) and Wanilla, South Australia (Stauffacher et al. 2000). Apart from being representative of different groundwater flow systems, more data is available for these case study catchments compared to most other catchments, and they are considered priority catchments for salinity investigation by state agencies.
The Catchment Characterisation Project was developed in an attempt to bring about informed decision making and integration of catchment management. The project aims to classify types of catchments, their salinity risk status, the management options available to the catchment community and the opportunities for risk reduction. The project uses catchments that have been studied within the Audit and the classification scheme of Coram (1998), as well as identifying and reporting on areas that may not be well-represented in the above classification schemes. Brymaroo is one such catchment.

The choice of salinity management options is dependent on an understanding of the groundwater system. Hence, a crucial part of the project is groundwater analysis and development of a conceptual model of the groundwater system of respective catchments. This was conducted using available hydrogeological analyses, bore logs, and simple water balances. The resultant conceptual model was then developed into a mathematical groundwater model. This was to provide a predictive framework from which to assess various management options. Finally, effective salinity management options depend on technical options being available. Biological recharge control is only possible if appropriate agronomic and agroforestry options are available for a given area that result in a reduction of recharge to a level that mitigates salinisation.

1.2 Aims

The aims of this investigation in Brymaroo Catchment were:

1. to elucidate the hydrogeological processes operating within the catchment and thereby understand the causes of the salting in the lower catchment
2. to quantify the relationship between these hydrogeological processes by simulating them using a groundwater model of the catchment
3. to use this model to test the efficacy of different salinity management strategies.

The hydrogeological information base for this catchment was extended from the work program undertaken by Queensland Department of Primary Industries (QDPI) in the early 1990s.
2. Site description

2.1 General

Brymaroo catchment is located approximately 50 km north-west of Toowoomba in south-eastern Queensland. It covers an area of 14 km² of which approximately four per cent is salinised. Cain Creek defines the northern boundary of the catchment follows. Figures 1 and 2 show an aerial view of the catchment with topographic contours and the catchment divides superimposed.

Surface run-off is to northward from the southern slopes. No clear drainage lines are present in this southern part of the catchment. The main stream in the catchment is Cain Creek, which drains a larger catchment to the north and east of Brymaroo. Only indistinct drainage lines occur along the floodplain adjoining Cain Creek.

2.2 Climate

The annual mean rainfall in the Brymaroo catchment of approximately 670 mm has been derived from daily rainfall records at the township of Oakey, 20 km to the south. Rainfall appears to be evenly distributed across the months with only slightly more rainfall occurring in the warmer months, between November and March. However, episodic recharge events are not uncommon in this area. Average class A pan evaporation for Oakey is 1900 mm/yr.

Figures 3 and 4, provided by the Bureau of Meteorology, show the mean monthly rainfall and the mean monthly temperature, respectively at the Oakey Aerodrome.
2.3 Geology

Three geological units are present in the study area:

1. the Tertiary Main Range Volcanics
2. the Jurassic Walloon Coal Measures
3. recent Alluvial Sediments

Brymaroo catchment is dominated by outcropping basalt on the hills and higher slopes in the south, with the recent alluvial sediments occurring throughout the floodplain of Cain Creek. The Walloon Coal Measures do not outcrop within the catchment.

Whilst in the upper part of the catchment there is a small exposure showing the extent of fracturing of the basalt, there is insufficient exposure elsewhere to map the aerial extent, density and main orientations of fracturing. Small outcrops of tuffaceous material can be found on the hills to the west of the catchment.

While the Walloon Coal Measures do not outcrop, their presence has been revealed in boreholes within the study area. Figure 5 shows the location of bores that were drilled prior to the investigation carried out by Doherty and Stallman (1992).

Where the Walloon Coal Measures were the only formation encountered, the bore is marked with a ‘W’. Where basalt was the only formation encountered, a ‘B’ is displayed next to the bore location. Where basalts were found to overlie mudstone and sandstone (presumably the Walloon Coal Measures) the bore is labelled, for example, ‘B-W30’ where the number represents the depth (in metres) at which the unit was intersected.
It is apparent from Figure 5 and the outcrop pattern that basalts underlie most of the higher slopes. However, the extent of the Walloon Coal Measures, particularly beneath the low ground, near the visually effected saline areas, is not clearly defined, nor is the contact between the basalt and the Walloon Coal Measures. From investigations of occurrences of salinity elsewhere in the Darling Downs, this boundary is considered to be hydrogeologically significant (Shaw et al. 1987, Thorburn et al. 1986).

As part of Queensland Department of Primary Industries (QDPI) investigations in the early 1990s, several holes were drilled within the northern third of the catchment in order to obtain a more informative picture of the hydrogeology around the areas affected by waterlogging and salinity as well as to infer the extent of the Walloon Coal Measure/Basalt boundary. Drill-hole locations are shown in Figure 6.
The following interpretation has been adopted from Doherty and Stallman (1992). While hole BRY5 encountered mudstone of the Walloon Coal Measures at a depth of 10.8 m under recent alluvium, BRY6A, which was drilled to 8 m, encountered only modern alluvium. In BRY9, mudstone underlies 7 m of soil, clay and weathered basalt. None of these holes yielded much water under airlift.

Holes BRY3, BRY12 and BRY15 encountered what appears to be an old stream channel within the recent alluvium. In places, gravel bands that include basalt fragments up to 5 cm in length, were encountered. Groundwater flows of about 2–3 L/s were airlifted from BRY12 and BRY15. This was not the case for BRY3 in which the alluvium was consistently more fine-grained (though some coarse basalt gravel was intersected at the bottom of the hole). The Walloon Coal Measures were encountered at depths of 11 m and 12 m respectively in holes BRY12 and BRY15.

BRY8, BRY10 and BRY14 encountered basalt throughout their entire depths of 14 m, 8 m and 20 m respectively. BRY8 appears to be an excellent water producer. Immediately after being drilled, it was pumped at approximately 4 L/s for three quarters of an hour with minimal resultant drawdown.

Holes BRY1 and BRY2 both encountered soft and porous tuff. In both cases, approximately 2 L/s could be airlifted.

2.3.1 Walloon Coal Measures

The following descriptions of the Walloon Coal Measures and the Main Range Volcanics have been sourced largely from Free (1989).
The Walloon Coal Measures consist of grey mudstone, siltstone, fine-grained labile sandstone, coal seams and minor limestone. Cranfield et al. (1976) interpret lacustrine and paludal depositional environments for the facies.

The Walloon Coal Measures lie unconformably on the Jurassic Marburg Formation which crops out to the east of the Main Range Escarpment in the form of fine grained labile and quartzose sandstone.

On the basis of plant microfossils, various authors, including Cranfield et al. (1976), have placed the age of the Walloon Coal Measures at Middle to Late Jurassic.

In the study area, the Walloon Coal Measures underlie the Tertiary volcanics and are exposed as a small inlier of sub-horizontal fine-grained sandstone and shale in the bank of Spring Creek, see Figure 1.

2.3.2 Main Range Volcanics

The Main Range Volcanics consist of volcanic and pyroclastic rocks of Oligocene to Miocene age (Stevens 1965) and form that part of the Great Dividing Range from Wilson’s Peak on the New South Wales Border, north through Toowoomba to the Bunya Mountains, Queensland.

In the Toowoomba area the Main Range Volcanics extend about 45 km west of the Main Range Escarpment. Their original extent may have been greater. Erosion associated with the development of the Condamine River drainage system may have removed significant areas of volcanics.

Stevens (1965) divided the Main Range Volcanics into a lower half consisting largely of alkali basalt and pyroxene trachyte, with up to three horizons of leuco-trachyte and breccia. The upper part of the formation is largely olivine basalt with two acid intermediate members near the New South Wales border. Cranfield et al. (1976) also sub-divided the Main Range Volcanics into lower and upper units of approximately equal thickness. The lower parts comprise basalt with intercalations of leucocratic trachyte and trachyte to rhyolitic breccia, while the upper part consists predominately of olivine basalt. They also suggest that the Main Range Volcanics were extruded onto an early Tertiary land surface of moderate to rugged relief. The Gomaren Basalt Member and the Cooby Trachyte Member (Stevens, 1969) filled old valleys cut into the Mesozoic surface. The later extrusions, the Toowoomba Volcanics, were largely from fissures and vents along and just east of the present escarpment and forms a sub-horizontal lava plain Dimmick (1951).

2.4 Hydrogeology

There is very limited groundwater information describing the hydrogeological character of the catchment. However, it is known that an extensive unconfined groundwater system contributes to an accumulation of water in the northern half of the catchment. Examination of drill logs and auger holes in the middle of the catchment (i.e. in the vicinity of the salt affected areas) indicates the presence of an east-west trending ridge of relatively impermeable shales of the Walloon Coal Measures. As a result, groundwater discharge occurs in this area in response to the permeability change. During times when the system becomes fully saturated and groundwater accumulates behind the ridge of Walloon Coal Measures, either the hydraulic head drives groundwater discharge directly to the ground surface or groundwater is transferred through the soil profile to the surface by capillary action. Both hydraulic heads and recharge rates in the upland basalts would have been significantly lower under natural vegetation cover and much smaller volumes of groundwater would consequently have discharged in downgradient parts of the system.

Groundwater levels within the basalts range from 0.5 to 15 m below the surface, where the shallower levels are a consequence of the thinning of the basalt aquifer over the Walloon Coal Measures. Within the alluvial sediments in the northern part of the catchment, depth to groundwater remains shallow, and the watertable surface is comparatively flat, ranging from 1 to 3 m below the surface. From here, the alluvial aquifer discharges groundwater to Cain Creek.
Typical hydrogeological characteristics that are representative of the groundwater system that flows through the different geologic units are:

- **Basalts**: Transmissivity is highly variable, ranging from 225 m²/d to 10 m²/d with the variable aquifer thickness mainly responsible for the change. The hydraulic conductivity ranges from 15 m/d to 2 m/d.
- **Walloon Coal Measures**: Considered impermeable bedrock.
- **Alluvial Sediments**: Transmissivity ranges from between 15 m²/d and 2 m²/d. Hydraulic conductivity is quite low, ranging from 3 m/d to 1 m/d.

The piezometric surface and groundwater flow directions are described below in Section 2.9.

### 2.5 Soils

Soils over most of the study area were mapped by Sellers in 1991 (cited in Doherty and Stallman 1992). The resultant unpublished soils map is summarised in Figure 7.

The predominant upland soils are thin lithosols developed over basalt. Lower in the catchment, overlying basalts and sandstones, are heavy dark-grey to black, calcareous self-mulching clays. Red-brown loams are developed on the alluvium comprising the floodplain of Cain Creek.
2.6 Land use

The dominant land use within the catchment is grain cropping. However, some of the upland parts of the catchment are under perennial pasture.

2.7 Salinity extent

The extent of secondary salinisation in the Brymaroo catchment has been inferred from aerial photos (see Figure 8) whilst minor ground truthing was undertaken in early 2001. The latter involved mapping the observed salt affected land. The main area where saline discharge has expressed itself lies in the northern half of the catchment surrounded by several smaller outbreaks.

Figure 8. Salt affected areas (dotted).
2.8 Geomagnetic profiles

A magnetic survey was undertaken by QDPI to define the boundary between the Walloon Coal Measures and the basalts of the Main Range Volcanics. As basalts contain ferromagnetic minerals, they normally have a strong magnetic response. Details of this survey are documented by Doherty and Stallman (1992).

The geomagnetic data allows the position of the basalt—Walloon interface to be located accurately along the traverse lines. Using this data, together with the geological information from drill holes and outcrop, the inferred position of this interface is shown in Figure 9.
2.9 Piezometric levels

Since the time of drilling in November 1991, water levels in the QDPI drill-holes have been measured intermittently. Other holes, drilled prior to 1991, are also being used for monitoring where water levels are not affected by pumping. Table 1 shows groundwater levels measured over the catchment on 16 January 1992. Figure 10 shows the location of bores represented in Table 1 which were drilled prior to 1991. Water elevations are contoured in Figure 11.

It is apparent from Figure 11 that there is a general downhill gradient and hence flow of water from the higher ground, where recharge is greatest, to the lower ground where waterlogging occurs locally. Water levels are locally high in parts of the upper catchment. This accords with observations by the landholders that water seeps from the ground at some sites on the hills for weeks to months after the wet season. The occurrence of these local seeps is quite common for predominantly flat-lying basalt layers, such as those in the study area, as the easiest path for water movement is often along vesicular and partly weathered zones occurring near the top of basalt flow units. The unweathered basalt below these zones and within the same basalt flow units may be relatively impermeable.

Thus, water will often flow along subhorizontal transmissive zones until the water intersects the sloping ground surface or some other constriction from where it will seep out as a spring.

<table>
<thead>
<tr>
<th>Bore</th>
<th>Water Depth (m)</th>
<th>Water Elevation AHD (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BRY1</td>
<td>2.75</td>
<td>417.88</td>
</tr>
<tr>
<td>BRY2</td>
<td>1.42</td>
<td>416.52</td>
</tr>
<tr>
<td>BRY3</td>
<td>1.87</td>
<td>413.67</td>
</tr>
<tr>
<td>BRY5</td>
<td>1.80</td>
<td>412.86</td>
</tr>
<tr>
<td>BRY6A</td>
<td>2.73</td>
<td>412.83</td>
</tr>
<tr>
<td>BRY8</td>
<td>0.65</td>
<td>416.54</td>
</tr>
<tr>
<td>BRY9</td>
<td>3.17</td>
<td>412.90</td>
</tr>
<tr>
<td>BRY10</td>
<td>1.25</td>
<td>416.64</td>
</tr>
<tr>
<td>BRY12</td>
<td>1.80</td>
<td>412.55</td>
</tr>
<tr>
<td>BRY13</td>
<td>0.66</td>
<td>414.80</td>
</tr>
<tr>
<td>BRY14</td>
<td>2.82</td>
<td>416.70</td>
</tr>
<tr>
<td>BRY15</td>
<td>1.72</td>
<td>413.63</td>
</tr>
<tr>
<td>19410</td>
<td>14.70</td>
<td>422.07</td>
</tr>
<tr>
<td>19412</td>
<td>7.68</td>
<td>422.63</td>
</tr>
<tr>
<td>19892</td>
<td>4.05</td>
<td>449.95</td>
</tr>
<tr>
<td>19894</td>
<td>6.04</td>
<td>417.81</td>
</tr>
<tr>
<td>83426</td>
<td>6.93</td>
<td>420.33</td>
</tr>
</tbody>
</table>

The water level data recorded in Table 1 and shown in Figure 11 were taken following a prolonged dry period and are, accordingly, unusually low. After a wet season, some of the lower catchment bore water levels are expected to be above ground surface due to the aquifers inability to effectively transmit reasonable quantities of groundwater.

Groundwater flow, as indicated by standing water levels from the bore data, is northward from the basalts in the upland parts of the catchment to the alluvial plain bordering Cain Creek. The piezometric surface essentially parallels the surface topography (shown in Figure 2). However, in the lower catchment the piezometric contour lines (Figure 11) indicate that there are variations in both the direction and gradient of groundwater flow. The topographic high in the north-east corner, along with a drainage line located between BRY5 and BRY9 at the base of this slight slope, causes a small amount of groundwater to flow towards the centre of the catchment before being forced northwards by the main groundwater flow regime. Of interest is the fact that saline discharge occurs where these two groundwater flow paths converge. This suggests that some pooling of groundwater may occur as a result of the latter groundwater flow direction opposing the general northerly trend. This fact alone would not be the only driving mechanism behind the amount of saline discharge seen in this part of the catchment. Importantly, the east-west striking ridge of the Walloon Coal Measures depicted in Figure 9 functions as a constriction and forces northward-flowing groundwater to rise.
Figure 11. Contours of groundwater elevations (m, AHD) within the study catchment as measured on the 16 January 1992. Solid circles show the piezometer locations and the arrows indicate general flow direction.
2.10 Groundwater geochemistry

On the 17 of January 1992 a sample of water was taken from each of the bores as part of an investigation carried out in the Brymaroo catchment by QDPI. Each sample was analysed for the common cations and anions and its electrical conductivity (EC) was measured. The results are summarised below and can be viewed in full in Doherty and Stallman (1992).

The EC (in dS/m) levels of each water sample is presented beside the respective bores in Figure 12. A zone of high EC values, indicative of high salt content, is apparent to the immediate north and east of the main salinised area (Figure 8). The zone is elongate in an approximate north-west to south-east direction. To the north of this zone ECs decrease again. In regions of high spatial variation of water quality, locally high salt content often indicates locally low transmissivity, i.e. water moves through the rocks slowly, and consequently, dissolves more salts. However, the elongate area also coincides with the subordinate drainage line, previously mentioned, which may contain semi-confining alluvial clay, and act as an evaporation sink (J. Amieson, pers. comm. 2001).

Figure 12. Electrical conductivity (in dS/m) of borehole water as measured in January 1992.
3. Conceptual model

3.1 Hydrogeology

Conceptualisation of the Brymaroo catchment hydrogeology involved the identification of the main aquifer characteristics and groundwater flow directions. Dryland salinity is likely to occur when the groundwater system cannot transmit all recharge waters. For this to eventuate, one of the following would normally occur along the groundwater flow path:

1. a decrease in permeability and/or transmissivity
2. change in gradient
3. a thinning of the aquifer
4. a narrowing of the aquifer.

In the case of Brymaroo, all of the above characteristics are represented which, in turn, inhibit the aquifers carrying capacity.

Groundwater elevations from 15 surveyed piezometers at screened depths of 8 to 26 m indicate that most of the flow in the Brymaroo catchment occurs within the Tertiary Main Range Volcanics (basalts) in the southern parts of the catchment. From here, groundwater flows northward towards Cain Creek, located within the alluvial sediments at the northern boundary of the catchment. Most present-day discharge is at the contact with the Walloon Coal Measures, expressed as salinised areas. The catchment topography largely influences the groundwater flow directions. Accordingly, the catchment can be classified as a Local groundwater flow system in the scheme of Coram et al. (2000).

Groundwater discharge preferentially occurs where shales, siltstones, mudstones and sandstones of the Walloon Coal Measures have been exhumed through erosion of overlying basalt. Here, the capacity of the aquifer to transmit water (also known as the ‘discharge capacity’) is reduced because of a reduction in aquifer thickness. When the discharge capacity is exceeded by recharge, land salinisation is promoted.
3.2 Recharge

Water that infiltrates downwards below the bottom of the plant root zone, often referred to as deep drainage, may eventually become groundwater recharge. The timing and rates of recharge can vary, depending on soil and substrate properties and the depth to the watertable.

Deep drainage estimates were initially carried out at several sample sites using the salt mass balance technique described in Doherty and Stallman (1992). These were calculated and averaged over the different soil types to obtain a recharge value of each soil type mapped as identified in Figure 7. Through this process, deep drainage was estimated to be 50 mm/yr for the upland lithosols on the basalt, 5 mm/yr for the dark, self-mulching clays found in the centre of the catchment and 1 mm/yr for the red brown loams of the lower catchment.

These deep drainage estimates were revised in May 2001, to incorporate the soil layer and its underlying geology as a single continuous layer, with the geological units acting as boundaries for each recharge zone. This procedure effectively increased the recharge estimates. The basalts were found to have a deep drainage of 150-100 mm/yr, whereas the estimate for the alluvial sediments was 10 mm/yr. The Walloon Coal Measures were excluded since they only occur in a very narrow strip within the catchment.

4. Groundwater modelling

Catchment-scale groundwater modelling was used to examine the influence of different recharge rates on the extent of manifested salinisation. This section of the report discusses the model description, calibration, parameterisation, sensitivity and results.

4.1 Description of the model

Groundwater heads in the Brymaroo catchment were simulated using FLOWTUBE (Dawes et al. 1997, Dawes et al. 2000, Dawes et al. 2001). This is a simple numerical one-dimensional groundwater flow model. It is a mass-balance model that calculates changes in hydraulic heads induced by recharge and discharge fluxes, and lateral transfers in the direction of flow. The results of FLOWTUBE relate to a hydraulic head transect along an aquifer.

The model considers a one or two layer system. In the case of a single layer, the aquifer is assumed to be unconfined and to have variable transmissivity dependent on the saturated thickness of the aquifer. In the case of a two layer system, the lower layer is assumed to contain any lateral transmission of water while the upper layer contributes storage capacity only. In this case the lower layer is usually confined or semi-confined.

Water sources considered by FLOWTUBE are: (i) point sources of run-off at the upstream end of the aquifer, often manifested as recharge beds collecting surface water from a steeper part of the catchment, and (ii) diffuse recharge or discharge spread in an arbitrary spatial and temporal pattern across the aquifer. The latter is the recharge component most altered by the replacement of native species with annual cropping and grazing systems in Australia.

FLOWTUBE allows a variety of boundary conditions for the aquifer. At the downstream end there are two options: (i) the flux is controlled by a specified groundwater head at a nominated distance, useful where a nearby permanent water source, such as a river or irrigation area, controls head build-up, or (ii) the flux is controlled by local aquifer properties and the groundwater surface drains freely, which can be useful when the groundwater catchment is poorly defined or only the upper part of a catchment is considered.

For diffuse recharge input there are three options: (i) a user-specified pattern of fixed recharge amounts with an evaporation
component controlled by an extinction depth, which is the conventional implementation within groundwater models, (ii) recharge calculated by FLOWTUBE internally as the difference between the present head and a reference elevation multiplied by an impedance factor, applicable where definite connection and transfers exist between a surface storage and a transmitting aquifer with little outside influence, and (iii) a continuous function of recharge/discharge based on Geographic Information Systems (GIS) analysis of depth-to-water from a Digital Elevation Model, most useful where there are near-surface water levels causing discharge that is governed by topographic features.

It should be noted that, with the current version of FLOWTUBE, the continuous recharge/discharge functions are mutually exclusive of the head-induced and fixed recharge pattern. This means that it is not possible to switch between recharge/discharge functions and a sudden flood or drought through a fixed recharge distribution within the one simulation. Spikes of recharge, however, may be superimposed on a head-induced recharge situation.

4.2 Catchment and aquifer description

Figures 2 and 11 show the surface topographic and piezometric contours respectively. The parallel character of the two sets of contours was noted above (Section 2.9). The study area was defined from both sets of contours. For those areas where data are sparse, groundwater levels were extrapolated from the land surface. The southern end of the catchment begins at a topographic ridge and extends north, past Brymaroo before being intersected by Cain Creek at the northern boundary of the catchment. The constant head boundary condition for the FLOWTUBE model was taken 500 m further north of Cain Creek. One flow tube was utilised to model the area, although this was sub-divided into three arms, as illustrated in Figure 15, to best accommodate the topography and groundwater system. The first arm, occupying the western side of catchment, contains Sections 1 to 11 and flows into the northern arm. The eastern arm contains Sections 12 to 21 and also flows into the northern arm. The northern arm encompasses Sections 22 to 25.

A point source of recharge (or flux) was specified in the upper part of the western arm to accommodate a small topographic high (Figure 2). Recharge was calculated by multiplying the area of this hill (500 m²) with the recharge at this point (2.74 x 10⁻⁴ m/d). Because the upper eastern boundary of the catchment coincides reasonably well with a surface topographic ridge, no point sources of recharge were imposed at this point.

4.3 Calibration and parameterisation of the model

4.3.1 Groundwater recharge

Recharge was determined to be 150–100 mm/yr in the basalts and 10 mm/yr in the alluvial sediments (Section 3.2 of this report). Table 2, in Appendix 1, gives the location of the recharge nodes with respect to the
sections in the flow tube arms. The recharge model used in all simulations is the GIS-based continuous recharge-discharge relationships described in the FLOWTUBE section, above.

4.3.2 Aquifer parameters

Little information is available on the fundamental hydraulic parameters of the aquifer of interest. Catchment parameters were estimated from drill-hole records and local hydrogeological information. Hydraulic conductivity ranges from 3 to 15 m/d, with the higher values occurring in the basalts. Specific yield was kept constant at one percent. Pearce (pers. comm. 2001) describes the thickness of the unconfined aquifer to be 20 m or more at the top of the catchment before thinning (2 m) in the vicinity of the salt affected area. Table 1, in Appendix 1 summarises the basic hydrogeological information.

These values generated conditions that are consistent with the limited information available. Figure 16 shows the calibrated head against the present-day head.

4.4 Groundwater modelling simulation and results

4.4.1 Clearing to present day

The first simulation performed was to determine the area of vertical recharge along the catchment, and to ensure appropriate long-term rates of groundwater rise across the study area. It was assumed that under pre-cleared conditions recharge would be the equivalent of 1 mm/yr everywhere as trees would have covered most of the study area. This value was selected from recharge studies conducted by Petheram et al. (2000) which showed that a catchment under trees with a rainfall of 700 mm/yr has a variable recharge rate of between 0 mm/yr and 5 mm/yr. Figure 17 shows the simulated groundwater rise over the 50 years since clearing. Levels are shown for 1950, 1960 and 2000 to illustrate the changing rates of rise in different parts of the catchment. It is assumed that the groundwater levels have not changed between 1992 and 2000.

It is clearly shown in Figure 17 that the assumed pre-cleared heads are significantly lower in the upland basalts due to very little recharge water entering the system. In fact, in some regions there is no permanent aquifer. This is plausible because, with increasing recharge, upwards filling occurs, and increased gradients push groundwater (and discharge) to the lower parts of the flow path.

4.4.2 Future trends

Two basic scenarios have been simulated for the catchment. These are aimed at two potential end-points, to reduce recharge rates by 50% and by 90%. Figure 18 shows the simulated water levels for two time frames, 2010 and 2020, for continual recharge that has been reduced by 50%. It should be noted that there is no change in the water level for simulations in excess
of 20 years, suggesting that the system reaches a new equilibrium by this time. The latter effect has been supported by work being carried out by Smitt et al. (2001) and Gilfedder et al. (2001) that investigates the outcome of changing recharge and the time it takes to respond to given recharge changes in several catchments that include Brymaroo.

Figure 19 shows simulated water levels for 2010 and 2020 with continual recharge that has been reduced by 90%. As in the scenario described above, there is no change in water levels after 20 years.

Comparable to the 50% reduction scenario (Figure 18), the greatest change in water levels are seen in the basalts; after 20 years, the watertable drops by over 7 m in places (Figure 19). There is very little change in the watertable in the alluvial sediments down-slope from the groundwater discharge area. This is largely due to the constant head boundary near Cain Creek influencing heads within the floodplain.

An additional simulation was aimed at demonstrating the effect of episodic recharge on the groundwater system because Brymaroo is geographically located where episodic recharge is common. For this simulation, recharge was reduced by ten per cent for nine years. Following this, recharge was doubled for one year to simulate the affect of an extremely wet year across the catchment. Figure 20 shows the height of the watertable one year after the high recharge event.

It becomes clearly evident that in the middle part of the catchment, above the Walloon Coal Measures and north of the break of slope, groundwater heads are above land surface and after two years the heads recede to the land surface level. This result is in accordance with observations of local landholders who note that bores in the mid and lower catchment become artesian after wet years.

---

**Figure 18.** Effects of reducing recharge by 50%. Water levels are simulated for 10 and 20 years into the future.

**Figure 19.** Effects of reducing recharge by 90%. Water levels are simulated for 10 and 20 years into the future.

**Figure 20.** Effect of simulating episodic recharge. Water level shown is one year after a large recharge event.
4.4.3 Comments on the groundwater model sensitivity to parameters

The most sensitive parameter in Brymaroo is aquifer transmissivity. If the transmissivity changed due to variations in aquifer thickness or hydraulic conductivity, then recharge would need to be scaled accordingly to keep the same recharge:transmissivity ratio. This ratio is important because it maintains the same calibrated heads, if the parameters are varied. For example, if transmissivity is doubled, the amount of water that can pass through a unit width of aquifer is doubled. Accordingly, heads will be lowered and/or gradients will be reduced. To compensate, recharge would be doubled, thus increasing the amount of water in the system to be disposed of.

Where data is sparse for a given catchment, concerns can arise over the meaningfulness and implications of the modelling results. In the case of the Brymaroo catchment, the combination of data collected by Doherty and Stallman (1992) and local knowledge, satisfactorily constrains the model.

4.4.4 Alternative scenarios

Common methods adopted to reduce groundwater levels include engineering schemes that predominantly involve pumping and disposal of excess groundwater. In Brymaroo catchment, groundwater is currently pumped from two bores, one located in the upland basalts and the second located closer to Cain Creek, in the alluvial sediments.

Figure 21 shows the effects on water levels of pumping from the catchment at a constant rate of 5 L/s for a year. At the end of the year, very little change is seen in the potentiometric surface within the basalts because of their high transmissivity. Within the alluvial sediments a deeper drawdown can be seen, locally lowering to the base of the aquifer.
5. Discussion

5.1 Assessment of salinity management options

The results of groundwater modelling for the present study have significant implications for the adoption of salinity management options. These options include:

- land use change
- engineering approaches
- management of salinised land
- maintaining the status quo.

5.1.1 Groundwater modelling scenarios

The implications of the modelling for these options are considered in greater detail in the following discussion, together with any constraints that are likely to prevent their implementation.

Groundwater modelling using FLOWTUBE simulated the effects of different recharge scenarios: the first involved a reduction of recharge across the catchment by 50%, and the second invoked a 90% recharge reduction. The following conclusions are drawn:

- For a 50% recharge reduction, the simulation predicts that, in the upper parts of the catchment, groundwater levels may fall by up to 5 m after 20 years, therefore slightly reducing the amount of salinised land within the discharge zone.
- For a 90% recharge reduction, the simulation predicts the watertable to fall by as much as 7 m in the upper parts of the catchment after 20 years. However, the amount of water discharging would only be slightly less than the amount discharging from the 50% recharge reduction simulation. Reintroducing woody vegetation over the majority of the catchment would probably bring about a reduction in recharge of this magnitude.

Similar case studies that have incorporated farm-scale modelling by Petheram et al. (2000) and Stauffacher et al. (2000) have shown that in order for a 50% recharge reduction to be achieved, the upper part of the catchment (where recharge is >100 mm/yr) needs to be placed under annual pasture. A 90% recharge reduction can be brought about by revegetating the catchment with native trees.

The above predictions are based on the assumption that salinity caused by high watertables is completely reversible once the water level drops and any mobilised salt can be flushed from the system.

5.1.2 Living with salt

Given the characteristics and underlying geology of the catchment and required land use change to minimise saline groundwater discharge, ‘living with salt’ is a realistic land use option. Even with the greatest degree of recharge reduction, saline discharge may be unstoppable above the ridge of the Walloon Coal Measures. Therefore, appropriate land use options may include the following:

- localised drainage to protect specific high value assets
- establishment of salt tolerant vegetation for biodiversity values, aesthetic values, stock fodder or carbon credits for greenhouse gas mitigation
- adoption of (preferably) more water efficient farming practices, such as the use of deeper rooted crops, phase farming, and alley farming, combined with the continuation of existing land uses over more productive parts of the catchment.

The greatest constraint to change probably lies within prevailing expectations that existing salinity is a transient and curable problem and that current land uses are appropriate to the local conditions. However, economic factors are also likely to impact on the adoption of ‘living with salt’ options. Where these options
can be shown to be cost-effective, they will be taken up, otherwise conventional land uses with immediate returns are more likely to continue to be applied (as discussed below in Section 5.1.3).

5.1.3 Status quo

Maintaining the status quo with respect to land use will result in only minor changes to the salinised area along the break of slope and towards Cain Creek as the system is believed to be in equilibrium. However, because data collection for the modelling component of this report followed a prolonged dry period, the simulations may not accurately represent average annual conditions, in which case the system may not be in true equilibrium. Inter-annual variability and prolonged periods of above or below average rainfall will lead to changes in the area of shallow groundwater and hence the area of land salinised. The simulations indicate that the salinised area is unlikely to spread uphill.

5.2 Portability of conceptual model, tools and results

5.2.1 Application of results to other areas

The main groundwater system within the Brymaroo catchment is the transmissive Tertiary basalts that underlie the majority of the catchment. Dryland salinisation is caused when groundwater passes through these rocks and is impeded by the bedrock high (1 to 10 m below the surface) of the less permeable Walloon Coal Measures. Groundwater pressures rise at this point and discharge to the surface occurs as a consequence.

Groundwater flow directions indicate that the Brymaroo catchment is a self-contained groundwater catchment independent from regional groundwater flow systems to the south. Groundwater in the Brymaroo catchment flows in a northerly direction, originating from the elevated areas of basalt in the south and moving towards Cain Creek in the north. Most of the discharge occurs in the southern half of the catchment where evapotranspiration processes exacerbate the broader-scale hydrogeological factors to promote outbreaks of salt in the landscape.

For this catchment type, the response time to any land use change is likely to be fairly rapid. With the exception of the bedrock high, this conceptual understanding is likely to be valid across a wide range of catchments of this geological and geomorphological type.

The FLOWTUBE catchment-scale groundwater model proved suited to this catchment type and it is expected to perform well elsewhere in similar catchments provided that a minimum quality data set is available.

The groundwater modelling results indicate that the Brymaroo catchment’s groundwater system is full and that extensive intervention will be needed for biological salinity control. Under similar climatic conditions, catchments with comparable topographic and geologic features are likely to present the same prospect. Similar catchments have been described in the Audit’s Australian Groundwater Flow System classification (Coram et al. 2000). Under the new classification that is being developed from the Audit’s classification, the Brymaroo catchment falls within the ‘Tertiary Rocks’ hydrogeological province, and has been identified as having local flow systems in basaltic fractured rock aquifers. The results of the approach used in the present study confirm this classification, and can be generalised to other catchments within the same hydrogeological province and groundwater flow system type. These analogous catchments include some on the Great Dividing Range (New South Wales) and on lower slopes of the Lachlan Fold Belt (New South Wales).

5.2.2 Minimum datasets required for this approach

In order to develop a plausible conceptual model of the catchment hydrogeology, sufficient groundwater level information needs to be available to construct a groundwater flow net for the catchment. Also requisite are stratigraphic descriptions and bore construction details from along and across the main groundwater flow paths. Information additionally needs to be available regarding the hydrogeological characteristics
of the hydrostratigraphic units, ideally from pumping tests within the catchment, or at least from correlative hydrostratigraphic units outside the catchment. Groundwater hydrographs also need to be available from bores representative of the range of hydrostratigraphic and geomorphic variation in the catchment, and a map of the current extent of salinised land needs to be available.

In this study there was a reasonable network of bores across the catchment to construct a groundwater flow net. Drilling logs provided a minimal baseline of lithostratigraphic information although there was a deficit of hydrogeological characteristics pertaining to respective hydrostratigraphic units.

5.2.3 Groundwater modelling

In general, if sufficient bore-lithology and watertable information is available to define a conceptual model of the groundwater flow system, the behaviour of that system can be simulated. For the simplest implementation of a FLOWTUBE model, the following data are required:

- groundwater levels from well distributed data points across the catchment to reconstruct a groundwater surface
- bore lithology data from well distributed data points across the catchment to estimate the physical dimensions of the conducting aquifer (i.e. thickness, extent, width, base of material, any confining layers)
- a representative distribution of measurements of, or surrogates for, static aquifer material properties (hydraulic conductivity, porosity, storage coefficient or specific yield)
- estimates of the locations of recharge areas and quantities of intake water to the conducting aquifer, i.e. point and diffuse recharge rates and their spatial distribution.

The first two data sets are the most important and will allow a generalised steady-state fitting to current groundwater levels. Either of the latter two may additionally be fitted to gain further insight into the behaviour of a given system.

For transient and more detailed simulations to be performed, the following additional data is needed:

- estimates of the temporal changes in recharge sources and rates
- long-term bore hydrographs to correlate temporal climatic variation and groundwater response
- water chemistry measurements to allow processes and rates to be better identified
- other supporting data describing temporal changes in water fluxes (stream/river gauging, increase in discharge area, seasonal waterlogging, groundwater pumping, irrigation, land use changes, etc.).

For the Brymaroo catchment, adequate data exists to reconstruct a groundwater surface, cross-sections of bore lithology, some measurements of static parameters, some hydrogeochemistry, long-term interpolated climate data, and hydrographs.
6. Conclusions

Brymaroo Catchment is relatively responsive to changes in the water balance, and the expansion of salinity as a result of clearing of the catchment has largely culminated. Further spread of salinisation is expected to be minimal if current land use is maintained.

Decreases in the area of salinised land within ten to 30 years can be expected in response to decreases in recharge.

- For a 50% recharge reduction, it is predicted that groundwater levels in the upper parts of the catchment may fall by up to 5 m after 20 years, therefore slightly reducing the amount of salinised land within the discharge zone.

- For a 90% recharge reduction, it is predicted that the watertable in the upper parts of the catchment may fall by as much as 7 m after 20 years. However, the amount of water discharging would only be slightly less than the predicted amount discharging from a 50% recharge reduction. Reintroducing woody vegetation over the majority of the catchment could probably bring about a recharge reduction of this magnitude.

However, it must be noted that due to the geological character of this catchment, saline discharge may possibly never be completely arrested. Reductions in recharge will help decrease the pooling of water (and hence area of salinised land) behind the ridge of the Walloon Coal Measures.
7. References


Aquifer parameters used as the FLOWTUBE input file to model the Brymaroo catchment.

#Brymaroo fractured basaltic aquifer

```plaintext
#gw surf width thick base cond len por idc
449.00 464.00 1100.00 20 440 02.00 275 0.01 2
447.00 459.00 1237.50 19 436 02.00 275 0.01 3
445.00 454.00 1237.50 21 433 02.00 275 0.01 4
441.00 448.00 1237.50 18 430 02.00 275 0.01 5
440.00 443.00 1237.50 15 428 05.00 275 0.01 6
438.00 438.00 1512.50 10 428 15.00 275 0.01 7
433.00 436.00 1842.50 06 430 25.00 275 0.01 8
433.00 434.00 1925.00 02 432 25.00 275 0.01 9
429.00 430.00 2062.50 02 428 01.00 275 0.01 10
423.00 424.00 1925.00 04 420 01.00 275 0.01 11
418.00 423.00 1787.50 06 417 01.00 275 0.01 12
447.00 464.00 3382.50 20 440 03.00 275 0.01 13
445.00 460.00 3135.00 19 438 03.00 275 0.01 14
441.00 456.00 3025.00 22 434 03.00 275 0.01 15
438.00 448.00 2887.50 20 428 03.00 275 0.01 16
434.00 440.00 2640.00 15 425 03.00 275 0.01 17
430.00 432.00 2337.50 10 422 15.00 275 0.01 18
428.50 430.00 2117.50 06 424 15.00 275 0.01 19
427.00 428.00 1952.50 03 425 15.00 275 0.01 20
423.30 425.00 1952.50 03 422 05.00 275 0.01 21
421.00 423.00 1787.50 04 419 01.00 275 0.01 22
416.00 418.00 1650.00 06 412 01.00 275 0.01 23
414.00 416.00 2805.00 08 408 01.00 275 0.01 24
413.50 415.00 2475.00 09 406 01.00 275 0.01 25
413.00 414.00 1980.00 10 404 01.00 275 0.01 26
413.00 413.00 1475.50 11 402 01.00 275 0.01 -1
```
TABLE 2. Summary of the basic hydrogeological parameters used in the calibration of the FLOWTUBE model.

<table>
<thead>
<tr>
<th>Geology</th>
<th>Section</th>
<th>Recharge (mm/yr)</th>
<th>Thickness (m)</th>
<th>Transmissivity (m²/d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basalt</td>
<td>1.00</td>
<td>150</td>
<td>20.00</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>2.00</td>
<td>150</td>
<td>19.00</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>3.00</td>
<td>100</td>
<td>21.00</td>
<td>63</td>
</tr>
<tr>
<td></td>
<td>4.00</td>
<td>100</td>
<td>18.00</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td>5.00</td>
<td>100</td>
<td>15.00</td>
<td>225</td>
</tr>
<tr>
<td></td>
<td>6.00</td>
<td>100</td>
<td>10.00</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>7.00</td>
<td>100</td>
<td>6.00</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>8.00</td>
<td>100</td>
<td>2.00</td>
<td>10</td>
</tr>
<tr>
<td>Alluvial Sediments</td>
<td>9.00</td>
<td>10</td>
<td>2.00</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>10.00</td>
<td>10</td>
<td>4.00</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>11.00</td>
<td>10</td>
<td>6.00</td>
<td>6</td>
</tr>
<tr>
<td>Basalt</td>
<td>12.00</td>
<td>150</td>
<td>20.00</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>13.00</td>
<td>150</td>
<td>19.00</td>
<td>57</td>
</tr>
<tr>
<td></td>
<td>14.00</td>
<td>100</td>
<td>22.00</td>
<td>66</td>
</tr>
<tr>
<td></td>
<td>15.00</td>
<td>100</td>
<td>20.00</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>16.00</td>
<td>100</td>
<td>15.00</td>
<td>45</td>
</tr>
<tr>
<td></td>
<td>17.00</td>
<td>100</td>
<td>10.00</td>
<td>150</td>
</tr>
<tr>
<td></td>
<td>18.00</td>
<td>100</td>
<td>6.00</td>
<td>90</td>
</tr>
<tr>
<td></td>
<td>19.00</td>
<td>100</td>
<td>3.00</td>
<td>45</td>
</tr>
<tr>
<td>Alluvial Sediments</td>
<td>20.00</td>
<td>10</td>
<td>3.00</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>21.00</td>
<td>10</td>
<td>4.00</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>22.00</td>
<td>10</td>
<td>6.00</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>23.00</td>
<td>10</td>
<td>8.00</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>24.00</td>
<td>10</td>
<td>9.00</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>25.00</td>
<td>10</td>
<td>10.00</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>End</td>
<td>10</td>
<td>11.00</td>
<td>11</td>
</tr>
</tbody>
</table>
Integrated catchment management in the Murray-Darling Basin

A process through which people can develop a vision, agree on shared values and behaviours, make informed decisions and act together to manage the natural resources of their catchment: their decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

Our values
We agree to work together, and ensure that our behaviour reflects the following values.

**Courage**
- We will take a visionary approach, provide leadership and be prepared to make difficult decisions.

**Inclusiveness**
- We will build relationships based on trust and sharing, considering the needs of future generations, and working together in a true partnership.
- We will engage all partners, including Indigenous communities, and ensure that partners have the capacity to be fully engaged.

**Commitment**
- We will act with passion and decisiveness, taking the long-term view and aiming for stability in decision-making.
- We will take a Basin perspective and a non-partisan approach to Basin management.

**Respect and honesty**
- We will respect different views, respect each other and acknowledge the reality of each other's situation.
- We will act with integrity, openness and honesty, be fair and credible and share knowledge and information.
- We will use resources equitably and respect the environment.

**Flexibility**
- We will accept reform where it is needed, be willing to change, and continuously improve our actions through a learning approach.

**Practicability**
- We will choose practicable, long-term outcomes and select viable solutions to achieve these outcomes.

**Mutual obligation**
- We will share responsibility and accountability, and act responsibly, with fairness and justice.
- We will support each other through the necessary change.

Our principles
We agree, in a spirit of partnership, to use the following principles to guide our actions.

**Integration**
- We will manage catchments holistically; that is, decisions on the use of land, water and other environmental resources are made by considering the effect of that use on all those resources and on all people within the catchment.

**Accountability**
- We will assign responsibilities and accountabilities.
- We will manage resources wisely, being accountable and reporting to our partners.

**Transparency**
- We will clarify the outcomes sought.
- We will be open about how to achieve outcomes and what is expected from each partner.

**Effectiveness**
- We will act to achieve agreed outcomes.
- We will learn from our successes and failures and continuously improve our actions.

**Efficiency**
- We will maximise the benefits and minimise the cost of actions.

**Full accounting**
- We will take account of the full range of costs and benefits, including economic, environmental, social and off-site costs and benefits.

**Informed decision-making**
- We will make decisions at the most appropriate scale.
- We will make decisions on the best available information, and continuously improve knowledge.
- We will support the involvement of Indigenous people in decision-making, understanding the value of this involvement and respecting the living knowledge of Indigenous people.

**Learning approach**
- We will learn from our failures and successes.
- We will learn from each other.