GOVERNMENT OF
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Department of
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Hydrological impacts of integrated oil mallee farming systems

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Hydrological impacts of integrated oil mallee farming systems

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Cover picture: Oil mallee alley system at Goodlands, WA (Photo: D Bennett)

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Summary

This study reports on the results from investigations at four sites into the effect of commercial-scale oil mallee systems on localised groundwater systems over seven years. It also reports the results of the use of a numerical model to forecast potential longer term impacts.

Research focused on four catchments with local or intermediate groundwater flow systems in the less than 450 mm rainfall zone of Western Australia (WA). These areas were chosen from districts where extensive test planting of oil mallee had been undertaken. The catchments were selected to represent the spectrum of rainfall, farming systems, soils and hydrogeology within the wheatbelt of WA. The study used existing plantings of oil mallees that had been integrated into the farming system.

Belts of oil mallees can use substantially more water than rainfall incident on the canopy and therefore have the potential to reduce recharge to groundwater over an area greater than that occupied by their canopies. From the analyses reported here, groundwater modelling shows that a belt canopy area of 3–10 per cent of the landscape accounted for up to a 30 per cent net decrease in recharge to groundwater systems across the four sites. Despite this multiplier, groundwater monitoring and hydrological modelling showed that this level of recharge reduction produced almost no discernable effect on catchment-scale groundwater levels or on the area of saline discharge during the study.

Forecasts made using Flowtube modelling show that in 50 years (under the current rainfall conditions and stated assumptions) the proportion of land protected from becoming saline would be similar to, or less than, the proportion of land occupied by the oil mallees. When the competition impact of the unharvested oil mallee belts on adjacent crop and pasture is included, the forgone agricultural land occupied by the oil mallees might, as a proportion of saline area avoided, be even greater.

The low ratio between the area of land protected and the area of land occupied emphasises the importance of commercial oil mallee harvesting both to manage competition and sustain overall profitability, and the need to continue to quantify the direct economic value of oil mallee products to farm profitability.

In catchments that have not yet reached hydrological equilibrium, the area affected by salinity can be expected to continue to expand if oil mallee planting is the only salinity control treatment used. The small hydrological response to the disproportionately large (in terms of area occupied by the oil mallee canopy) reduction in recharge is controlled by the hydrogeological characteristics of wheatbelt catchments. The inherent low gradient and low hydraulic conductivity of the aquifers mean that the rate of groundwater outflow from wheatbelt catchments is also very low. Therefore, a significant amount of the additional recharge resulting from the replacement of native vegetation with annual agriculture must be removed using a range of technologies before significant responses, in terms of lowering groundwater levels and reducing the extent of salt affected land, will result.

By contrast, at a local scale, oil mallees (at > 50 m) may have a role in salinity mitigation where the catchment is at or near hydrological equilibrium and tree belts can be planted with access to shallow fresh groundwater. However, land with these conditions occupies only a very small proportion of the wheatbelt. It should also be considered that the long-term growth rates of trees using these low capacity aquifers is likely to decline if, or more likely when, the trees have used up the stored groundwater and are solely reliant on rainfall and lateral water flows into the aquifer.

Over most of the wheatbelt, to achieve large enough and timely reductions in groundwater levels that translate into useful reductions in the area of saline groundwater discharge, the spacing between the typical two-row oil mallee belts would need to be substantially reduced to less than 50 m (that is, between 15 and 30 m). These distances may need to be further reduced where the oil mallees are regularly harvested. These spacings are unlikely to be manageable or viable where broadscale cropping is the predominant inter-belt land use, although they may be suitable where livestock graze permanent pastures. The reduction in pasture productivity from competition from the oil mallees could be substantial under this arrangement and would need to be considered on a region by region and farming system basis.

Measurements and modelling undertaken in this study indicate that using dense oil mallee systems as in situ recharge control over broad valley landscapes to lengthen the time before shallow groundwater levels develop, appears to be an effective strategy where groundwater is deep and there is a long time before the risk is realised. Further investigation is required to determine if this strategy is effective where groundwater levels are much shallower and there is more imminent risk. However, this strategy requires the development of a cost effective method to determine the depth to groundwater and therefore the salinity risk in valleys across the wheatbelt.

It should be emphasised that salinity remediation is only one potential benefit of this revegetation system—aesthetics, wind erosion and an economic return from the sale of fibre, carbon, bio-fuel or other products are other potential benefits that require better quantification.

1. Introduction

During the 1990s many large-scale oil mallee plantings were established across the wheatbelt region of Western Australia (WA). Landholders were motivated by the potential for multiple benefits, including the potential for Eucalyptus oil production, biomass production, salinity control and other landcare and biodiversity benefits. At that stage little was known about the magnitude of these potential benefits and the fledgling oil mallee industry was keen to obtain these data. The prior oil mallee planting activity provided the opportunity in 2002 to use a range of catchments where extensive oil mallee belt planting had been undertaken to commence assessment of the impact of these plantings on groundwater systems at the catchment-scale at various sites across the wheatbelt.

Prior to this work commencing it had proved difficult to assess the contribution of tree planting to salinity control given the long timescale required for assessment, the considerable regional biophysical variation and the paucity of long-term data. When this study was designed, the potential value of tree planting for land salinity benefits was generally considered to exceed the commercial opportunity. Since then, the potential for oil mallees to contribute to climate change adaptation and mitigation and provide renewable biomass energy sources has increased, potentially adding to the commercial value of oil mallee plantings. However, just as this study aimed to quantify on-site salinity benefits by using hydrological investigation methods, it is now even more important to quantify the direct economic value of oil mallee products to farm profitability using appropriate methods.

This study reports on the results from hydrological investigations at four catchments located across the WA wheatbelt into the effect of commercial-scale oil mallee systems on localised groundwater systems over seven years. It also reports the results of the use of a numerical model to forecast potential longer term impacts. Research focused on four catchments with local or intermediate groundwater systems in the less than 450 mm rainfall zone of WA. These areas were chosen from districts where extensive test planting of oil mallee had been undertaken.

Rising groundwater systems are primarily responsible for the secondary dryland salinity that has developed in the valleys at each of the sites. The groundwater levels have risen over the last 50–60 years in response to increased recharge as the land was cleared of deep-rooted, woody, perennial vegetation and replaced with annual crops and pastures. When and where the groundwaters rise enough to intersect the ground surface (or are close enough to lose water to the atmosphere by evaporation), salts that are contained in the groundwater can accumulate near the soil surface, causing secondary salinity (Nulsen 1981).

In most cases in the wheatbelt the discharge from the groundwater systems is passive which means that evaporation is the main mechanism that removes water from them. The systems are passive because the aquifer properties and geometry limit the groundwater throughflow to rates lower than is removed by evaporation over the discharge area (George 1992a).

The primary factor that determines the geometry and severity of the discharge is the depth to groundwater and rate of discharge. This is why the depth to groundwater (spatial and temporal responses at the catchment-scale) is the primary measure of the conditions that are responsible for salinity developing and also for assessing the impact of management systems.

Introducing perennial vegetation, such as oil mallees, that have the capacity to transpire more water (potentially from both saturated and unsaturated sources of groundwater) than annual crops and pastures has long been proposed as a means of removing water that would otherwise contribute to existing or potential areas of groundwater discharge (soil salinity). How effective they are in doing this will first be reflected by groundwater level changes measured at various locations across a catchment. The analysis of the magnitude of these changes (also considered against the backdrop of changes in rainfall conditions) at four locations where oil mallee systems have been established for a period of seven years is the basis of the assessment undertaken in this study.

To help forecast longer term impacts of the four commercial-scale oil mallee systems, we combined water level measurements and observations of aquifer and regolith profile characteristics in a groundwater model, Flowtube (Argent et al. 2001). While subject to many assumptions, using such models is the only way to assess potential outcomes and objectively plan for future monitoring and evaluation programs.

This report does not address other impacts or benefits that may accrue from oil mallee systems, such as:

- aesthetics, wind erosion and economic return from the sale of fibre, carbon, bio-fuel or other products
- changes to the rate of groundwater discharge
- changes to the rate of salt discharge
- changes in the rate, frequency or volume of surface run-off
- other downstream/off-site impacts
- changes to soil water storage within the unsaturated zone.

2. Methodology

2.1 Site descriptions

Figure 1 shows the locations of the four sites that were investigated. The sites were chosen because they:

- were located in areas that are best suited to the development of large-scale industries based on commercial sale of oil mallee products
- were within centres of interest and activity of the fledgling oil mallee industry
- had extensive, catchment-scale, areas of typical oil mallee planting
- were well suited to measuring and modelling the effect on groundwater at the catchment-scale.

At the beginning of the study, a detailed site description and hydrological investigation, including preliminary Flowtube modelling, was undertaken at each site. Preliminary Flowtube modelling was done to determine the range of possible effects that the plantings may have on the groundwater system and also ensured that the intensity of the bore network was sufficient to adequately describe the groundwater system.

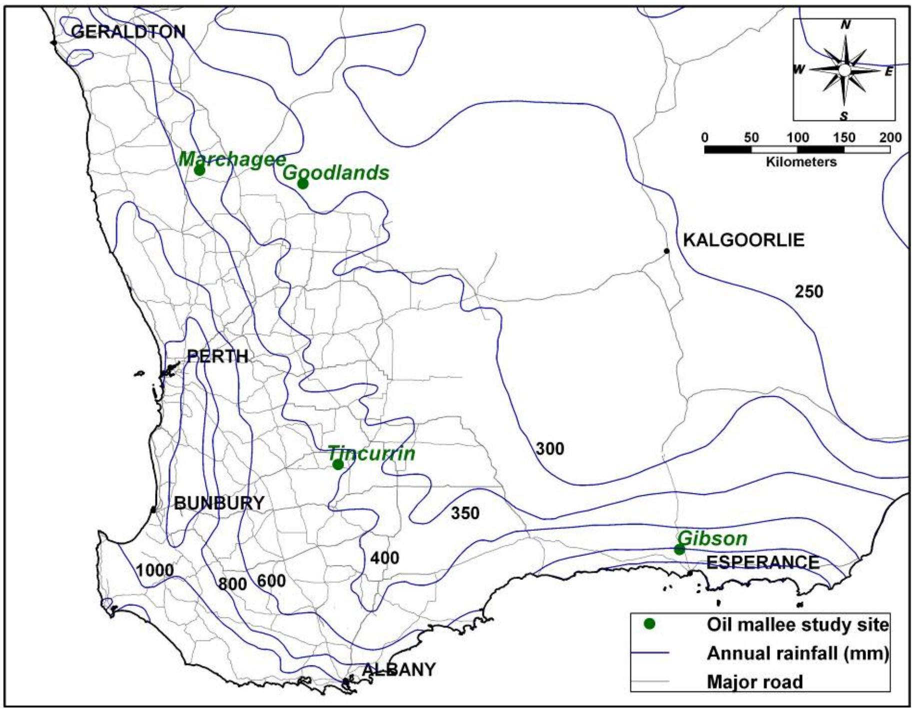

Figure 1 **Location of the four oil mallee study sites in the WA wheatbelt**

2.1.1 Marchagee

At Marchagee, *Eucalyptus kochii* ssp. *borealis* were planted in 2000 in a configuration of two-row belts (rows within belts spaced two metres apart), with the belts spaced at about 120 m centres across a 150 ha catchment (Figure 2). Bennett and Goodreid (2009) give a detailed site description and the results of the preliminary hydrological investigation. The site is typical of the western end of the northern wheatbelt sandplain where the deep yellow sands are non-acidic and generally highly productive for cropping, given adequate growing season rainfall. These sands are underlain by a silcrete layer at several metres depth that overlays saprolite formed from the underlying Archaean granitoid basement which is between five and 30 m deep. A saline groundwater discharge area had developed in the lower slope prior to the oil mallees being planted. At the start of groundwater monitoring in 2003, groundwater levels beneath the oil mallee system were between 0.5 and 14 m below the surface, and brackish to saline quality (electrical conductivity, EC, of 200–1400 mS/m). Preliminary Flowtube modelling indicated that the catchment was almost at hydrological equilibrium, meaning that groundwater discharge approximated recharge inputs.

2.1.2 Goodlands

At Goodlands, *E. polybractea* and *E. kochii* ssp. *plenissima* were planted in 1995 as two-row belts spaced at 100 m centres across a 300 ha catchment (Figure 3). Bennett et al. (2005a) gives a detailed site description and the results of the preliminary hydrological investigation. The site is typical of the north eastern wheatbelt sandplain having deep, acidic, yellow sands in the mid and upper slopes and clayey valley soils. Annual crop and pasture productivity is often constrained by the endemic, high subsoil acidity of these soils. As for Marchagee, the sandplain is also underlain by a silcrete layer which at Goodlands is overlain by a brackish, perched aquifer of limited extent in the mid-slope. The site was also a focus for a detailed investigation into the hydrological implications of this silcrete layer for oil mallee growth and water use (Bennett et al. 2005b) which concluded that:

- Plant roots are unlikely to be able to penetrate the silcrete which may restrict the growth potential of oil mallees, particularly where it is shallow.
- Ephemeral, perched groundwater systems may develop on silcrete in mid-slope areas and may provide an opportunistic, yet small scale, additional water resource for oil mallees.
- While silcrete forms a variable partial aquitard, in most situations it readily leaks recharge waters into the basement aquifer.

Beneath the silcrete, saprolite overlays the Archaean granitoid basement at up to 40 m depth. The main valley at the base of the catchment has extensive dryland salinity which has gradually developed since clearing. The basement aquifer within the catchment is brackish to saline (EC up to 2000 mS/m), having a piezometric pressure near the surface in the lower slopes and about 20 m below the surface in the upper slopes. Preliminary Flowtube modelling indicated that groundwater will continue to rise, particularly in the mid and upper slopes, under annual agriculture. The regional groundwater system associated with Lake Moore, a nearby large primary saline salt lake, has a dominating influence on the groundwater in the lower slopes.

2.1.3 Tincurrin

At Tincurrin the oil mallee alley system straddles a section of a large valley within the 20 000 ha Scriveners Soak catchment of Lake Toolibin (Figure 4). Monitoring since 1997 indicates that the groundwater, while still deep, is rising beneath the valley at a rate of about 0.20 m/yr and large sections of the valley are at risk from developing dryland salinity in the future. The risk of salinisation was one of the reasons why the landholder decided to plant an oil mallee alley system over a large section of the valley, as well as some adjoining hillslopes, in 2003 and 2004. Species planted include *E. myriadena, E. angustissima, E. kochii* ssp. *plenissima* and *E .loxophleba* ssp. *gratiae* planted in four-row belts separated by various widths of crop and pasture alleys. The alley widths range from 45 m (22 per cent tree cover) on the valley flats to 65 m (16 per cent tree cover) on the mid-slopes and 90 m (10 per cent tree cover) on some upper slopes. Additionally, an area of about 10 ha on the valley floor was densely planted (individual oil mallees planted at two by four metre spacing). One hillslope area was previously planted in 1999, with four-row belts of *E. horistes* at about 100 m spacing.

Preliminary hydrological investigation and Flowtube modelling was undertaken for this site by Bennett (2005). This site is a typical broad valley of the central wheatbelt, with duplex loamy valley soils and duplex sandy and gravelly loams in the mid and upper slopes. The groundwater level is deep (about 20 m) and saline (EC of 1500–5000 mS/m). While no surface salinity has developed at the site, soil salinity has been gradually extending up the valley with the closest affected area being about five kilometres from the trial site. The valley soil profile also has a layered sandy and clayey alluvial horizon at its surface of about six metres thickness which has been known to saturate, creating a fresh, perched aquifer following very wet periods. Below this, granitoid saprolite comprises the regolith to basement rock at about 30 m depth.

There were two main hydrologically-related reasons for targeting the site with oil mallee plantings. One hypothesis was that oil mallees planted over the temporary, alluvial perched aquifer that sometimes develops could take advantage of the additional water available during these periods so increasing growth and substantially reducing leakage to the deeper groundwater system. These so-called ‘episodic recharge events’ have been shown to produce rapid increases in deep groundwater levels in the wheatbelt and therefore can be important drivers of the long-term rate of groundwater rise (Lewis & Walker 2002). The second hypothesis was that valley plantings could, by reducing in situ recharge, significantly reduce the rate of groundwater rise thereby extending the time to salinity development in the valley. This concept of using revegetation located in the valley areas at risk to ‘buy time’ was based on modelling by George et al. (2004) which showed that within the Scriveners Soak catchment (and other wheatbelt catchments), reducing recharge by half, just within the valley areas at risk, increased the time before groundwater was forecast to intersect the soil surface by 40 years. By contrast, similar levels of recharge reduction dispersed across the mid- and upper slope areas (remote from the projected eventual location of the salinity) had almost no effect.

A study was also undertaken within the Scriveners Soak catchment to test the hypothesis that, if catchment-scale runoff could be reduced by, for example, planting contour belts of oil mallees throughout the catchment, it could make a meaningful reduction to in situ recharge caused by floodwaters infiltrating along the drainage line. Bores located near the main drainage line towards the bottom of the catchment (LT01 and LTC15 in Figure 4), where the groundwater was close to the surface, were equipped with dataloggers during 2005. This was done to measure the magnitude of any groundwater response to flood events to determine if this run-off rapidly recharged the groundwater at rates above the long-term background rate in lower lying, receiving areas.

2.1.4 Gibson

At Gibson, oil mallee belts were planted across the whole 2000 ha farm in 2001. The area studied in greatest detail is a 170 ha catchment containing a small swamp at its outlet (Figure 5). Secondary salinity has developed around the uphill edge of the swamp, also affecting adjacent farmland upslope. A combination of eight-row (16 m width) and six-row (12 m width) oil mallee belts were planted across the catchment on the contour at 90 m and 140 m centres respectively. Species planted were *E. polybractea* and *E. loxophleba* ssp. *lissophloia.* Additionally, within the narrower alleys in the mid and lower slope areas of the catchment, lucerne (*Medicago sativa* var. Sceptre and Aquarius) was planted in September 2003, although these did not persist, probably because they were adversely affected by the waterlogged conditions that occurred at the site during the winter following establishment.

Bennett et al. (2005c) gives a detailed site description and the results of the preliminary hydrological investigation. The site is typical of the Esperance Sandplain and is characterised by gently undulating topography incised by poorly developed drainage systems. Soils are sandy duplex, derived from either weathered Mesoproterozoic gneiss in the upper slopes or Tertiary sedimentary assemblages in the lower slopes. The depth of regolith at the site is less than 30 m, with shallow groundwater of fresh to brackish (300 mS/m) to saline (2500 mS/m) quality.

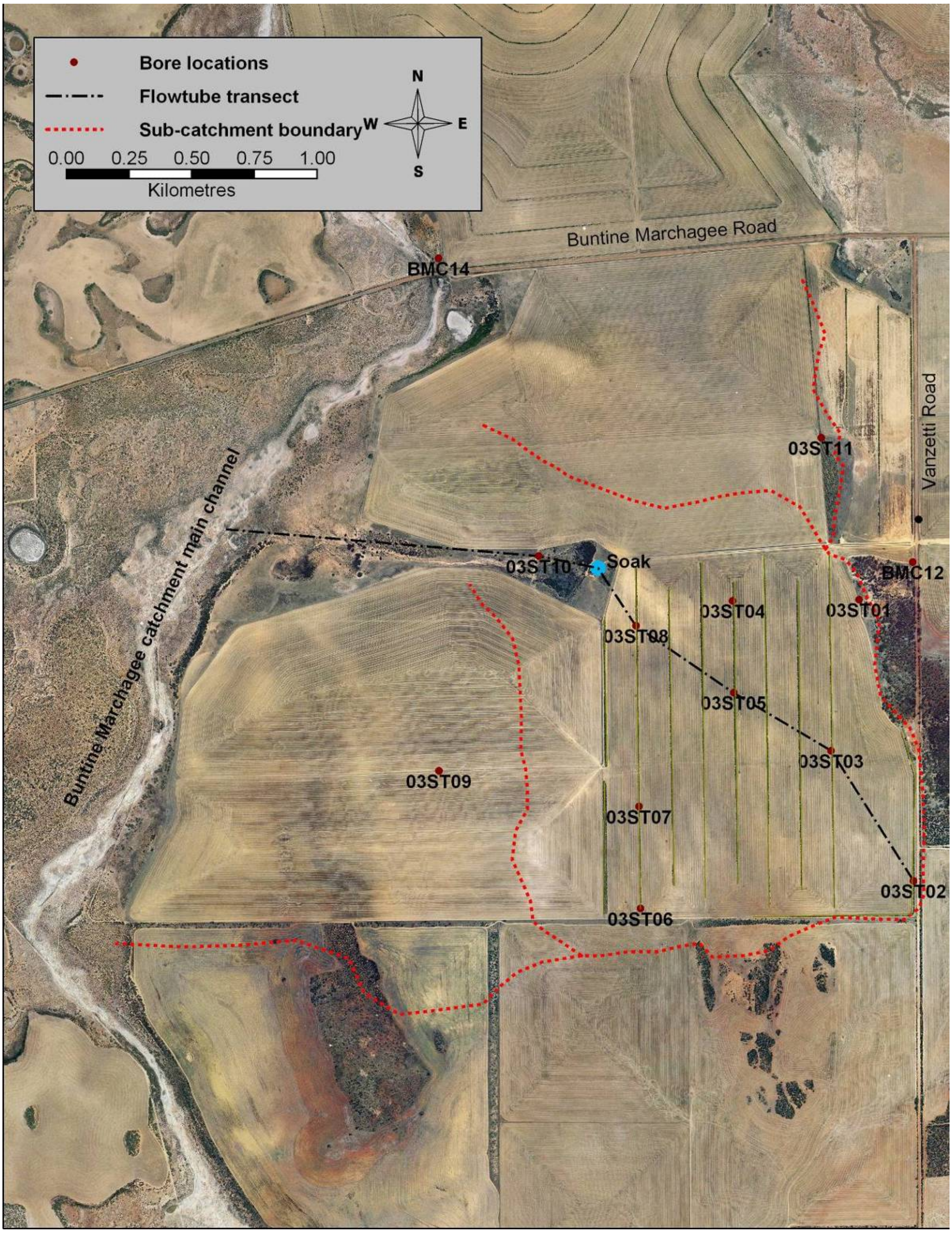

Figure 2 **The Marchagee site showing the bore site locations and oil mallee belts**

Figure 3 **The Goodlands site showing the bore site locations and oil mallee belts**

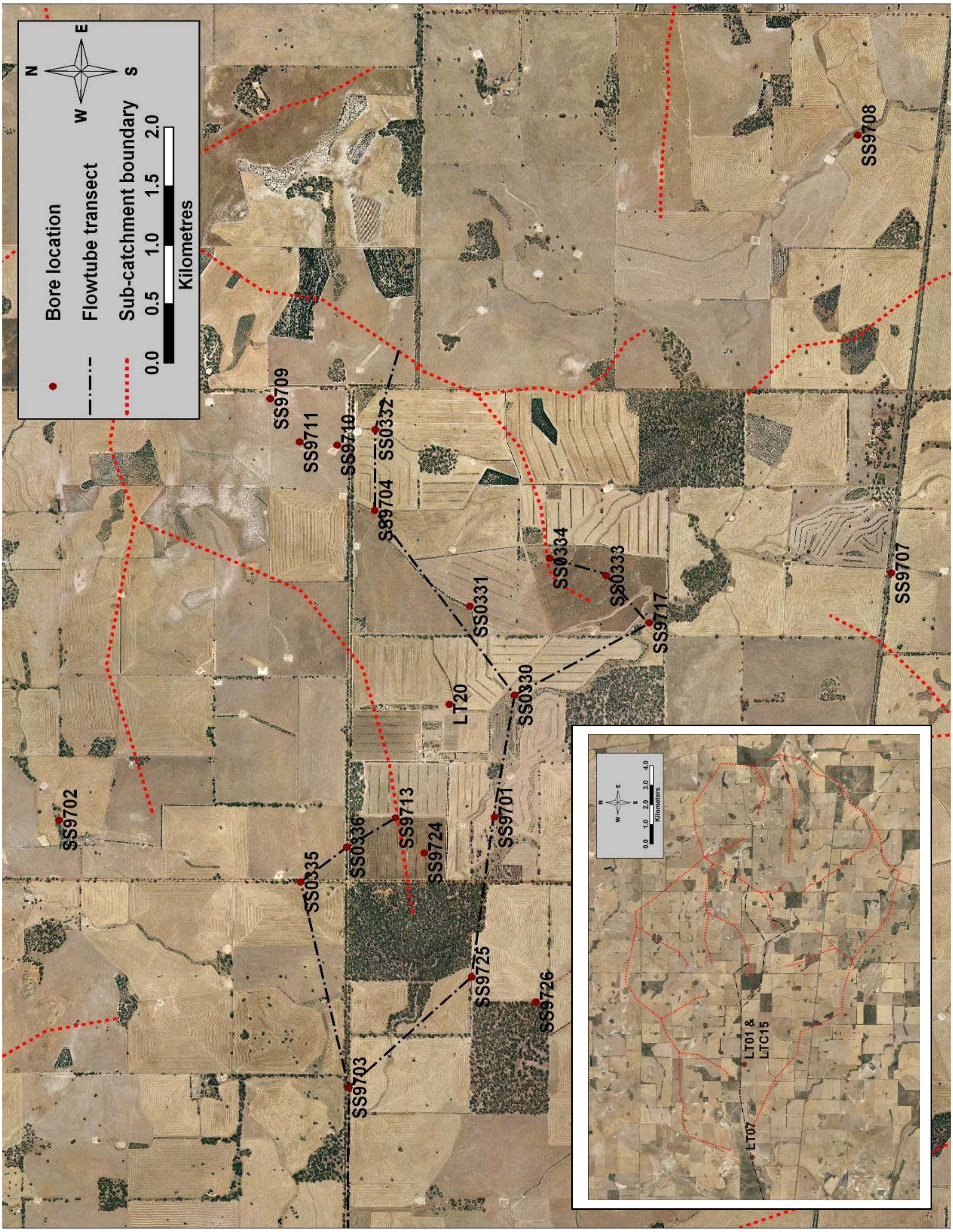

Figure 4 **The Tincurrin site showing the bore site locations and oil mallee belts. Comparison bore site SS91716 (not shown) is located about 7 km south of SS9703**

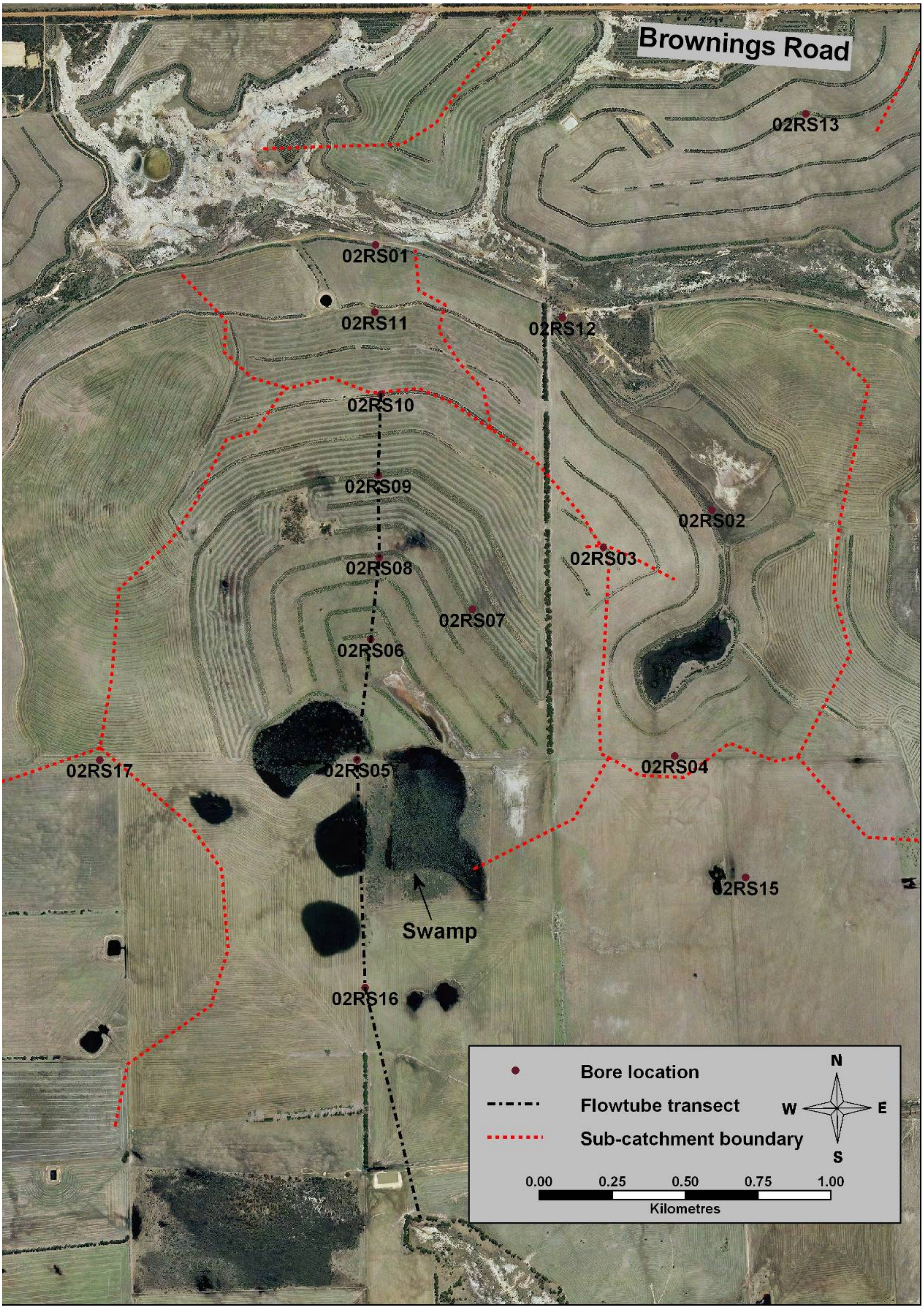

Figure 5 **The Gibson site showing the bore site locations and oil mallee belts. Bore site 02 RS14 (not shown) is located about 1.5 km east of 02RS13 and is also within the oil mallee belt system**

2.1.5 Catchment vegetation proportion summary

Table 1 shows the proportion of the catchment occupied by the oil mallee belt canopy, the natural and other existing perennial woody vegetation, the total canopy, the oil mallee belt ‘Competition Zone’, and the total proportion occupied by the ‘Mallee Zone’ at each site. The area occupied by the oil mallee belt canopy was calculated by multiplying the length of belt by its width, which was the distance between the two outer rows of the belt plus one metre on each side. The area of the Competition Zone, which is defined as the lateral extent where the oil mallee roots are likely to be in competition with those of agricultural crops and pastures for water and nutrients, was calculated to extend 10 m from the edge of the belt canopy on each side (Sudmeyer et al. 2004). The Mallee Zone is the sum of the width of the oil mallee belt canopy and the width of the Competition Zone (on each side). The area of remnant vegetation and other tree plantings and the lengths of the oil mallee belts were measured using a GIS linked to scaled, aerial photography.

Table 1 **The proportion of each site’s catchment occupied by the oil mallee belt canopy, the canopy of other perennial woody vegetation, the total canopy, the oil mallee belt Competition Zone and the total Mallee Zone**

Site	Catchment area (ha)	Oil mallee belt canopy (%)	Natural and other existing revegetation canopy (%)	Total canopy (%)	Oil mallee belt Competition Zone (%)	Total Mallee Zone (%)
Marchagee	150	3	5	8	15	18
Goodlands	300	4	5	9	13	17
Tincurrin (valley section)	220	10	18	28	37	47
Gibson	170	10	2	12	14	24

2.1.6 The influence of rainfall variability on groundwater levels

Variability in rainfall can have an effect on the catchment water balance and therefore groundwater levels over time. Major reductions in rainfall in south-western WA appear to have occurred in 1975 and 2000. In the Northern region (which includes the Marchagee and Goodlands sites) Speed and Kendle (2008) observed that prior to 2000, groundwater levels were generally rising or at equilibrium. However, since 2000, drier climatic conditions have prevailed and groundwater levels are now predominantly declining, apparently irrespective of geology, depth to groundwater or land management. George et al. (2008) reported that across the agricultural region of WA, the number of bores showing rising groundwater trends and their rates of rise have decreased since 2000. This response varies spatially, with most reductions in the Northern region and none in the eastern South Coast region (where the Gibson site is located). In the Central region (Tincurrin site), George et al. (2008) report that the post-2000 reduction in rainfall was not yet sufficient to have caused an observable change in the rates of groundwater rise.

Analysis of the effect of tree planting on groundwater levels should therefore take account of the underlying changes that may be due to rainfall. A useful method for analysing and displaying the changes in rainfall patterns over time is to use Accumulative Monthly Residual Rainfall (AMRR) because AMRR tends to have low, within year, fluctuations (Ferdowsian et al. 2001). AMRR is calculated as the sum of the difference between the observed monthly rainfall and the average rainfall for the corresponding month determined over the period of interest (expressed in millimetres). Extended periods where AMRR is generally increasing indicate a corresponding period of increasing rainfall, while periods of AMRR reduction indicate a drying trend. Figure 6 shows the AMRR at each of the oil mallee sites since 1975.

It shows the large change in rainfall that occurred in 2000, followed by a period of decline for the Marchagee, Goodlands and Tincurrin sites and a period of increase for the Gibson site (rainfall data extracted from SILO, 2009). The largest decline occurred at the Marchagee site, followed by Goodlands and Tincurrin. Tincurrin has a relatively stable AMRR after 2003 in particular. Based on the AMRR analysis alone (that is, if the sites were at hydrological equilibrium and there were no other factors) it could be expected that after 2003, groundwater levels would tend to show a rising trend at Gibson and falling trends at Marchagee, Goodlands and Tincurrin (listed in decreasing order of magnitude).

However, because rates of groundwater change are affected by many factors, including management, landscape position and the degree to which the catchment has responded to clearing, at each location control and comparison bores were also monitored to determine the rates of change under untreated conditions (no revegetation). Sites were selected to best match the underlying hydrological conditions influencing the bores located within the oil mallee systems. Control bores were installed in adjacent catchments with similar hydrogeology and agriculture. Comparison bores for each site were selected from the closest catchment containing existing DAFWA bores (from the long-term, regional groundwater monitoring bore network) that has similar hydrogeological characteristics to each site. Comparison bores are within catchments located about 20 km north-west, 10 km west-north-west and 10 km north of the Marchagee, Goodlands and Gibson sites respectively (not shown in Figures 2, 3 and 5).

The agricultural management of the comparison sites reflects the dominant land use of each region. Comparison bores therefore provide additional regional comparative groundwater trend data as another method of examining the influence of rainfall variability for each oil mallee site.

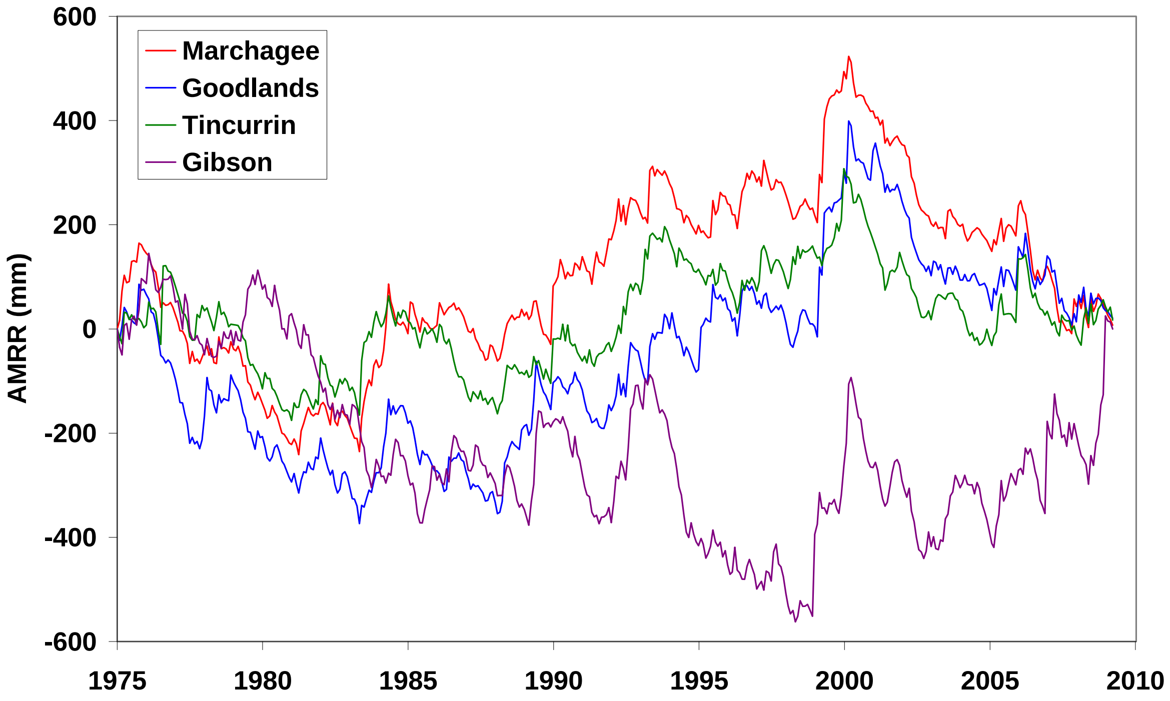

Figure 6 **Accumulative Monthly Residual Rainfall (AMRR) since 1975 at the four study sites**

2.1.7 Determining the groundwater level trend

Hydrograph and Rainfall Time Trends, HARTT, (Ferdowsian et al. 2001) is a method for statistically estimating trend (average annual rate of change) in groundwater levels. The approach separates the effect of atypical rainfall events from the underlying time trend, with rainfall analysed and represented as an accumulation of deviations from average rainfall (AMRR). HARTT analyses were undertaken for all of the bores at all sites. However, it was found, particularly at Gibson, that HARTT often predicted that groundwater levels fell (negative rates of rise) when the bore hydrographs showed that groundwater levels had risen during the monitoring period (Appendix A). HARTT also under-predicted the rate of recession of the groundwater level in some bores at Marchagee.

These inconsistencies may be because HARTT requires the use of a long period of historical rainfall data to define a ‘typical’ AMRR trend on which it bases its water level predictive statistics (R Ferdowsian [Hydrologist, DAFWA] 2009, pers comm. 2 Sept.). In this study, monthly rainfall since 1975 was used because 1975 is recognised as when the last major change in rainfall in south-western WA occurred (Berti et al. 2004). From Figure 6 it can be seen that the overall trend in AMRR since 1975 is one of decreasing rainfall at Gibson to 2000, with a generally increasing trend at the other sites. However, groundwater monitoring during this study coincided with the relatively short period since 2000 when these longer term trends were reversed at all sites, most dramatically at Marchagee and Gibson. Just using the rainfall since 2000 was not a long enough timeframe on which HARTT could be based to determine a statistically valid underlying rainfall trend.

Therefore, three other methods of determining the trend in the groundwater levels were compared to determine the most appropriate method to be used to analyse the effects of the oil mallee plantings. They were:

1. A graphical method involving plotting the groundwater level over time and calculating the dominant trend. Hydrographs with monotonic linear trends were simple to assess; however, where there was significant seasonal variability, trends were derived from a line of best fit connecting summer minima in groundwater levels.
2. Simple linear regression using the Microsoft Excel regression function to calculate the slope of the regression line of best fit to the groundwater monitoring data.
3. Arithmetic calculation where the trend was calculated by dividing the total change in groundwater level during the monitoring period by the number of years of monitoring. The total change in groundwater level was calculated as the difference between measurements obtained in April or May of the first year of monitoring and April or May of 2009. In this way, the potential effect of the annual, seasonally related cycles of groundwater level change (evident in some bores) on long-term trend was minimised.

The relationship between the trends obtained from the graphical analysis method and the other three methods (for all bores at all of the sites) are shown in Figure 7. There is more variability associated with the HARTT-derived trends than the other methods. Both the arithmetic and linear regression methods produce very similar trends to the graphically analysed trends, with the linear relationship between the methods being statistically highly significant and having a slope of almost unity. The graphical method was chosen above the other methods because it also allowed the additional flexibility to either ignore or include data outliers. For all bores, the trends calculated using each method are contained in Appendix A.

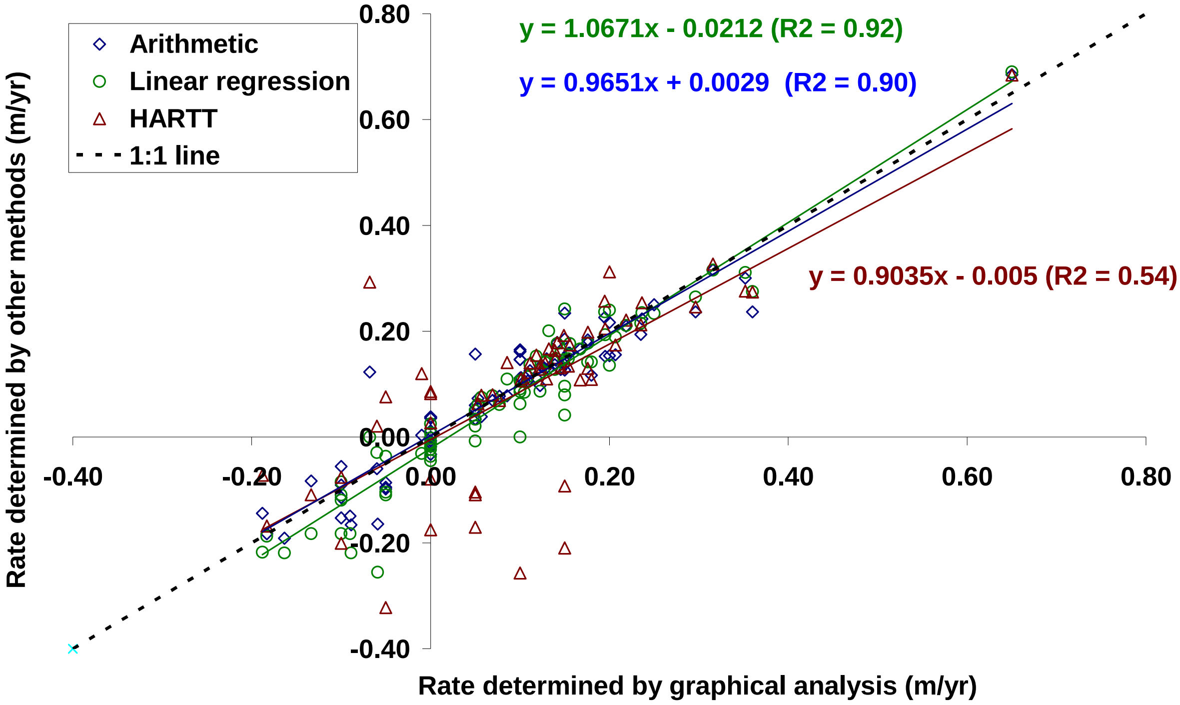

Figure 7 **Relationship between methods of determining the trend in groundwater levels for all of the bores used in the analysis (HARTT data that is not significant [P > 0.005] for time has been excluded)**

2.1.8 Using dataloggers to measure groundwater levels

At each site dataloggers (*STS* ® series DLN64 and DLN70 with pressure transducer sensors) were installed in several selected bores at the start of the study (late 2002 and early 2003). The dataloggers electronically recorded the water level every four hours. They were installed so that aquifer responses, such as evidence of the oil mallees transpiring groundwater or the short-term effect of large rainfall events, could be recorded in detail that manual measurements obtained about every two months on average would fail to capture. However, when the logger data was compared to the manually obtained measurements it was found that they did not provide much useful additional information, apart from confirming that the intensity of the manual measurements was sufficient to adequately represent the aquifer response trends for the purposes of this study in most cases. Only at one bore site at Marchagee was the logger data able to show a diurnal response indicating that the oil mallee belt was directly transpiring groundwater from the groundwater surface and/or capillary fringe.

The loggers were not particularly reliable and had frequent malfunctions, including loss of calibration and ingress of moisture causing circuitry malfunction and premature battery discharge, which resulted in substantial data gaps. Because of their unreliability, the considerable increased effort required for maintenance and data manipulation, as well as the absence of much useful additional information being obtained, their use is not recommended for similar long-term groundwater monitoring studies. The bore hydrographs contained in Appendixes B–E show the logger data obtained, together with the manually measured water levels.

2.1.9 Flowtube modelling

Preliminary Flowtube modelling along transects that best represented the main groundwater flow lines at each site was undertaken in conjunction with the initial hydrological investigations at the start of the study. This modelling was undertaken to assess the likely groundwater equilibrium condition and the likely range of hydrological effect of the oil mallee plantings. Flowtube is a two-dimensional, cross-sectional transient groundwater model, based on Darcian flow rules (Dawes et al. 2000; Argent et al. 2001). It is a mass balance model that produces outputs that include groundwater heads and gradients along a transect or flowtube, the rates of head change along the flowtube, and the length of the flowtube that is saturated (LSF) to within a pre-definable range of depths from the ground surface. Flowtube has been widely used to forecast equilibrium groundwater conditions and the effect of a range of treatments (George et al. 2001). It has also been used in the Toolibin catchment along with another groundwater model, MAGIC (Mauger 1996). Both models agreed closely in their forecasts of equilibrium extent and treatment response (Dogramaci et al. 2003). More recently, George et al. (2004) and George and Bennett (2004) used Flowtube to forecast that a focus on valley recharge reduction strategies was likely to be more effective in managing salinity than a hillslope focus at several wheatbelt sites.

Drill log descriptions, on-site hydraulic conductivity measurements and published values (George et al. 1992a; Clarke et al. 2000) were used to set the aquifer conditions for the model at each site. The major parameters used in the model at each site were based on the following assumptions:

- The weathered basement saprock aquifer was assumed to be the main controlling aquifer.
- The measured saturated hydraulic conductivities of the saprock aquifer at each bore location were used.
- The model upper layer (saprolite) porosity was set at 0.1.
- The model upper layer (saprolite) hydraulic conductivity was 0.05 m/day.
- The maximum evaporation depth was set to be either one or two metres, depending on whether the majority of the flowtube that had shallow groundwater was located in sandy (Marchagee, Tincurrin and Gibson) or loamy clay soils (Goodlands) respectively.
- The groundwater level at clearing was assumed to be within one metre of the basement in the mid and upper slope locations. In lower slope locations it was governed by areas of primary salinity which were assumed to have groundwater levels near the surface at clearing.
- The constant head point chosen at each site was at an area of primary groundwater discharge located at a substantial distance down gradient from the oil mallee areas.

Seven stages of Flowtube modelling were undertaken at each site:

1. To assist in calibrating the model at each site and define the likely long-term rates of recharge that resulted in the heads observed when monitoring commenced, model simulations with assumed various long-term average annual rates of recharge (ARR) were run from the groundwater heads that were assumed to be present at clearing. The groundwater heads generated by the model were then compared to the observed levels and the modelled rates of rise were also compared to those reported in the district. From this, an ARR for each site was determined, based on the model results that most closely matched the observed heads and reported head rate of change. Acceptable calibration was when the modelled heads were within 0.5 m of the observed head at all bore sites along the flowtube. Modelled rates of head change were then compared to reported rates for similar landscape positions in the district to ensure that the modelled rates were realistic. ARR was assumed to be zero under areas of uncleared vegetation.

2. Once model calibration was established, Flowtube was then used to forecast the groundwater heads 50 and 100 years into the future (to 2053 and 2103) under the calibrated long-term recharge rates and scenarios of recharge reduction and groundwater use that might result from installing an oil mallee system. The oil mallee belts were modelled to have a hydrological width of influence equal to the width of the belt canopy plus the Competition Zone which is about 10 m on each side. This is distinct from the remainder of the inter-belt alleys where the oil mallees have no effect on water use, termed the ‘Alley Zone’. This distance was chosen on the basis of data reported in Sudmeyer et al. (2004), Wildy et al. (2004) and Robinson et al. (2006). The latter two reports showed that oil mallee belts have caused a reduction in soil water storage between nine and 15 m from the belt. While the modelled Mallee Zone width is at the lower end of this range, the modelled scenarios ranged from recharge being completely eliminated to high rates of net groundwater usage, not just some soil water extraction and partial recharge elimination, so this distance is probably generous.

The methodology and the results of the modelling for Stages 1 and 2 are contained in the hydrological investigation reports for each site (Bennett et al. 2005a and 2005c; Bennett 2005; Bennett & Goodreid 2009).

3. In 2009, the next phase of modelling imposed new recharge scenarios on the existing flowtubes (that were previously calibrated to the conditions at the start of groundwater observations) for the period from the start of monitoring (2002 for Gibson and 2003 for other sites) until 2009. Because of the changed rainfall conditions since 2000, which approximately coincided with the start of the study, the underlying ARRs used in Flowtube for this period needed to be reassessed (assumed without oil mallees for the purposes of calibration). This was done by simulating unplanted conditions with various ARR scenarios and then comparing the predicted rates of groundwater head change to the observed rates of control or comparison bores during this period. In this way the new underlying ARRs likely for annual agriculture were determined for each site.
4. Once the ARRs for the post-2000 period were chosen, Flowtube scenarios were run for the period coinciding with the observation period at each site, additionally imposing various scenarios of recharge reduction and/or groundwater abstraction (negative ARR) within the Mallee Zones. These scenarios are discussed separately for each site along with the modelling results. The modelled and observed heads in 2009, together with the modelled and observed rates of head change during the observation period, were then compared along the flowtube to determine the most likely effect that the oil mallee belts had on recharge. The modelled rates of head change were compared to the rates obtained in Stage 3 of the modelling to determine the theoretical effect of the oil mallees on groundwater trend.
5. Flowtube was also used to simulate the effect on groundwater heads assuming that the ‘with mallee’ recharge conditions were maintained for 50 years, commencing in either 2002 (Gibson) or 2003. The 50-year timeframe was chosen because it was considered long enough for changes to become evident, yet short enough to still be within a reasonable farm management planning timeframe encompassing one to two generations of farm owners or managers. It was considered to be not relevant to go beyond 50 years because the uncertainties, in terms of climate, the development of new farming technologies and the ability to make land management decisions, increase greatly beyond this time period.
6. At each site another simulation was run from the start of observation for 50 years with zero recharge (ARR set to zero) for the full length of the flowtube to simulate what would happen to groundwater heads under a theoretical agricultural system that has no leakage. This was undertaken to gauge how responsive the groundwater system at each site would be to the ultimate long-term level of recharge control.

7. Finally, multiple simulations were undertaken, using the hydrological conditions that prevailed at the start of groundwater level observation as a starting point, by sequentially reducing the ARR until heads started to reduce along the entire length of the flowtube. This was undertaken as a way to assess the capacity of the aquifer to transmit groundwater, measured in terms of the ARR and converted to a proportion of the calibrated baseline ARR. This procedure was termed ‘Aquifer Capacity Modelling’ and was undertaken to theoretically examine what the ARR would need to be reduced to for the aquifer to be able to entirely cope with recharge.

The LSF outputs from Flowtube are used as a convenient way of reporting and comparing the modelled effects on the length of shallow groundwater at each site. However, it should be noted that shallow groundwater does not necessarily result in land salinity. Factors such as soil type, salinity of the groundwater and rainfall, influence the severity of the effect of shallow groundwater on annual crops and pastures. LSF can be approximately converted to proportions of the catchment, dependent on the cross-sectional shape of the landscape, using the following equations (Mouat & Clarke, 2004):

- for ‘V’ shaped catchments (Marchagee), area (m^2) = (0.2921 x LSF) + 1.1821
- for ‘U’ shaped catchments (Goodlands, Tincurrin, Gibson), area (m^2) = 0.312 x $e^{(0.0597 \times LSF)}$.

3. Results and discussion

3.1 Observations of the impact of oil mallee systems on catchment-scale groundwater systems

3.1.1 Marchagee

The average annual trends in groundwater heads between 2003 and 2009 at all bore sites at Marchagee are presented in Table 2. The data has been grouped into categories of bores within the oil mallee planting, control bores and comparison bores, along with the mean and median values for each category. No bores in any grouping had an upward trend, with most having downward trends (indicated by a negative number) and some having no discernable trend. These results support the hypothesis, based on modelling undertaken at the start of monitoring in 2003 (Bennett & Goodreid 2009), that the site was likely to be close to hydrological equilibrium prior to oil mallees. Since 2003, rainfall at the site has declined substantially—by 490 mm between 2003 and 2009 based on analysis of AMRR (Figure 6).

While it could be expected that the oil mallees reduced recharge and/or transpired groundwater, from the analysis we could not determine a higher rate of reduction between water levels in bores beneath the oil mallee alley system and either the control or comparison bores. The mean and median rates calculated for each of the groupings of bores are not statistically different (95 per cent confidence level). In fact, the comparison bores have the highest mean and median rates of reduction, although this difference (0.03 m/yr) is likely to be within the range that could be expected to be caused by other site variables.

However, at one bore site 03ST08I (Figure 8) the groundwater response indicates that the adjacent oil mallee row has influenced the shallow, unconfined groundwater, by reducing the recharge and possibly by directly transpiring groundwater from the upper part of the aquifer above the silcrete layer. The response of the bores 03ST08D and 03ST08I is compared in Figure 8, along with bore CA6D and the plot of AMRR. The comparison bore CA6D, which is in a catchment not planted with oil mallees, has a very similar response and trend as 03ST08D. The water level in bore 03ST08I (installed into sands above the silcrete) appears to fall more rapidly than that within bore 03ST08D, which is the deeper bore at the site and installed into the partially confined (by the silcrete layer) basement aquifer below the silcrete. This is the only bore site at Marchagee where the oil mallees have access to unconfined, reasonable quality (1400 mS/m) groundwater that outcrops the silcrete layer. It corresponds with an area of greatly increased oil mallee growth, evident in Figure 9. Carter and White (2009) report that the above ground biomass of these oil mallees was six times higher than in other areas where groundwater was below the silcrete hardpan. Water level data collected by the use of a datalogger installed at 03ST08I displays a faint diurnal pattern over the summer months in particular, with levels falling about 0.01 m during the day and then recovering during the following night (Appendix B, Figure B8). This pattern suggests direct uptake from the groundwater or at least the capillary fringe by the trees during the day.

The observed impact of the oil mallees in the area where groundwater outcrops the silcrete does not extend across the site. Mapping of the extent of the area where the oil mallees exhibit the greatly increased growth, together with the comparison of observed groundwater levels to the depth to silcrete from drilling logs, indicates that the lateral extent of shallow groundwater outcrop above the silcrete comprises less than 10 per cent of the catchment. Beyond this area, data from bores (including all deep bores) shows that the hydrological effect does not appear to translate to the underlying, catchment-scale, groundwater flow system.

Table 2 **The rates of change of groundwater head between 2003 and 2009 at Marchagee**

	Bore site name	Landform	Rate (m/yr)
Oil mallee bores	03ST02D	Upper slope	-0.09
	03ST06D	Upper slope	0.00
	03ST11D	Upper slope	-0.13
	03ST03D	Upper mid-slope	-0.06
	03ST07D	Upper mid-slope	-0.07
	03ST04D	Mid-slope	-0.09
	03ST05D	Mid-slope	-0.05
	03ST08D	Lower mid-slope	-0.10
	03ST10D	Lower slope	-0.06
Control bores	03ST01D	Upper slope	-0.16
	03ST09D	Mid slope	0.00
	BMC12D	Lower slope	-0.10
	BMC14D	Valley	-0.05
Comparison bores	CA2D	Upper slope	-0.10
	CA26D	Upper mid-slope	-0.18
	CA12D	Lower mid-slope	0.00
	CA6D	Lower slope	-0.19
	CA3D	Valley	-0.01
Summary	**Oil mallee mean**		**-0.07**
	Oil mallee median		**-0.07**
	Control mean		**-0.07**
	Control median		**-0.05**
	Comparison mean		**-0.10**
	Comparison median		**-0.10**

The pronounced upward hydraulic head at 03ST08 indicates that the silcrete layer is acting as a partial aquitard in this location—at least to the extent that it restricts the rate of vertical flow of the groundwater to somewhat less than the transpirative capacity of the adjacent oil mallee row. Bennett et al. (2005) concluded that silcrete is unlikely to be a complete aquitard, so some upward flux of groundwater at this site is probable. EC measurements indicate that the groundwater at 03ST08I has higher salinity (1400 mS/m) than the deeper groundwater at 03ST08D (600 mS/m). Salts may have concentrated in the upper groundwater perhaps due, in part, to the transpiration of the oil mallees. While the current salinity of the groundwater is apparently low enough to enable some use of the water by the oil mallees, it is possible that the salt concentration may increase to a level that becomes unsuitable in future if continued water use occurs. Possible increases in water salinity and aquifer depletion (this part of the aquifer was completely depleted to the top of the silcrete in 2008) suggest there is a risk that the current high growth rates of the oil mallees in the area around 03ST08 may not be able to be sustained in the future.

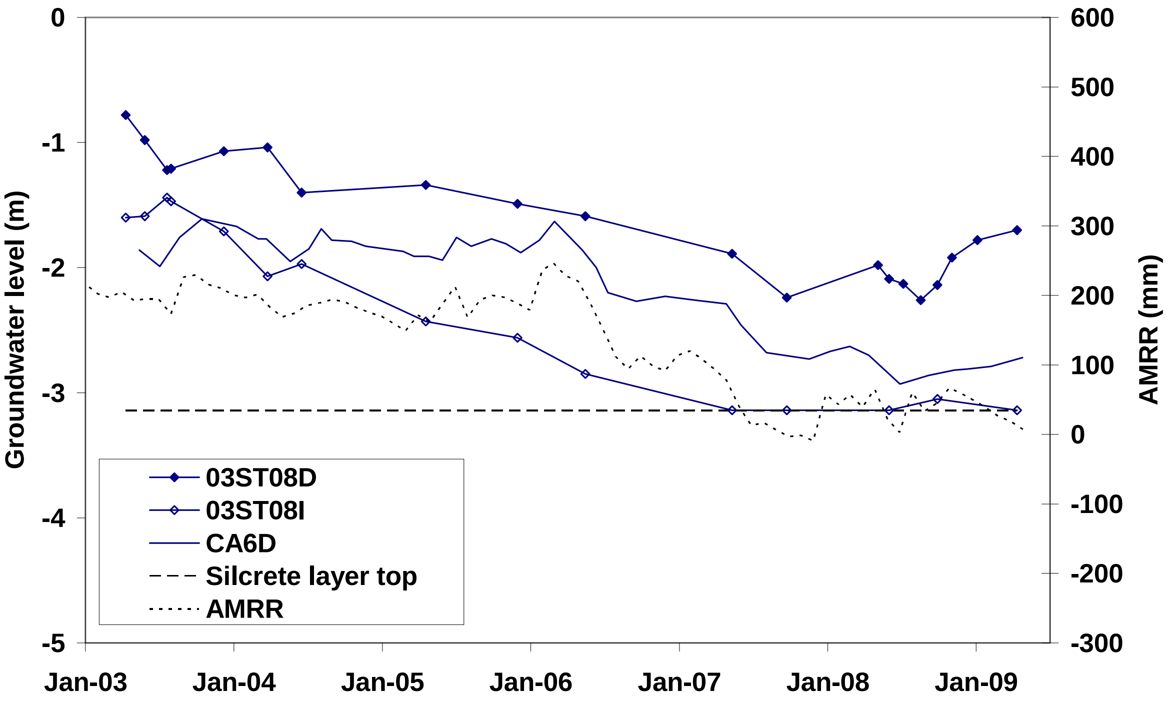

Figure 8 **Hydrographs for deep (03ST08D) and shallow (03ST08I) bores together with bore CA6D as an untreated comparison and the plot of AMRR at Marchagee**

Depletion of shallow, thin, relatively fresh sandplain aquifers in the wheatbelt by belts of trees has been previously observed (George, 1990). In that instance, transpiration by a young, 250 m long, six-row tree belt rapidly exceeded the supply of groundwater being delivered laterally by a shallow aquifer over a silcrete hardpan. George (1992b) estimated that the actual supply of groundwater being delivered laterally to the tree belt was small—1000 kL/yr, representing six millimetres of annual recharge. By contrast, recharge to the deeper aquifer was reported to be approximately twice this amount (two orders of magnitude larger than its transmission capacity at the outlet) and it had a transmissivity 10–50 times higher than the shallow aquifer. This example highlights that tree belts are much more effective at intercepting groundwater in small shallow systems, and hence addressing salinity or waterlogging at local scales, than in larger catchment-scale systems. Catchment-scale aquifers have a much higher transmissivity, contain much larger volumes of groundwater, are usually located deeper than can be explored by the roots of trees and may be below impenetrable horizons and are often much more saline than shallow aquifers.

On the basis that there is very little difference between the average groundwater response under the oil mallees and either the control or comparison areas, it appears that the oil mallee system has had minimal measurable hydrological effect on groundwater levels at the catchment-scale at Marchagee. This result agrees with the visual observation that there has been no apparent reduction in area or severity of the visibly saline area downslope of the oil mallee system. This is also perhaps not surprising given the somewhat modest net reductions in groundwater level in lower slope positions, for example 0.54 m at bore 03ST10. The similar reductions in groundwater levels observed across the treated and untreated areas suggests that they are more as a result of the substantial reduction in rainfall experienced at the site since 2000. Some of this effect can be attributed to the catchment likely having been in a state of groundwater quasi-equilibrium at the start of groundwater observations.

Figure 9 **Increased growth of oil mallees near bore site 03ST08 corresponding to the area containing shallow and brackish groundwater at Marchagee**

3.1.2 Goodlands

At Goodlands, groundwater levels mostly continued to rise or remained static beneath the oil mallee system, with the trends being similar to those of the comparison bores located in areas growing only annual crops and pastures (Table 3). The mean and median rates of groundwater rise under the oil mallees were 0.11 m/yr and 0.12 m/yr respectively, 0.02 m/yr less than in the comparison area. However, this difference was not significant (95 per cent confidence interval).

The generally rising groundwater trend contrasts with the falling trend observed at Marchagee which is located only about 100 km to the north-west. There are two main possible reasons for this difference: firstly, the cumulative deviation from long-term average rainfall since 2000 was 200 mm less at Goodlands than at Marchagee—based on AMRR data (Figure 6); and secondly, unlike Marchagee, the Goodlands catchment does not appear, based on the Flowtube modelling undertaken at the start of the study, to be near hydrological equilibrium following final clearing of the catchment in the 1970s. So, unlike Marchagee, which had clearing completed in the 1950s and is a much shorter and steeper catchment, groundwater levels are expected to continue to rise in the long-term, given recharge remains similar.

There is no trend evident in depth to groundwater at bore 03IS01D (Table 3 and Appendix C, Figure C1) located in the upper slope of the oil mallee planting. The absence of trend is in contrast to the strong rising trends evident in mid-slope (0.22 m/yr), the lower slope (0.09 m/yr) and the valley (0.15 m/yr) positions within the oil mallee area, as well as the upper slope comparison bore (0.32 m/yr). The likely main reason for the absence of trend is that the groundwater system is quite undeveloped in the upper slope under the oil mallee site. At 03IS01D, the saturated layer remains thin and contained entirely within the relatively high hydraulic conductivity saprolite grit layer situated at the base of the regolith. Additionally, it has a higher hydraulic gradient (about three per cent) than the rest of the transect (about 0.3 per cent) and the comparison bore transect. These factors indicate that the aquifer at this point may have a large enough capacity to transmit the incident recharge it receives. This hypothesis is supported by the Flowtube modelling (Bennett et al. 2005a) that indicated it will take about 50 years of continued recharge before the water levels at 03IS01D begin rising, in response to the reduction in hydraulic gradient downslope.

Table 3 **The rates of change of groundwater head between 2003 and 2009 in bores at Goodlands**

	Bore site name	Landform	Rate (m/yr)
Oil mallee bores	03IS01D	Upper slope	0.00
	03IS02D	Mid-slope	0.22
	03IS03D	Lower slope	0.09
	03IS04D	Valley	0.15
Comparison bores	GD18D	Upper slope	0.32
	GD17D	Mid-slope	0.08
	GD15D	Lower slope	0.00
	GD11	Valley	0.12
Summary	**Oil mallee mean**		**0.11**
	Oil mallee median		**0.12**
	Comparison mean		**0.13**
	Comparison median		**0.10**

A thin, brackish (960 mS/m), perched aquifer overlying the prevalent silcrete layer is present at bore location 03IS02. This aquifer, together with soil type and depth, was the subject of a detailed investigation to determine its influence on the growth rates of the oil mallees (Pracilio et al. 2006). It was initially thought that the perched aquifer may be extensive and could be an important factor in determining oil mallee growth rates. However, none of 15 additional locations drilled at Goodlands by Pracilio et al. (2006) had a perched aquifer present. It seems that the perched aquifer as measured by bore 03IS02OB is highly localised (perhaps less than one hectare in size) and therefore of little consequence at the catchment-scale to the overall oil mallee productivity, or hydrology at the site. This finding supports the conclusion of Bennett et al. (2005b) that in the north-eastern wheatbelt region, silcrete, while prevalent, is unlikely to support permanent perched aquifers that are of much consequence to the productivity of oil mallee systems. Pracilio et al. (2006) found that the most important determinant of oil mallee growth at Goodlands was the thickness of the sandy loam horizon above the silcrete layer, with growth being significantly higher where the thickness was greater than four metres, compared to thinner sequences.

The relatively shallow, unconfined sandy aquifer at 02IS02OB has similar properties to that present under a section of the Marchagee site (as previously discussed). While at Marchagee the groundwater level fell, the depth to the perched groundwater at 03IS02OB did not change substantially during the seven years of monitoring (Figure 10). This result is surprising particularly when compared to the apparent effect that the oil mallees had on the groundwater (where it outcropped the silcrete) at Marchagee, even though there it is a much shallower profile. The groundwater level response at 03IS02OB follows the AMRR without any apparent effect from the adjacent oil mallee row. Given its small capacity (it has small lateral extent and is thin) the oil mallees could be expected to rapidly deplete the aquifer if they were accessing it. Additionally, there is no diurnal pattern evident in the logger data. The lack of response could be because the aquifer is too deep for the oil mallees to effectively access or use. The absence of the oil mallees' impact on the perched system is also reflected in the deeper groundwater in this location. The water level in the deep bore (03IS02D) installed next to 02IS02OB into the basement aquifer (beneath the silcrete layer) has continued to rise in an almost linear trend. The trend and pattern of response of 03IS02D is also very similar to that of the untreated comparison bore GD17D.

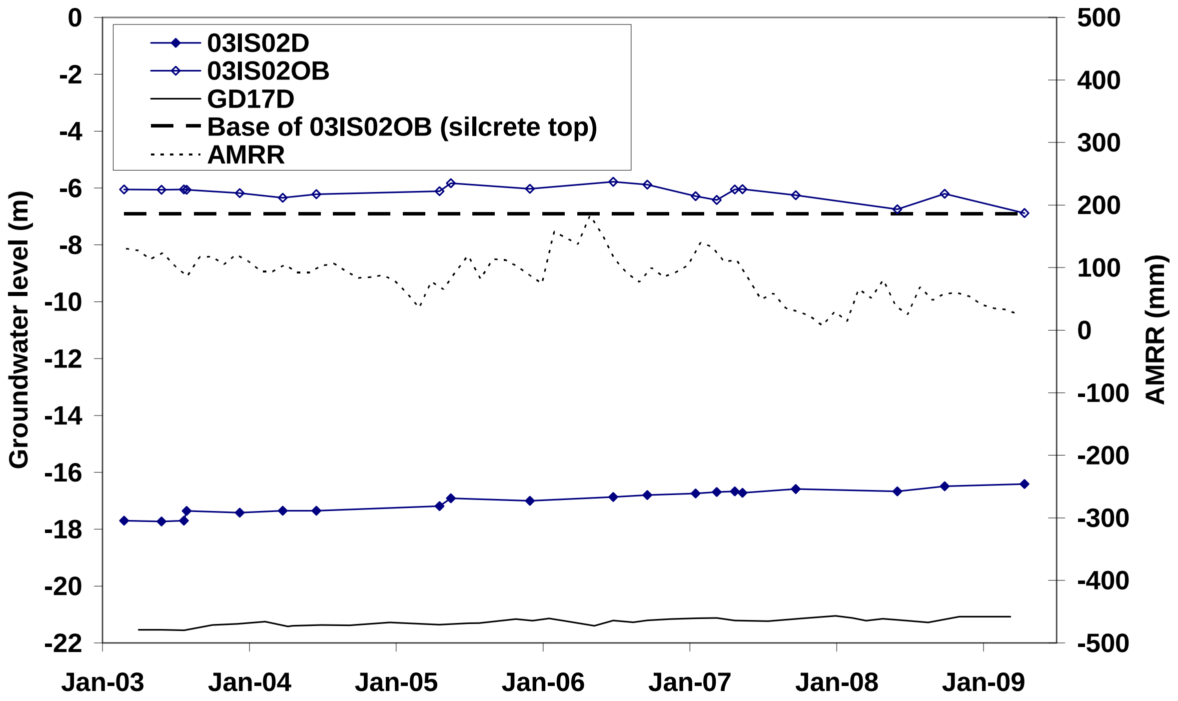

Figure 10 **Hydrographs for deep (03IS02D) and shallower (03IS02OB) bores together with bore GD17D as an untreated comparison and the plot of AMRR at Goodlands**

On the basis that groundwater levels continue to rise uniformly and monotonically under the oil mallees at substantial average rates that are also similar to the untreated comparison areas, it appears that the oil mallee system has had minimal effect on groundwater heads at the catchment-scale at the Goodlands site.

3.1.3 Tincurrin

At Tincurrin, groundwater monitoring records are available since 1997, both for parts of the oil mallee area planted in 2003 and the adjacent cleared and unplanted farmland for comparison. The available groundwater data allowed comparison of water level trends between not only planted and unplanted areas, but also between trends prior to and after oil mallees were planted. Table 4 shows the water level trends for the periods before and after the oil mallees were planted, as well as the calculated differences between the two periods. A trend prior to 2003 could not be calculated for bores installed in 2003 (shown as ‘na’). Appendix D contains the hydrographs for all bores used in the analysis of groundwater depth trends at Tincurrin.

The water levels recorded in every bore had an upward trend during both periods, irrespective of whether they were positioned within the oil mallee system or in unplanted locations. Following planting, bores within the oil mallee system showed a reduction in the rate of water level rise, by an average of 0.08 m/yr. However, the comparison bores also showed a decrease in the rate of rise after 2003, by a slightly higher average of 0.12 m/yr, although this difference is not significant at the 95 per cent level of confidence. It should also be noted that although the average reduction in the rate of rise was higher in the comparison bores, these bores also had a higher average rate of rise prior to 2003. After 2003 the average rate of rise in the oil mallee bores was slightly lower than in the comparison bores (0.12 m/yr verses 0.15 m/yr). Again there was a non-significant difference. It therefore seems that the rate of rise in water levels in the catchment declined in the period after planting, irrespective of whether the area was planted or not, reflecting the reduction in rainfall experienced in the area since 2000 of 290 mm of AMRR (Figure 6).

On the basis of the groundwater monitoring it appears that after seven years, the oil mallee system has had no measurable effect on the rates of rise of the groundwater at Tincurrin.

Table 4 **The rates of change of groundwater head in bores within comparison and treated areas at Tincurrin before and after the oil mallees were planted**

	Bore site name	Landform	Before rate (m/yr)	After rate (m/yr)	Change in rate (m/yr)
Oil mallee bores	LT20	Valley	0.16	0.13	-0.03
	SS0330D	Valley	na	0.12	na
	SS0331D	Valley	na	0.13	na
	SS0332D	Mid-slope	na	dry	na
	SS0333D	Mid-slope	na	0.11	na
	SS0334D	Upper slope	na	dry	na
	SS9701D	Valley	0.15	0.11	-0.05
	SS9713D	Upper slope	0.24	0.06	-0.18
	SS9724D	Mid-slope	0.13	0.07	-0.06
	SS0336D	Lower slope	na	0.20	na
Comparison bores	SS0335D	Lower slope	na	0.14	na
	SS9703D	Valley	0.21	0.10	-0.11
	SS9704D	Valley	0.35	0.19	-0.16
	SS9709D	Upper slope	dry	dry	dry
	SS9710D	Mid-slope	dry	dry	dry
	SS9711D	Mid-slope	dry	dry	dry
	SS9717D	Valley	0.15	0.11	-0.03
	SS9725D	Valley	0.17	0.14	-0.03
	SS9708D	Valley	0.30	0.18	-0.18
	SS9707D	Lower slope	0.18	0.14	-0.04
	SS9702D	Valley	0.30	0.24	-0.06
	SS9716D	Upper slope	0.65	0.20	-0.45
	SS9726D	Valley	0.13	0.12	-0.01
	LT01	Valley	na	0.05	na
	LTC15	Valley	0.18	0.05	-0.12
Summary	**Oil mallee mean**		**0.17**	**0.12**	**-0.08**
	Oil mallee median		**0.16**	**0.12**	**-0.05**
	Comparison mean		**0.27**	**0.15**	**-0.12**
	Comparison median		**0.19**	**0.14**	**-0.08**

Hydrographs for bores SS9701D and SS9708D show the typical reduction in rate of water level rise associated with the reduction in AMRR over the monitoring period (Figure 11). Bore SS9701D is in the valley and near the lower edge of the oil mallee system and bore SS9708D is within the same valley but upslope from the planting by about three kilometres and therefore is unlikely to be influenced by the planting.

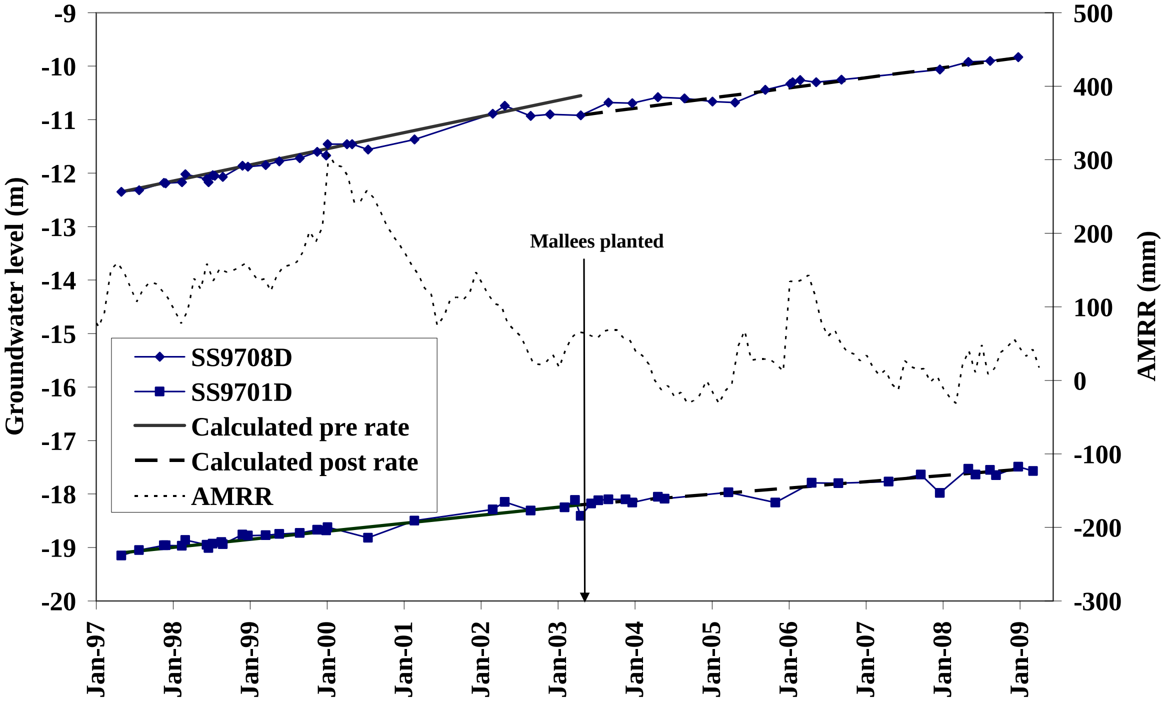

Figure 11 **Water levels in valley bores within (SS9701D) and upslope (SS9708D) of the planted area, and the calculated linear trend lines displayed for the periods before and after the oil mallees were planted**

The groundwater data were also analysed on the basis of whether the bores were located within the section of the valley encompassed by the oil mallee system, within the valley but upstream of the oil mallee system, or within the main valley downstream of the oil mallee system (Table 5). The data were also further sub-divided into the periods before and after planting. Groundwater heads had an increasing trend at all sites. The heads in bores located above the planting had a higher rate of rise than those within or below, for both periods. Before the oil mallees were planted the mean and median rates of head rise in the bores located in the valley above the planting were almost double those of the bores located further down the valley, although this difference was not significant at the 95 per cent confidence level. There were similar mean and median rates of rise within and below the planting, for both periods. The higher rates observed in the upper valley could be because the valley is narrower in this location, therefore having an aquifer that has both a reduced storage capacity and a reduced flow capacity per unit area of surrounding hillslope recharge. Also, the upper areas of the catchment could have higher rates of groundwater recharge because the surrounding slopes have a greater proportion of deep sandy and gravelly soils than further down the valley.

Table 5 **The mean and median groundwater head trends of valley bores calculated on the basis of their location for the periods before and after the oil mallees were planted at Tincurrin**

Bore location	Before rate (m/yr)	After rate (m/yr)	Rate change (m/yr)
Valley above mean	0.27	0.17	-0.10
Valley above median	0.24	0.16	-0.05
Valley planted mean	0.16	0.13	-0.04
Valley planted median	0.16	0.13	-0.04
Valley below mean	0.17	0.11	-0.07
Valley below median	0.17	0.12	-0.07

The groundwater monitoring was also designed to examine the oil mallee system's effect on perched groundwater systems, thought to develop within the relatively thin alluvial layer covering the valley following episodic rainfall events or prolonged periods of high rainfall. However, groundwater levels collected both manually and from dataloggers in bores installed to the base of the alluvial sequence (about 6 m depth) at sites SS9701 and SS0330 showed no evidence of perched groundwater developing at any time after 2003. The only evidence of a perched aquifer was at site SS9717 (Figure 12) where manual observations taken in the shallow (1.9 m deep) bore (SS9717S) indicate that a short-lived, perched aquifer occasionally developed. However, because this bore is located next to the main valley creek line, it is likely that the observed perched aquifer response reflects a localised area of shallow saturation that developed when the creek flowed. The localised extent and short duration mean that it is likely to be of minor hydrological consequence at the valley-scale. As for the other bore sites, the 6 m deep bore installed to the base of the alluvial layer at SS9717 remained dry and the deep bore did not respond to the flow events.

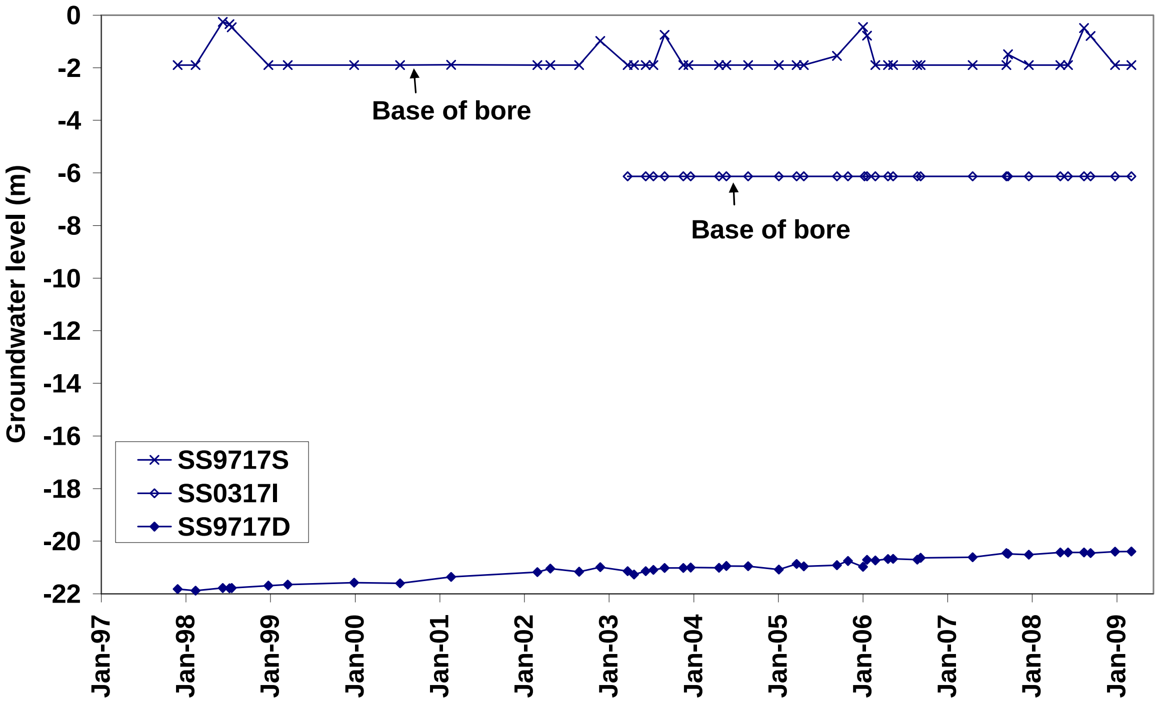

Figure 12 **A highly transient perched aquifer develops at SS9717 in response to creek flow with no measurable evidence of perched water effects deeper in the profile**

The hydrographs showing groundwater heads collected using dataloggers installed in bores located much further down the Scriveners Soak catchment (Figure 4) during 2005 and 2006 are shown in Figure 13. Two catchment-scale run-off events occurred—one over a two-day period in May 2005 and the other in January 2006. The depth to groundwater measured at LTC15I, a shallow (7.2 m deep) observation bore located adjacent to the main creek line, responded rapidly to the surface flow, and declined again within seven days, presumably by drainage into surrounding soils. No head response to these events was evident in piezometer LT01D installed to the basement aquifer 5 m away from LTC15I. This response is similar to that measured at site SS9717, indicating that transient flooding causes a highly localised and short duration response adjacent to the creek line. It also appears there is no, or very limited, hydraulic connection between surface layers and the deeper aquifer during episodic flooding. No run-off events were recorded after 2006 at a gauge located further down the catchment at the entrance to Lake Toolibin. While the data is limited in that it captures the only two catchment-scale run-off events that occurred over a period of four years (and is localised) it suggests that reducing the catchment run-off may not effectively reduce the piezometric pressure in the catchment valley and thus have minor effect on the long-term development of salinity in the catchment. However, it could reduce the severity of short-term waterlogging in areas immediately adjacent to the creek line, particularly at the bottom end of the catchment.

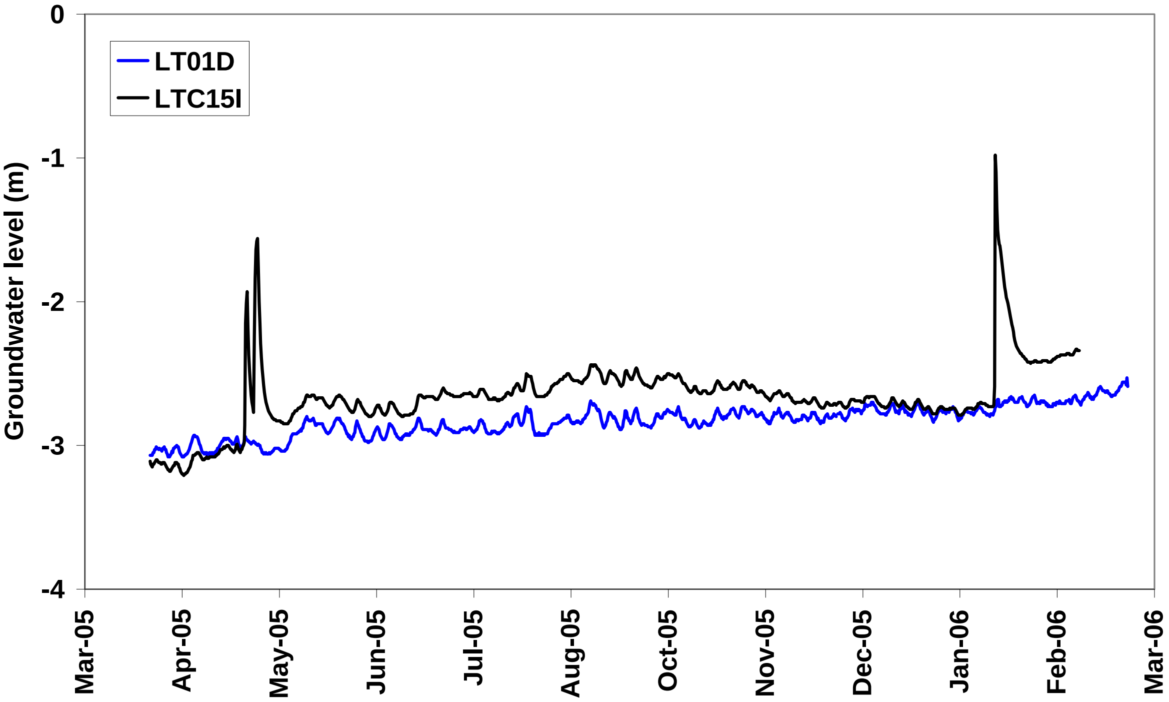

Figure 13 **The groundwater head response to flooding events in bores located adjacent to the main creek line at the lower end of Scriveners Soak catchment**

3.1.4 Gibson

Within the oil mallee area at Gibson, the groundwater heads in eight bores had a rising trend, five bores had no discernable trend, and one bore had a falling trend after 2002 (Table 6). The mean trend within the oil mallee area was 0.06 m/yr upwards, approximately half that of unplanted areas and slightly lower than the 0.09 m/yr trend of the comparison bores in the district. However, these differences were not statistically significant (95 per cent confidence level).

Table 6 **The rates of change of groundwater head between 2002 and 2009 in bores at Gibson**

	Bore site name	Landform	Rate (m/yr)
Oil mallee bores	02RS03D	Upper slope	0.10
	02RS04D	Upper slope	0.20
	02RS10D	Upper slope	0.15
	02RS02D	Mid-slope	0.00
	02RS09D	Mid-slope	0.15
	02RS11D	Mid-slope	0.00
	02RS05I	Lower slope	0.10
	02RS06I	Lower slope	0.00
	02RS07D	Lower slope	0.05
	02RS08D	Lower slope	0.05
	02RS13D	Simple slope	-0.10
	02RS14D	Simple slope	0.15
	02RS01D	Valley	0.00
	02RS12D	Valley	0.00
Control bores	02RS17D	Upper slope	0.00
	02RS15I	Lower-slope	0.15
	02RS16D	Valley	0.25
Comparison bores	ET06/EDB2	Lower slope	0.10
	GS7	Lower slope	0.05
	GS8	Lower slope	0.10
	GS9	Lower slope	0.10
Summary	**Oil mallee mean**		**0.06**
	Oil mallee median		**0.05**
	Control mean		**0.13**
	Control median		**0.15**
	Comparison mean		**0.09**
	Comparison median		**0.10**
	18% cover mean		**0.06**
	18% cover median		**0.05**
	9% cover mean		**0.06**
	9% cover median		**0.05**

There was continued expansion in the area of land affected by salinity at the Gibson site. There was no apparent trend in the depth to groundwater at 02RS06I, an 11.5 m deep bore located at the head of the salt-affected groundwater discharge area (Figure 14). This bore is useful for describing the effect of the oil mallees on the extent of land salinity in the catchment because it provides direct indication of the groundwater head conditions within the saline area.

The water level responded, with a slight time lag, to monthly rainfall in a very similar pattern to the control and comparison bores located in areas with similar shallow groundwater levels. While the groundwater level fell markedly during the drier period in 2007, it then responded rapidly to the period of above average rainfall in the latter half of 2008. This pattern is almost identical to that seen in bores 02RS17I and GS8OB (Appendix E, Figures E17 and E20), which are control and comparison bores respectively, indicating that rainfall had the dominating influence on the groundwater, irrespective of whether the catchment had been planted to oil mallees or not. The absence of a continuing rising trend at 02RS06I is probably because the aquifer is at capacity in this location and that the increase in piezometric pressures in upslope locations is being dissipated by increased groundwater discharge above 02RS06I. Observations made of soil conditions and pasture growth around 02RS06I also indicated that salinity effects continued to worsen.

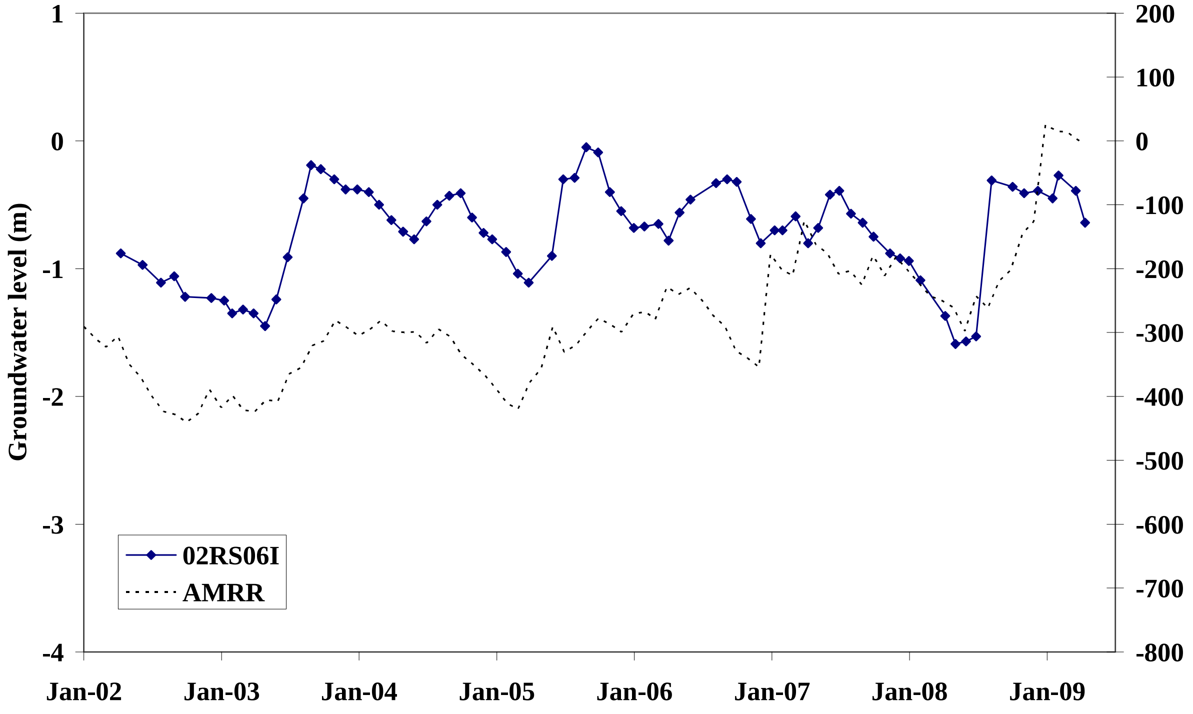

Figure 14 **The groundwater levels recorded in bore 02RS06I, located at the head of the saline area within the catchment planted to belts of oil mallees at Gibson**

The only bore that had a declining trend in groundwater head was 02RS13D. Here, the aquifer dried to the basement in 2007 and has since remained dry (Appendix E, Figure E13). At this site the weathered granitoid regolith is shallow (less than five metres deep), contains no restrictive clay or ironstone layers, has low salinity, and had a thin (about one metre thick on average) saturated thickness (when present) that was highly responsive to rainfall.

With the exception of 02RS13D, there is not a clear piezometric response attributable to the oil mallees at any of the bore sites (Figure 14 and Appendix E, Figure E13). The lack of response is perhaps surprising, particularly at bore sites 02RS07 and 02RS08 because they are located within wide belts of oil mallees and have shallow, brackish (200–580 mS/m) groundwaters.

High frequency water level measurements obtained from the dataloggers installed in bores 02RS07D (14 m deep), 02RS07I (5 m deep) and 02RS07S (2 m deep) show no evidence of the diurnal response expected if the oil mallees were transpiring significant groundwater during the daytime. The lack of diurnal response indicates that the oil mallees are not transpiring enough groundwater to have an observable effect on the groundwater heads. There are several possible reasons for the lack of effect including plant physiological limitations, such as their inability to use the brackish groundwater, hydrogeological influences, such as the soil profile characteristics that limit root penetration, and the large seasonal oscillations in the depth to the groundwater, which may limit their ability to maintain roots in a seasonally saturated phreatic zone.

It is not possible to define the reason why no groundwater use could be detected at this site based on the available data as no specific investigation into this aspect was undertaken. However, the available observations that may relate to the absence of groundwater use are worth discussing. Firstly, high salinity groundwater may not be the reason because the groundwater at 02RS07 and 02RS08 has an EC of 580 and 200 mS/m respectively, which is much lower than measured at the groundwater surface in the area where the oil mallees were using groundwater at the Marchagee site. Soil conditions could be a reason because at bore sites 02RS07and 02RS08 (and indeed at other sites where a layer of Pallinup formation was described), drilling encountered fine sandy clay and associated cemented ironstone layers between one and three metres deep. The hard layers could cause a restriction to root penetration and access to groundwater. However, Sudmeyer et al. (2004) and Sudmeyer and Goodreid (2007) found that in the Esperance district, several species of *Pinus* and *Eucalyptus* planted on farmland had accessed soil water to greater than four metres depth into Pallinup siltstones. It is unknown if the oil mallee species have a similar ability to these species or if the presence of cemented ironstone layers at this site provides an additional barrier. The clayey layers may also act as partial aquitards, restricting the upward flux of groundwater into the oil mallee root zone. It may be that several factors, including groundwater salinity, a clayey profile, and the large seasonal oscillations in the depth to groundwater causing seasonal waterlogging, combine to limit groundwater use by the oil mallees at this site.

In more elevated positions in the catchment, oil mallee bores exhibit water level responses that are closely linked to incident rainfall. The notable exception, at 02RS13D, indicates that transpiration of the groundwater by the oil mallees contributed significantly to the observed groundwater response. At this bore site, no restrictive soil conditions and the availability of fresh, relatively shallow and thin aquifer may be the factors that allowed this response. However, these conditions were not typical at Gibson.

The planting layout and monitoring design at Gibson allowed comparison between the effects of two different oil mallee densities on groundwater heads (Table 6). No significant difference in response (95 per cent confidence interval) was evident between the area planted with eight-row wide belts spaced at 90 m centres (18 per cent canopy cover) and areas planted with six rows spaced at 140 m centres (nine per cent canopy cover).

The lower mean and median rate of groundwater rise under the oil mallees (compared to control and comparison areas, Table 6), while not statistically significant, suggests that it is possible that the oil mallees may have reduced the rate of groundwater rise at Gibson. If this reduction is due to the oil mallees it is important because this site is the only one that had an increasing rainfall trend over the monitoring period—260 mm of additional AMRR (Figure 6). It is suggested that monitoring continue over several more years to determine if a larger reduction eventuates. The observations made of salinity extent and severity at the site indicate that the saline area expanded and worsened and suggests that the oil mallee system has had little hydrological effect to date. These observations are consistent with the analysis of the groundwater trends which show that groundwaters either continued to rise or remained stable over most of the area.

3.2 Comparison with other studies in WA

There have been some studies of the impact of revegetation on groundwater levels in WA. George et al. (1999) reviewed all available groundwater response data from a wide range of partially revegetated sites in the south-west and wheatbelt. While many of their 80 sites were not specifically designed to affect salinity and some were assessed at a comparatively early stage, their review concluded:

- that trees are best planted in recharge areas
- discharge plantings rarely reclaim saline areas
- responses are generally confined beneath the planting
- extensive plantings (perhaps influencing as much as 80 per cent of the landscape) are required to significantly reduce depth to groundwater and significantly reduce the area of salinity.

Bennett and George (2008) reported the effect on depth to groundwater after 10–21 years of various levels of integrated revegetation (mainly with commercial sawlog and woodchip species), designed to mitigate salinity on farmland at 24 sites in the medium rainfall zone (500-800 mm/yr). They found that the proportion revegetated was the most significant factor influencing groundwater reduction with at least 50 per cent revegetation required to provide significant salinity benefits within the treated areas. Effects were localised beneath the revegetation system as almost complete revegetation was required to affect groundwater levels (or the extent of saline land) downslope of the revegetation. They also found that although the bulk of the hydrological impacts appear to have been reached comparatively quickly—after only 10 years of revegetation—the proportion of revegetation required for significant on-farm salinity benefit would be three to five times the proportion of land affected by salinity at hydrological equilibrium.

These findings indicate that the proportions of the catchments revegetated with oil mallees in this study may fall far below that required for significant groundwater responses. This may be one reason for the generally poor responses observed. However, these two studies did not specifically examine the effect of oil mallee systems located in lower rainfall wheatbelt areas. While there are no reported specific studies of the catchment-scale effect of oil mallee systems on groundwater levels in the wheatbelt, there have been three important studies that have examined oil mallee water use at the individual belt scale.

Robinson et al. (2006) measured soil water contents up to 11 m under and 25 m laterally from the edge of five to nine year old, unharvested oil mallee belts from six wheatbelt sites that had a range of soil profile properties. They found large reductions in soil water content as far as 9–15 m from the belt edge, which were attributed to soil water extraction by the oil mallees. There was little or no effect on soil water measured at 20 or 25 m (or greater) from the belt at any site. They converted these results into zones of hydrological influence which they proposed extended 6–20 m from the edge row of the belts. Using the ratio of tree belt leaf area to natural vegetation leaf area index measurements, they predicted that the equivalent no recharge zone could extend 2.5–26 m from the edge row, depending on site properties. Robinson et al. (2006) thus concluded that oil mallee belts consisting of two to four rows would need to be spaced less than 20–30 m apart to achieve zero net recharge in typical wheatbelt situations. They also concluded that if the belts were harvested on a two to three year cycle, this width would need to be further reduced.

Wildy et al. (2003) constructed water budgets of individual belts of oil mallees and their adjacent alleys of annual pasture at a site located 10 km from the Goodlands site in this study. Their site had very similar soils and hydrogeology to the Goodlands site. They concluded that five to seven year old, unharvested, two-row oil mallee belts acquired water from up to 12.5 m away from the belt edge and belts would need to be spaced at about 28 m centres (17 per cent of the landscape) to eliminate recharge under the site. For oil mallee belts coppiced every two years, they said that one-third coverage is required because the coppiced trees used less water, although it was noted that a system on a three-year harvest rotation should have a smaller planted proportion requirement than a two-year rotation. These dimensions and proportions required for hydrological control were reduced in Wildy et al. (2004) to 10 per cent coverage (at 50 m belt centres) for unharvested oil mallees and 20 per cent (25 m belt centres) for harvested oil mallees by using a different method of calculation which included an additional soil drying effect of the oil mallees compared to pasture alone. However, Wildy et al. (2003, p 44) state that ‘this method may in turn be an overestimation since trees used soil water at faster rates than deep water or groundwater’.

Wildy et al. (2003) found that in a situation where the oil mallee rows were located above a shallow fresh aquifer (perched on a silcrete hardpan), the spacing of oil mallee rows could be increased (10 per cent landscape cover for five to seven year old saplings and 17 per cent for harvested oil mallees). The increase was because the oil mallees transpired more water, presumably from the perched aquifer, and in this way were able to regain some of the recharge that escaped beyond the extent of their root systems. However, they noted that fresh perched aquifers were likely to be only present in less than five per cent of the landscape and were therefore of a small overall consequence to the hydrology of the wheatbelt generally. This hypothesis is supported by the results obtained during the hydrological investigations undertaken in this study where, of the four sites studied, a persistent, fresh, perched aquifer was found at only the Goodlands site and was of very limited spatial extent (less than one per cent of the catchment).

Wildy et al. (2003) also calculated water budgets for the Alley Zone (width of alley unaffected by the oil mallees) together with the Mallee Zones (zone beneath the belt canopy plus the adjacent width of alley occupied by the roots of the oil mallees, both sides) for coppiced and un-harvested oil mallee belts (30 m wide zone of influence, or 15 m each side of the belt centre), with and without access to perched groundwater. It was found that in the typical situation (where there is no perched aquifer present), the 30 m wide Mallee Zone had a net leakage of 15 mm/yr, compared to 100 mm/yr leakage under the Alley Zone of annual pasture (Table 7). Leakage increased to 64 mm/yr for harvested belts. There was a net water uptake of 119 mm/yr in the Mallee Zone where unharvested oil mallees had access to fresh groundwater, reducing to 16 mm/yr for two-year old coppiced belts.

Table 7 **Water budgets of five to seven year old oil mallee belts and annual pasture at Goodlands (Wildy et al. 2003)**

	No perched aquifer			**Perched aquifer**		
	Unharvested Mallee Zone	Coppiced Mallee Zone	Annual pasture	Unharvested Mallee Zone[§]	Coppiced Mallee Zone[§]	Annual pasture
22-month budget (mm)	27	117	183	-218	-30	159
Annualised budget (mm)	15	64	100	-219	-16	87

[§] Negative numbers indicate net water depletion.

Because the alley dimensions required for hydrological control in any of the situations outlined above are impractical for broadscale cropping enterprises, Wildy et al. (2003) discussed the possibility of doubling the alley widths with an associated doubling of the oil mallee belt widths (achieved by doubling the number of rows in each belt) to be more practical while still achieving the desired ‘no recharge’ effect. However, they concluded that this arrangement was unlikely to be effective for two reasons. Firstly, because the oil mallees were primarily relying on the soil below the adjacent alleys for water, in belts comprised of more than two rows, the trees in the middle rows may simply become more water stressed. Secondly, water draining below the crop/pasture in the middle of the alley (out of reach of lateral tree roots) would percolate directly to the groundwater and was unlikely to be able to be later accessed by the oil mallees.

At the Marchagee site, Carter et al. (2007) used intensive measurements of transpiration, canopy interception, soil evaporation, crop evapotranspiration, soil water content and rainfall, collected between 2003 and 2005, to develop water budgets for the oil mallee belts and adjacent annual crop and pasture alleys. Water budgets were calculated for three areas: in the lower slope where the brackish groundwater was less than 2 m deep (near bore site 03ST08), in the mid-slope (between bores 03ST08 and 03ST07) where the groundwater was less than 4 m deep, and in the upper slope (near bore 03ST06) where the oil mallee roots did not have access to the groundwater as it was below the silcrete layer. They found that the oil mallee belts had an influence on soil water extending from their canopy edge to a distance equivalent to their height multiplied by 3.5. This equated to distances of 14 m in the lower slope (where the oil mallees had fast growth rates and were large), 7 m in the mid-slope and 5.25 m in the upper slope. A high rate of evapotranspiration (about 1800 mm/yr in the area beneath the oil mallee canopy) by the oil mallee belt in the lower slope location was observed and it was estimated that about 40 per cent of the water was directly transpired from the groundwater. The water balance and soil moisture data was then used to ascribe average annual water budgets to the lower, middle and upper landscape measurement locations: the area beneath the oil mallee belt canopy, the adjacent paddock where the oil mallees had a lateral influence, and the remainder of the alley (Table 8).

The data in Table 8 can be used to calculate the average net water uptake across the Mallee Zone by integrating the widths and water budgets for each of Carter et al.’s (2007) ‘beneath mallee belt canopy’ and ‘adjacent zone of influence’ zones, and then averaging their sum across the entire Alley Zone width. When this calculation is made it results in an Alley Zone net water removal of 303, 112 and 84 mm/yr for the lower, middle and upper locations respectively.

Table 8 **Average annual water budgets for different oil mallee belt zones in different landscape positions at Marchagee (Carter et al. 2007)**

	Beneath mallee belt canopy		Adjacent zone of influence*		Alley remainder	
	Water budget[§] (mm/yr)	Width (m)	Water budget[§] (mm/yr)	Width (m)	Water budget (mm/yr)	Width (m)
Lower slope	-1470	4.0	-109	24.0	32	92.0
Mid-slope	-371	4.0	-10	10.0	10	96.0
Upper slope	-247	4.0	-11	6.5	18	109.5

* Zone on both sides of the belt included in the calculation.

[§] Negative numbers indicate net water depletion.

On the basis of their water budgets, Carter et al. (2007) also calculated the proportion of the landscape that would be required to be covered by oil mallee belts, and their dimensions, to achieve no recharge across the landscape. Based on the lower slope site, where oil mallees could transpire from the groundwater, Carter et al. (2007) concluded that the existing configuration would provide hydrological balance. However, if the conditions present in the mid-slope were uniform across the landscape, oil mallee coverage would need to be 14 per cent (belts of two rows providing a 4 m wide canopy cover, belts spaced 24 m apart) for it to be in hydrological balance. This denser spacing is required because the groundwater is deeper and the oil mallees have a reduced capacity to recapture the recharge from the unplanted alleys. Under the hydrological conditions present in their upper slope site where the oil mallees had no ability to transpire from groundwater, they calculated that oil mallee coverage would need to be 23 per cent obtained by spacing the two-row belts 14 m apart. The latter groundwater conditions are more typical of those within most of the catchment and indeed the wheatbelt generally.

Each of the above studies indicate that the most effective way of achieving hydrological control (defined as zero net recharge) using oil mallee belts is to disperse them across the landscape at quite narrow spacing. Under typical wheatbelt conditions, from the above studies, it seems that two-row belts that are not regularly harvested would need to be spaced between 14 and 30 m apart (17–23 per cent canopy coverage, 100 per cent root zone coverage) to achieve zero net recharge. In systems that are regularly harvested for commercial purposes, these spacings are likely to be required to be reduced by about half to result in about 33 per cent canopy cover. Either of these configurations is more closely spaced than at any of the four sites examined in this study, which may be one reason why the oil mallee systems had no observed meaningful effect on groundwater at the catchment-scale.

3.3 The question of time

The monitoring undertaken at the four study sites has shown that the oil mallee systems influenced some localised, shallow, fresh or brackish aquifers but did not have a measurable catchment-scale effect on groundwater. Because the period of monitoring was relatively short, both in terms of hydrological process timeframes and oil mallee longevity, a justifiable question could be asked: would oil mallee systems begin to have a greater effect in future as they mature? To help tackle this question and establish a forecast for a number of management scenarios that could be tested in the future, Flowtube modelling was undertaken.

3.4 Modelled effect of oil mallee systems on groundwater levels at the catchment-scale

3.4.1 Marchagee

The annual rate of recharge (ARR) conditions for the belt and Alley Zones applied to Flowtube for the 2003–09 period were based on those observed by Carter et al. 2007 and used to derive the water budgets in Table 8). Their reported large rates of water use by the Mallee Zones and the associated rates of recharge in the alleys in the lower and mid locations were applied to the relevant sections along the flowtube, coinciding with where the groundwater is known to overlie the silcrete layer allowing the oil mallees potentially unrestricted access to it. The rate measured in the upper location was applied to the rest of the flowtube.

For the ‘2053—with mallee’ scenario it was assumed that after 2009 the Mallee Zones in the mid and upper slope locations had an ARR of zero and the rates of net water removal in the Mallee Zones in lower slope locations were reduced by one-quarter. These changes were made for two reasons—firstly, the water use of oil mallees in the upper landscape positions that do not have access to fresh groundwater could be expected to decline when plant available stored soil water is depleted so that net evapotranspiration will equal rainfall (that is, have an ARR of zero); and secondly, the greater water use of oil mallees in the middle and lower positions may be enough to permanently deplete the shallow aquifer that currently overlies the silcrete. Transitory depletion of this aquifer occurred during 2008 and 2009 (Figure 8). Once the supply of this fresh groundwater is limited by the rate at which groundwater can be delivered through the silcrete layer which forms a partial aquitard, tree water use could be expected to decline until it reaches equilibrium with the rate of supply.

The observed and modelled groundwater trends and length of the Flowtube transect that is saturated (has groundwater) to within 1 m of the surface (LSF1) are shown in Table 9. There is a good agreement between observed and modelled groundwater trend and LSF1 for the period 2003–09 indicating that, at the catchment-scale, the water balance characteristics applied to Flowtube are likely to be representative. It should be noted that the discrepancy between the modelled and observed trend in bore 03ST10D was probably because water was pumped (for on-farm requirements) from a soak located upslope of the bore. Because the amount and timing of abstraction could not be quantified, it was not possible to incorporate this effect in Flowtube.

Table 9 **Observed and modelled groundwater trends along the Flowtube transect and the observed and modelled lengths saturated to within 1 m of the surface (LSF1) at Marchagee**

Landscape location	Bore site	Observed 2003 (m/yr)	Observed 2009—with mallee (m/yr)	Modelled 2009—with mallee (m/yr)	Modelled 2009—no mallee (m/yr)	Modelled 2053—with mallee (m/yr)	Modelled 2053—no mallee (m/yr)
Upper slope	03ST02D	na	-0.09	-0.06	-0.03	-0.02	-0.01
Upper mid-slope	03ST03D	na	-0.06	-0.05	0.00	-0.01	0.00
Mid-slope	03ST05D	na	-0.05	-0.05	0.00	0.00	0.00
Lower mid-slope	03ST08D	na	-0.10	-0.09	0.00	0.00	0.00
Lower slope	03ST10D	na	-0.06	0.00	0.00	0.00	0.00
LSF1 (m)		1670	1400	1380	1700	1360	1840

The absence of trend in the results of the ‘2009—no mallee’ scenario indicates that the catchment water balance would have been in quasi-equilibrium during this period if there had been no oil mallee system in place. The ARR of annual crop and pastures applied in Flowtube during this period was 12 mm across the upper and mid-slope areas (Carter et al. 2007) which is approximately half the rate used to calibrate the model to the observed water levels in 2003, and is consistent with the expected reduction in ARR associated with the reduction in rainfall observed at the site after 2000. Comparing the ‘2009—with mallee’ and ‘2009—no mallee’ scenarios indicates that the oil mallees had an additional effect (above that resulting from reduced rainfall), causing groundwater heads to fall by 0.03–0.09 m/yr. If these conditions persist, Flowtube forecasts that heads will continue to fall for at least 50 years, although the magnitude of the rates of fall decline rapidly to almost zero, particularly in the mid and lower slopes (for example, at bore 03ST08 after 10 years). However, this sustained reduction in water level in the upper slopes does not result in a significant change in the LSF1 compared to current conditions because the section below bore 03ST010 is forecast to maintain a shallow groundwater under these conditions. Flowtube forecasts that, if the current conditions persist, the oil mallees reduce the LSF1 by about 500 m or nearly one-quarter of the catchment length after 50 years. When this length reduction is converted to area, it is equivalent to about 4.5 per cent of the catchment.

Some of the results from the modelling scenarios are presented in Figure 15. The oil mallee effect is readily apparent in the mid and upper slopes (above 03ST08) by 2053, although there is minimal effect downslope. In the area immediately above bore 03ST08, the oil mallees have an effect additional to the ‘2053—no recharge after 2003’ scenario because they are modelled to have the capacity to extract groundwater in this area. Even with no recharge, the model forecasts that shallow groundwater persists near bore 03ST10 for at least 50 years, indicating how sluggishly the groundwater system behaves in this section.

Under the assumptions stated above, if recharge is eliminated entirely from the catchment (ARR equal to zero), Flowtube forecasts that it will take about 150 years for shallow groundwaters to contract so they remain only near the primary salt lake system, indicating a comparatively sluggish groundwater system with low transmission capacity. This analysis suggests that it requires about 150 years of no recharge to reverse 50 years of recharge associated with the beginning of annual agriculture, implying that the aquifer throughflow capacity is about one-third (8 mm) of the recharge it had received under annual agriculture prior to 2003.

The results of Aquifer Capacity Modelling indicate that modest reductions in recharge (about half) cause reversal in heads in the mid and upper slopes, indicating a relatively responsive aquifer along this higher gradient section. However, an ARR of less than 6 mm, or less than 20 per cent of the ARR measured under annual agriculture by Carter et al. (2007), is required to allow heads to fall consistently across the lower slopes (below bore 03ST10) indicating that the aquifer has a much lower capacity to transmit water in this lower gradient section.

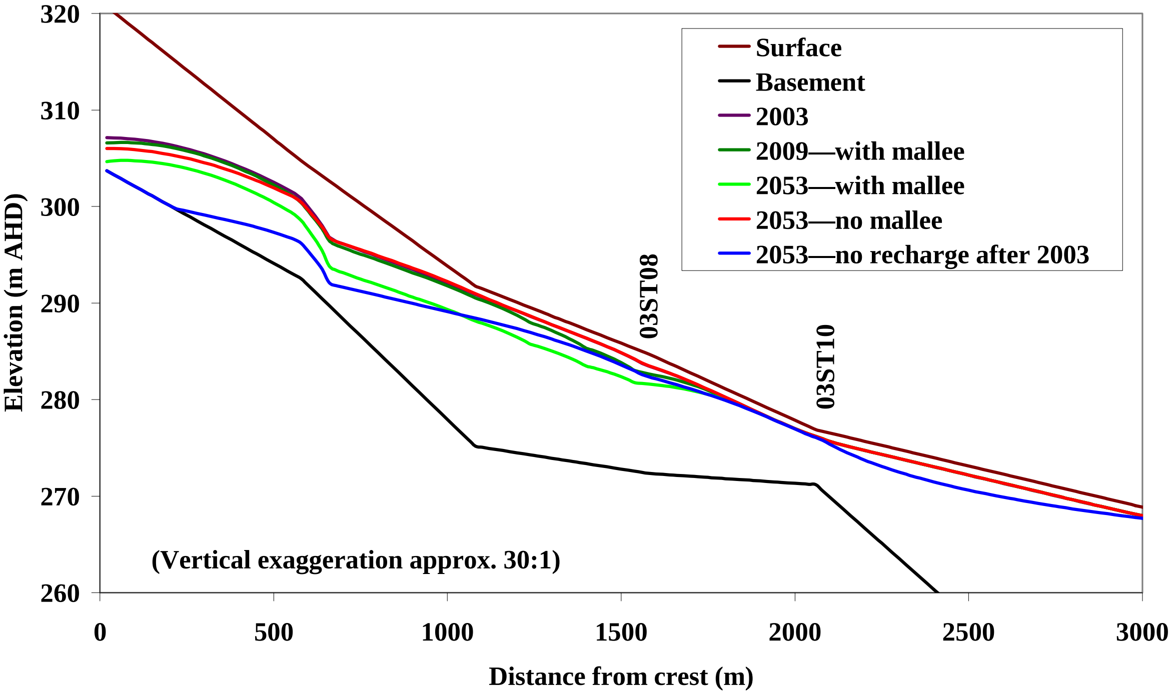

Figure 15 **Modelled Flowtube scenario outputs at Marchagee. Lines show forecast groundwater levels**

3.4.2 Goodlands

Flowtube modelling was at first undertaken using recharge scenarios based on the reported rates from Wildy et al. (2003), as shown in Table 7. However, these resulted in unrealistic rates of modelled groundwater rise, by far exceeding those observed between 2003 and 2009 and unsupported by longer term regional and local groundwater monitoring. Even when a combination of the highest rate of water use reported by Wildy et al. (2003) for unharvested oil mallees growing over perched groundwater was combined with the lowest rate of recharge reported in the alleys, improbable rates of groundwater rise resulted. The large discrepancy between the water use and recharge rates reported by Wildy and the observed and modelled changes in groundwater levels is likely to be because the ARR under annual pasture (87–100 mm/yr) reported by Wildy et al. (2003) is much larger than the expected long-term average conditions for the site and is much higher than was likely to have occurred during the 2003–09 period. Wildy et al.'s (2003) recharge rate is also much higher than the average long-term rate (25 mm/yr) used to calibrate Flowtube to the water levels observed in 2003. Rainfall during Wildy et al.'s (2003) period of measurement was much higher than the long-term average conditions which may explain part of the discrepancy. Because the higher rainfall conditions also probably resulted in increased soil water availability, Wildy et al.'s (2003) observed rates of transpiration by the oil mallees also likely exceeds the expected long-term average rate.

In subsequent scenarios the ARR in the modelled, 30 m wide Mallee Zone was assigned to be zero, which is slightly less than estimated by Wildy et al. (2003), and recharge in the Alley Zone was varied until the closest match resulted between modelled and observed rates of groundwater level change between 2003 and 2009. The best match was obtained when the Alley Zone had an annual recharge rate of 20 mm, slightly less than the 25 mm used to calibrate the model to 2003 conditions. This reduction is realistic given the modest reduction in rainfall experienced at Goodlands since 2000. Using these model inputs there was a very good fit between modelled and observed groundwater trends (Table 10). Bore 03IS04D was the exception where it was not possible to match the modelled head change to the observed rate of piezometric rise. However, at this site the shallow observation bore (03IS04OB) had no observed trend (approximating the modelled trend) indicating that the deeper aquifer is most likely confined, which is a situation that cannot be meaningfully reproduced using Flowtube.

Flowtube forecast that the oil mallees had a slight effect on the rate of rise of groundwater, reducing it by about 0.05 m/yr in the mid-slopes. However, the modelling indicates that groundwater levels will continue to rise for at least 50 years and the length of Flowtube saturated to within 2 m of the surface (LSF2) will also continue to lengthen under the current combination of revegetation and recharge. The oil mallee system results in a minor change in the LSF2 in 2053, reducing it by about 75 m, compared to the scenario of '2053—no mallee' in place. However, by 2053, the LSF2 may not have reached its maximum dimension, because the projected continuing rising trend of the heads in mid and upper slope bores in 2053 indicates that the catchment will still not be in hydrological equilibrium.

Table 10 **Observed and modelled groundwater trends along the Flowtube transect and the observed and modelled lengths saturated to within 2 m of the surface (LSF2) at Goodlands**

Landscape location	Bore site	Observed 2003 (m/yr)	Observed 2009—with mallee (m/yr)	Modelled 2009—with mallee (m/yr)	Modelled 2009—no mallee (m/yr)	Modelled 2053—with mallee (m/yr)	Modelled 2053—no mallee (m/yr)
Upper slope	03IS01D	na	0.00	0.01	0.01	0.09	0.11
Mid-slope	03IS02D	na	0.22	0.23	0.28	0.11	0.14
Lower slope	03IS03D	na	0.09	0.12	0.19	0.01	0.01
Valley	03IS04D	na	0.15	-0.02	-0.02	0.00	0.00
	03IS04OB	na	0.00	-0.02	-0.02	0.00	0.00
LSF2 (m)		2200	2200	2250	2350	2875	2950

When Flowtube was run using the 2003 head conditions, with ARR set to zero along the entire length, the LSF2 reduced to 800 m after 50 years and to 400 m after 100 years. However, the LSF is very dependent on the depth to which it is measured. For example, the Flowtube length that has a groundwater level within 2.5 m of the surface (just 0.5 m deeper than the model maximum depth of evaporation) remains almost unchanged from 2009 conditions under the above scenario. This lack of response, even under conditions of no recharge, suggests that evaporation has the dominant influence on the water balance in this part of the catchment and that the groundwater throughflow component is negligible. Very low rates of throughflow are expected given that the hydraulic gradient in the lower slopes is still projected to be less than 0.1 per cent in 2053 which, combined with the low hydraulic conductivity, indicates an extremely sluggish groundwater flow system. The Aquifer Capacity Modelling scenarios indicated that the aquifer has a transmission capacity that is the equivalent of about 2 mm of ARR, or only one-tenth of the modelled current rate.

Some of the modelling results are presented in Figure 16. The increases in groundwater head in the mid and upper slopes observed between 2003 and 2009 are evident. In the '2053—with mallee' scenario, the groundwater rises less than the '2053—no mallee' scenario, even though both scenarios result in similar increases in the LSF2 (between bores 03IS03 and 03IS04). The slightly shorter LSF2 equates to about a one per cent reduction in area with a shallow groundwater after 50 years with oil mallees. If recharge was eliminated (ARR of zero) after 2003, the groundwater still does not change in the mid and lower slope areas by 2053. The low hydraulic gradient in this area is apparent and severely limits the capacity of the aquifer to transmit groundwater. The hydraulic gradient is restricted by the surface gradient and is also dominated by the influence of Lake Moore and the associated primary salt lake chain at the bottom of the catchment.

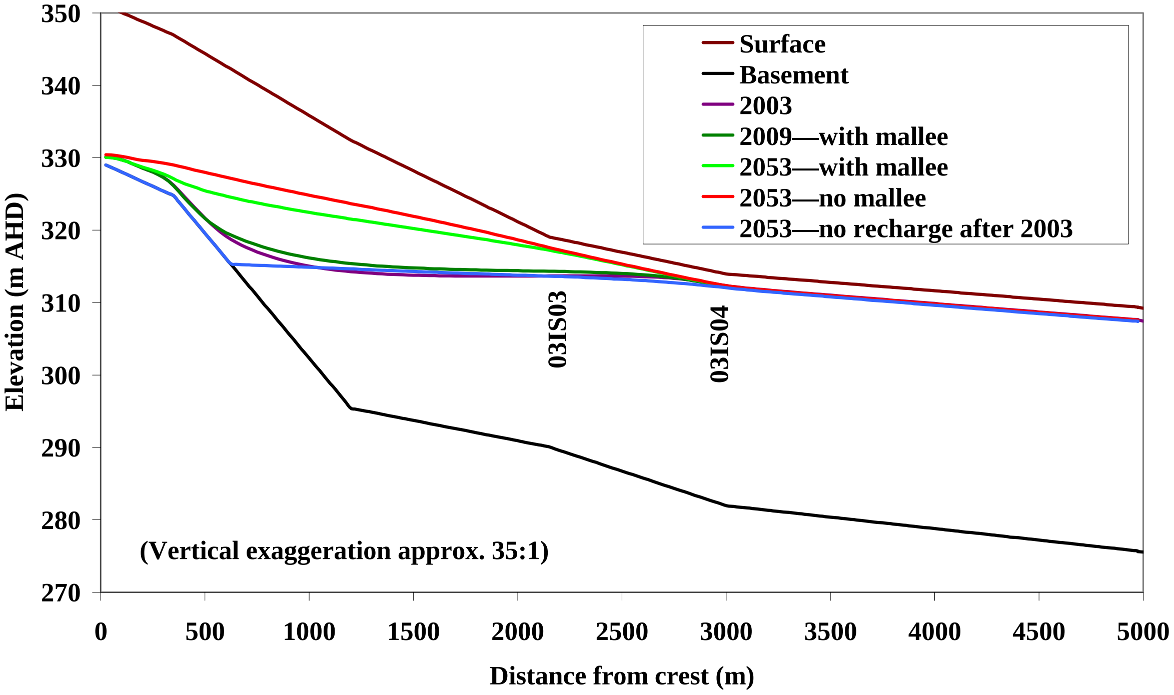

Figure 16 **Modelled Flowtube scenario outputs at Goodlands. Lines show forecast groundwater levels**

3.4.3 Tincurrin

Table 11 shows there is a good agreement between observed and modelled groundwater head trend and LSF1 for the period 2003–09 indicating that the water balance characteristics applied to Flowtube were representative and suitable for evaluating a set of scenarios. The ARR applied to Flowtube for the Alley Zone was 14 mm, slightly less than the 18 mm used to calibrate it to 2003 conditions, which is consistent with the modest reduction in rainfall since 2003. The modelled ARR in the 32 m wide Mallee Zone was set at zero because it is unlikely that the oil mallees use any groundwater as it is deep (18–23 m), saline (1500–5000 mS/m), and overlain by clayey, sedimentary horizons in the valley which are likely to restrict root penetration. Flowtube over-predicted the LFS1 by 500 m in 2009 and by 300 m in 2003 (2003 data not shown). However, this error is considered acceptable (about 2.5 per cent of the total length of Flowtube and six per cent of the observed LSF1 in 2009) given that the length of the flowtube is long; about 20 000 m in this catchment.

Table 11 **Observed and modelled groundwater trends along the Flowtube transect and the observed and forecast lengths saturated to within 1 m of the surface (LSF1) at Tincurrin**

Landscape location	Bore site	Observed 2003 (m/yr)	Observed 2009—with mallee (m/yr)	Modelled 2009—with mallee (m/yr)	Modelled 2009—no mallee (m/yr)	Modelled 2053—with mallee (m/yr)	Modelled 2053—no mallee (m/yr)
Mid-slope	SS0332D	na	dry	dry	dry	dry	dry
Valley	SS9704D	0.29	0.18	0.16	0.18	0.09	0.14
Valley	SS0330D	na	0.13	0.11	0.18	0.10	0.16
Valley	SS9701D	0.16	0.11	0.10	0.15	0.11	0.16
Valley	SS9725D	0.18	0.14	0.17	0.17	0.13	0.14
Valley	SS9703D	0.15	0.10	0.12	0.13	0.12	0.13
Valley	LT01D	0.20	0.05	0.09	0.10	0.00	0.00
Valley	LT07D	-0.08	0.00	0.00	0.00	0.00	0.00
LSF1 (m)		6800	7900	8400	8400	11 500	11 700

In terms of the impact of the oil mallees, Flowtube predicted that there was a slight reduction (0.02 m/yr on average) in the rate of groundwater head rise with the oil mallees in place; compared to if they had not been planted. However, this reduction in rate translates to no reduction in the LSF1 in 2009. By 2053, the reduced rate of rise forecast under the ‘2053—with mallee’ scenario continues, with the reduction being largest in the section between bores SS0332 and SS9701, and being only minor further downslope. This effect can be seen in Figure 17 by comparing the ‘2053—with mallee’ and ‘2053—no mallee’ scenario outputs. By 2053, heads remain substantially lower upslope of SS9701 but rapidly converge further downslope, where the LSF1s become indistinguishable. This convergence indicates that any effect is substantially limited to beneath the area planted, as expected given the low gradient and large size of this catchment. By 2053, the oil mallees reduce the LSF1 by only 200 m, equating to less than one per cent of the catchment area.

The difference between the ‘2003’ and ‘2009—mallee’ scenarios is also hard to detect. Figure 17 shows that if the ARR is reduced to zero beneath the entire area encompassed by the current oil mallee belt layout, Flowtube forecast that heads would remain roughly the same in 2053 as they were in 2009. It can also be seen that the hydraulic gradient is the reverse of the surface gradient between SS9701 and LT01. An explanation for the reverse gradient was proposed by George et al. (2004) who suggested that it is because of the temporal and spatial pattern of clearing in the catchment, with the land being progressively cleared starting in the early 1900s at the valley floor and reaching the top of the catchment in the mid-1950s. If this hypothesis is correct, it implies that groundwater response in the valley is caused mainly by in situ recharge conditions rather than by conditions in the hydrologically remote hillslopes. It also implies that the aquifer has a low capacity to transmit groundwater to balance the resultant uneven groundwater head conditions. The dominant influence of in situ recharge (as a result of the low aquifer transmissivity) suggests that valley farmers have the potential, while groundwaters are still deep, to provide their own in situ salinity risk mitigation.

Part of the rationale for installing the oil mallee system at Tincurrin was the desire by the landholders to delay the development of salinity on their land upslope of bore SS9701. Flowtube was used to forecast (given the assumption of a similar climate) that shallow groundwater would encroach up to bore SS9701 in about 100 years with no oil mallee system in place. With the current oil mallee system in place, Flowtube forecast that the time taken would increase to about 160 years, meaning the oil mallee system is forecast to have 'bought' an extra 60 years without shallow groundwater. Using similar input parameters, Flowtube forecasts that the catchment comes to hydrological equilibrium in the year 2270 with the current oil mallee system in place and that equilibrium will happen sooner (in the year 2203) without the oil mallee system. It must be stressed that these long-term forecasts are only indicative, as they are well outside the usual forecast periods for this modelling.

The Aquifer Capacity Modelling suggests that the aquifer has a transmission capacity of the equivalent of less than 1 mm of ARR (the smallest increment of ARR modelled) which highlights how sluggish the groundwater system is at Tincurrin and that the recharge would need to be substantially reduced (to near zero) before groundwater levels could be expected to fall along the entire length of the catchment.

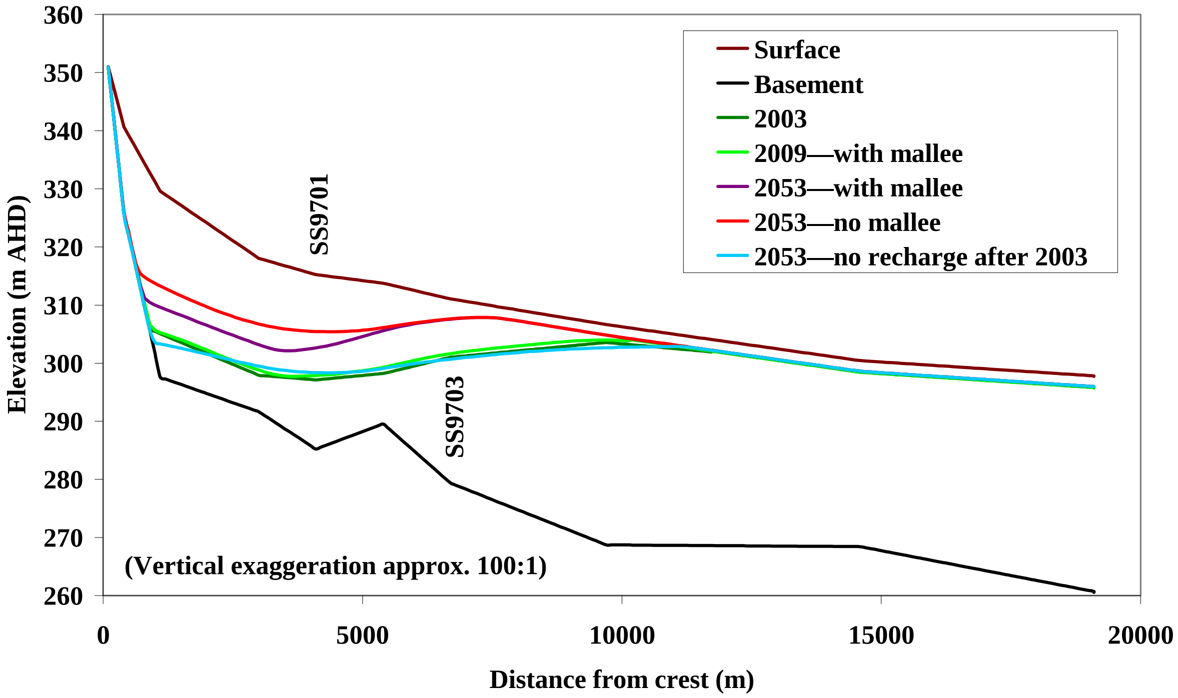

Figure 17 **Modelled Flowtube scenario outputs at Tincurrin. Lines show forecast groundwater levels**

3.4.4 Gibson

The observed and modelled groundwater trends and LSF1 for Gibson are shown in Table 12. Many Flowtube scenarios were modelled with various combinations of ARR in the Alley Zones and rates of net water use (modelled in 50 mm increments) in the Mallee Zones. The combination that produced the best calibration to the groundwater observations made between 2002 and 2009 was:

- ARR under annual agriculture in the Alley Zone of 40 mm (compared to 35 mm prior to 2002)
- ARR in the Mallee Zone set to zero for all belts except those between bore sites 02RS08 and 02RS06
- between bore sites 02RS08 and 02RS06, the Mallee Zone had a net water use of 100 mm per year.

The increase in modelled ARR in the Alley Zone from 35 mm prior to 2002 to 40 mm subsequently is consistent with the trend of increasing rainfall since 2000. Downslope of bore 02RS06I, net water use within the Mallee Zone is unlikely because the groundwater is saline (2600 mS/m at bore 02RS05S) and so the Mallee Zones were modelled as preventing recharge (ARR of zero) in this section. Likewise, upslope of bore 02RS08, the Mallee Zones were modelled as having no net recharge because in this area the groundwater is deep and below thick layers of fine and indurated clayey Pallinup sediments (Bennett et al. 2005c), which are likely to restrict root penetration. In this area, the modelled groundwater head responses were particularly sensitive to any modelled net water use in the Mallee Zones—for example, only 50 mm of modelled annual net water use resulted in groundwater heads that were improbable (much lower than observed in 2009). Between bores 02RS08 and 02RS06, 100 mm of net water uptake within the Mallee Zones produced the best fit to the groundwater observations made between 2002 and 2009. Net groundwater use in this area is plausible because the groundwater is shallow (located just above the first clayey Pallinup horizon) and brackish (200–600 mS/m), although continued abstraction is potentially limited by the clayey layers. These layers could eventually limit the maximum root depth of the oil mallees as well as constrain the rate of upward flux of groundwater into the root zone. In this area the modelled heads were insensitive to Mallee Zone net water uptake rates up to 100 mm/yr, yet became very sensitive at rates above 100 mm and fell dramatically. This level of net water uptake seemed to be the ‘tipping point’, as rates above 100 mm produced unrealistic modelled reductions in head along this zone.

Table 12 **Observed and modelled groundwater trends along the Flowtube transect and the observed and forecast lengths saturated to within 1 m of the surface (LSF1) at Gibson**

Landscape location	Bore site	Observed 2002 (m/yr)	Observed 2009—with mallee (m/yr)	Modelled 2009—with mallee (m/yr)	Modelled 2009—no mallee (m/yr)	Modelled 2052—with mallee (m/yr)	Modelled 2052—no mallee (m/yr)
Upper slope	02RS10D	na	0.15	0.12	0.22	0	0
Mid-slope	02RS09D	na	0.15	0.11	0.22	0	0
Lower slope	02RS08D	na	0.05	0.05	0.18	0	0
Lower slope	02RS06I	na	0.00	0.02	0.02	0	0
Lower slope	02RS05I	na	0.10	0.01	0.01	0	0
Valley	02RS16D	na	0.25	0.08	0.08	0	0
LSF1 (m)		400	750	720	850	940	1140

Table 12 shows that there is a good agreement between modelled and observed trends in groundwater head at all bore sites except for the piezometric levels in the deeper bores (02RS05 and 02RS16) in the lower slope section. At these sites the modelled trends were much lower than the observed and did not increase even if the ARR was increased substantially in this area. At bore 02RS05 the underestimation is likely to be because the main aquifer is confined below the Pallinup formation and therefore under pressure, as detected in bore 02RS05D. However, this situation is unable to be accurately represented by Flowtube which has its upper head governed by the input depth of evaporation. At bore 02RS16 (the end of the transect), the flowtube head appears constrained by the constant head point at the primary saline seepage, some 800 m distant. However between 02RS16 and the modelled constant head point, the presence of any geologic anomalies that affect the hydraulic gradient or the hydraulic conductivity of the main aquifer could override this constraint and cause the observed rates to be higher than the modelled. The model could not be rectified for this possible under-estimation because no aquifer parameter information was available for the section downslope of bore 02RS16.

Flowtube predicted that the oil mallees had a slight effect, reducing the rate of groundwater rise by about 0.10 m/yr between 2002 and 2009 in the upper slopes. In the mid and lower slopes, it predicted minimal effect and under-predicted the rate of rise, as detailed above. Flowtube forecast that groundwater heads will continue to rise for a further 19 years, from 2009, before equilibrium with oil mallees, and 22 years without oil mallees. There is also a 200 m forecast reduction in LSF1 with the oil mallee system in place by 2052, which equates to a 4.2 per cent reduction in area affected by shallow groundwater.

When Flowtube was run using the 2002 head conditions and with recharge set to zero along the entire length, the LSF1 reduced to zero within 50 years. Under these conditions it takes about 160 years for the heads to fall to the assumed pre-clearing levels, or about four times as long as it took for the groundwater to rise to current levels after the area was cleared for annual agriculture. The Aquifer Capacity Modelling indicated that the aquifer has a transmission capacity that is the equivalent of about 2 mm of ARR, or only one-twentieth of the assumed current ARR.

Some of the modelling results are presented in Figure 18. The increase in water levels in the upper slopes observed between 2002 and 2009 are apparent, as well as the increase at the end of the transect. With the oil mallee system in place, by 2052 the groundwater has risen and is almost indistinguishable from the 'no mallee' scenario, except in the area between bores 02RS08 and 02RS06. Figure 18 also shows that completely eliminating recharge, while the heads appear to fall only modestly, is enough to eliminate shallow groundwater from the transect.

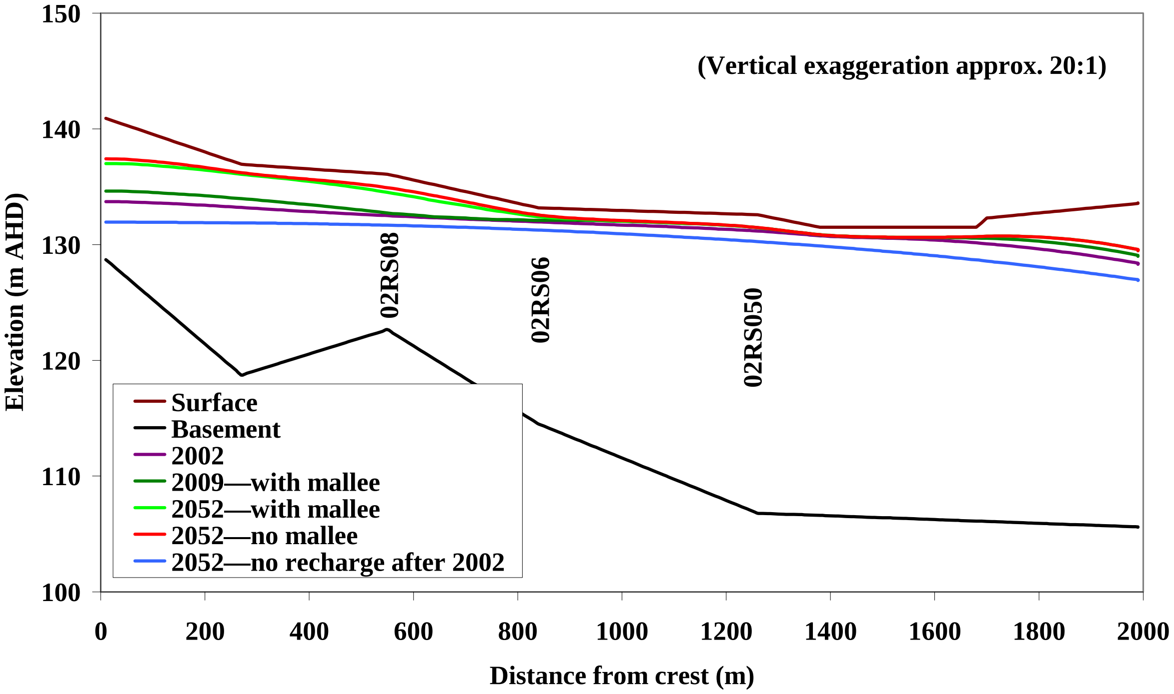

Figure 18 **Modelled Flowtube scenario outputs at Gibson. Lines show forecast groundwater levels**

3.5 Factors that may impact on the longer term water use of oil mallee systems

Oil mallee belt systems are designed to maximise tree growth by making use of the so-called ‘edge effect’ (Wildy et al. 2000). The ‘edge effect’ maximises growth per unit area within narrow belts because the oil mallees in the edge rows have greater access to nutrients, water and light than they would in a block configuration. However, even with the ‘edge effect’ the growth rate of oil mallee belts will eventually plateau when their roots reach their maximum lateral extent and they have depleted the stored soil moisture in the rootzone. While there are limited specific data available to show at what age this may occur, Sudmeyer and Goodreid (2007) and Robinson et al. (2006) showed that oil mallees aged less than eight years had exhausted available stored soil water to at least 10 m depth. Beyond eight years, in typical landscapes where the oil mallees do not have access to useable groundwater, growth and water use is likely to become dependent on rainfall incident on the rootzone. Eight years is similar to the age of the oil mallees at Marchagee, younger than those at Goodlands, and two to three years older than those at Tincurrin and Gibson. For regularly harvested (coppiced) belts, maximum water use is likely to be additionally limited by leaf area in the period immediately after harvest (Raper 1998).

It may be reasonable to conclude that the rate of water use of a oil mallee belt under the optimal commercial harvesting regime will never exceed that of an equivalent aged, unharvested belt and therefore harvested oil mallee systems may have lower water use capability than those in this study and, if anything, the observations made in this study could be over-emphasising their effect on catchment water budgets.

However, while there remains uncertainty about whether there will be additional hydrological effects at the sites in the long-term, it is recommended that a basic level of monitoring (at least an annual measurement of groundwater depth) is continued at the four study sites for the next five to 10 years. Ideally, the oil mallees should also be harvested under the optimal commercial harvest regime during the monitoring period. However, continued monitoring of unharvested systems would also provide useful information on their maximum potential effect.

3.6 Summary

This study examined the catchment-scale groundwater responses to the establishment of oil mallee alley systems planted across four wheatbelt catchments over a seven year period. The four sites measured encompass the main geographical, hydrological, climatic and agricultural conditions of the parts of the WA wheatbelt where industries based on the sale of oil mallee products have been proposed. Flowtube modelling was used to investigate the potential range of longer term effects of oil mallee plantings in terms of salinity management, as well as to help define the main hydrological factors that control these observed and forecast effects. The modelling was also used to place the results from other studies, which have reported the water use characteristics at the individual belt scale, into the context of their effect at the catchment-scale.

Monitoring at the study sites has shown that:

- Changed rainfall conditions since 2000 had an observed effect on groundwater systems. At three sites, the reduction in rainfall caused reductions in the rate of groundwater rise, while at the remaining site (Gibson) increased rainfall has caused an increase.

- At three of the four sites, groundwater levels were observed to continue to rise under the oil mallee systems, with an accompanying increase in the land affected by shallow groundwater. At one site (Marchagee), groundwater levels receded slightly during the monitoring period.
- The oil mallee systems did not cause a statistically valid (95 per cent confidence level), measurable groundwater response that could be attributed to them, at any of the catchments examined.
- Oil mallees only appeared to directly use groundwater where it was relatively fresh (less than 1400 mS/m) and close to the surface (1–3 m deep). This water use was associated with an increase in oil mallee growth. This type of aquifer overlies aquitards or layers that restrict root depth and only occurred across a small proportion of the Marchagee catchment and are not prevalent enough in the wheatbelt to be of consequence to a large-scale oil mallee industry or to catchment water balances. By contrast, horizons that are likely to restrict vertical root penetration were encountered beneath most of the catchment at all four sites.

While the groundwater monitoring undertaken did not (for the most part) show significant changes because of the oil mallee systems, Flowtube modelling at each site indicated that over the next 50 years (under the current rainfall conditions and stated assumptions) that:

- Oil mallee planting might be expected to reduce the length of the flowtube that is saturated (LSF), by two to 26 per cent relative to un-revegetated scenarios (Table 13). When LSF is converted to a spatial extent, using the conversion developed by Mouat and Clarke (2004), it equates to between 0.8 and 4.5 per cent of the catchment protected from salinity or shallow groundwater after 50 years. For two of the catchments, the proportion of catchment protected is of similar order of magnitude to the area occupied by the oil mallee belt canopies. However, when the Competition Zone is included, there is a much greater proportion of agricultural land likely to be affected by reduced productivity because of the oil mallees, than protected by them.
- Even with oil mallee plantings, the LSF will continue to increase over the next 50 years at three of the sites. The oil mallees were most effective at reducing LSF at sites where groundwater systems were more fully developed and therefore closer to equilibrium (Gibson and Marchagee), and where trees were able to access shallow, fresh groundwater (Marchagee).
- Where the time for groundwater equilibrium to be achieved exceeds 100 years, the time taken for hydrological benefits of oil mallee plantings, as modelled, to become evident is also extended outside the 50-year model time span of this study. A 100 year time span is probably also outside the planning or economic timeframes for most land managers and is certainly beyond the predictive capacity of the model.
- Oil mallees reduced recharge by about 30 per cent at Marchagee and Goodlands, 37 per cent for the treated section at Tincurrin, and 25 per cent at Gibson. These modelled reductions are between three and 10 times greater than the area occupied by the tree canopy, and reflect the far larger area occupied by oil mallee roots because of the ‘edge effect’ as well as groundwater use where it is fresh and close to the soil surface.
- In all the catchments, groundwater heads in the upper slopes are lower with the oil mallee systems in place than without them. However, oil mallees will not reduce groundwater levels in the lower slopes at any site.
- The lack of response in lower slopes is largely because of the very low capacity of the groundwater systems studied, and of the WA wheatbelt generally, to be able to transmit additional groundwater inputs (associated with annual agriculture) fast enough to prevent on-site groundwater discharge. Modelling indicated that this capacity is between five and 20 per cent (depending on the site’s hydrogeological conditions) of the inputs received

under annual agriculture. The typical low gradient landscape and associated low hydraulic gradient is probably the main factor controlling the observed poor aquifer transmission capacity.

- Hypothetically reducing the recharge to zero for a 50 year period removed shallow groundwater from the Gibson catchment, reduced their extent at Marchagee, and made almost no difference at Goodlands and Tincurrin. This result highlights that the hydrological characteristics of catchments limit their salinity control response (over the maximum, practical planning timeframes) to even very large changes in water balance (100 per cent reduction in recharge). Because the reductions in recharge resulting from the oil mallee systems at the studied sites are much less than 100 per cent, it is likely that they fall short of the changes required to make meaningful reductions in the area of salinity in the wheatbelt.
- In situ reduction in recharge over broad valleys at risk can significantly delay the development of salinity where groundwater is still deep and there is a long time (50–100 years) before the risk is realised. However, it was not determined whether useful delays can be achieved in situations where groundwater is shallower and there is a more imminent risk of salinity developing.

Table 13 **Modelled comparison of the changes to the length of saturated flowtube (LSF) and the proportion of land protected from shallow groundwater after 50 years with oil mallee, compared to the proportion of land occupied by the oil mallee systems**

Site	Reduction in LSF by oil mallee (m)	Proportional reduction in LSF by oil mallee (%)	Proportion of catchment protected by oil mallee (%)	Proportion of catchment under oil mallee canopy (%)	Proportion of catchment under the Mallee Zone (%)
Marchagee	480	26	4.5	3	18
Goodlands	75	2	0.9	4	17
Tincurrin	200	2	0.8	10	47
Gibson	200	17	4.2	10	24

4. Conclusions and implications

Belts of oil mallees can use substantially more water than rainfall incident on the canopy and therefore have the potential to reduce recharge to groundwater over an area greater than that occupied by their canopies. Groundwater modelling has shown that a belt canopy area of 3–10 per cent of the landscape accounted for up to a 30 per cent net decrease in recharge to groundwater systems across the four sites in this study. Despite this multiplier, groundwater monitoring and modelling showed that this level of recharge reduction produced almost no discernable effect on catchment-scale groundwater levels, or on the area of saline discharge during the seven years of study.

Forecasts made using Flowtube modelling show that in 50 years (under the current rainfall conditions and stated assumptions) the proportion of land protected from becoming saline would be similar to, or less than, the proportion of land occupied by the oil mallees. When the competition impact of the unharvested oil mallee belts on adjacent crop and pasture is included, the forgone agricultural land occupied by the oil mallees might, as a proportion of saline area avoided, be even greater.

The low ratio between the area of land protected and the area of land occupied emphasises the importance of commercial oil mallee harvesting both to manage competition and sustain overall profitability, and the need to quantify the positive economic benefits of oil mallees to farming systems.

In catchments that have not yet reached hydrological equilibrium, the area affected by salinity can be expected to continue to expand if oil mallee planting is the only salinity control treatment used. The small hydrological response to the disproportionately large (in terms of area occupied by the oil mallee canopy) reduction in recharge is controlled by the hydrogeological characteristics of wheatbelt catchments. The inherent low gradient and low hydraulic conductivity of the aquifers mean that the rate of groundwater outflow from wheatbelt catchments is also very low. Therefore, a significant amount of the additional recharge resulting from the replacement of native vegetation with annual agriculture must be removed using a range of technologies before significant reductions in both depth to groundwater and land salinity will result.

By contrast, at a local scale, oil mallees (at more than 50 m spacings) may have a role in salinity mitigation where the catchment is at or near hydrological equilibrium and tree belts can be planted with access to shallow fresh groundwater. However, land with these conditions occupies only a very small proportion of the wheatbelt. It should also be considered that the long-term growth rates of trees using these low capacity aquifers is likely to decline if, or more likely when, the trees have used up the stored groundwater and are solely reliant on rainfall and lateral water flows into the aquifer.

Over most of the wheatbelt, to achieve large enough and timely reductions in groundwater levels that translate into useful reductions in the area of saline groundwater discharge, the spacing between the typical two-row oil mallee belts would need to be substantially reduced from 50 m to 15–30 m. These distances may need to be further reduced where the oil mallees are regularly harvested. These spacings are unlikely to be manageable or viable where broadscale cropping is the predominant inter-belt land use, although they may be suitable where livestock graze permanent pastures. The reduction in pasture productivity from competition from the oil mallees could be substantial under this arrangement and would need to be considered on a regional and farming system basis.

Achieving a similar overall oil mallee density over the landscape by increasing the number of rows within each belt, while maintaining wide belt spacing, is likely to be far less hydrologically effective because the edge rows capture much more water than inside rows. While two-row belts are the most practical and hydrologically effective design, they may not meet the current width specifications for carbon capture forests.

WA wheatbelt catchments contain hydrogeological systems that have limited capacity to transmit enough groundwater to prevent groundwater rise, causing extensive groundwater discharge areas. However, because catchments vary in this capacity it is recommended that hydrogeological assessment be made on an individual site basis, where the primary rationale for oil mallee plantings is salinity management. A rapid and cost effective method of undertaking such assessments is required in the longer term.

Measurements and modelling undertaken in this study indicate that using dense oil mallee systems as in situ recharge control over broad valley landscapes to lengthen the time before shallow groundwater develops, appears to be an effective strategy where groundwater is deep and there is a long time before the risk is realised. Further investigation is required to determine if this strategy is effective where groundwater is much shallower and there is more imminent risk. To do this requires the development of a cost effective method to determine the depth to groundwater and therefore the salinity risk in valleys across the wheatbelt.

In areas with existing shallow (less than 3 m) groundwater, oil mallee species that have salinity or waterlogging tolerance may be useful for managing salinity by eliminating or reducing in situ recharge. Further investigation of this management system is required to determine their: longevity in salt-accumulating environments, resistance to episodic flooding, optimal belt density, additional management requirements, and benefits that these types of systems bring to downstream environments. These aspects were not a focus of this study.

It is recommended that groundwater monitoring be continued at a reduced intensity at the four study sites for the next five to 10 years to strengthen and further validate the findings of this study. Ideally, during this time, the oil mallees would be regularly harvested to mimic the most likely commercial systems, although useful information could be gained on their maximum hydrological impact if the oil mallees were to remain unharvested.

The results of groundwater monitoring and catchment modelling in this and other studies show that planting belts of oil mallees at wide spacing (more than 50 m) as a land management system can provide only limited groundwater control or potential for salinity recovery in the broader WA wheatbelt. However, salinity remediation is only one potential benefit of this revegetation system, with aesthetics, wind erosion and an economic return from the sale of fibre, carbon, bio-fuel or other products being other potential benefits. The value of the hydrological changes achieved with oil mallee plantings in this study ultimately should consider the cost of establishing and maintaining the oil mallees plus the forgone value of production from the land occupied by the oil mallees. The costs must be assessed against the value of any products harvested from the oil mallees, the value of production from the area that would otherwise have become salt-affected, plus the value of any off-site benefits that may stem from reduced stream flow rates and salt loads.

5. References

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Appendix A: Comparison of four methods of calculating rates of change of piezometric level

Table A1 **Comparison of four methods of calculating rates of change of piezometric level**

Site and bore site	Water level change (m)	Graphical	Arithmetic	Linear regression	HARTT	No. of measurements	R^2 of linear regression	R^2 of HARTT trend	P value of HARTT rainfall	P value of HARTT time
Marchagee										
03ST01D	-1.15	-0.16	-0.19	-0.22	-0.09	35	0.68	0.88	0.00	0.88
03ST02D	-0.90	-0.09	-0.15	-0.18	-0.05	14	0.74	0.83	0.03	0.46
03ST03D	-0.99	-0.06	-0.16	-0.26	-0.03	19	0.64	0.87	0.00	0.19
03ST04D	-1.00	-0.09	-0.17	-0.22	-0.12	29	0.78	0.90	0.00	0.30
03ST05D	-0.57	-0.05	-0.09	-0.11	0.02	19	0.63	0.85	0.00	0.06
03ST06D	0.07	0.00	0.01	0.00	0.09	24	0.00	0.39	0.00	0.01
03ST07D	0.74	-0.07	0.12	0.00	0.29	27	0.00	0.48	0.00	0.00
03ST08D	-0.92	-0.10	-0.15	-0.18	-0.07	19	0.82	0.89	0.01	0.08
03ST09D	-0.27	0.00	0.00	-0.04	-0.03	15	0.53	0.69	0.03	0.29
03ST10D	-0.36	-0.06	-0.06	-0.03	0.02	32	0.16	0.43	0.00	0.04
03ST11D	-0.50	-0.13	-0.08	-0.18	-0.11	33	0.79	0.87	0.00	0.01
BMC12D	-0.80	-0.10	-0.11	-0.11	-0.02	37	0.66	0.84	0.00	0.28
BMC14D	-0.56	-0.05	-0.09	-0.04	0.08	33	0.05	0.48	0.00	0.00
CA2D	-0.54	-0.10	-0.09	-0.08	-0.08	36	0.97	0.97	0.01	0.00
CA3D	0.02	-0.01	0.00	-0.03	0.12	34	0.06	0.70	0.00	0.00
CA6D	-0.86	-0.19	-0.14	-0.22	-0.07	41	0.80	0.94	0.00	0.00
CA12D	0.12	0.00	0.04	-0.04	0.08	40	0.08	0.62	0.00	0.00
CA26D	-1.13	-0.18	-0.18	-0.19	-0.17	37	0.97	0.97	0.01	0.00
Site mean	**-0.53**	**-0.08**	**-0.08**	**-0.12**	**-0.01**					
Goodlands										
03IS01D	-0.20	0.00	-0.03	-0.02	0.03	19	0.22	0.74	0.00	0.02
03IS02D	1.29	0.22	0.21	0.21	0.22	19	0.95	0.95	0.19	0.00
03IS03D	0.48	0.09	0.08	0.11	0.14	19	0.53	0.78	0.00	0.00
03IS04D	0.91	0.15	0.15	0.15	0.19	29	0.75	0.86	0.00	0.00
GD11D	0.58	0.12	0.10	0.09	0.13	36	0.20	0.37	0.01	0.00
GD15D	-0.11	0.00	-0.02	-0.02	0.00	36	0.03	0.08	0.17	0.98
GD17D	0.46	0.08	0.08	0.06	0.07	36	0.67	0.70	0.05	0.00
GD18D	1.88	0.32	0.32	0.32	0.33	36	0.98	0.98	0.01	0.00
Site mean	**0.66**	**0.12**	**0.11**	**0.11**	**0.14**					

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Table A1 continued

Site and bore site	Water level change (m)	Graphical	Arithmetic	Linear regression	HARTT	No. of measurements	R^2 of linear regression	R^2 of HARTT trend	P value of HARTT rainfall	P value of HARTT time
Tincurrin (pre-oil mallees)										
SS9701D	1.04	0.15	0.16	0.15	0.13	21	0.94	0.96	0.01	0.00
SS9702D	1.48	0.30	0.24	0.26	0.25	22	0.97	0.98	0.00	0.00
SS9703D	0.92	0.21	0.16	0.19	0.17	23	0.94	0.95	0.03	0.00
SS9704D	1.77	0.35	0.30	0.31	0.28	22	0.97	0.98	0.01	0.00
SS9707D	0.72	0.18	0.12	0.14	0.11	20	0.86	0.89	0.04	0.00
SS9708D	1.45	0.36	0.24	0.27	0.27	23	0.97	0.98	0.02	0.00
SS9709D	dry	dry	dry	dry	dry	23				
SS9710D	dry	dry	dry	dry	dry	23				
SS9711D	dry	dry	dry	dry	dry	23				
SS9713D	1.03	0.24	0.19	0.21	0.21	16	0.93	0.96	0.01	0.00
SS9716D	4.11	0.65	0.11	0.69	0.68	16	0.94	0.98	0.00	0.00
SS9717D	0.68	0.15	0.13	0.16	0.13	15	0.95	0.97	0.02	0.00
SS9724D	1.25	0.13	0.13	0.20	0.17	16	0.81	0.87	0.02	0.00
SS9725D	0.57	0.17	0.17	0.17	0.11	15	0.83	0.90	0.01	0.00
SS9726D	0.69	0.13	0.15	0.14	0.11	14	0.92	0.95	0.04	0.00
LTC15	1.63	0.18	0.18	0.14	0.13	14	0.71	0.78	0.08	0.00
LT20	0.74	0.16	0.16	0.18	0.17	5	0.90	0.91	0.84	0.05
Site mean	**1.29**	**0.24**	**0.21**	**0.23**	**0.21**					
Tincurrin (post-oil mallees)										
SS9701D	0.84	0.11	0.11	0.11	0.12	21	0.84	0.86	0.09	0.00
SS9702D	1.64	0.24	0.22	0.24	0.25	17	0.96	0.97	0.10	0.00
SS9703D	0.73	0.10	0.11	0.11	0.11	28	0.85	0.87	0.07	0.00
SS9704D	1.48	0.19	0.23	0.24	0.26	30	0.84	0.87	0.01	0.00
SS9707D	0.82	0.14	0.14	0.13	0.16	17	0.90	0.93	0.03	0.00
SS9708D	1.09	0.18	0.18	0.18	0.20	16	0.95	0.96	0.06	0.00
SS9709D	dry	dry	dry	dry	dry	16				
SS9710D	dry	dry	dry	dry	dry	16				
SS9711D	dry	dry	dry	dry	dry	16				
SS9713D	0.65	0.06	0.04	0.07	0.08	28	0.45	0.48	0.32	0.00
SS9716D	1.33	0.20	0.22	0.24	0.31	16	0.92	0.98	0.00	0.00
SS9717D	0.88	0.11	0.13	0.14	0.14	30	0.93	0.94	0.03	0.00
SS9724D	0.41	0.07	0.07	0.08	0.08	28	0.94	0.95	0.01	0.00

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Table A1 continued

Site and bore site	Water level change (m)	Interpreted	Arithmetic	Linear regression	HARTT	No. of measurements	R^2 of linear regression	R^2 of HARTT trend	P value of HARTT rainfall	P value of HARTT time
SS9725D	1.04	0.14	0.15	0.15	0.15	19	0.87	0.89	0.10	0.00
SS9726D	0.96	0.12	0.11	0.15	0.16	18	0.86	0.86	0.42	0.00
SS0330D	0.80	0.12	0.13	0.13	0.13	14	0.98	0.98	0.87	0.00
SS0331D	na	0.13	0.24	0.17	na	14				
SS0332D	dry	dry	dry	dry	dry	14				
SS0333D	0.63	0.11	0.11	0.08	0.11	16	0.59	0.73	0.02	0.00
SS0334D	dry	dry	dry	dry	dry	16				
SS0335D	1.04	0.14	0.18	0.18	0.18	28	0.98	0.98	0.00	0.00
SS0336D	0.91	0.20	0.15	0.19	0.21	28	0.65	0.72	0.02	0.00
LTC15	0.44	0.05	0.07	0.06	0.06	18	0.40	0.54	0.05	0.00
LT20	0.75	0.13	0.13	0.14	0.14	29	0.97	0.98	0.02	0.00
Site mean	**0.91**	**0.13**	**0.14**	**0.15**	**0.16**					
Gibson										
RS01D	-0.05	0.00	-0.01	-0.01	-0.09	36	0.00	0.18	0.01	0.05
RS02D	0.26	0.00	0.04	-0.01	-0.18	75	0.00	0.27	0.00	0.00
RS03D	1.16	0.10	0.17	0.09	-0.26	75	0.02	0.21	0.00	0.02
RS04D	1.08	0.20	0.15	0.14	-0.12	75	0.10	0.32	0.00	0.08
RS05I	1.03	0.10	0.15	0.11	-0.07	74	0.12	0.35	0.00	0.12
RS06I	0.24	0.05	0.03	0.03	-0.10	75	0.03	0.35	0.00	0.00
RS07D	1.09	0.05	0.16	0.02	-0.13	34	0.00	0.24	0.01	0.10
RS08D	0.37	0.05	0.05	0.05	-0.17	75	0.03	0.41	0.00	0.00
RS09D	1.63	0.15	0.23	0.04	-0.21	30	0.01	0.38	0.00	0.03
RS10D	1.29	0.15	0.19	0.08	-0.09	31	0.09	0.65	0.00	0.04
RS11D	0.25	0.00	0.04	0.03	-0.08	75	0.05	0.51	0.00	0.00
RS12D	-0.69	-0.05	-0.10	-0.10	-0.32	72	0.10	0.39	0.00	0.00
RS13D	-0.39	-0.10	-0.06	-0.12	-0.20	75	0.27	0.38	0.00	0.00
RS14D	0.96	0.15	0.14	0.10	-0.09	74	0.08	0.29	0.00	0.10
RS15I	0.89	0.15	0.13	0.24	0.00	75	0.24	0.35	0.00	0.97
RS16D	3.47	0.25	0.25	0.23	-0.12	29	0.13	0.50	0.00	0.38
RS17D	-0.08	0.00	-0.01	0.01	-0.04	33	0.01	0.30	0.00	0.05
ET06	1.45	0.10	0.15	0.00	-0.12	42	0.01	0.16	0.02	0.20
GS9A	0.38	0.10	0.11	0.06	-0.07	28	0.41	0.66	0.00	0.44
GS8A	0.94	0.10	0.16	0.09	0.02	28	0.21	0.29	0.02	0.33
GS7A	0.28	0.05	0.06	-0.01	-0.11	27	0.01	0.41	0.00	0.00
Site mean	**0.74**	**0.08**	**0.10**	**0.05**	**-0.12**					
All bores mean	**0.52**	**0.08**	**0.08**	**0.06**	**0.04**					

Appendix B: Marchagee bore hydrographs

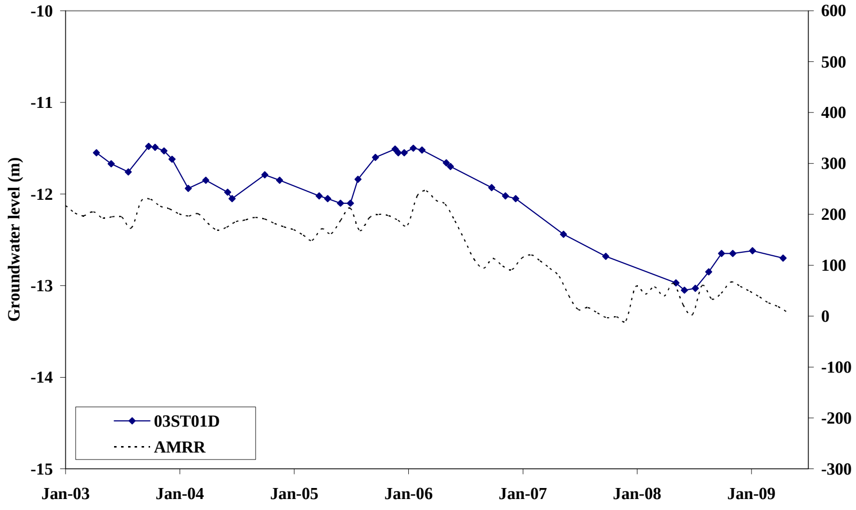

Figure B1 **Hydrograph for bore 03ST01D**

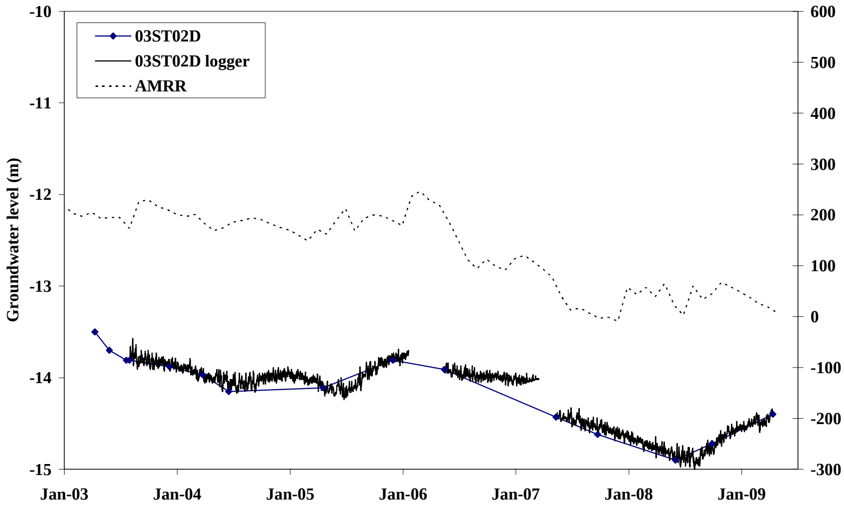

Figure B2 **Hydrograph for bore 03ST02D**

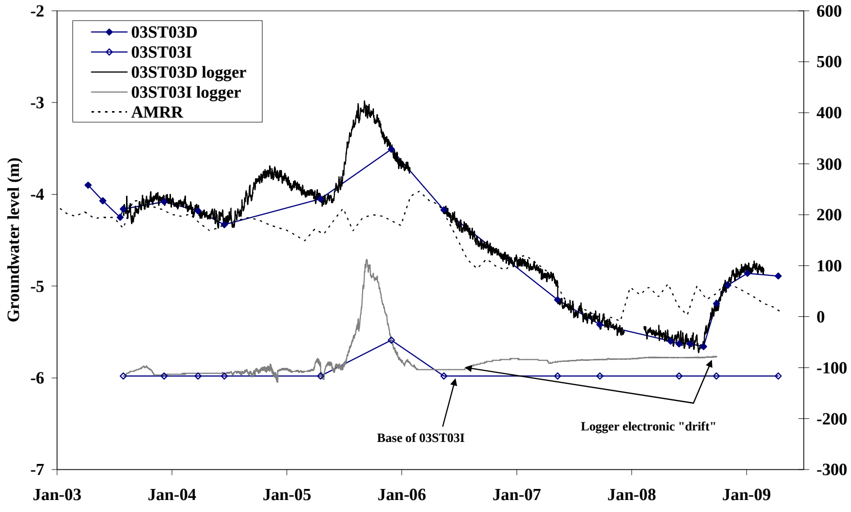

Figure B3 **Hydrographs for bore site 03ST03**

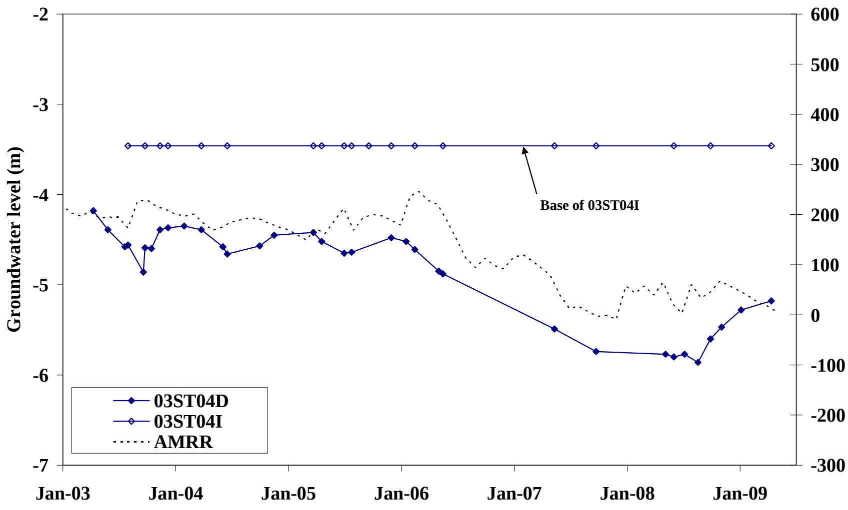

Figure B4 **Hydrographs for bore site 03ST04**

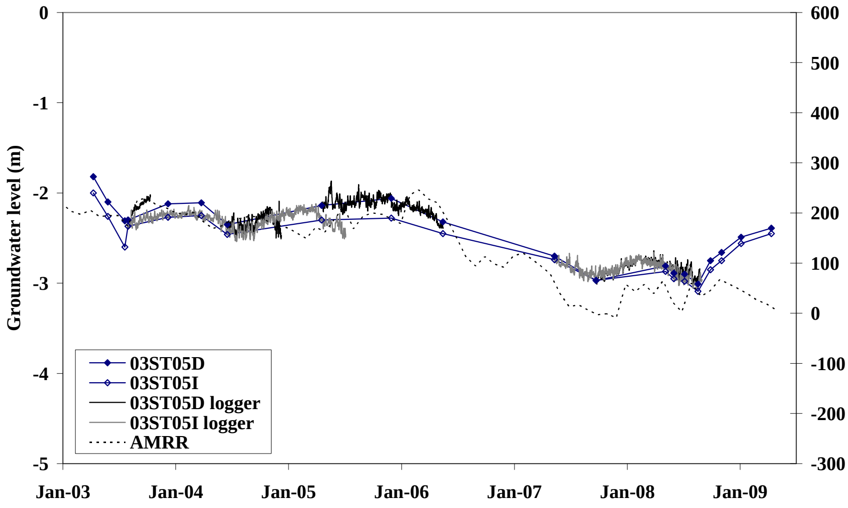

Figure B5 Hydrographs for bore site 03ST05

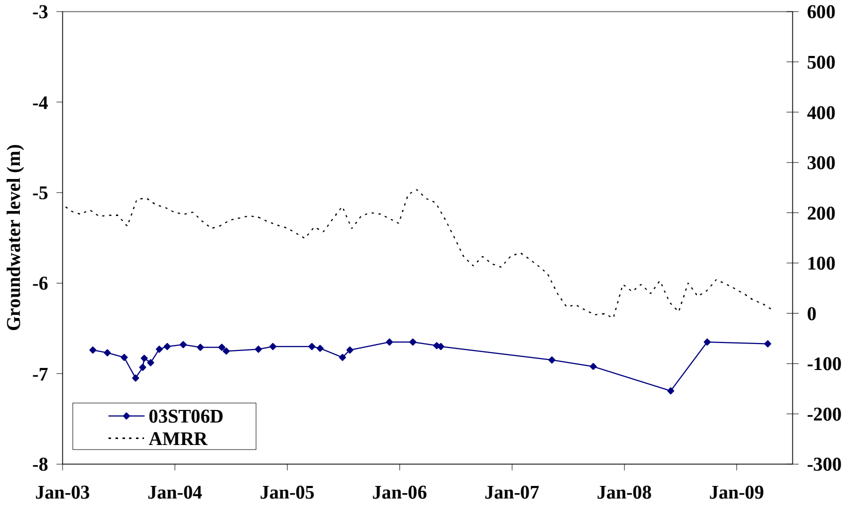

Figure B6 **Hydrograph for bore 03ST06D**

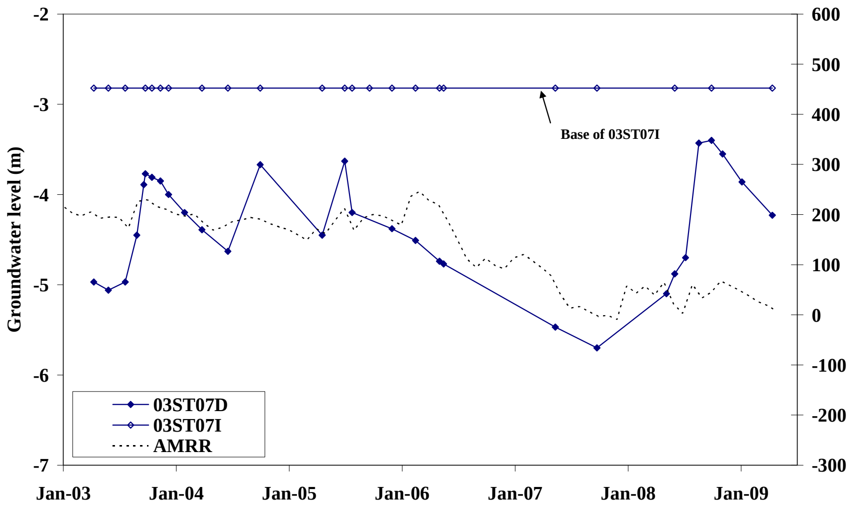

Figure B7 **Hydrographs for bore site 03ST07**

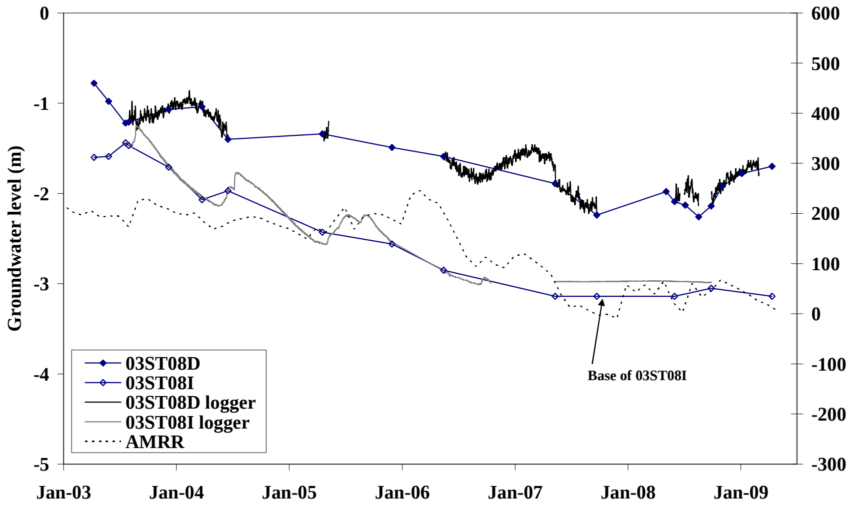

Figure B8 **Hydrographs for bore site 03ST08**

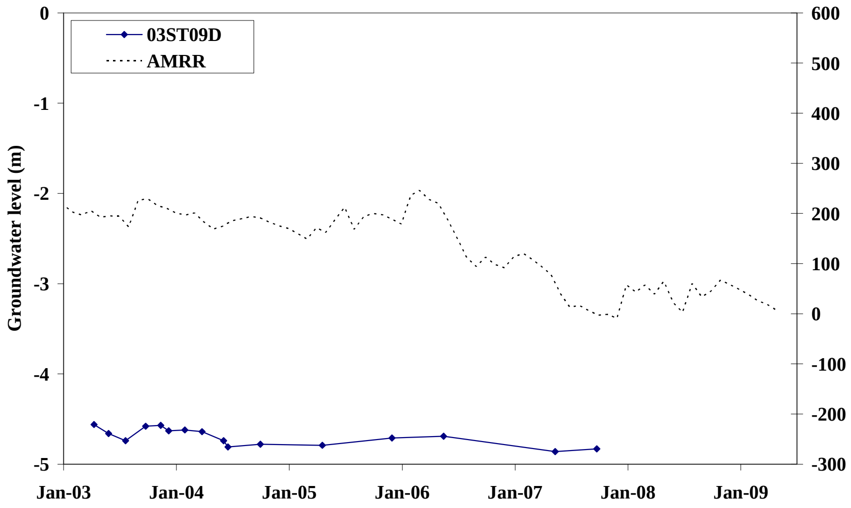

Figure B9 **Hydrograph for bore 03ST09D**

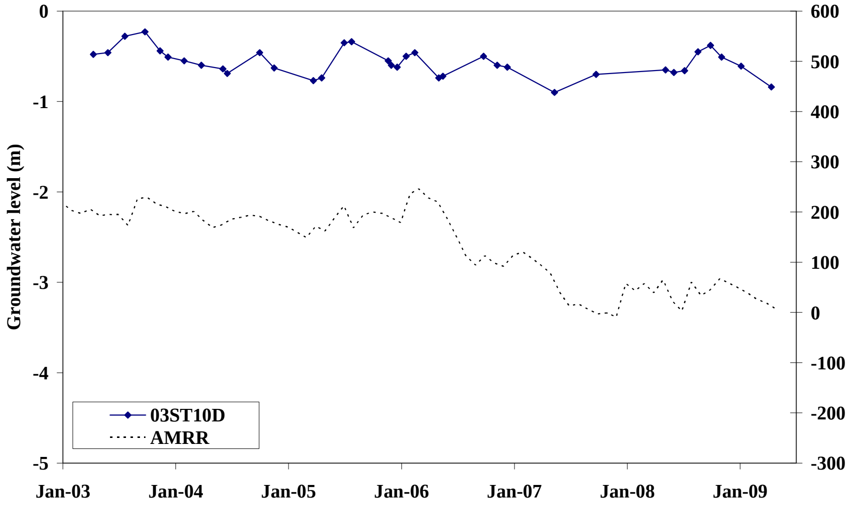

Figure B10 **Hydrograph for bore 03ST10D**

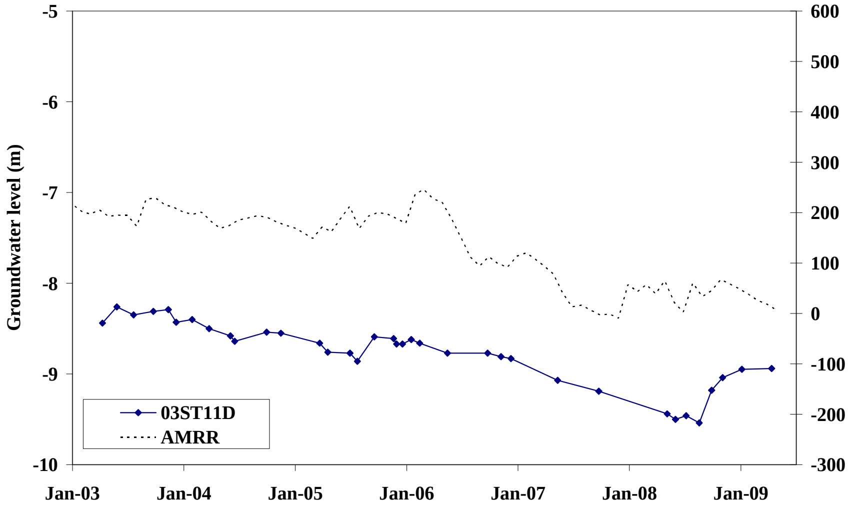

Figure B11 **Hydrograph for bore 03ST011D**

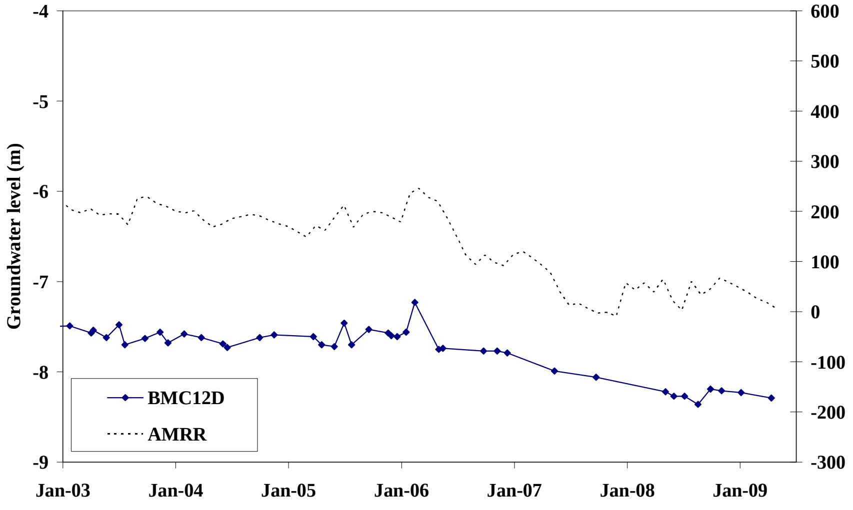

Figure B12 **Hydrograph for bore BMC12D**

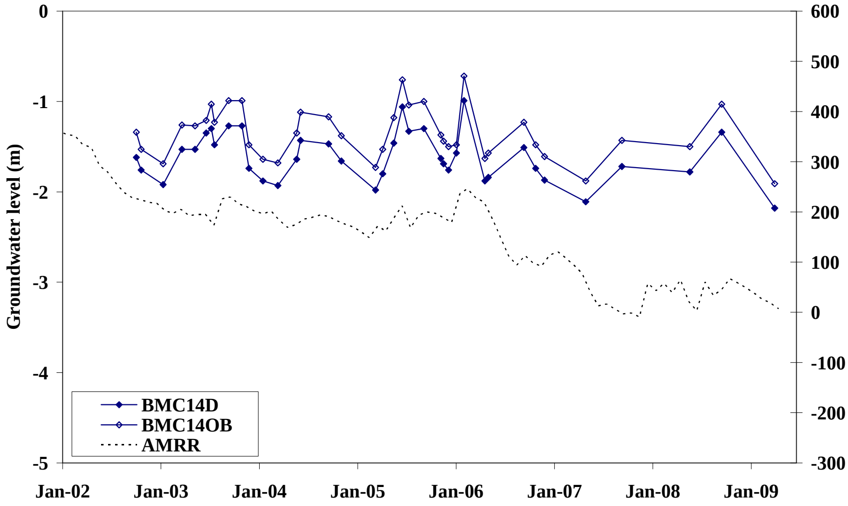

Figure B13 **Hydrographs for bore site BMC14**

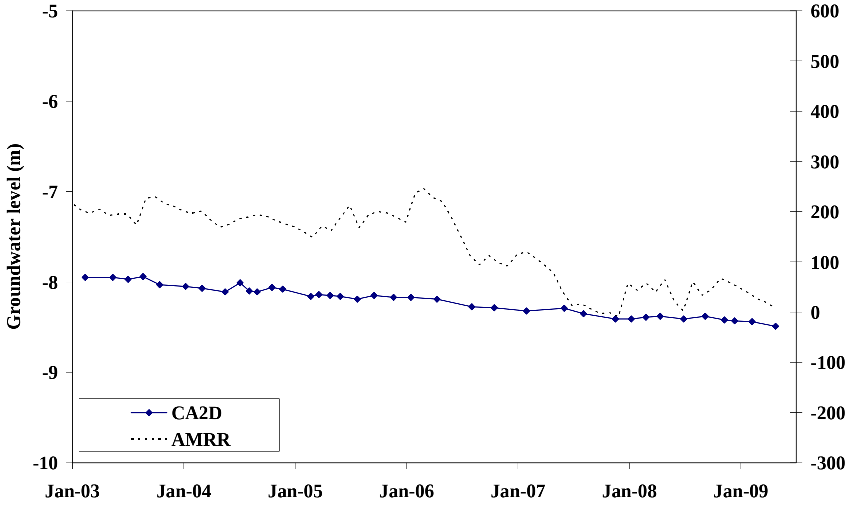

Figure B14 **Hydrograph for bore CA2D**

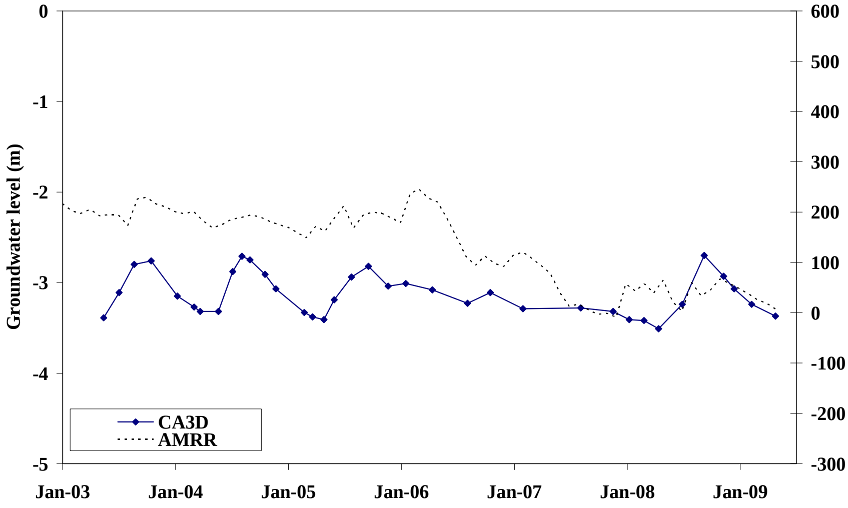

Figure B15 **Hydrograph for bore CA3D**

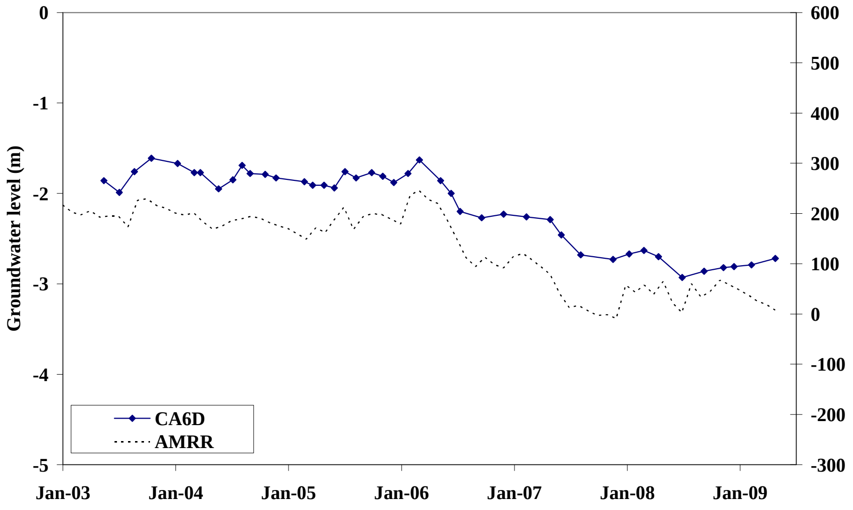

Figure B16 **Hydrograph for bore CA6D**

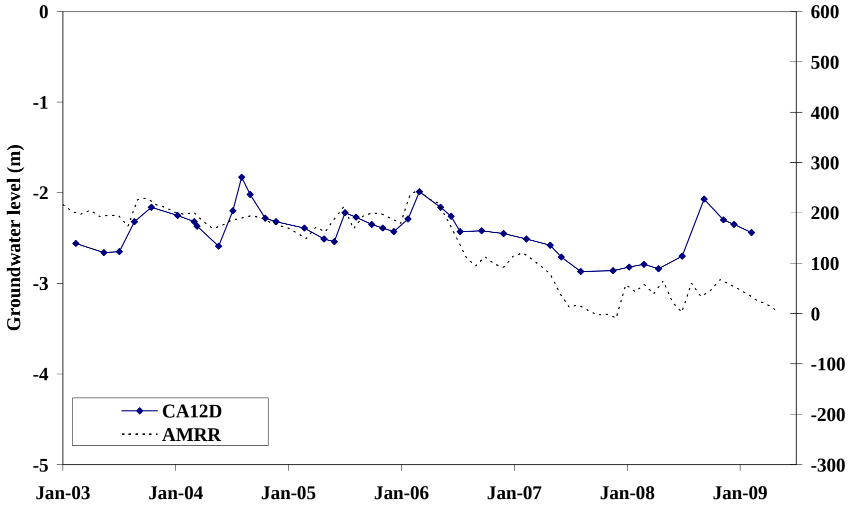

Figure B17 **Hydrograph for bore CA12D**

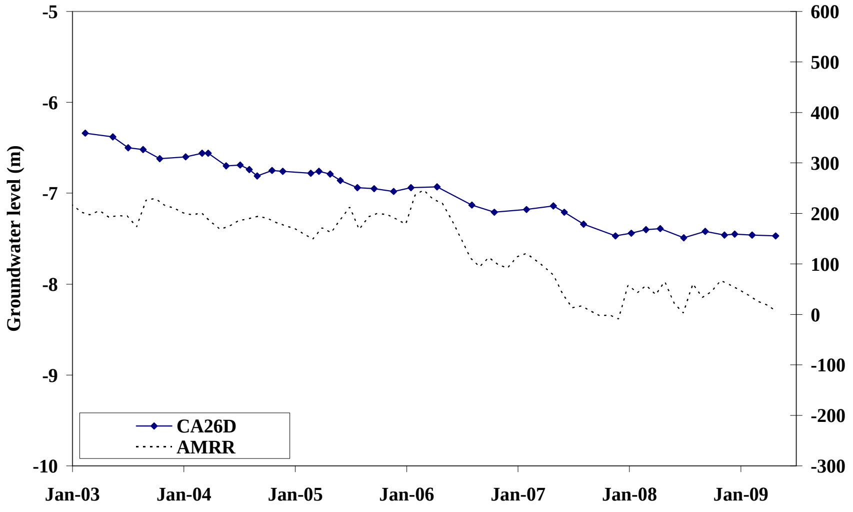

Figure B18 **Hydrograph for bore CA26D**

Appendix C: Goodlands bore hydrographs

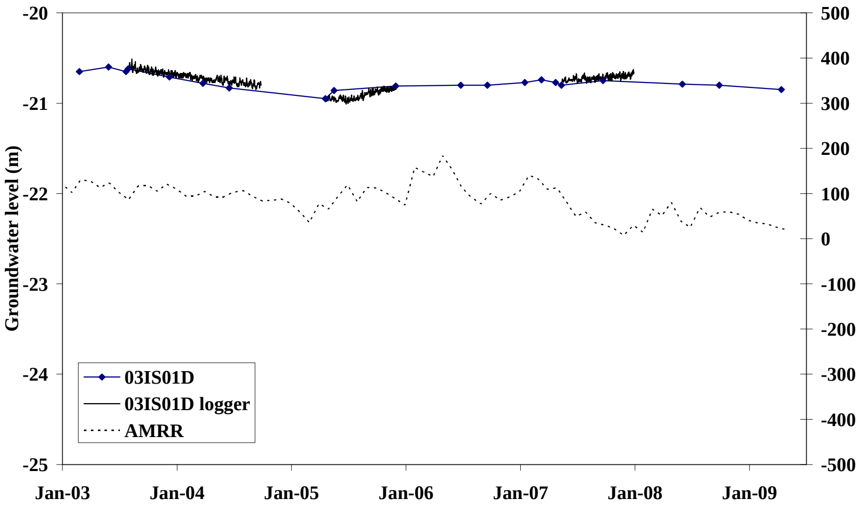

Figure C1 **Hydrograph for bore 03IS01D**

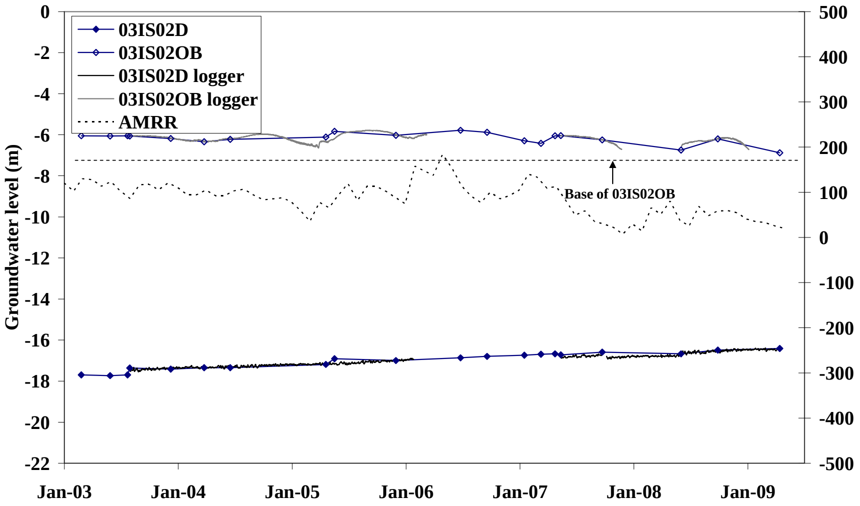

Figure C2 **Hydrographs for bore site 03IS02**

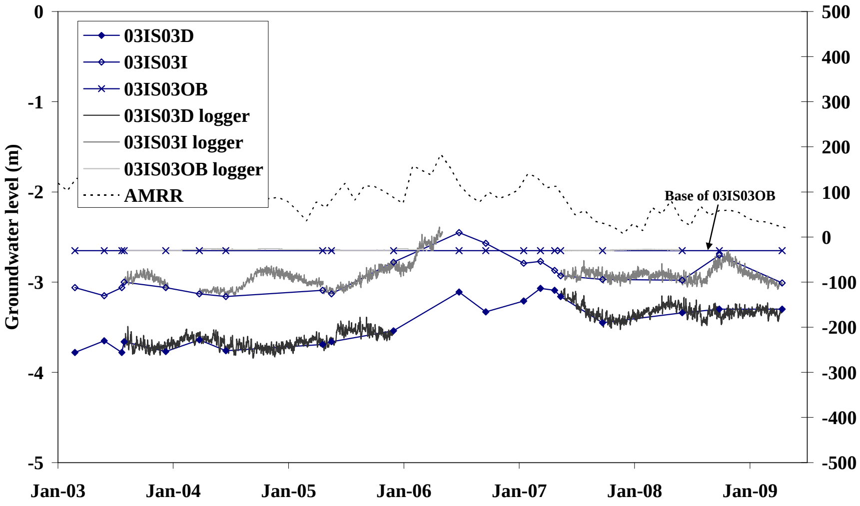

Figure C3 **Hydrographs for bore site 03IS03**

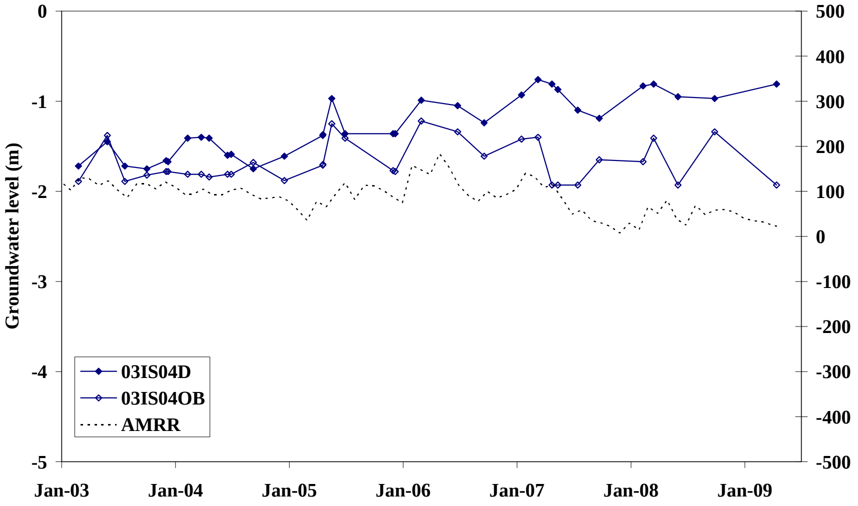

Figure C4 **Hydrographs for bore site 03IS04**

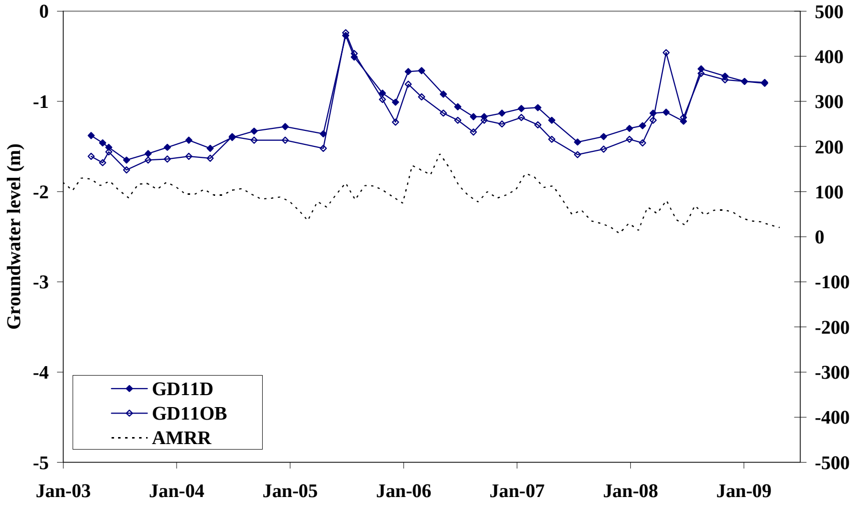

Figure C5 **Hydrographs for bore site GD11D**

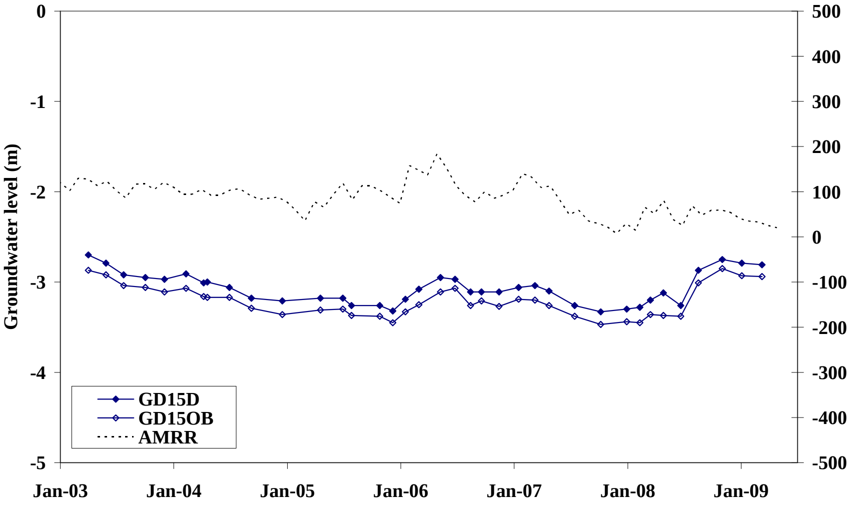

Figure C6 **Hydrographs for bore site GD15**

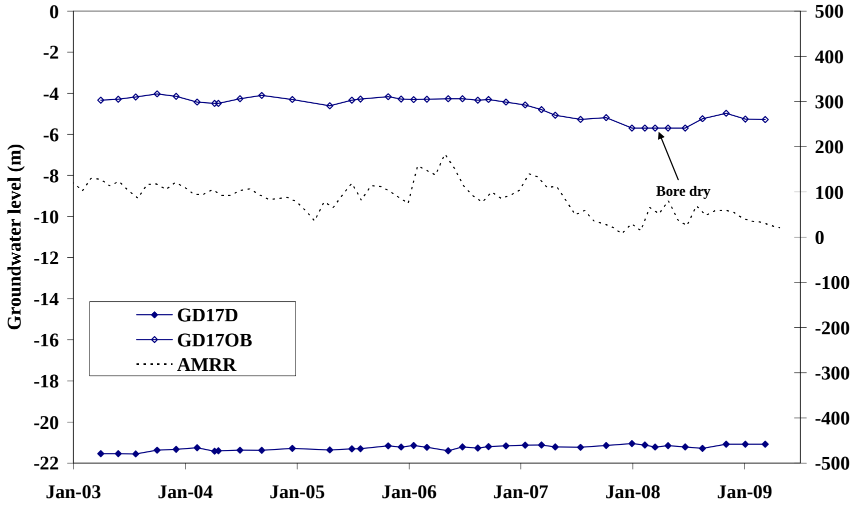

Figure C7 **Hydrographs for bore site GD17**

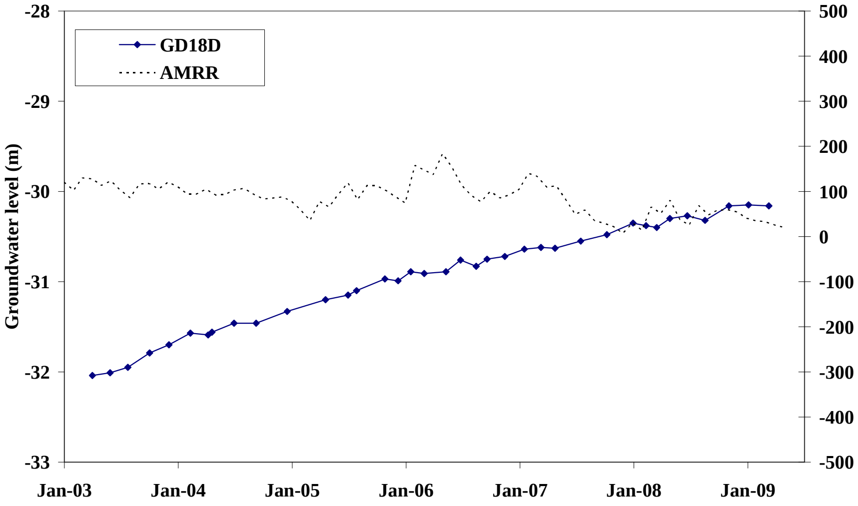

Figure C8 **Hydrograph for bore GD18D**

Appendix D: Tincurrin bore hydrographs

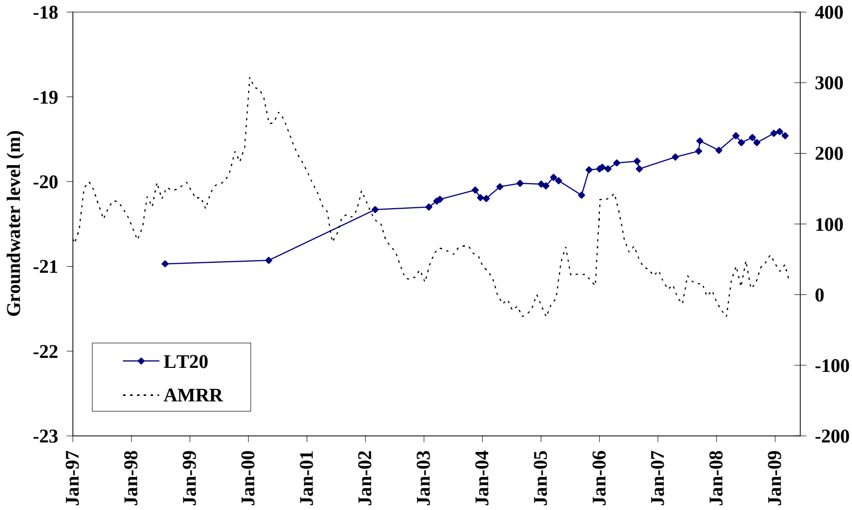

Figure D1 **Hydrograph for bore LT20**

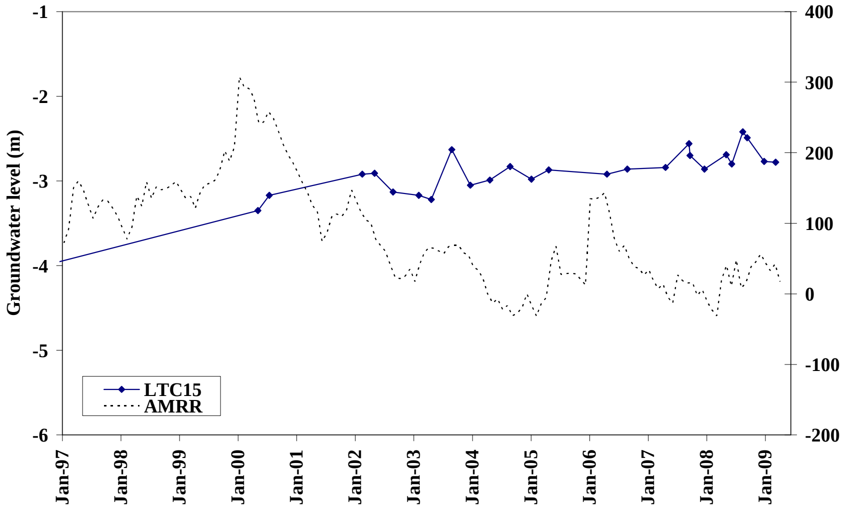

Figure D2 **Hydrograph for bore LTC15**

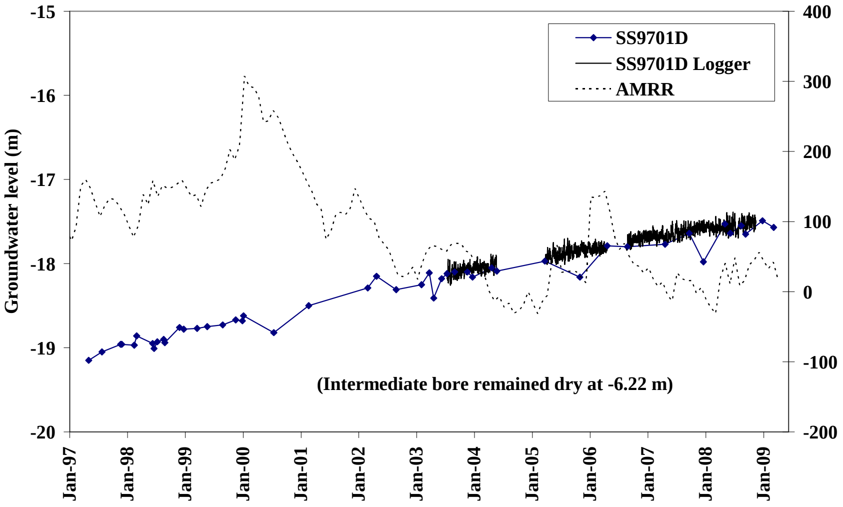

Figure D3 **Hydrograph for bore SS9701D**

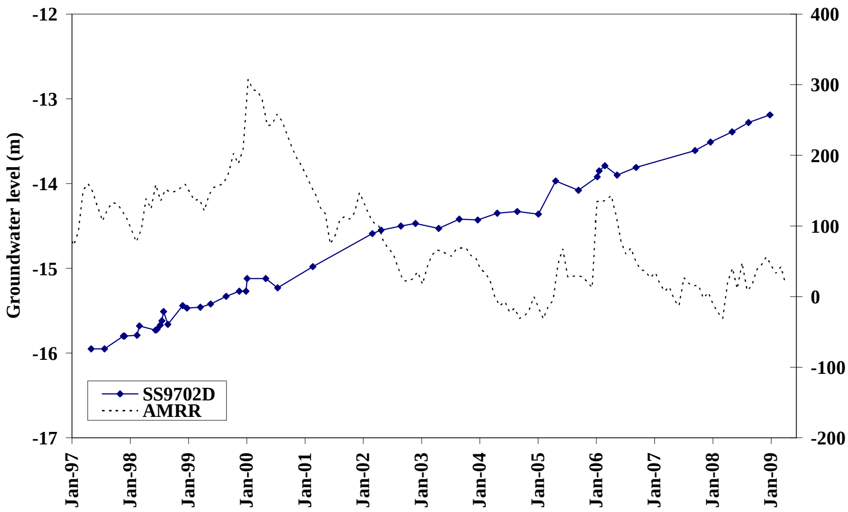

Figure D4 **Hydrograph for bore SS9702D**

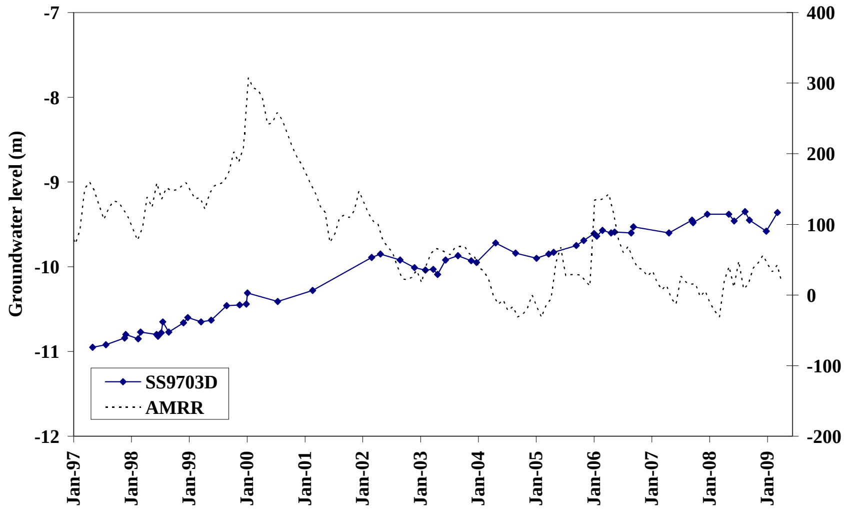

Figure D5 **Hydrograph for bore SS9703D**

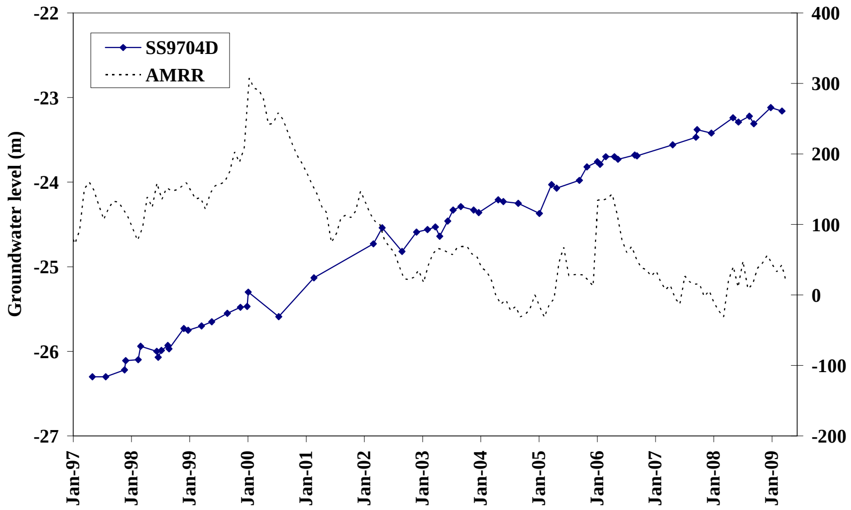

Figure D6 **Hydrograph for bore SS9704D**

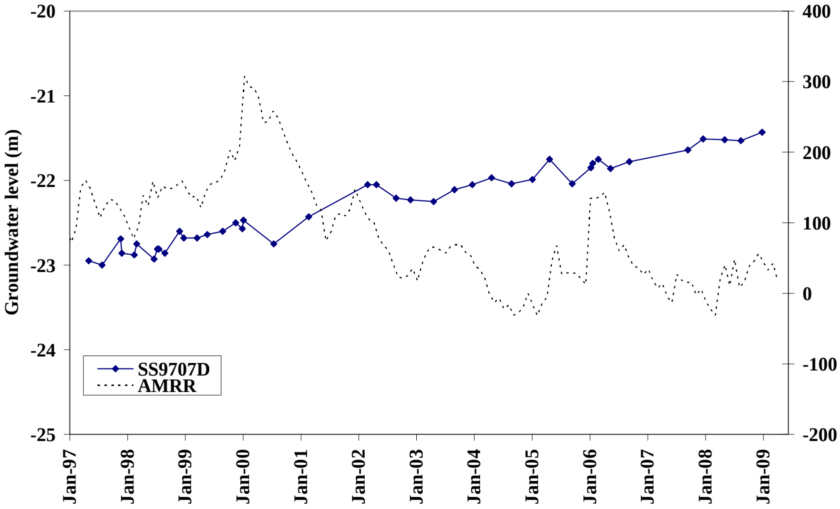

Figure D7 **Hydrograph for bore SS9707D**

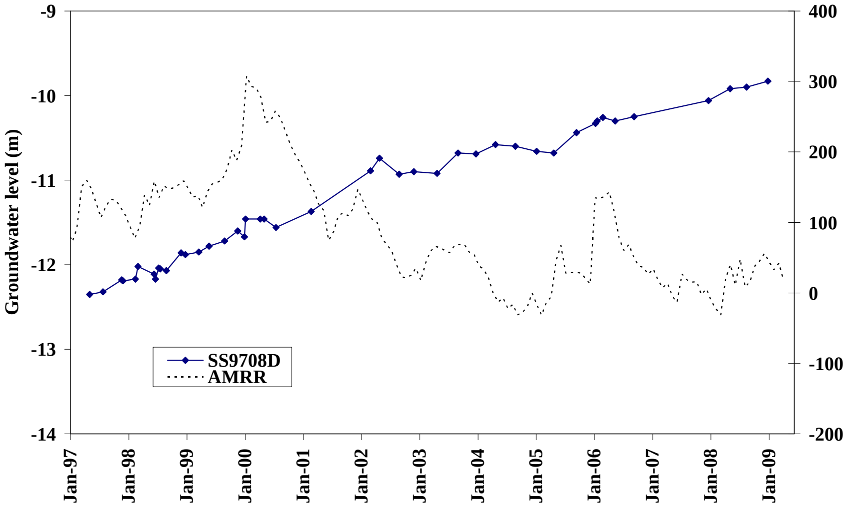

Figure D8 **Hydrograph for bore SS9708D**

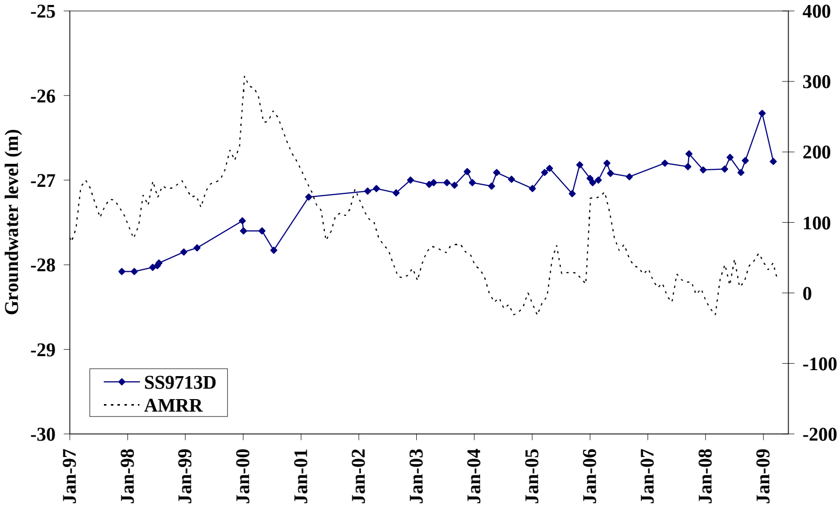

Figure D9 **Hydrograph for bore SS9713D**

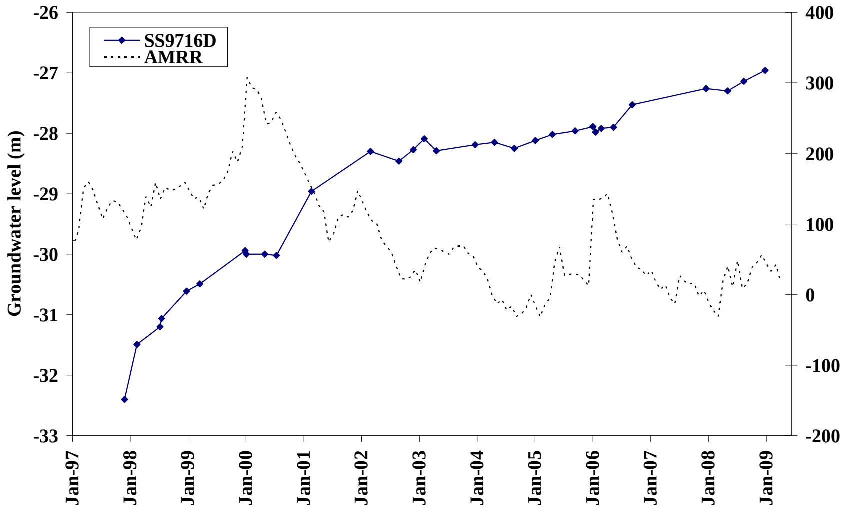

Figure D10 **Hydrograph for bore SS9716D**

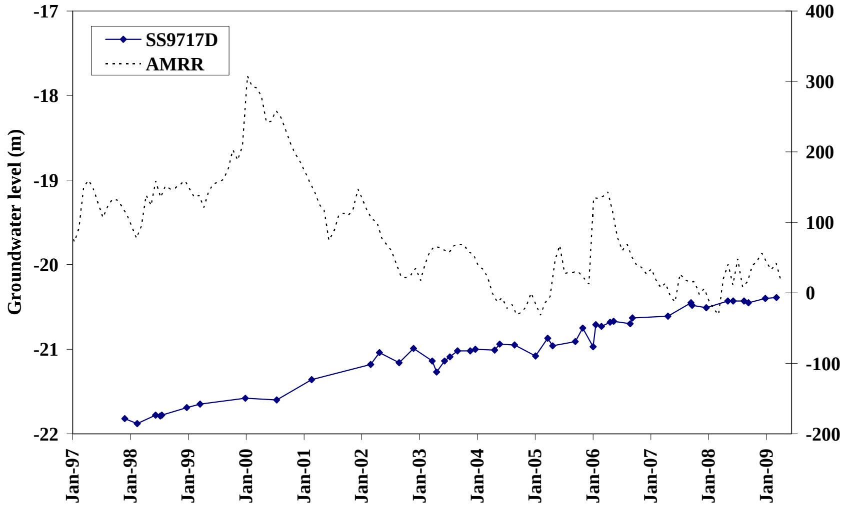

Figure D11 **Hydrograph for bore SS9717D**

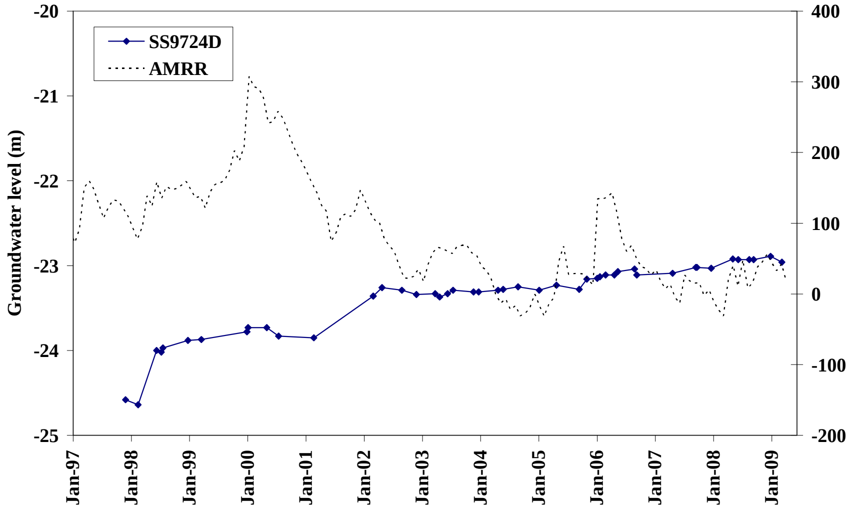

Figure D12 **Hydrograph for bore SS9724D**

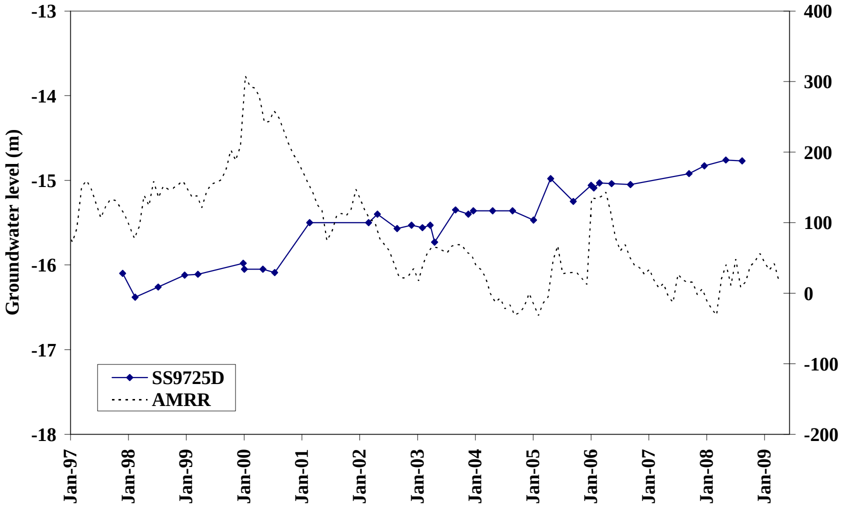

Figure D13 **Hydrograph for bore SS9725D**

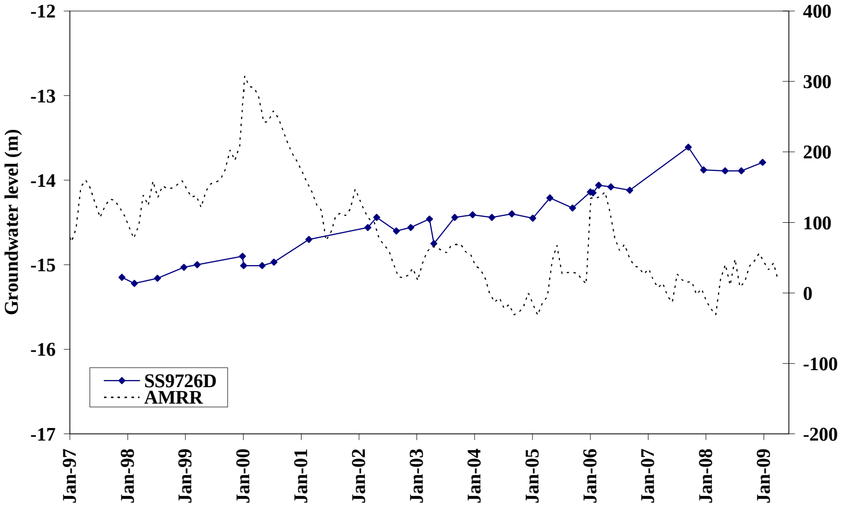

Figure D14 **Hydrograph for bore SS9726D**

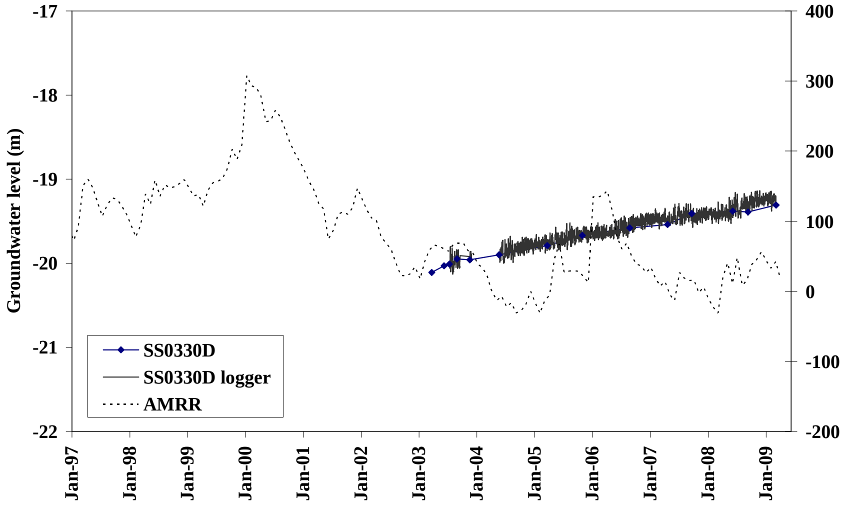

Figure D15 **Hydrograph for bore SS3001D**

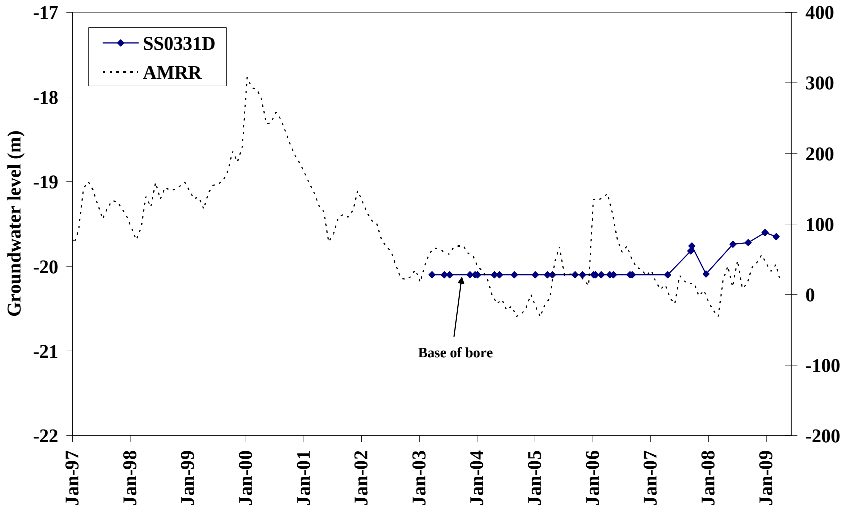

Figure D16 **Hydrograph for bore SS0331D**

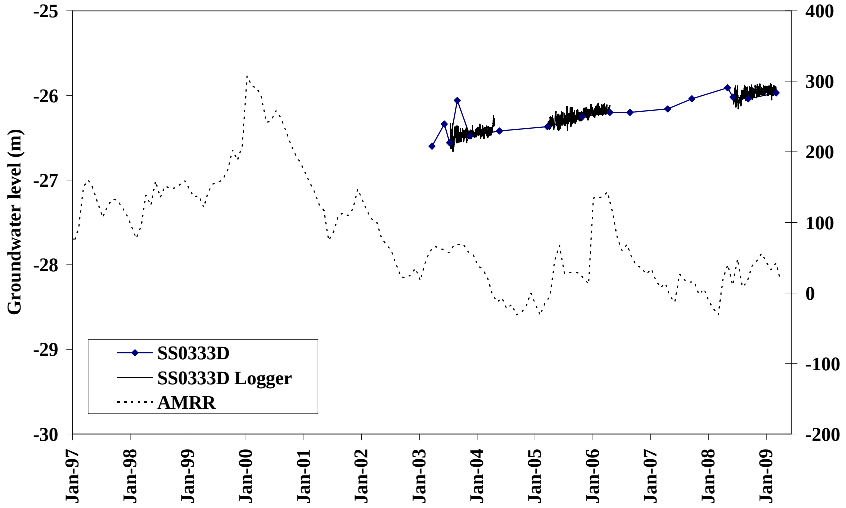

Figure D17 **Hydrograph for bore SS0333D**

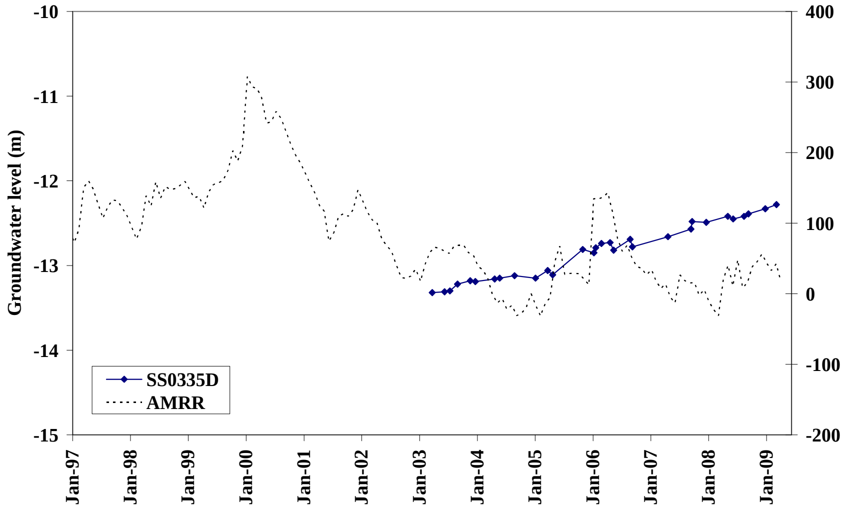

Figure D18 **Hydrograph for bore SS0335D**

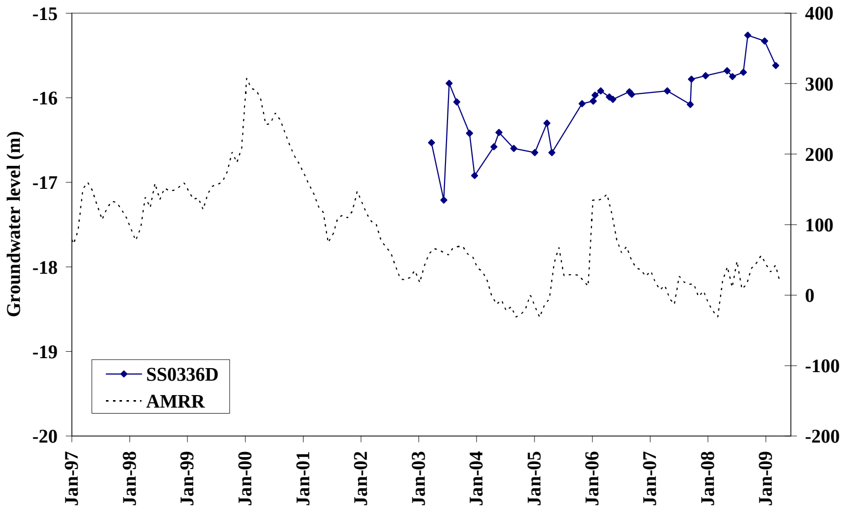

Figure D19 **Hydrograph for bore SS0336D**

Appendix E: Gibson bore hydrographs

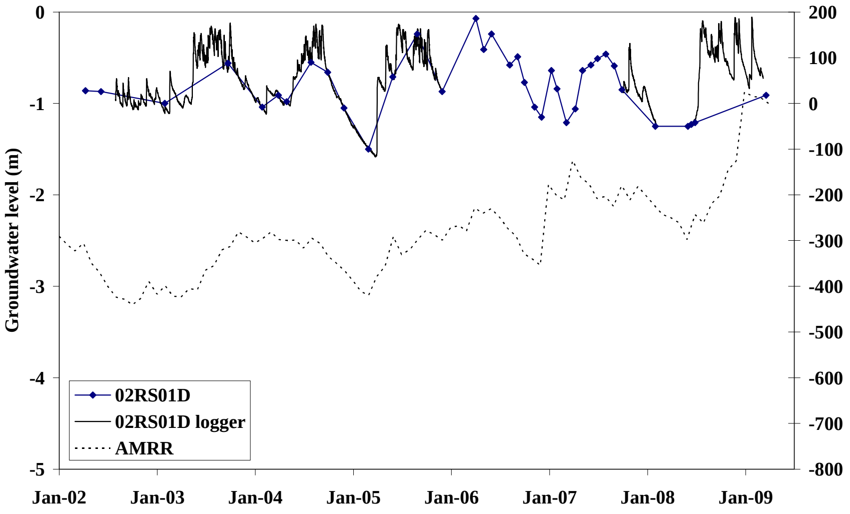

Figure E1 **Hydrograph for bore 02RS01D**

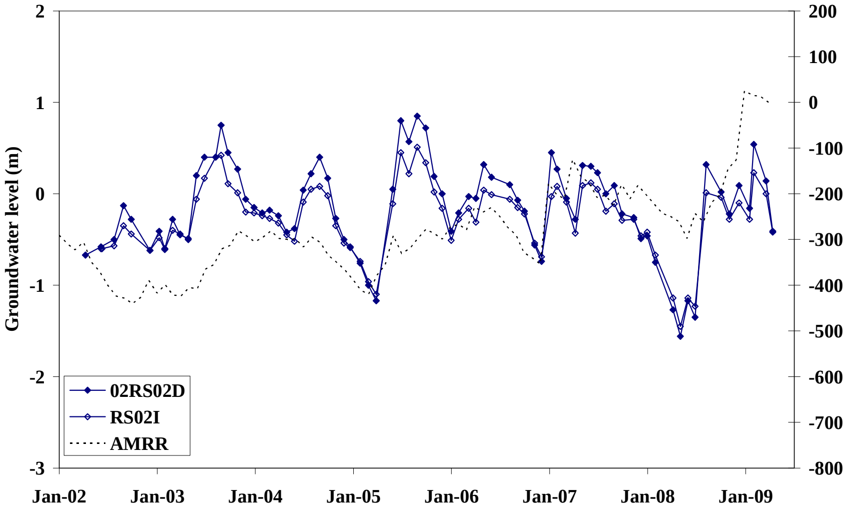

Figure E2 **Hydrographs for bore site 02RS02**

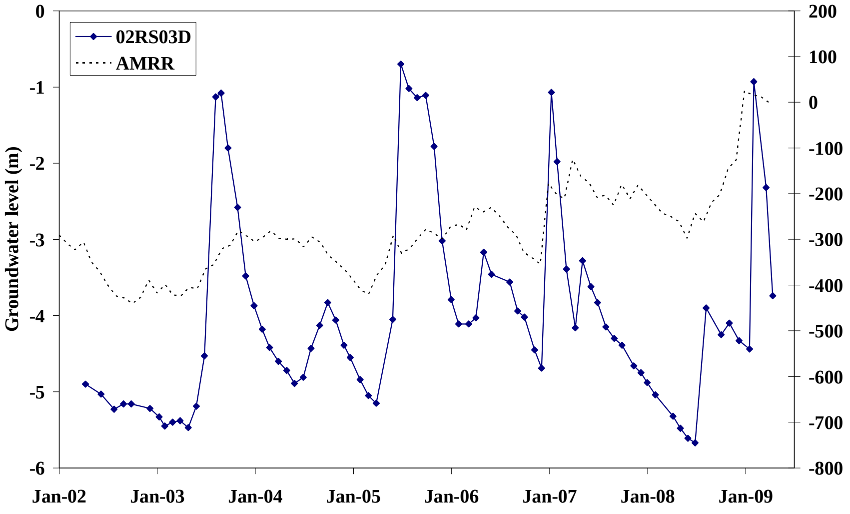

Figure E3 **Hydrograph for bore 02RS03D**

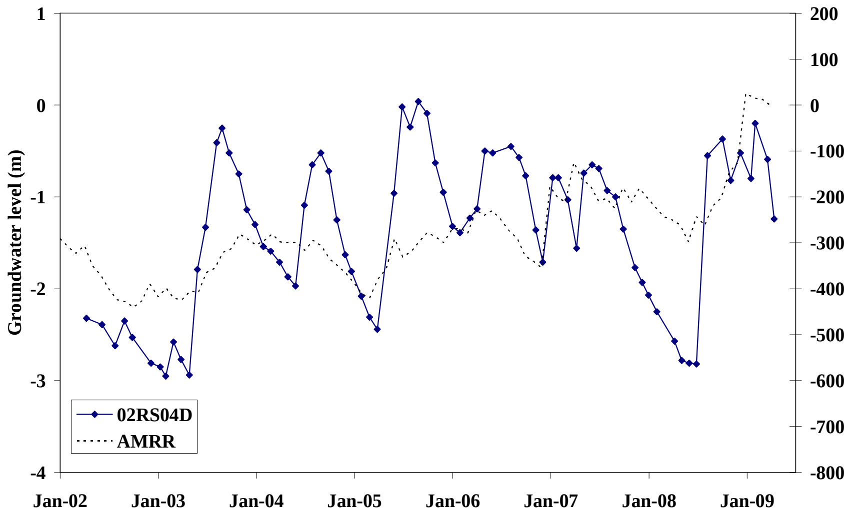

Figure E4 **Hydrograph for bore 02RS04D**

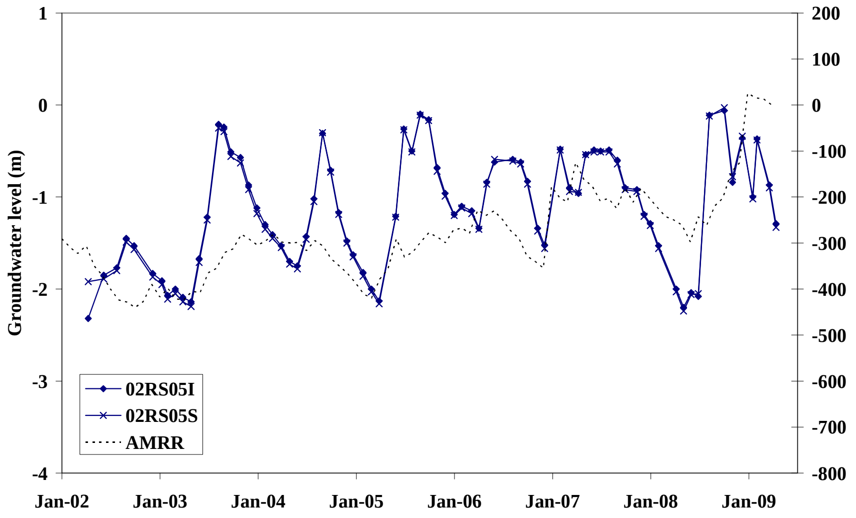

Figure E5 **Hydrographs for bore site 02RS05**

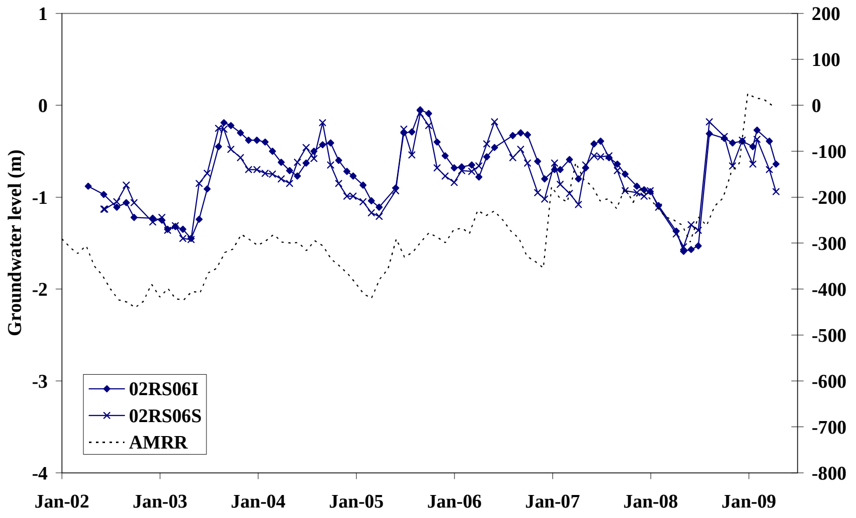

Figure E6 **Hydrographs for bore site 02RS06**

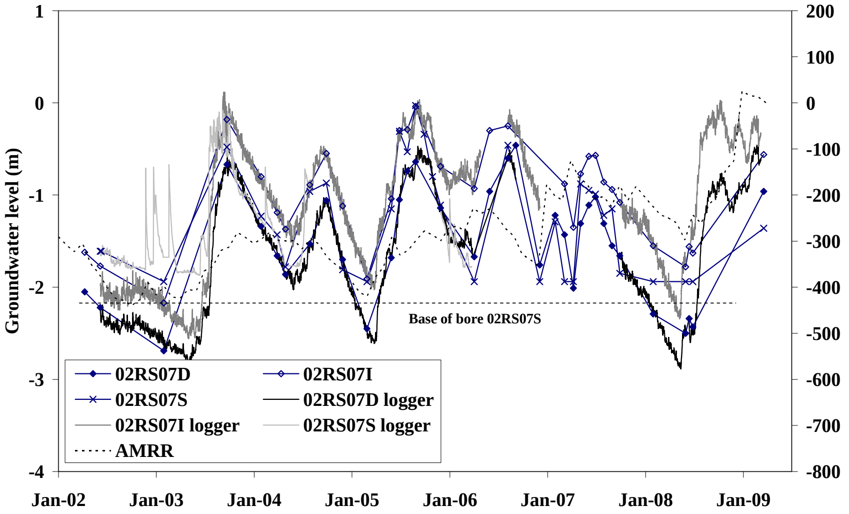

Figure E7 **Hydrographs for bore site 02RS07**

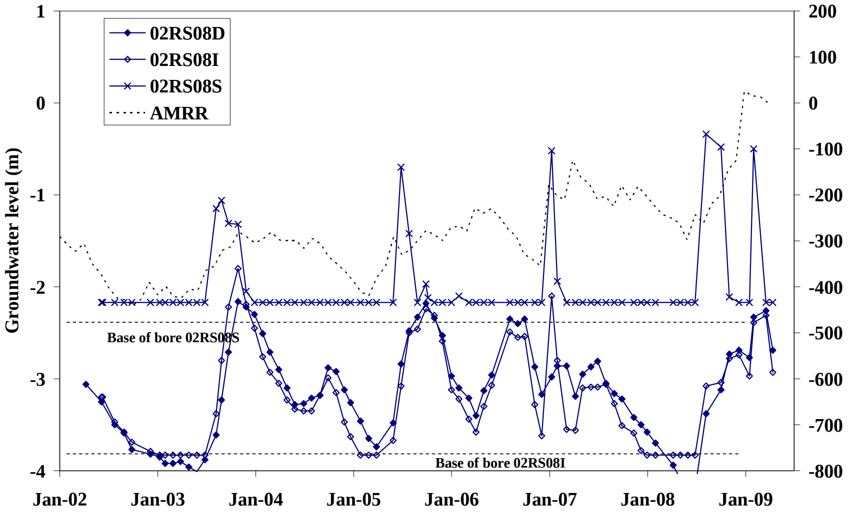

Figure E8 **Hydrographs for bore site 02RS08**

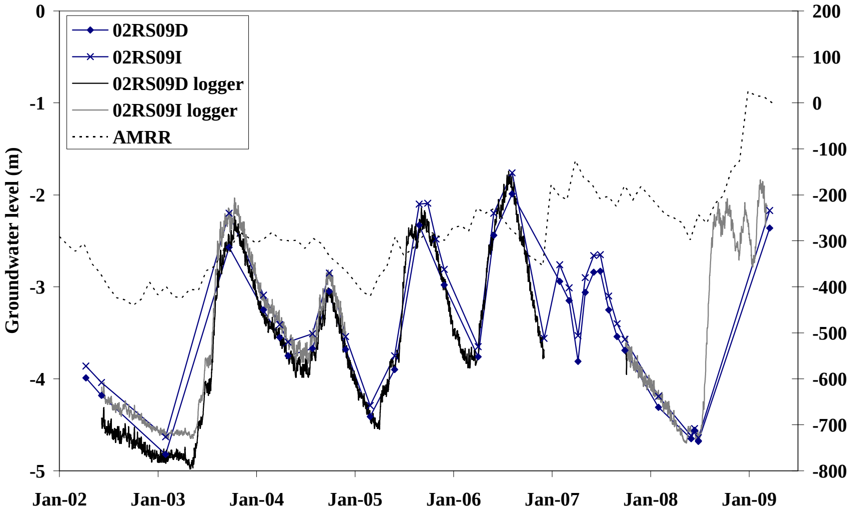

Figure E9 **Hydrographs for bore site 02RS09**

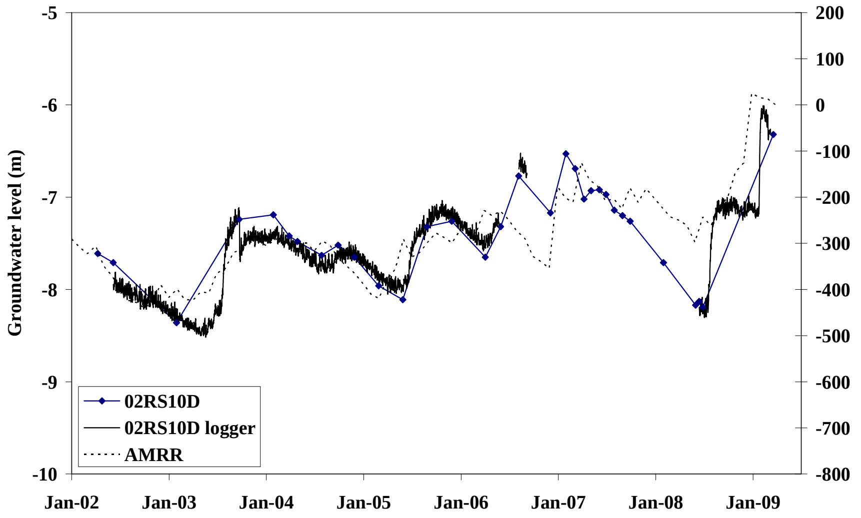

Figure E10 **Hydrograph for bore 02RS10D**

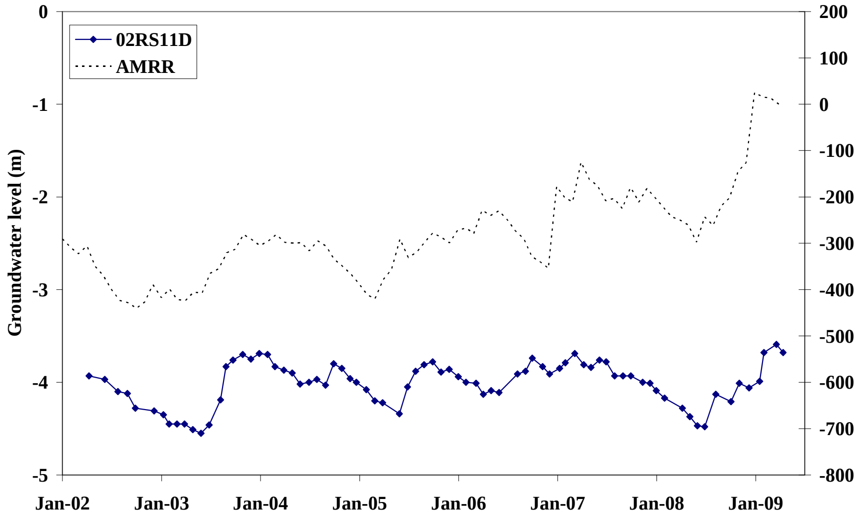

Figure E11 **Hydrograph for bore 02RS11D**

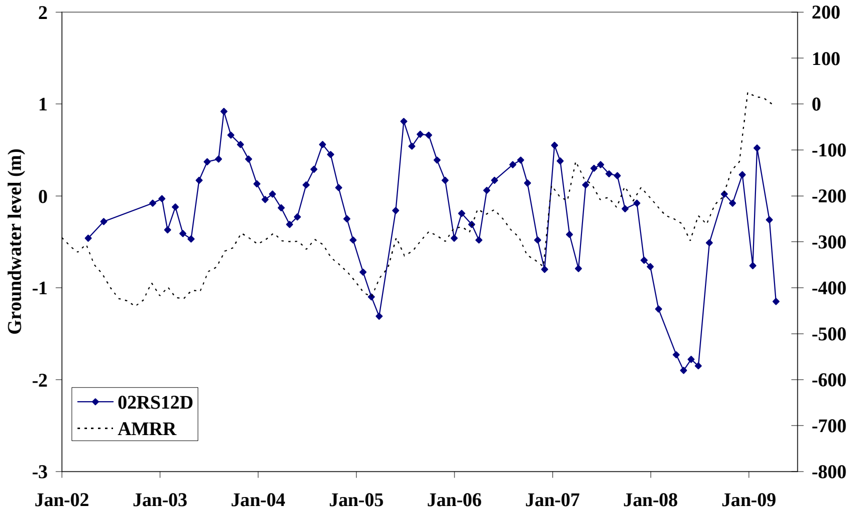

Figure E12 **Hydrograph for bore 02RS12D**

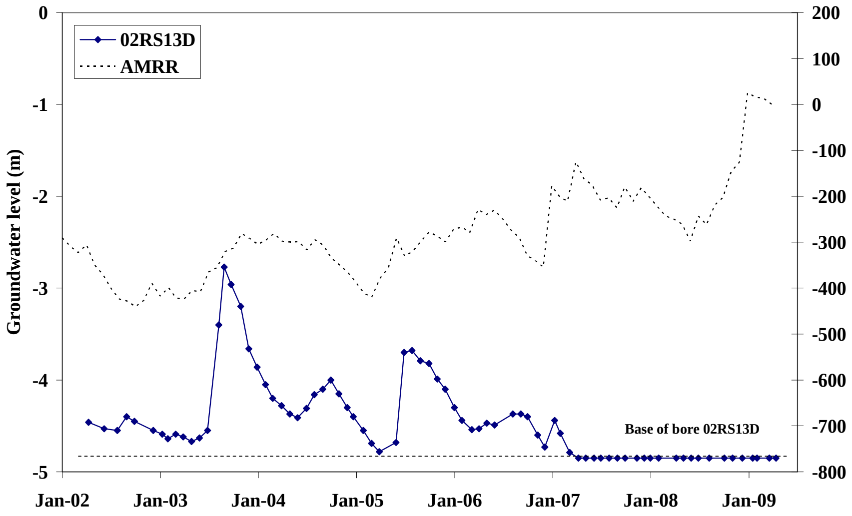

Figure E13 **Hydrograph for bore 02RS13D**

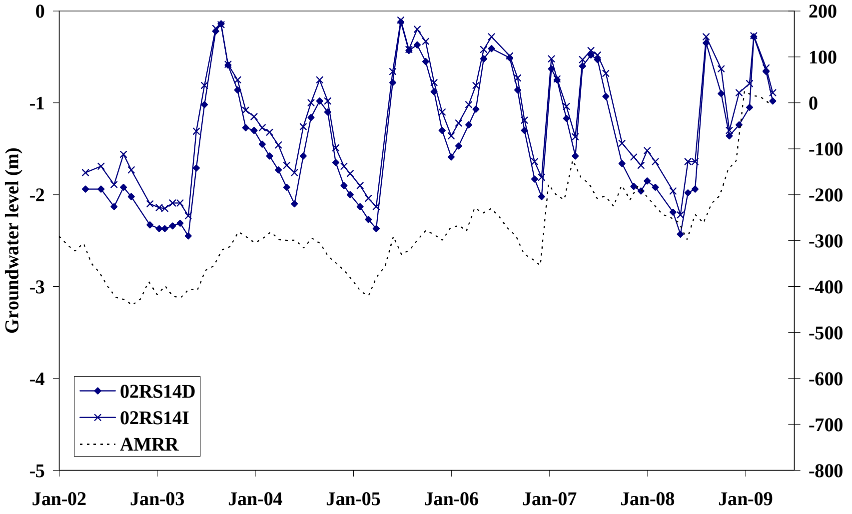

Figure E14 **Hydrographs for bore site 02RS14**

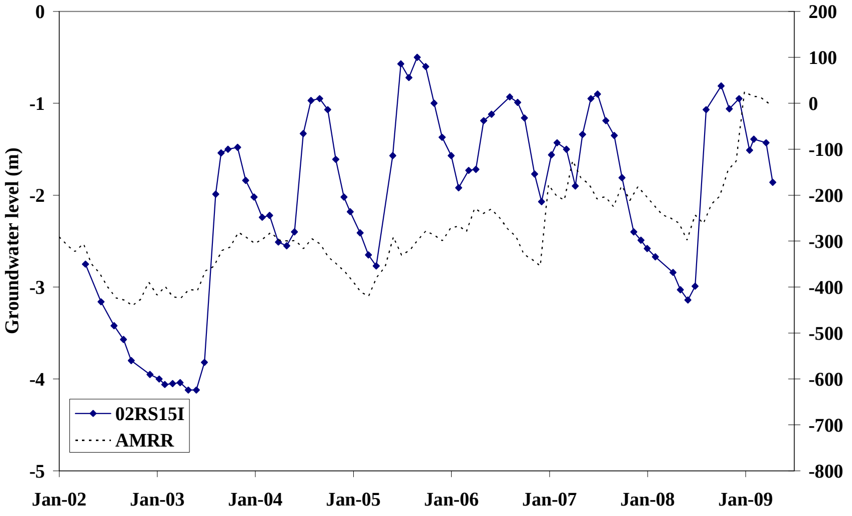

Figure E15 **Hydrograph for bore 02RS15D**

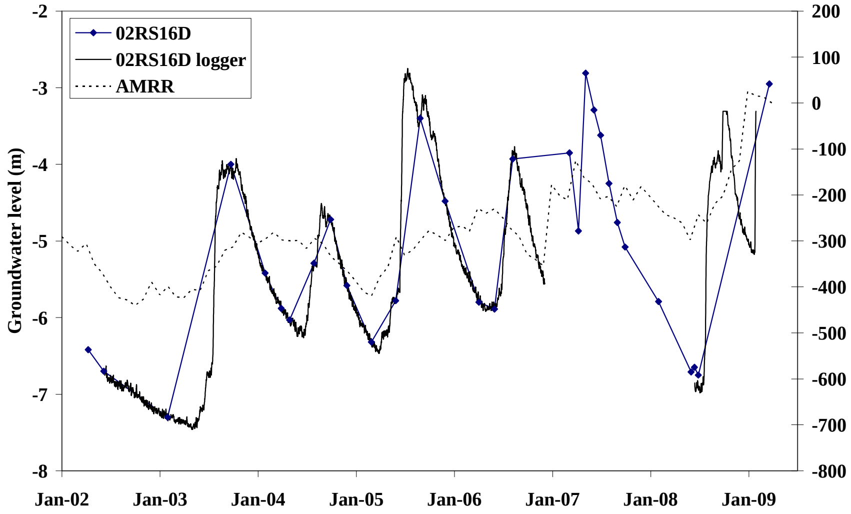

Figure E16 **Hydrograph for bore 02RS016D**

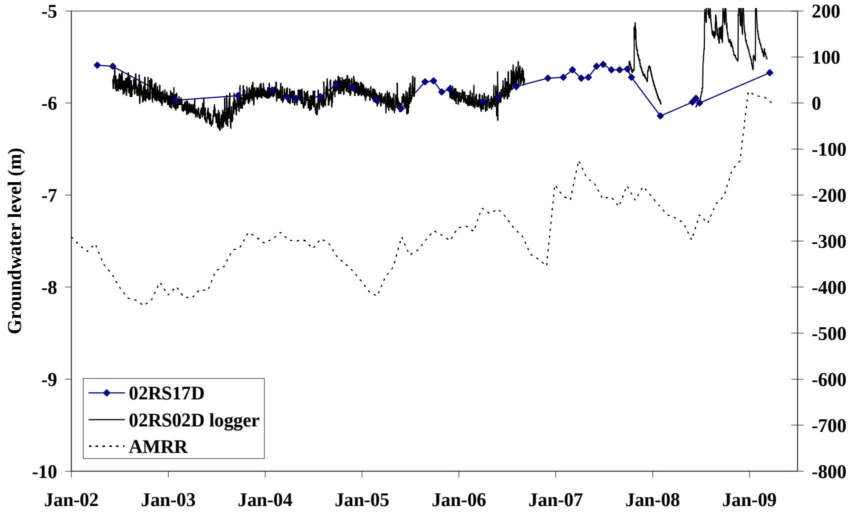

Figure E17 **Hydrograph for bore 02RS17D**

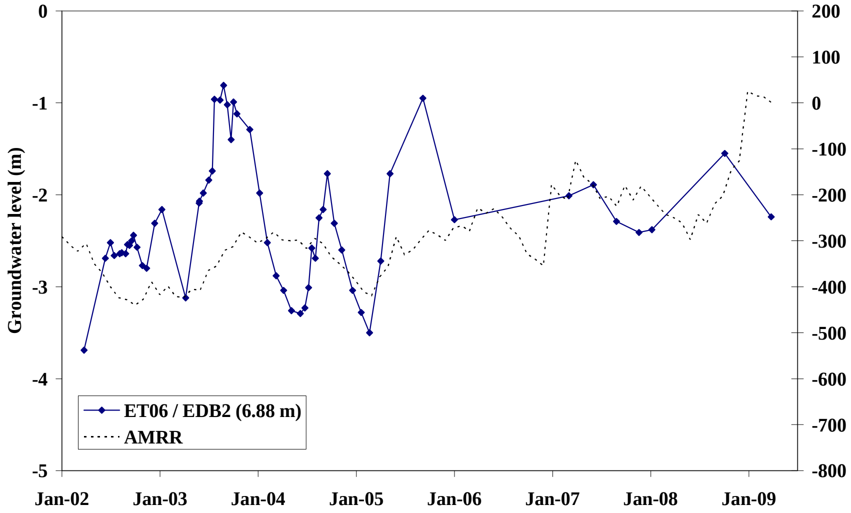

Figure E18 **Hydrograph for bore ET06/EDB2**

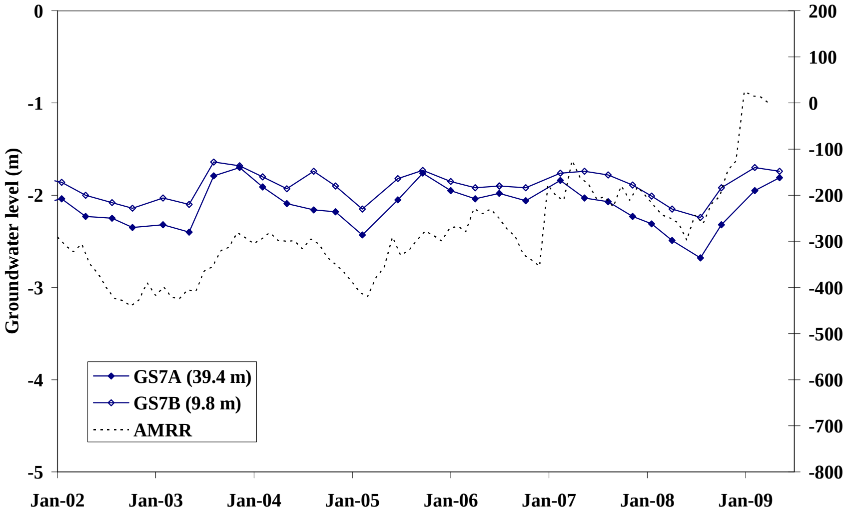

Figure E19 **Hydrographs for bore site GS7**

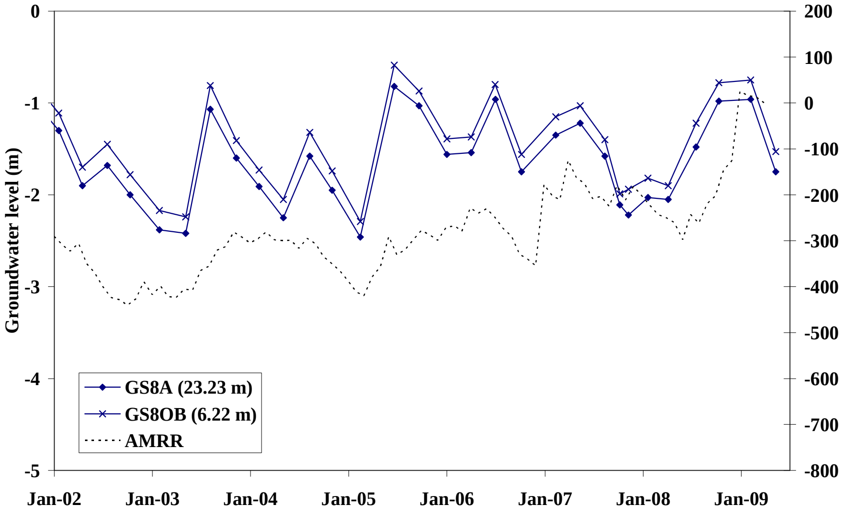

Figure E20 **Hydrographs for bore site GS8**

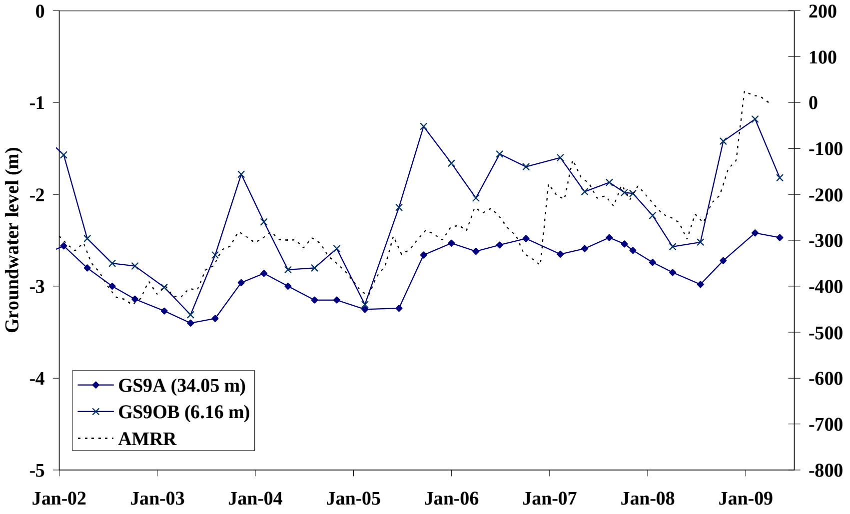

Figure E21 **Hydrographs for bore site GS9**