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Groundwater pumping to control the watertable at Tammin



Salinity and land use impacts series

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Looking after all our water needs

Groundwater pumping to control the watertable at Tammin

by
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Summary

Groundwater pumping is considered in agricultural communities as a method of controlling rising watertables that cause salinisation. Pumping to depressurise the palaeochannel aquifer to lower the watertable is thought to enhance leaching of accumulated salt from the soil to help recover saline areas for agricultural production. This study trialled such pumping.

Pumping groundwater from a semi-confined palaeochannel at Tammin was intensively studied for 16 months to work out the rate of groundwater level decline and the extent of the cone of depression. This trial at Tammin has been part of the Engineering Evaluation Initiative that attempts to test engineering solutions to lower/control the watertable in the Wheatbelt of Western Australia.

The type of aquifer that characterises the palaeochannel has an important bearing on the volume and the rate of water produced from the site. The deep aquifer in Tammin is separated from the unconfined shallow aquifer by material of relatively low conductivity. Pumping from this palaeochannel aquifer resulted in a head difference between the two aquifers and downward leakage of groundwater from the shallow to the palaeochannel aquifer lowered the watertable.

There is insufficient data to provide either a map of palaeochannels in the Wheatbelt or the types of aquifer at any given site. Because the channels are buried the best sites for production bores initially need to be identified by means such as ground geophysical surveys. The geophysical survey proved to be a reliable tool for identifying the geometry of the channel and siting successful deep groundwater bores in Tammin. The added cost of surveys, however, should be considered as part of the economic viability of similar projects in the Wheatbelt.

Pumping groundwater from the palaeochannel aquifer resulted in lowering the hydraulic head at the production bore by 22 m and 0.26 m in a monitoring bore 450 m downgradient. The width of the ellipsoidal cone of depression was restricted by the width of the palaeochannel (approx. 300 m).

Pumping resulted in watertable drawdown beneath 20 hectares (ha) of land by > 0.5 m. As the cone of depression expanded an additional 21 ha had maximum and minimum watertable drawdown of 0.5 m and 0.15 m respectively.

Groundwater modelling suggests that about 80% of the pumped water may have originated from the shallow unconfined aquifer as vertical leakage to the confined aquifer. The total volume pumped out of the system over the 14 months was 32 600 m³ (average 61 m³/d).

The episodic nature of rainfall, particularly in summer, means that large volumes of water can recharge the shallow aquifer. A water level decline of 0.5 m in most of the shallow aquifer required about four months of pumping but the water levels recovered to their pre-pumping levels after one episode of rainfall in January 2006. It then took four months for the watertable to fall to the pre-January 2006 levels.

The power to operate the pump had to be produced on-site by a generator as there was no access to the electricity grid. Many times pump failure was not detected until someone visited the site. Meanwhile, the head in the palaeochannel aquifer had recovered enough to allow the watertable to rise.

At Tammin, it cost about \$60 000 to locate the palaeochannel and to pump and lower the watertable by a minimum of 0.5 m on about 20 ha of land. The data and modelling results suggest that the head in the deep palaeochannel aquifer can be lowered enough for the shallow aquifer to start seeping into the deep aquifer. However, due to the low specific yield of the deep aquifer, small recharge events can negate the effects of pumping: the head in the deep aquifer quickly recovers to the pre-pumping levels.

1 Introduction

Pumping at this site was part of the Engineering Evaluation Initiative (EEI) Program, a \$4 million priority project under the National Action Plan for Salinity and Water Quality focused on finding and demonstrating better ways to implement engineering works to tackle salinity without further damaging the environment. Eight on-ground projects were initiated by the EEI program since it began in 2002. Groundwater pumping from a palaeochannel buried in the valley floor north of Tammin was part of an investigation of engineering options to manage valley-floor salinity in the Wheatbelt of Western Australia.

The Tammin site (Fig. 1) has a significant area, approximately 1800 (ha) hectares, of degraded agricultural land resulting from secondary salinity. The site's groundwater systems comprise two aquifer systems separated by a layer of (mainly) clay. The deeply incised channel (deep aquifer) is buried with overlying saturated sandy-clay alluvials (shallow aquifer). The aim of this study was to depressurise the deep (palaeochannel) aquifer by pumping, to create a head difference between the two aquifers and allow leakage from the shallow aquifer and so lower the watertable, and so dewater the surficial alluvials (shallow aquifer). Depressurising the deep aquifer is considered as a potential method of lowering the watertable and improving agricultural production.

Because palaeochannels are buried and meander, they are difficult and expensive to locate and define using drilling techniques alone. To reduce drilling costs an interpretation of its location and cross-sectional form were identified with five geophysical transects that adequately describe its basic geometry.

Based on geophysical surveys (gravity and Transient electromagnetic), a production bore and observation bores were established in a drilling program.. Previous investigations of these systems suggest that the water-bearing formation produces a comparatively large volume of water in sediments that generally occur in the bottom half of the palaeochannel system. These relatively coarse sediments occur in a sinuous deposit, and may influence groundwater levels over a relatively large area (Commander et al. 1994; Salama et al. 1989; George & Dogramaci 2000; Dogramaci et al. 2003; George et al. 2005)

The flow and salinity of water pumped from the production bore were monitored prior to discharge into the main waterway. CSIRO, Murdoch University and the University of Western Australia have studied the downstream impacts of discharging saline groundwater into the waterway as part of the EEI, including the effects of constant saline discharge on waterway biota (Silberstein et al. 2008)

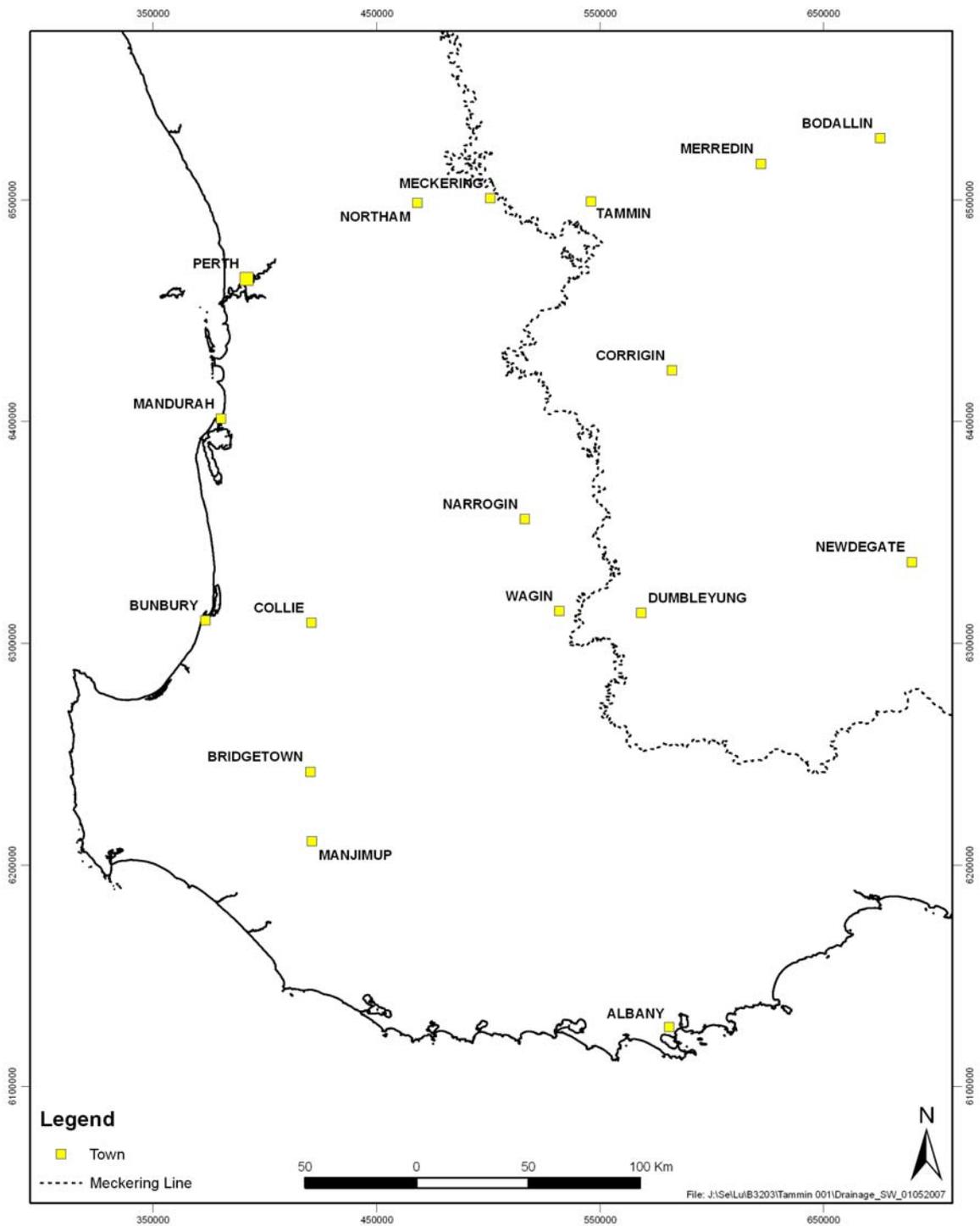


Figure 1 South-west Western Australia showing Tammin and other sites

1.1 Objectives

The objectives of this study were:

- Better understand the lateral and vertical extents of the palaeochannel aquifer.
- Define aquifer characteristics.
- Investigate the potential of lowering the watertable by depressurising the deep palaeochannel aquifer.
- Review the costs, benefits and the practicality of such pumping to recover agricultural land.

1.2 Land salinisation

Large-scale clearing has changed the hydrological balance in the Wheatbelt, with most drainage lines developing secondary salinisation.

The first areas cleared were the broad valley floors with red-brown loamy soils supporting salmon gum and gimlet forests. These naturally fertile soils adjacent to the (natural) primary salinity in the drainage lines and the salt lakes were first and worst affected by the development of secondary salinity. The most severe land salinisation occurs where groundwater discharges into the alluvial sediments of the palaeodrainage channels (Williamson et al. 2001).

Generally, the saline watertable under these areas is within two metres of the natural surface. Discharge of shallow groundwater during rainfall events in winter and through capillary action in summer results in salinisation of the soil and the discharge areas. In addition, the upward leakage from the deep very saline palaeochannel aquifer to the shallow aquifer exacerbates the problem and results in further rise of the shallow watertable. This occurs when the head in the deep aquifer is higher than the watertable in the shallow aquifer.

1.3 Testing the hypothesis

Groundwater pumping has been widely considered among agricultural communities as a method of controlling rising watertables. The hypothesis is that, by pumping from a palaeochannel aquifer, the shallow overlying aquifer can be depressurised and lower the watertable. The drop in watertable may enhance leaching of accumulated salt from the soil and help recover these saline areas for agricultural production.

1.4 Previous work

Groundwater pumping (artificial discharge) is widely used in Australia to lower watertables; for example, the ongoing large-scale groundwater interception schemes at Woolpunda and Waikerie in South Australia pump out thousands of tonnes of saline groundwater each year to prevent it seeping into the Murray River (SA Water 2006).

Many smaller-scale pumping schemes across Western Australia's Wheatbelt operate already to prevent or manage salinisation of agricultural land and infrastructure. An example is the Toolibin Lake groundwater pumping scheme in Western Australia to prevent further salinisation of the lake and degradation of the lake's ecology (George & Dogramaci 2000; Dogramaci et al. 2003; Dogramaci 2004 a, b; George et al. 2005).

The technical feasibility of pumping to lower the watertable in defined hydrogeological settings is well demonstrated but there are problems when the hydrogeology of the landscape, due to the complexity of aquifer hydraulics, is poorly understood.

The results of the few previous investigations of such systems cannot be extrapolated to this site because of the complexity of the settings of buried palaeochannels within the weathered-granite aquifers; the asymmetry of the aquifer materials; and the hydraulic property differences between the weathered granite material and the embedding palaeochannel sediments.

Although palaeochannel systems have been studied in detail in central Australia (Van de Graaff et al. 1977; Jacobson & Jankowski 1989) there have been very few studies into the depth, geometry and hydrogeological characteristics of such systems in the Wheatbelt (Commander et al. 1994; Salama 1997; Kalaitzis et al. 2002).

It has been widely speculated that groundwater in palaeochannels is easily removed by pumping but few studies have focused on the viability of such pumping in the Wheatbelt and the results are contradictory.

- A scheme on the Salt River system suggested that the palaeochannel had a transmissivity of 110 m²/d and is connected to the surficial aquifers (Salama et al. 1989). Salama speculated that the production bore had a lateral impact of one kilometre downgradient.
- The production bores in Toolibin Lake have a smaller lateral impact: around 300–500 m (Dogramaci 2000; George & Dogramaci 2000). The transmissivity of the Toolibin palaeochannel aquifer is 10 m²/d.

A key difference between these systems is that the Toolibin palaeochannel has a semi-confined aquifer and is not well connected to surficial sediments. The difference in the hydrological setting of these aquifers has a profound impact on the recovery of saline land.

1.5 Palaeochannel aquifers in the Wheatbelt

The hydrogeology of the Wheatbelt agricultural areas falls into two broad groups:

- thin surficial sediments and narrow palaeochannel in broad flat valleys
- weathered basement rock in the gently sloping hill slopes, also known as saprolite aquifers.

The broad flat valleys of the Wheatbelt may have buried palaeochannels where ancient rivers flowed. Some broad valley floors of the Wheatbelt have relict drainage systems filled

with alluvial, colluvial and aeolian sediments of variable mineralogy and particle size. These relatively deeply incised palaeochannels are also filled with sediments. They are thought to have developed during the late Cretaceous or Tertiary period (van de Graaff et al. 1977) flowing westward into the Indian Ocean (Beard 1998).

By the Late Miocene–Early Pliocene there appears to have been substantial modification of the Eocene drainage pattern by uplift along the Darling Range, with dissection of lateritised bedrock and Eocene sediments. The Meckering Line marks the eastern extent of this rejuvenation, west of which current river valleys are generally youthful and incised (Mulcahy & Bettenay 1972). This line of rejuvenation also partly coincides with the South West Seismic Zone (Beard 1998). Unlike the Eocene drainage, river systems in the Pliocene may have been able to cut more easily through deeply weathered crystalline bedrock (saprolite).

The uplift of the Darling Range, consequent gradient changes and damming have filled these drainage systems with transported sediments. The uplift also reversed the drainage pattern resulting in internal drainage and the development of salt lakes.

The valley sediments fall into two broad types (Fig. 2). They include thick (up to 70 m) Eocene, and Pliocene alluvial or lacustrine palaeochannel sediments, which occur in deeply incised narrow palaeochannels in the centres of the valleys, and the thinner (up to 20 m) Quaternary colluvial, alluvial and lacustrine (salt lake) sediments which cover the full width of the valleys (Commander et al. 2002).

Palaeochannel sedimentary profiles are well preserved east of the Meckering Line where the modern drainage system is not well defined. However, west of the Meckering Line, the profiles are dissected into the rejuvenated drainage lines of the modern rivers such as the Avon–Mortlock, Blackwood, Frankland and Kent. Modern rivers have been able to erode these sedimentary profiles through the Meckering Line towards the Darling Scarp in the east.

Most palaeochannels have a common pattern of sediment deposition: alluvial sands and gravel at the base with lignitic beds trending upwards into lacustrine clays and finally into modern alluvial and aeolian (wind-blown) sands and clays (Dogramaci 2000; George & Dogramaci, 2000; Dogramaci et al. 2003). The alluvial sands and gravel at the base form the major groundwater aquifer of the palaeochannel sedimentary profile (Fig. 3). The lacustrine clay layer forms the confining layer for the sand/gravel aquifer. In places, where Quaternary sands and clay were deposited, these sediments form the surficial aquifer.

There can be three broad categories of groundwater systems depending on the degree of preservation of the sedimentary profile in valleys. With greater relief, sedimentary profiles west of the Meckering Line may be thinner than east of the Line and so, from a hydrogeological point of view, groundwater systems from east to west may change from multi-aquifer environments to unconfined groundwater systems.

- Multi-aquifer environments consist of a surficial aquifer, a confining clay layer and a main palaeochannel aquifer. An example is the Dumbleyung palaeochannel, west of Dumbleyung (Dogramaci 2006).

- Confined aquifer environments consist of a confining clay layer and the main palaeochannel aquifer such as Toolibin palaeochannel. At Lake Toolibin, a thick plastic clay layer about 10 m deep confines the palaeochannel aquifer (De Silva 1999; Dogramaci 1999).
- Unconfined aquifer systems consist of a sandy clay aquifer open to the atmosphere. An example is the Salt River sediments found by Salama (Salama et al. 1989).

The sedimentary profiles may change, the confining clay layer may be eroded and expose the underlying sand aquifer along the drainage line which in most cases results in the discharge of saline groundwater into waterways and surface water bodies. In the upper Kent catchment, the Pallinup Siltstone, at elevations above 230 m AHD, confines the palaeochannel. However, where the Kent River dissects the sedimentary sequence below 230 m AHD, the palaeochannel aquifer becomes unconfined and starts discharging saline groundwater into the Kent River (De Silva et al. 2007). Similar discharges also occur in the adjoining two catchments (Gordon–Frankland and Warren–Unicup). In some places, the discharged groundwater forms lakes such as Lake Nunijup and pools along the drainage line in the upper Kent catchment (Bari & De Silva in press).

Managing the land above saline groundwater of the palaeochannel aquifers depends on being able to lower the watertable and/or head of the confined aquifer by pumping and to stop the groundwater discharge. Lowering the watertable in unconfined aquifers is rather slow. Since the release of water from groundwater storage is mostly due to dewatering the zone through which the water is moving, the watertable decline is measurable only relatively close to the pumped bores. The fall of the watertable in unconfined aquifers is much slower than the fall of the hydraulic head in confined aquifers.

Pumping from confined aquifers leads to a reduction in hydraulic head. The loss caused by pumping propagates quickly and the loss of head may still be measurable a few hundred metres from the bore if the lithology is very permeable and with large pumping rates. The important characteristic of confined aquifers is the relatively fast recovery of the hydraulic head once pumping stops. However, the more extensive the drawdown in hydraulic head, the greater the confinement, which means very little vertical leakage from the overlying shallow aquifer will occur.

Enhanced drainage in the unconfined part of the aquifer can also lead to reduced groundwater pressures in the confined part of the aquifer. Effective management of multi-aquifer groundwater systems may need pumping from both superficial and deep palaeochannel aquifers.

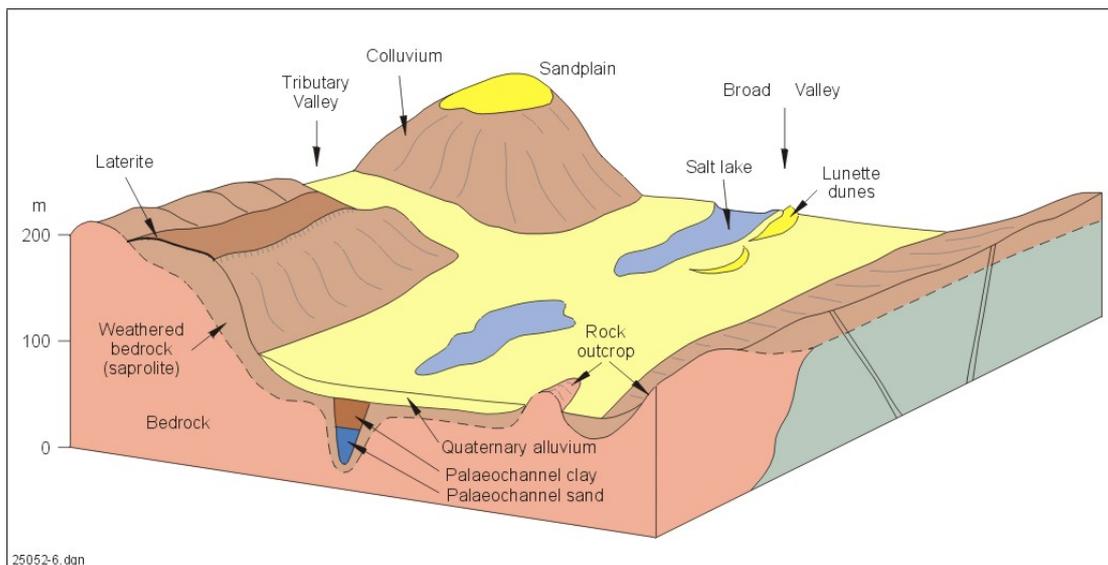


Figure 2 Block diagram showing schematic geology of a Wheatbelt valley (after Commander et al. 2002). Note how little of the valley floor is occupied by the palaeochannel.

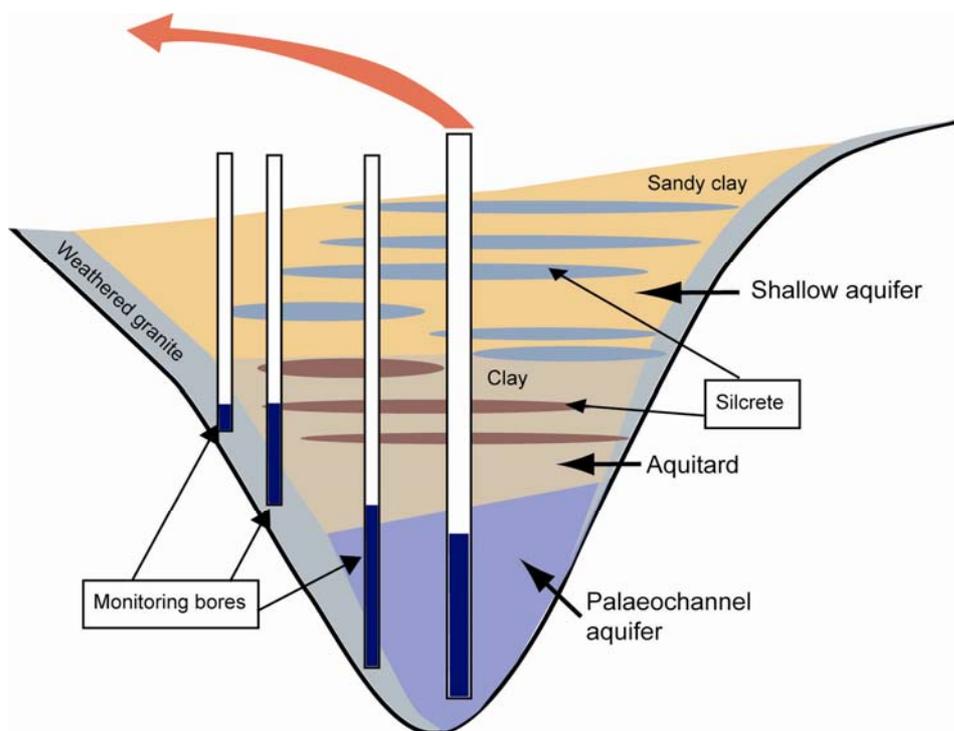


Figure 3 Conceptual diagram showing the confined palaeochannel aquifer and the production and monitoring bores at Tammin

2 Site characteristics

2.1 Study area

The Tammin area was first settled in the 1890s for agriculture. The land is mainly used for growing annual crops and grazing sheep and cattle. The Tammin town site is 184 km east of Perth on the Great Eastern Highway, and between Cunderdin and Kellerberrin (Fig. 4). The study area is approximately 3 km north-west of the Tammin town site.

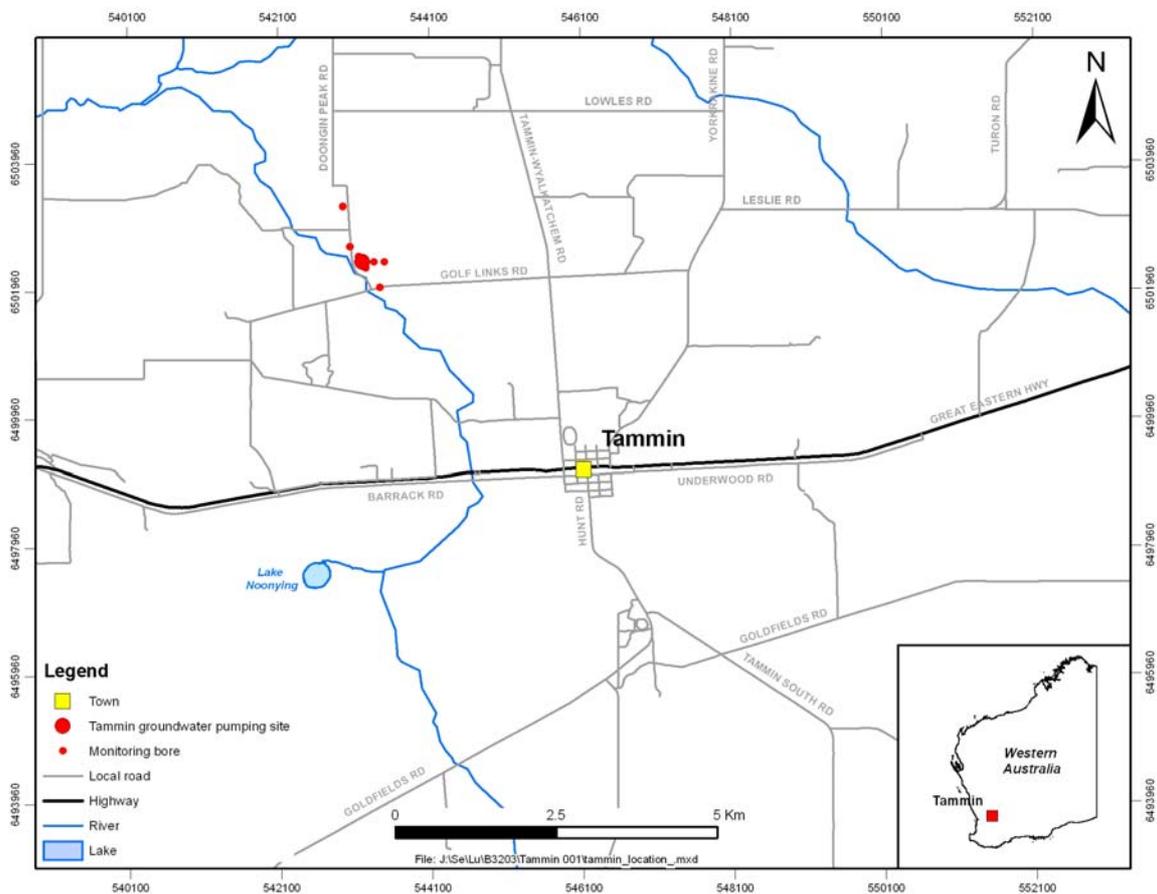


Figure 4 Study area

2.2 Climate

The site has a Mediterranean-type climate with warm to hot summers and mild, moderately wet winters. More than two thirds (73%) of the annual rainfall falls in winter (May–September) (Bureau of Meteorology 2005). Rainfall during summer is generally very localised with heavy thunderstorms delivering much more rain in some areas than in others, whereas rainfall over the winter season affects larger areas.

Rainfall during summer (October–May) is generally tropical in origin moving from north–north-west towards the south and south-east. Some of the differences in groundwater levels may result from local differences in the amount or intensity of rainfall. Figure 5 shows the rainfall pattern in 2004–06 during which the Tammin project was carried out.

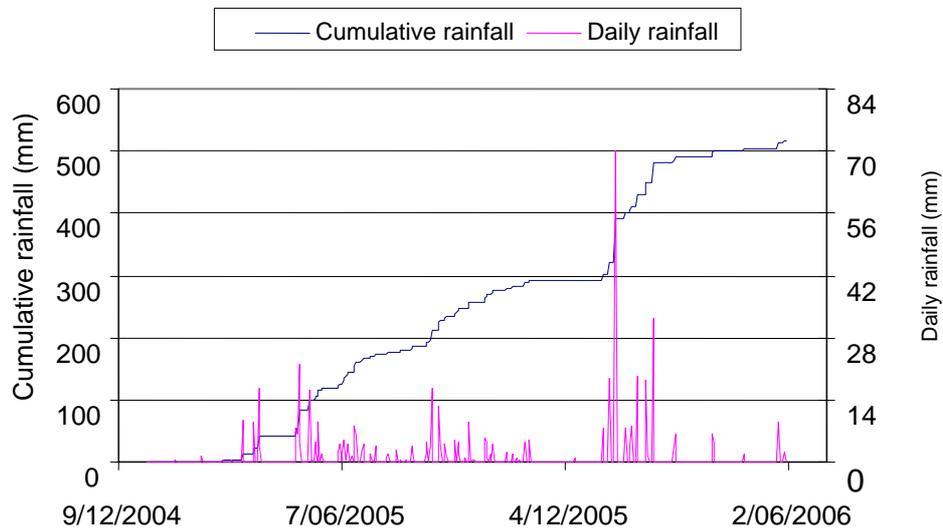


Figure 5 Annual and cumulative rainfall for 2004–06 at the Tammin site

The record shows that the rainfall totals for 2004, 2005 and 2006 are 248, 293 and 222 mm respectively and are below the average of 342 mm. The plot of cumulative rainfall from December 2004 to June 2006 shows little rain at the site during the summers, except for a significant summer (71 mm) storm event on 31 January 2006. This storm event was followed by four minor rain events of 20–32 mm. A total of 197 mm rainfall was recorded — 60% of the 2006 annual rainfall.

The average annual rainfall, based on 95 years of record (1911–2006) is 342 mm. Annual rainfalls for Tammin from 1912 to 2006 range from 141.2 to 606 mm with a mean of 306 mm (Fig. 6a). Figure 6b shows the differences between annual and the long-term average (mean) rainfalls.

The cumulative differences between annual and long-term mean rainfalls (Fig. 6c) illustrate how these annual departures from the mean can have cumulative effects on groundwater levels. For example, after a series of years with lower than average rainfall, groundwater levels may be lower. Figure 6c illustrates how the differences between annual rainfall and the average rainfall, accumulated from one year to the next, produce trends of ‘excess’ or ‘deficit’ rainfall or ‘wetter’ and ‘drier’ periods. ‘Deficit’ rainfall early in the period 1911 to about 1918, and 1952–62 produced cumulative ‘deficits’ of rainfall (bars below the zero line) whereas higher-than-average annual rainfall after 1918, 1962 and 1992 produced ‘excesses’ (bars above the zero line).

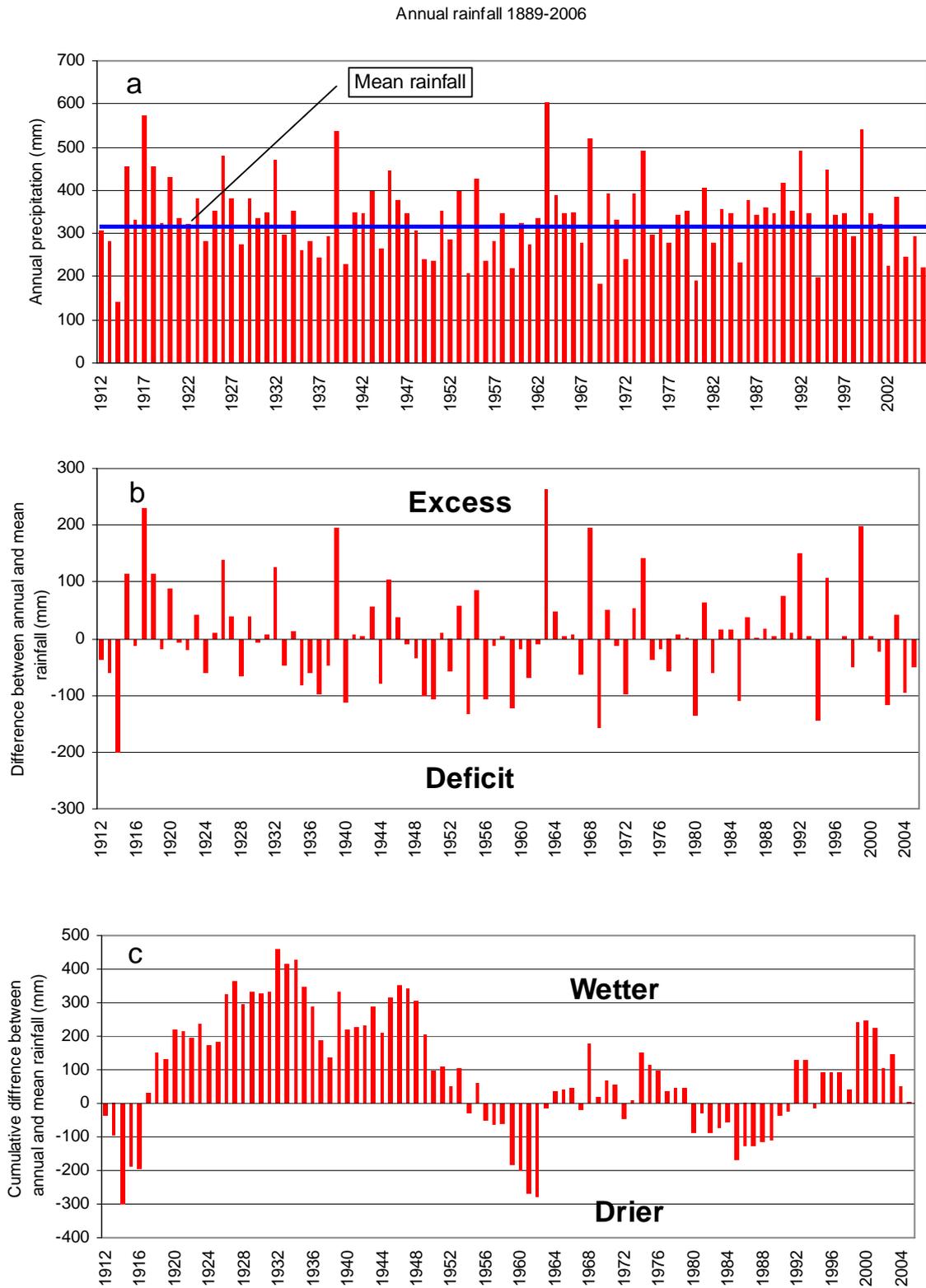


Figure 6 (a) Annual rainfall at the Tammin site (b) the difference between annual and mean rainfall (c) the cumulative differences between annual and mean rainfall

2.3 Topography and drainage

The Tammin site falls within the broad physiographic unit of the Darling Plateau at an elevation of 230 m AHD. The broad, flat valley that passes through the site is a part of the Swan–Avon palaeodrainage (Chin 1986). The Mortlock River East and its tributaries form the modern drainage system. The Meckering Line crosses the east-west-flowing Mortlock River East at 200 m. There is about 30 m elevation difference between the palaeodrainage at the Tammin site and the modern rejuvenated drainage. Doongin Peak is the highest point (288 m AHD).

2.4 Geology

Chin (1986) mapped the surficial geology of the area as *Cza* (alluvium — silt and sand in broad valley flats) and *Qc* (colluvium — silt, sand and gravel derived from underlying and adjacent laterite and bedrock). Granitic basement rock, *Agv*, Seriate adamellite is exposed on hilltops such as Doongin Peak.

Some of the Cainozoic geology common to the Darling Plateau (Chin 1986):

- An undulating sand plain (now largely eroded) overlies Tertiary duricrust consisting of massive and nodular laterite.
- Silcrete occurs in the lower part of the ferricrete layer, above the kaolinised zone over granitoid rocks. As the laterite erodes, the silcrete horizon breaks down to form a secondary residual deposit of silcrete boulders.
- Playa lakes and their sediments occur in many valleys. Evaporation leads to the concentration of brine within the sediments precipitating gypsum.
- Stabilised dunes of quartzose and gypsiferous sand (*Qd*) occur on the eastern and south-eastern sides of playa lakes.

2.5 Hydrogeology

The regional geological map indicates the presence of an extensive north-south trending sedimentary system where the waterway occurs at the Tammin project site. The site was investigated by CSIRO with a drilling program in 2002 to better understand the local hydrogeology (Richard Silberstein pers. comm. 2007). Three sets of nested piezometers (2.5, 8 and 47 m deep) and nine bores of various depths were installed (Fig. 7; Table 1).

The interpretation of the drilling logs suggests the existence of a deep sedimentary sequence more than 1500 m wide and 50 m deep along the main waterway. The thickness of the palaeochannel decreases towards the flanks of the valley (Fig. 3). The southern limb of this system appears to pass close to the Tammin town site. Saturated duricrust and surficial alluvials overlie the buried valley aquifer. The geological map, KELLERBERRIN, indicates that surficial deposits overlying the sand aquifer are quite extensive and extend beyond Tammin site to the south (Chin 1986). The surficial deposits extend in an east-west direction beyond Meckering town site to the west.

Table 1 Location and depth of the existing bores at Tammin

Well ID	Type	X location	Y location	Depth (m)	Screen length (m)	Water level below top (3/10/2002) (m)
TY01D	Deep	542577	6503952	47.40	3.00	2.18
TY01M	Medium	542577	6503952	9.00	3.00	2.65
TY01S	Shallow	542577	6503952	2.80	2.50	2.09
TY02D	Deep	543076	6503865	47.56	3.00	2.81
TY02M	Medium	543076	6503865	8.29	3.00	3.00
TY02S	Shallow	543076	6503865	2.65	2.00	2.79
TY03D	Deep	542805	6502923	47.75	3.00	3.39
TY03S	Shallow	542805	6502923	3.00	2.00	
TY04D	Deep	544012	6503912	14.00	3.00	7.78
TY05M	Medium	543701	6502827	4.80	3.00	4.12
TY06M	Medium	542309	6504777	7.80	3.00	1.90
TY06S	Shallow	542309	6504777	2.80	2.00	
TY07M	Medium	542083	6503990	8.54	3.00	1.87
TY07S	Shallow	542083	6503990	2.83	2.00	
TY08M	Medium	543336	6503844	8.90	3.00	2.38
TY09M	Medium	543203	6504375	7.50	3.00	2.92
TY09S	Shallow	543203	6504375	2.70	2.50	2.06

Based on the identical responses of the deep and shallow bores to rainfall events (Fig. 8), a high degree of hydraulic connectivity between the deep sediment aquifer and the saturated surficial alluvials was inferred. The deep sediments are assumed to have moderate hydraulic conductivity (preliminary modelling based on a value of 2 m/d), whilst the sandy-clay materials of the surficial alluvials are assumed to have limited conductivity (upper limit likely to be no greater than 0.5 m/d).

The identical responses of the watertable in the nested piezometers to the rainfall events despite the marked difference in hydraulic conductivity suggest well-connected aquifers in this part of the Tammin project site.

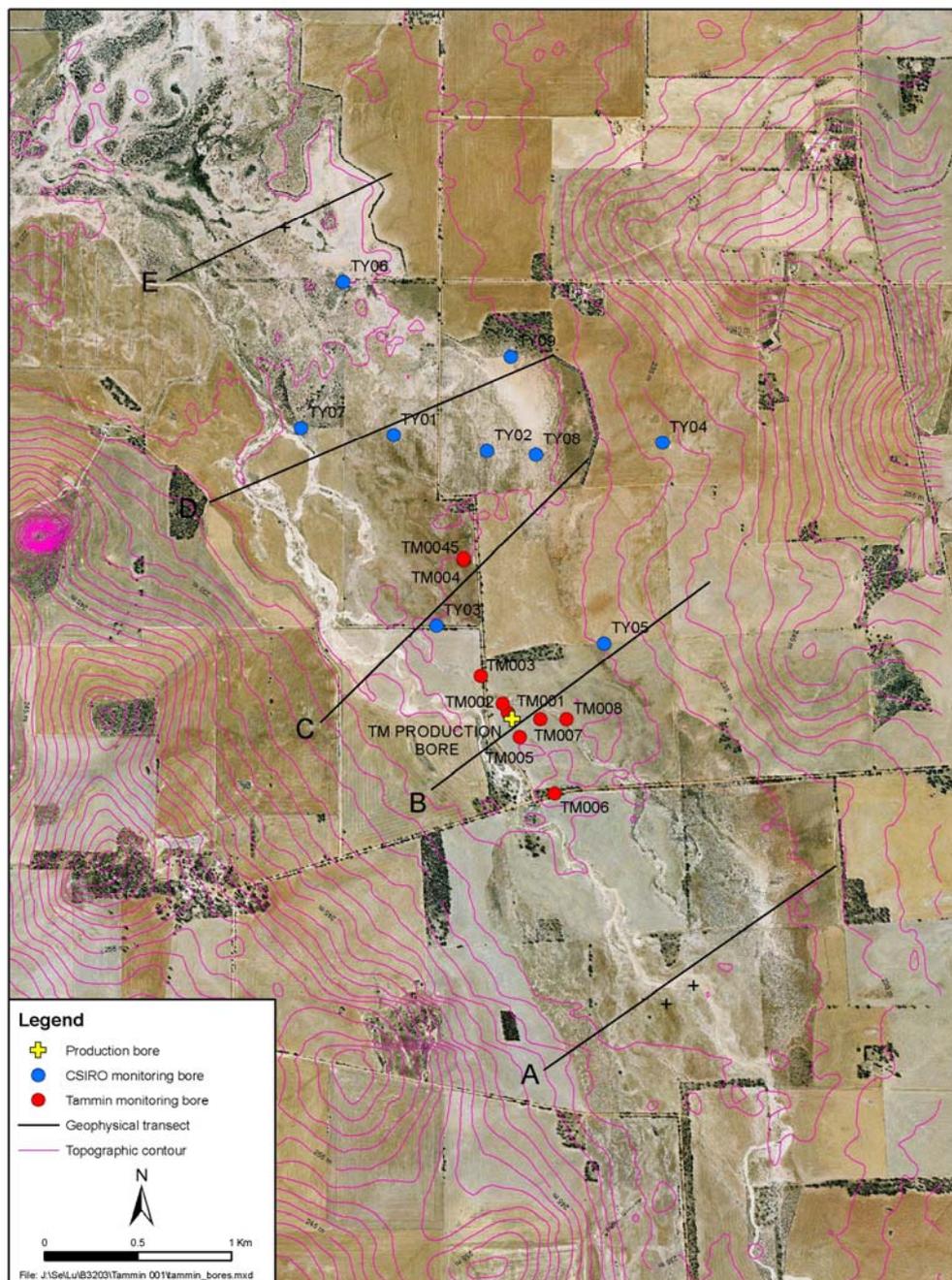


Figure 7 Site location map showing the main drainage line and five geophysical transects

2.6 Groundwater discharge

Groundwater discharge from the shallow aquifer to the waterways during winter and through evaporation and capillary rise during summer currently affects about 1800 ha. The lower-lying area to the north of the pumping site may suggest the thinning of the aquitard by erosion, which makes the site more vulnerable to saline discharge from the underlying sand aquifer. At an elevation of 220 m AHD, the aquitard might be thinner than the approx. 10-m thick aquitard logged at the upgradient production bore. The extensive saline seepage and the salt lakes downgradient suggest higher rates of seepage than at the pumping site. The

thinning of the aquitard was also observed in the drilling profiles in the Salt River system in the adjoining catchment.

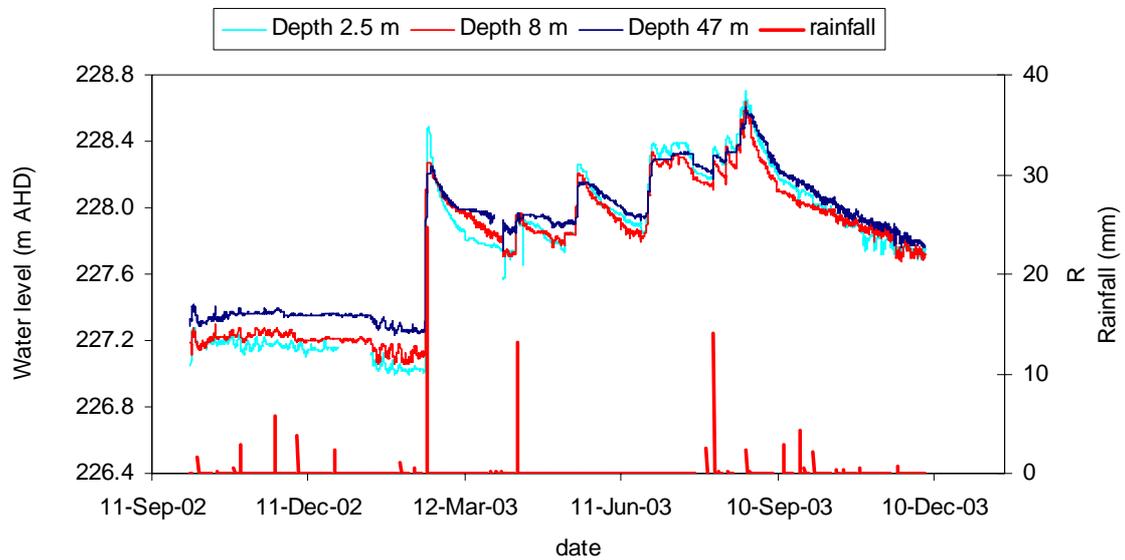


Figure 8 The watertable variation in the three nested bores in Tammin (CSIRO data)

At elevations below 220 m AHD the broad valley floor is salt affected. So the exposure of the sand aquifer may also play an important role in the development of salinity in the lower parts of the main drainage system in Tammin (Photo 1).



Photo 1 Groundwater discharge from the Tammin palaeochannel aquifer, downgradient of the pumping site

3 Methodology

3.1 Geophysical survey

Five transects perpendicular to the main waterway were selected for the geophysical survey. Gravity stations were established on lines A, B, C, D and E at 25 m intervals (Fig. 7). The survey lines were 1.25–2 km. The Scintrex CG3 gravity meter used for this work is capable of 0.01 mgal resolution, does automatic tidal corrections and stores the gravity data digitally for download to a portable computer at the end of each day. Two 60 second gravity measurements were made at each station.

The elevations of the transects were measured to millimetre accuracy by optical levelling. The horizontal coordinates were recorded from handheld GPS measurements using Garmin GPS units. The stations were laid out by tape measure on predetermined lines. Required heights to better than 5 cm accuracy and horizontal positions to better than 10 m to provide 0.01 mgal bouguer gravity data were both easily achieved. The likely repeatability of the GPS horizontal position measurements was within ± 5 m.

Transient electromagnetic (TEM) data were acquired on the same transects with 50-m transmitter loops and 50-m station spacing. The Zonge equipment used for this work — an NT 20 transmitter which produces about 9 amps, a TEM 3 vertical receiver antenna, positioned at the centre of each loop, and a GDP 32 electronics receiver — provides 32 channels of information after current switch-off. Each measurement stacks the data for approximately 3 minutes to ensure low-noise results.

The detailed description of the survey in Tammin is documented by Wilkes et al. (2005). The gravity method relies on density contrasts between the sediments within buried valleys and the surrounding regolith and bedrock (Reynolds 1997; Tracey & Dirreen 2002). The TEM method is used to detect the distribution of electrical conductivity beneath the surface. Because the groundwater is saline to hypersaline compared with the surrounding less saline basement rock and/or saprolite below, the buried valleys may be highly conductive. In some circumstances, weathered basement can also be electrically conductive complicating the data interpretation. When the basement rock and the palaeochannel sediments have similar electrical conductivities this method is not useful in delineating the palaeochannel sediments.

The gravity method is useful because the formations of interest, for example, palaeochannel sediments, have densities appreciably different from those of surrounding weathered granites.

3.2 Geophysical interpretation of the buried palaeochannel

There is a south-east–north-west trending in-filled valley system parallel to the main drainage and with a maximum basement depth of about 50–65 m below the surface in Tammin. The valley system is offset by 200 m to the north of the main drainage line. The geometry of the valley ranges from relatively narrow (approximately 250 m wide) at transect B to broader and

shallower 1000 m downstream at transect E. Neither the existing surface drainage nor the saline land correlates with the identified buried valley. The production bore is installed at the deepest part in transect B (Fig. 9).

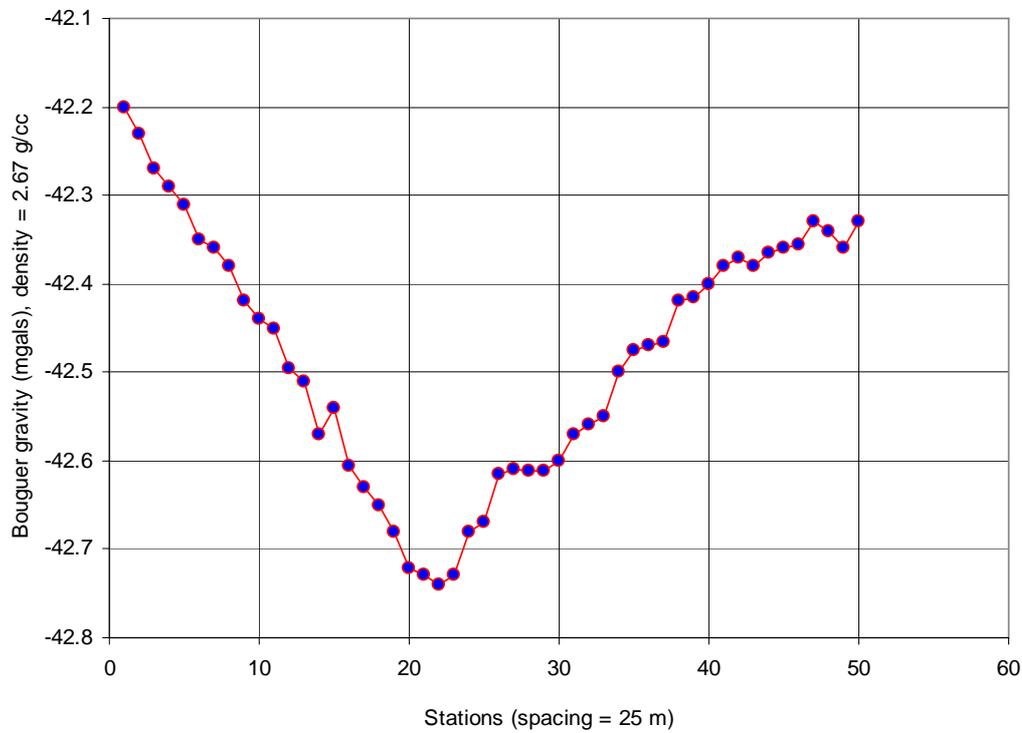


Figure 9 The gravity data for the transect B (the production bore is located at deepest part)

3.3 Drilling and bore construction

The drilling program included installing a production bore to bedrock and six nested piezometers along the 1000 m NW–SE-trending palaeochannel (Table 2). The water levels in the shallow nested bores were consistently higher than in the deep bores except for TM003 (2). The medium bores were located on a transect perpendicular to the palaeochannel system to monitor the effects of pumping on the weathered granite aquifer. The drill cuttings were logged in 1-m intervals. The drilling logs showed a generally sandy profile below 16 m from the surface. The 11-m thick aquitard comprised mainly clay and multiple silcrete layers that crushed to angular sand with drilling. The top five metres had clay with minor fine sand within the body of the clay material. To ensure that the nested bores were separated and represented the deep and shallow aquifers on the site, the deep bores were gravel packed up to 5 m below ground and then sealed using concrete, and the shallow and intermediate bores were gravel packed to 1 m below the surface and sealed using concrete.

Table 2 The location and depth of the production and nested piezometers in Tammin

Bore ID	Bore type	Distance from production bore (m)	X location	Y location	Bore depth (m)	Screen (m)	Depth to head/WT (m)
TM001PROD	Deep	Production bore	543210	6502414	54	12	1.06
TM001S	Shallow	50	543187	6502452	5	3	1.72
TM001D	Deep	50	543187	6502452	51	12	1.85
TM002S	Shallow	100	543160	6502499	5	3	1.18
TM002D	Deep	100	543160	6502499	51	12	1.34
TM003S	Shallow	300	543043	6502650	5	3	1.80
TM003D	Deep	300	543043	6502650	48	12	1.76
TM004S	Shallow	900	542952	6503286	5	3	1.71
TM004D	Deep	900	542951	6503277	48	12	1.84
TM005S	Shallow	105	543251	6502317	5	3	1.62
TM005D	Deep	105	543251	6502317	50	12	1.74
TM006S	Shallow	450	543437	6502015	5	3	1.88
TM006D	Deep	450	543437	6502015	49	12	1.89
TM007	Medium	150	543360	6502414	15	3	1.42
TM008	Medium	300	543500	6502414	15	3	1.89

3.4 Pump operation and pumping test

The production bore was equipped with a centrifugal pump operating on a 2-megawatt diesel generator and with 150 m³/d capacity. The pump discharge was logged for conductivity and flow. The pumping rate ranged from 130 to 50 m³/d. The variation in the rate in the early stages was due to the system shutting down when the pumping rate exceeded 130 m³/d and the pressure head fell below the pump level. The production bore was later installed with an automatic sensor that switched off the pump when the water level fell below the 35-m pump installation depth.

Watertable responses to pumping depend on the hydraulic properties of the aquifer. An eight-hour pumping test was designed to calculate the transmissivity and storage coefficient of the palaeochannel aquifer as the hydraulic parameters are essential to calculate the lateral impacts of the pumping scheme. The production bore was pumped at an average rate of 100 m³/d for 8 hours: the total volume produced was 43 m³ and the maximum drawdown was 44.5 m. The pressure responses during pumping and for two hours recovery after pumping stopped were monitored in bores TM002D (54 m deep) and TM002s (6 m deep).

3.5 Groundwater monitoring and disposal

Groundwater levels were measured using data loggers and manual fortnightly readings. Pumping rates, electrical conductivity (EC) and temperature of discharging water were monitored at 15–20 minute intervals. Water samples were collected for full chemical analysis.

The saline groundwater was discharged into the creek line 400 m west of the production bore (Photo 2).



Photo 2 The flow meter measuring groundwater discharge from the production bore to the creek line

4 Results

4.1 Pumping test analysis (short-term)

The most reliable and commonly used method of working out aquifer characteristics is controlled aquifer pumping tests. Groundwater flow varies depending on the hydraulic properties of the aquifers and the boundary conditions imposed on the groundwater system. Pumping tests provide results more representative of aquifer characteristics than results from slug or bailer tests. Aquifer characteristics obtainable from pumping tests include hydraulic conductivity (K), transmissivity (T), specific yield (Sy) for unconfined aquifers, and storage coefficient (S) for confined aquifers. These parameters can be worked out by graphical solutions and computer programs. The method selected to find the hydraulic properties of an aquifer depends largely on the hydrogeological conditions at the test site. The method involves several assumptions:

1. The aquifer is homogenous, isotropic and of infinite extent.
2. The production bore fully penetrates the aquifer.
3. The transmissivity is constant with time.
4. The discharge from the production bore is constant throughout the pumping test.
5. The flow to the aquifer is laminar.

The hydraulic parameters were calculated by analysing the results of eight hours of pumping and then recovery. Step-test analysis was used to work out the pumping capacity of the bore and the capacity of the submersible pump. Drawdown data from the first five weeks of continuous pumping after pump installation was analysed to confirm that the initial results from the 8-hour pumping test accurately represented the aquifer characteristics. The hydraulic parameters then were used to calculate the lateral impacts of pumping and to estimate the potential area of watertable fall around the production bore. The measured heads and water levels in the monitoring and production bores are shown in Figure 10.

The hydraulic head in the production bore was lowered by 41 m and then stabilised. The head in the deep monitoring bore (55 m downgradient) was lowered by ~ 1 m but the water level in the shallow bore did not respond to the pumping, which may suggest that the shallow aquifer is not well connected to the deep aquifer at this site.

The narrow cone of depression interpreted from the pumping data also suggests that the deep palaeochannel aquifer is confined or semi-confined.

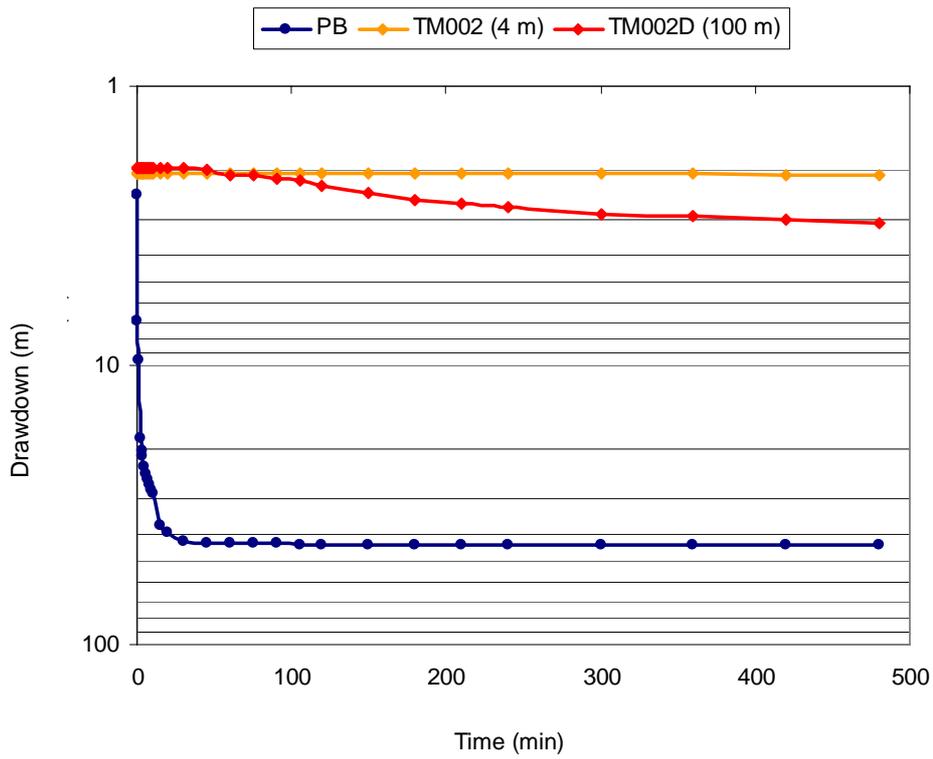


Figure 10 The pressure heads and water levels in the production bore (PB)(blue) and deep (red) and shallow (brown) monitoring bores 55 m from PB

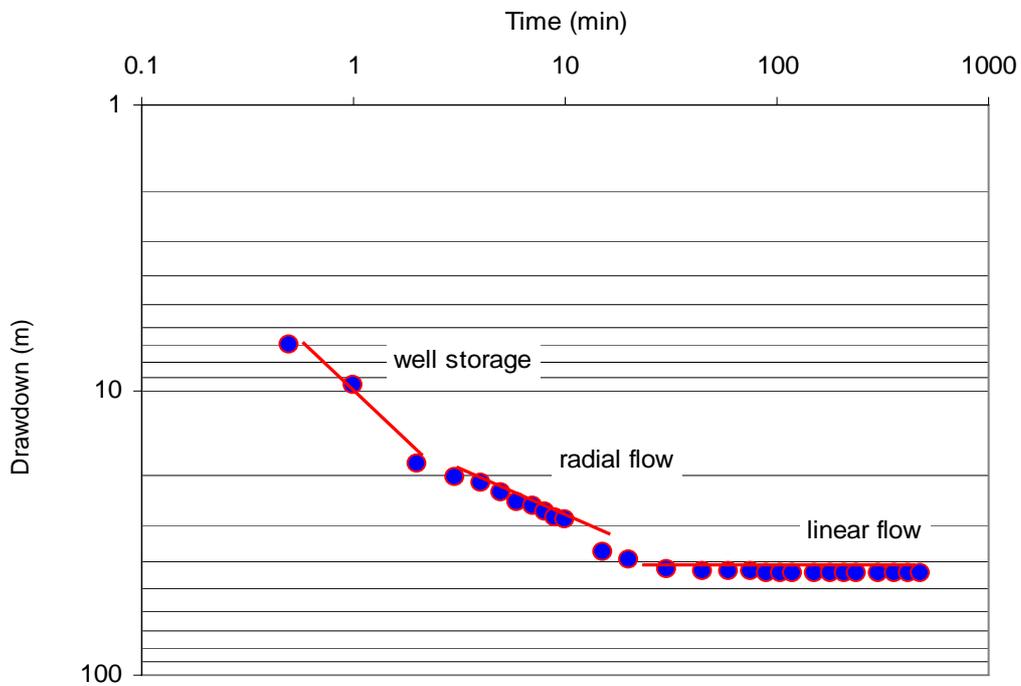


Figure 11 Log-log drawdown time curve for the production bore

The interpretation of the log–log diagnostic plot of drawdown versus pumping time (Fig. 11) shows several different flow regimes for the production bore. The effects of bore storage and well efficiency dominated the very early time response (up to about 5 minutes). Then there appears to be a step with relatively unstable periods of 5 to 15 min. This step is inferred to result from the presence of multiple layers with different hydraulic heads. Finally, later (from about 50 to 480 min), the curve is flat which is indicative of linear flow into the production bore.

The calculation of hydraulic properties from the production bore data is problematic because of the changes in drawdown during pumping. T and S should be calculated from the first part of the time–drawdown curve. Generally, the value of the drawdown for the later part of the curve represents an anomaly distant from the pumping site and does not represent aquifer hydraulic properties. One reason for the flatness of the curve may be a thickness change in one direction of the aquifer which results in an abundance of water to be removed and not a change in the aquifer hydraulic properties. This represents a geological anomaly within the radius of influence. Another reason for the flatness of the slope is the existence of a layer with higher conductivity within the zone of influence. However, in this case and due to the limited nature of the aquifer (250 m wide), the later part of the curve represents leakage from the aquifer into the bore.

The Theis (1963) and Jacob (Cooper & Jacob 1946; Jacob 1950) methods of analysis were selected because the time–drawdown graph (the plot of the drawdown of the water level or head (Δs) on an arithmetic scale vs the elapsed pumping time (t) on the logarithmic scale) produced a straight line when the values of (t) become larger and the hydraulic system may have reached steady state). The static watertable in the shallow observation bore during pumping test suggests that the aquifer is semi-confined; confirming that these methods are appropriate for the Tammin site.

The calculation of hydraulic conductivity of the aquifer by the Theis equation applies Darcy's Law to flow into a cylinder (the open part of the well). The equation is derived for the situation of horizontal radial flow to a cylindrical well that fully penetrates an aquifer. The Tammin production bore penetrates the semi-confined but heterogeneous and anisotropic palaeochannel aquifer; therefore, the estimates of transmissivity (T) and storage coefficient (S) from the equation are approximations. The Jacob equation is based on the same principles as the Theis equation, with some modifications.

The values for T and S, using these methods, are given in Figures 12 and 13. The values for T are 17.9 and 11.5 m²/d, averaging 14.7 m²/d, which means that in one day 14.7 m³ of water can move through each vertical strip of the aquifer 1 m wide extending the full thickness of the aquifer under unit head gradient. The average value of S of 0.0019 from observed bore TM 002 indicates the confined condition of the aquifer. The hydraulic conductivity, calculated by dividing the transmissivity by the 30 m aquifer thickness on the site, is 0.49 m/d. The specific capacity of the production bore, defined as the yield of the bore in cubic metres per day per metre of drawdown, is 3.24 m³/d.

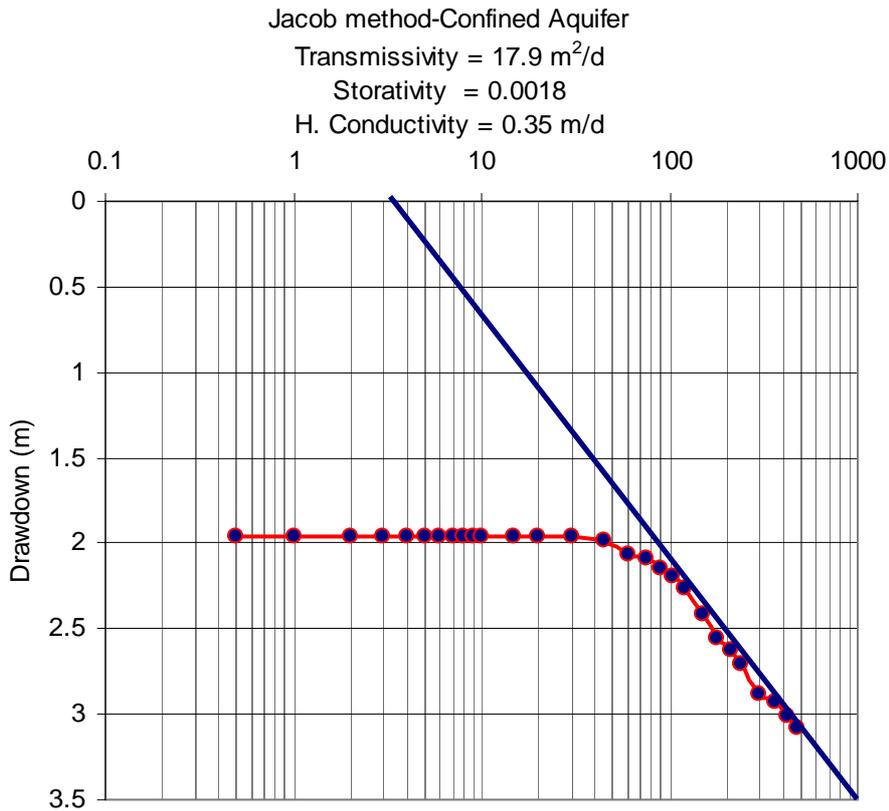


Figure 12 Time-drawdown graph for observation bore TM002 (Jacob method)

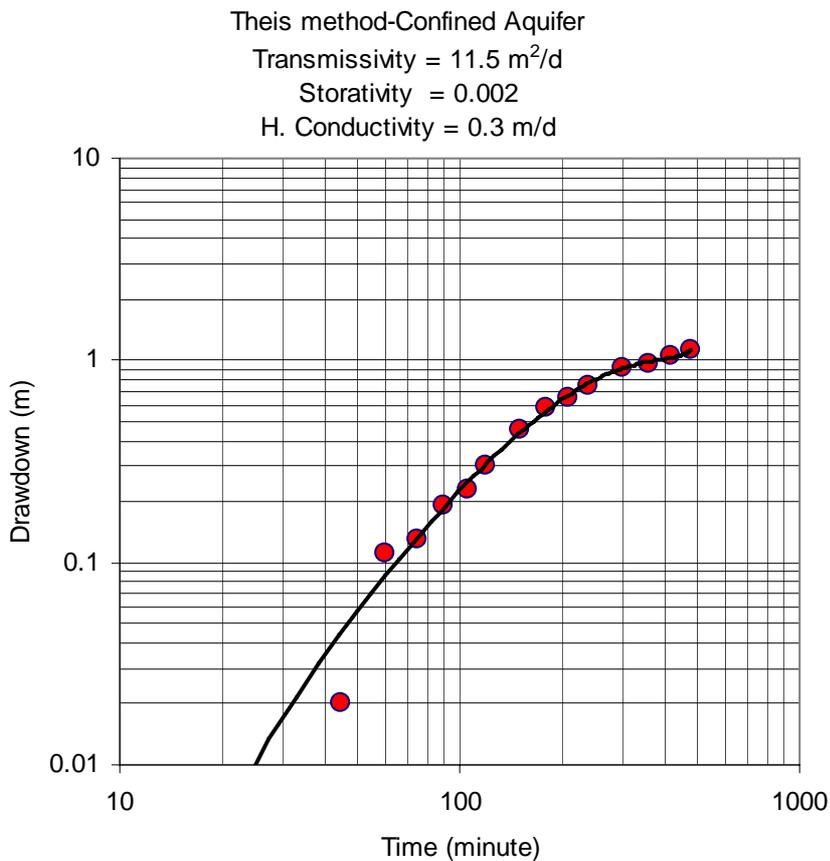


Figure 13 Time-drawdown graph for observation bore TM002 (Theis method)

Drawdown was plotted on the arithmetic scale as a function of the distance from the production bore on the logarithmic scale. A line extended through the data points to intercept the zero drawdown line (Fig. 12) indicates the extent of the production bore's lateral impact. The calculated distance is ~140 m from the production bore. It has to be emphasized that the lateral extent of the cone of depression was based on just eight hours of pumping. This number is verified by analysis of longer-term pumping (5 weeks) described in the following section.

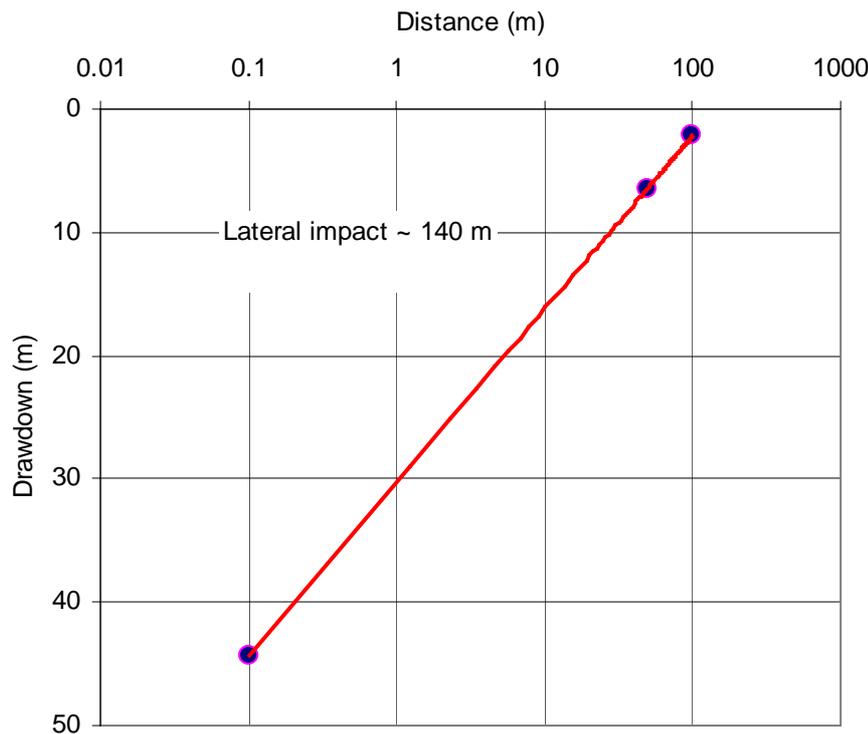


Figure 14 Distance–drawdown graph for the production bore and observation bores TM001 and TM002 (8-hour pumping test)

4.2 Pumping test analysis (long-term)

The long-term pumping data can be used to recalculate the hydraulic properties of the aquifer and verify the data from the one-day pumping test. The water from the semi-confined aquifer is accessed through mining the elastic or specific storage of the aquifer. The water discharged by pumping is released from storage by elastic compaction of water as the pressure in the aquifer is reduced and by expulsion as the pore spaces reduce as the aquifer compacts.

In the absence of recharge, the area of drawdown in a deep aquifer will expand indefinitely as pumping continues. So, the lateral impact of pumping at Tammin grew as pumping

continued and the heads in some deep monitoring bores declined. Figure 15 shows the responses of deep monitoring bores 50, 100, 300 and 900 m from the production bore. The reductions in heads decreased with distance from the production bore: about 3 m (50 m NW), about 2 m (100 m NW), about 0.5 m (300 m NW) and about 0.25 m (450 m SE) during the first five weeks of pumping, with no response in the bore 900 m downgradient.

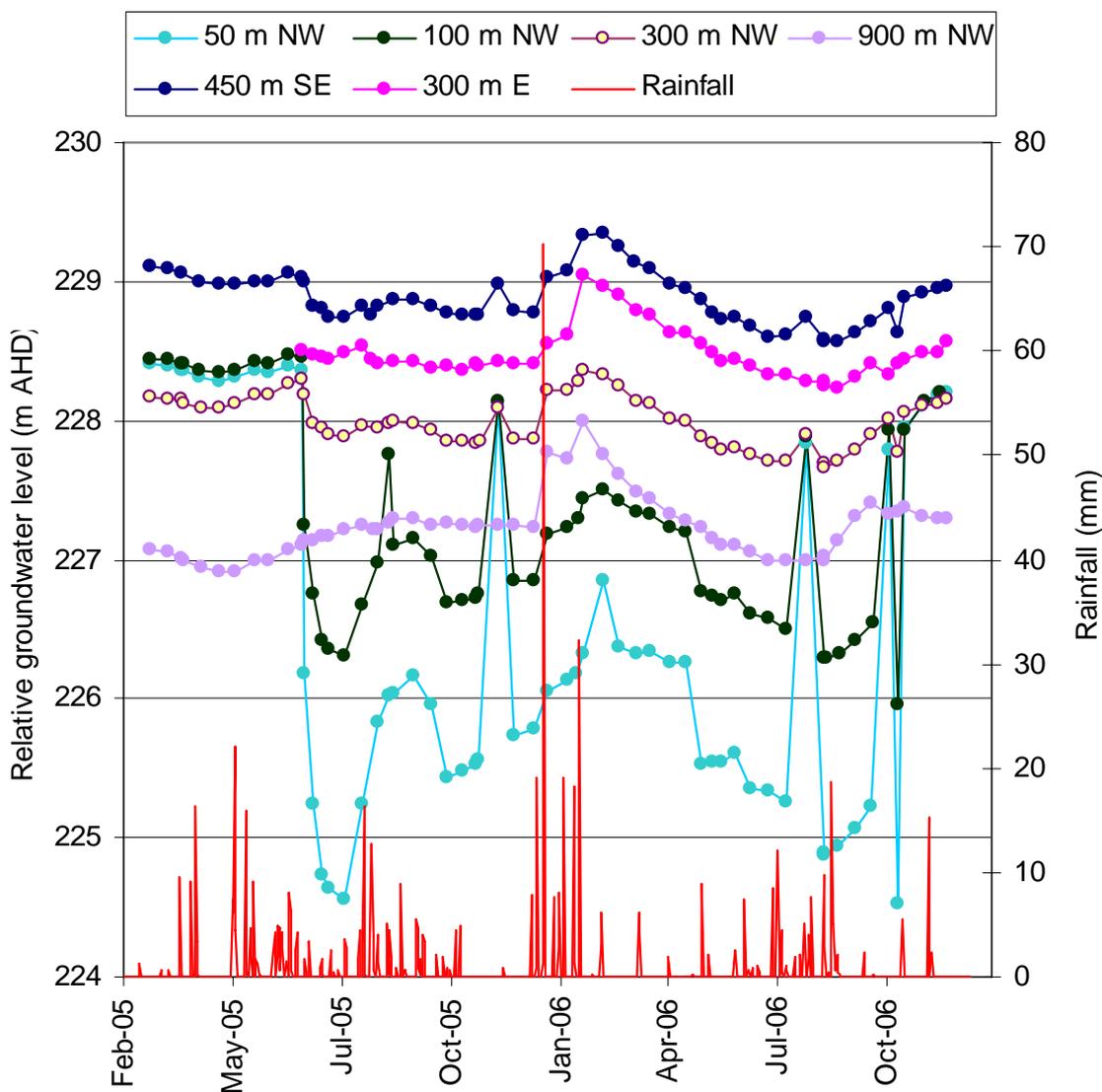


Figure 15 Logged heads in the monitoring bores on a longitudinal transect

The calculated T and K of the palaeochannel aquifer for TM001 (50 m downgradient) using five weeks of continuous data are 21 m²/d and 0.4 m/d respectively. These values are slightly higher than from the pumping test analysis by the Theis (1963) and Jacob (Cooper & Jacob 1946; Jacob 1950) methods (transmissivity range 11.9–17 m²/d and hydraulic conductivity range 0.3–0.35 m/d).

The recovery of the groundwater head at the monitoring bore 50 m downgradient was also used to calculate aquifer characteristics (after the system was switched off). The head in the observation bore recovered rapidly overnight to its pre-pumping value (Fig. 16). The estimated value for the transmissivity is 11.5 m²/d: the same as the value from other methods. The results of the long-term and recovery tests suggest that an 8-hour pumping test may be adequate to calculate the hydraulic properties and to estimate bore capacity. This will help to reduce the cost of implementing similar projects.

Complex weathering of the granite aquifer in the Wheatbelt results in local aquifer systems with layers that vary in porosity and respond variably to groundwater pumping. Despite the hydraulic variations of the materials comprising the water-bearing formation, hydraulic conductivity and bore yield in the weathered granite may range over one order of magnitude, 0.1–1.0 metre per day (m/d), and 20–200 m³/d, respectively (Peck 1983; George 1992; Clarke et al. 2000). These numbers were used for the weathered granite aquifer to model the long-term impact of groundwater pumping on the shallow watertable in Tammin.

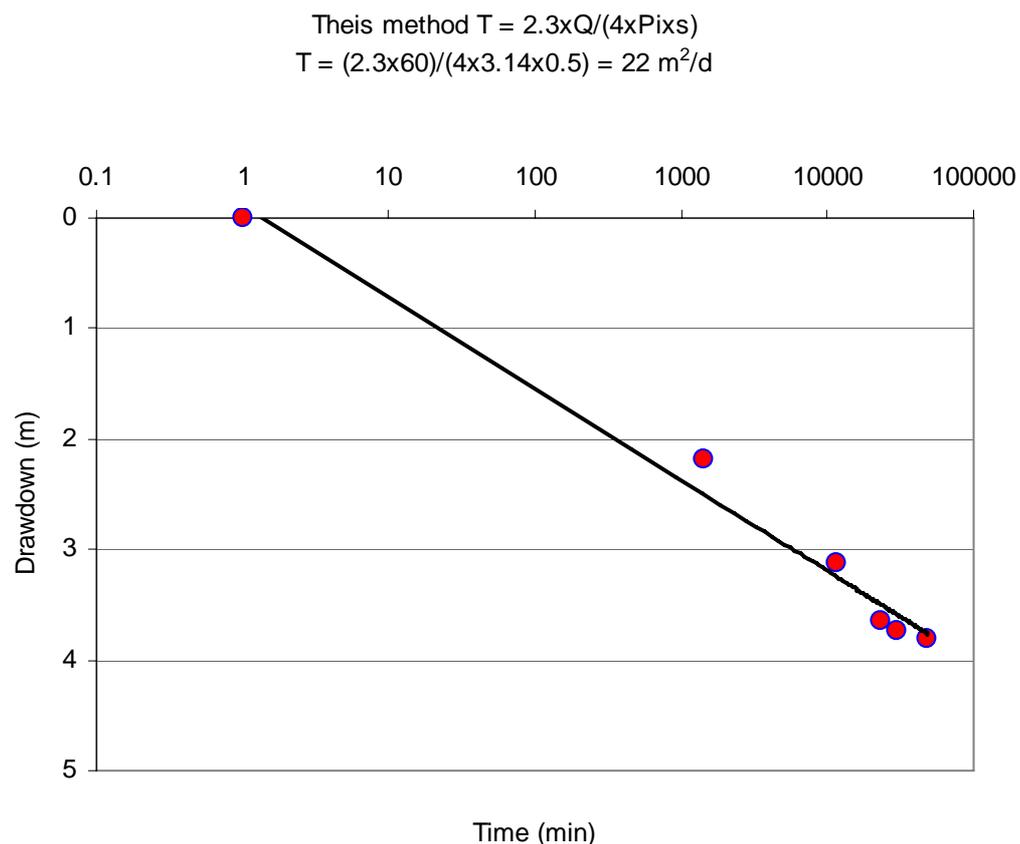


Figure 16 Five-week pumping test for the observation bore TM 001 (50 m)

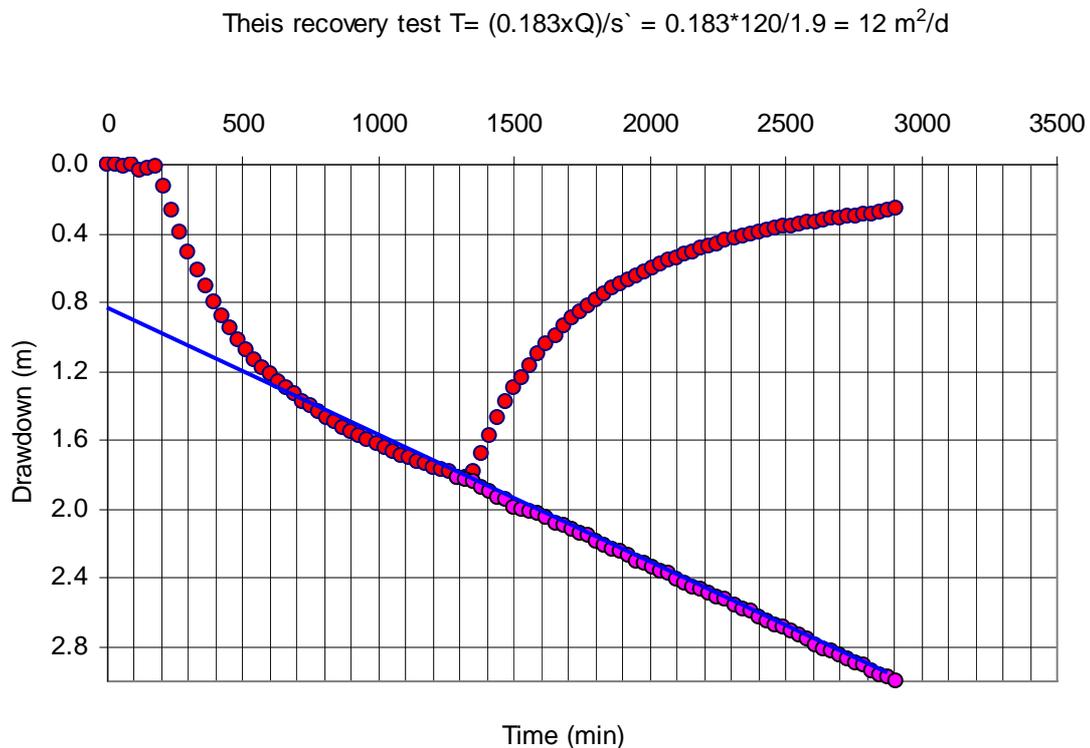


Figure 17 Recovery data for the observation bore TM 001 (50 m)

4.3 Pumping rates and bore efficiency

The pumping rate was adjusted to 1 L/s (86 m³/d) but it has gradually declined to a rate of 0.6 L/s (50 m³/d). The rate then increased to ~ 0.8 L/s (70 m³/d) from April to October 2006 (Fig. 18). The pressure head in the production bore is rising with the gradual decrease in the pumping rate (Fig. 19). The variation in the pumping rate in the early stages of pumping was due to the decline of the head below the pump resulting in the shut-down of the system at about 130 m³/d. The reduction in discharge rate coupled with rising pressure head is indicative of the partial clogging of the pump inlet. If the reduction in the pumping rate were due to the clogging of the well screen, the head in the bore would have declined with the decline in the pumping rate.

The efficiency of the production bore was calculated using the Mogg (1968) method where bore efficiency is defined as the ratio of measured specific capacity after a specific time of continuous pumping to the maximum specific capacity measured from hydraulic parameters and bore geometry. A detailed description of the method is described in Driscoll (1986). The calculated drawdown from the observed data is 28.6 m while the observed drawdown in the pumping bore was 42 m. The theoretical value is then divided by the observed value; the result is that the bore in Tammin is only 68% efficient. Generally, efficiency of 70–80% is considered a good result for a production bore.

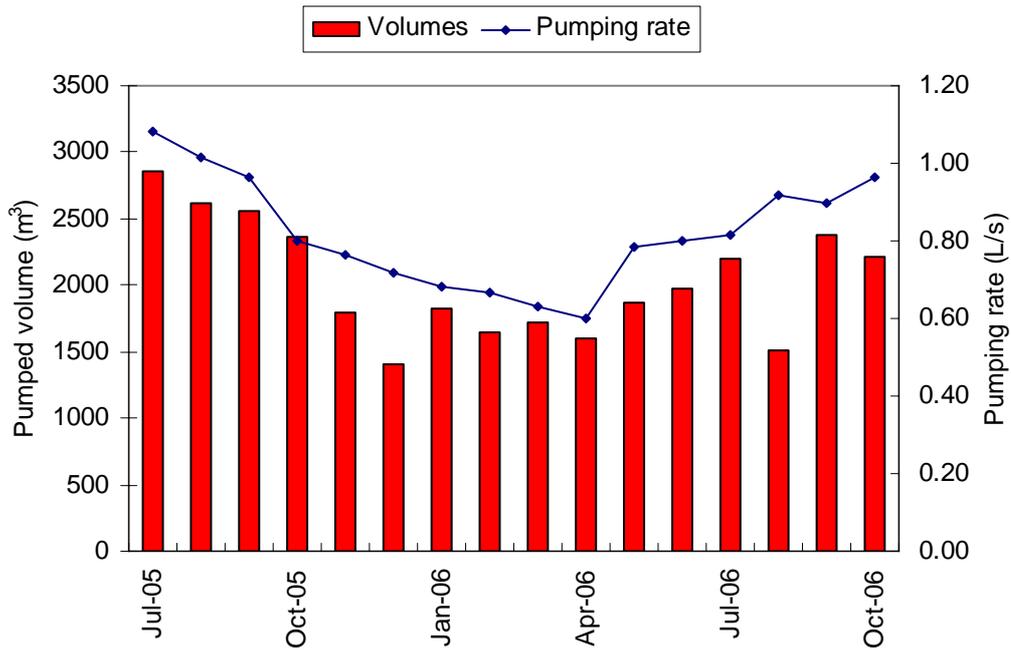


Figure 18 Monthly pumping rates and volumes

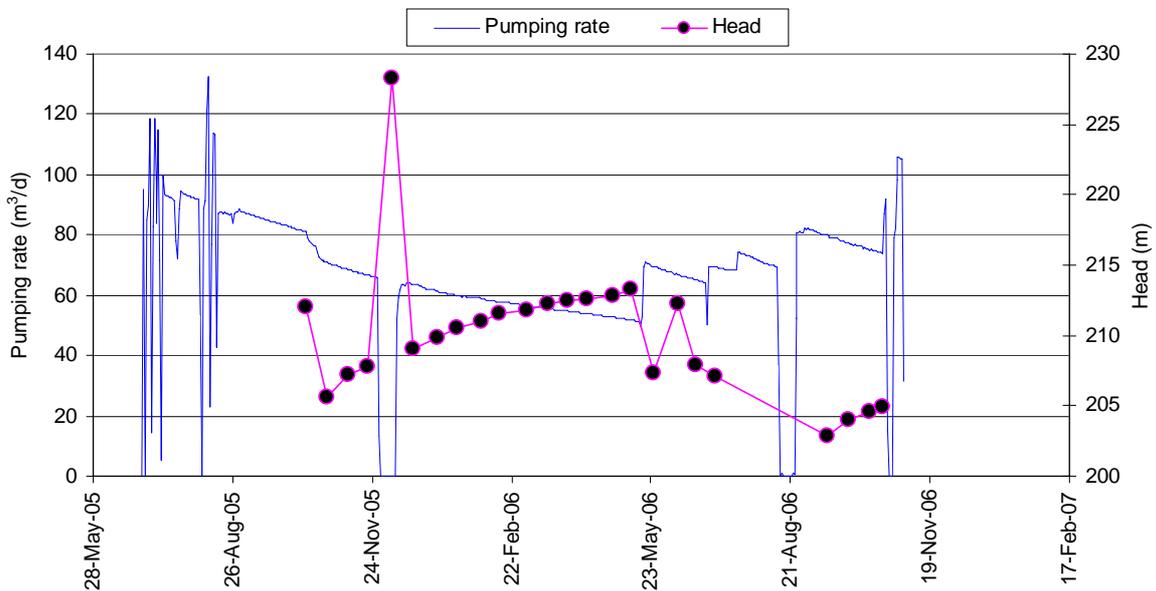


Figure 19 Pumping rates and head responses in the production bore

4.4 Rainfall response and head difference

The extents of rises and falls and the seasonal highs and lows of the watertables in the monitoring bores in Tammin are related to five principal factors: the type of aquifer in the

area; the amount and rate of recharge; the depth to the watertable; the relation of the point to the general recharge–discharge pattern and the pumping rate from the production bores. These factors are illustrated by the hydrograph of observation bore TM003s and TM003D (Fig. 20) where, for easy comparison, is also plotted the rainfall minus evaporation, which may represent recharge and water level during the pumping period for the 2004–06 record. The rises and falls of water levels in the hydrographs correlate with the pumping data and rainfall events.

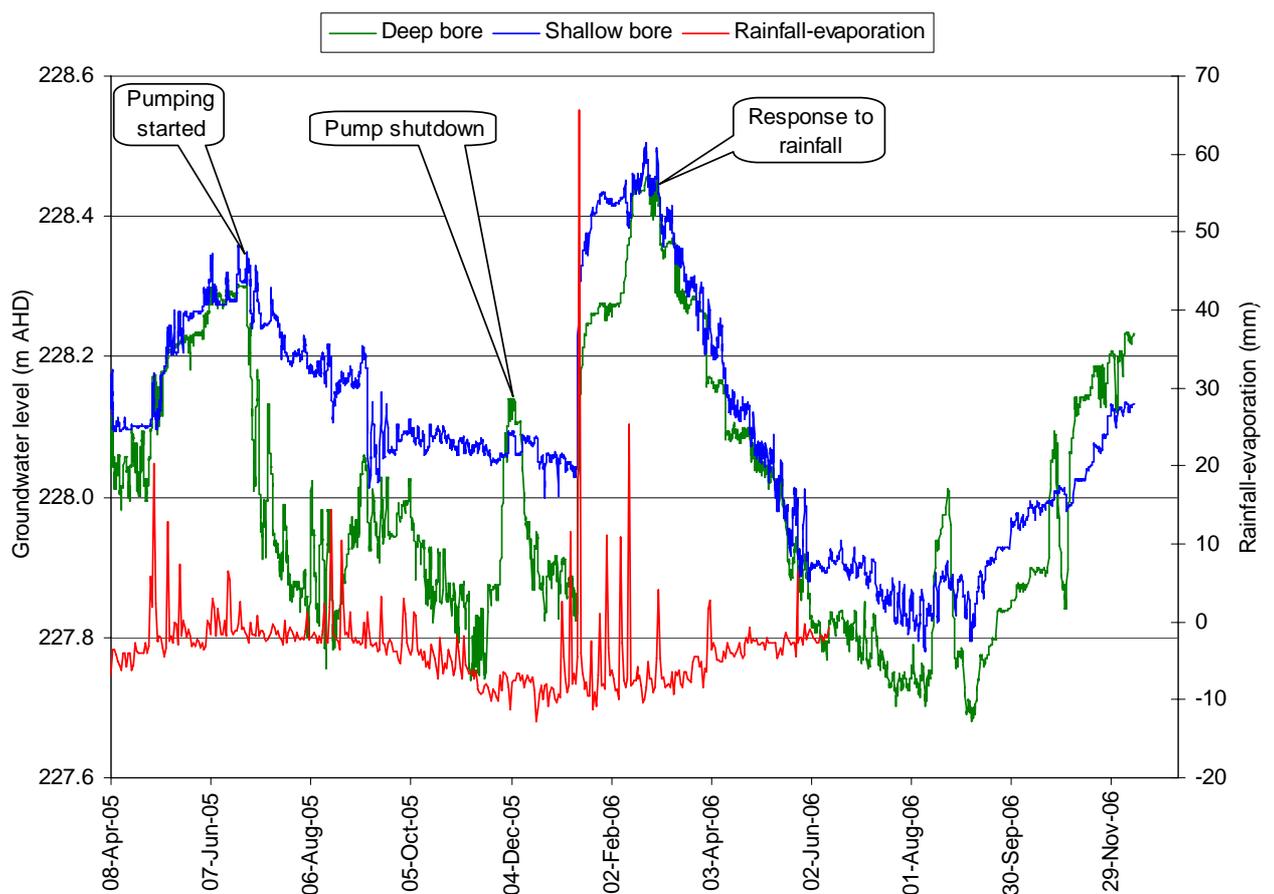


Figure 20 Daily rainfall minus evaporation and water level data for shallow observation bore TM003s and TM003D

Because of groundwater pumping and natural recession, the head in the deep aquifer in TM003 dropped by 0.5 m and the watertable dropped by 0.3 m (Fig. 21). However, following their lowest levels around 10 August 2005, the deep and shallow heads and watertable recovered in response to the 71 mm storm event in January 2006 (Table 3). Similar to TM003, other monitoring bores showed that the hydraulic head difference is downward although the pressure difference is quite small. With the start of groundwater pumping the difference in head and watertable increased because the semi-confined aquifer responded

more rapidly to the pumping. When pumping stopped, the deep groundwater head rose above the water levels of shallow aquifer indicating a potential for leakage to the shallow aquifer. Both aquifers responded immediately to the rainfall event in January 2006 (Fig. 20). At this time, the watertable of the shallow aquifer rose above the head in the deeper aquifer resulting in leakage from shallow to the deeper aquifer. This scenario reversed again around March 2006, with the watertable of shallow aquifer dropping below that of deep aquifer.

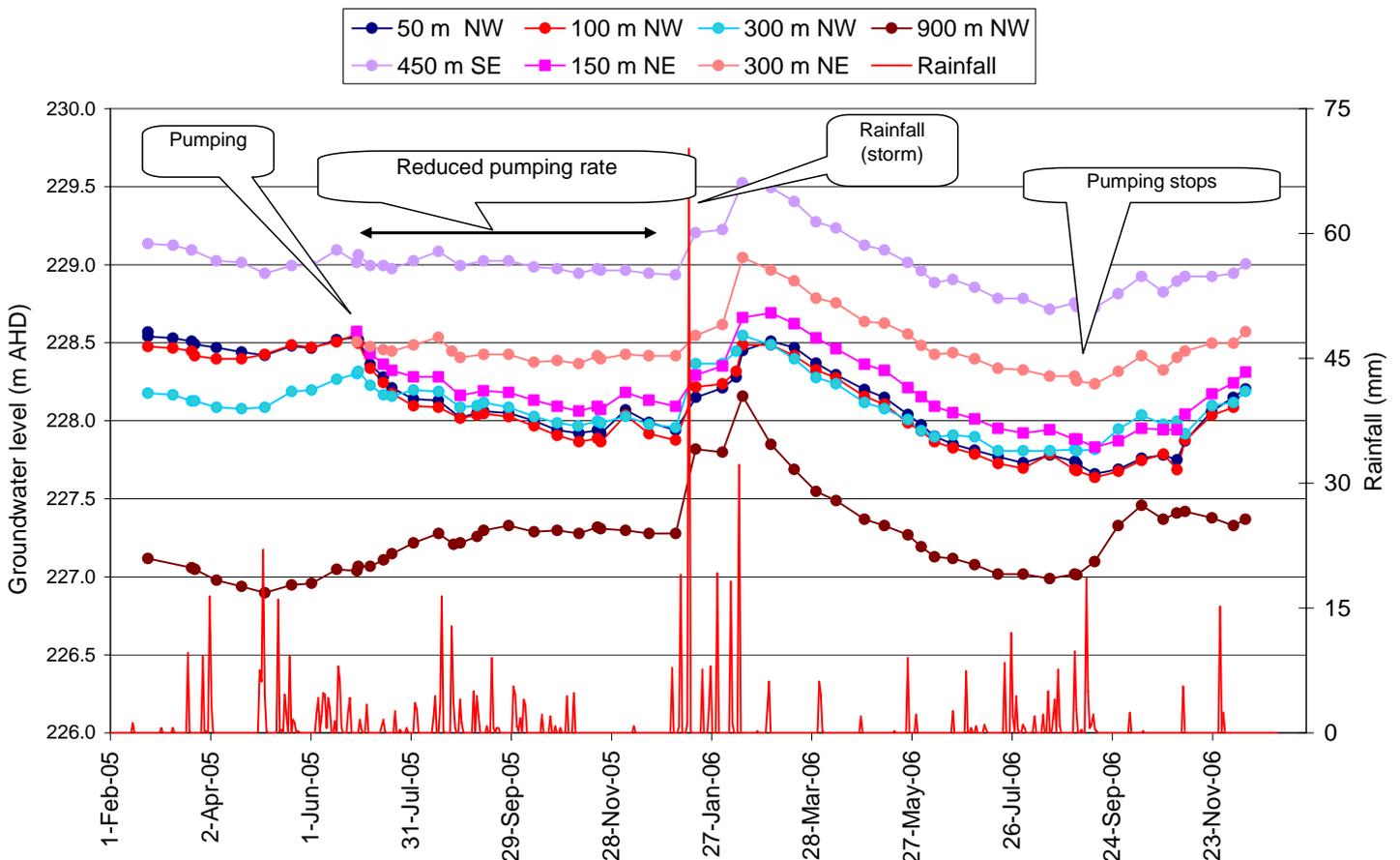


Figure 21 Shallow watertable responses to the pumping trial in the monitoring bores on a longitudinal transect

Recession of shallow groundwater during the period February to May 2006 was significantly steeper than the recession observed from June 2005 to January 2006 (Fig. 21). This may have been a result of higher rate of vertical leakage from the shallow to the deep aquifer due to a head large difference between the aquifers. At 450 m upstream of the production bore; in TM006, groundwater pumping was still having an effect and the drop in pressure head was ~ 0.26 m for the deep aquifer (Fig. 22). Similar to TM003; the TM006 hydrograph also shows groundwater level recession characteristics for the shallow aquifer.

Groundwater level recedes at a much faster rate following the recharge event in January 2006. The pressure head of the deeper aquifer remained lower than water levels of the shallow aquitard throughout the monitoring period. Four months from the January rainfall, the watertables were still higher than in the pre-pumping period (Fig. 21). Shallow-bore data was used to calculate the rate. The watertable recession is ~ 0.5 m for all the bores within a 450 m radius regardless of their distance from the production bore, except in bore TM004 (900 m downgradient) where the rate of decline was faster. This was because the watertable in this bore after the rain was 0.9 m higher than the creek bed and groundwater discharged to the adjacent creek.

Water levels in the observation bores (TM001, TM002, and TM003) had similar elevations to the creek bed so there was virtually no lateral flow between the shallow aquifer and the creek, except during rainfall events when pressure heads or watertables were higher than the creek bed. The rate of decline of 0.1 m/week is similar to the rate of decline of shallow groundwater due to pumping observed during early stages of groundwater pumping (Fig. 21).

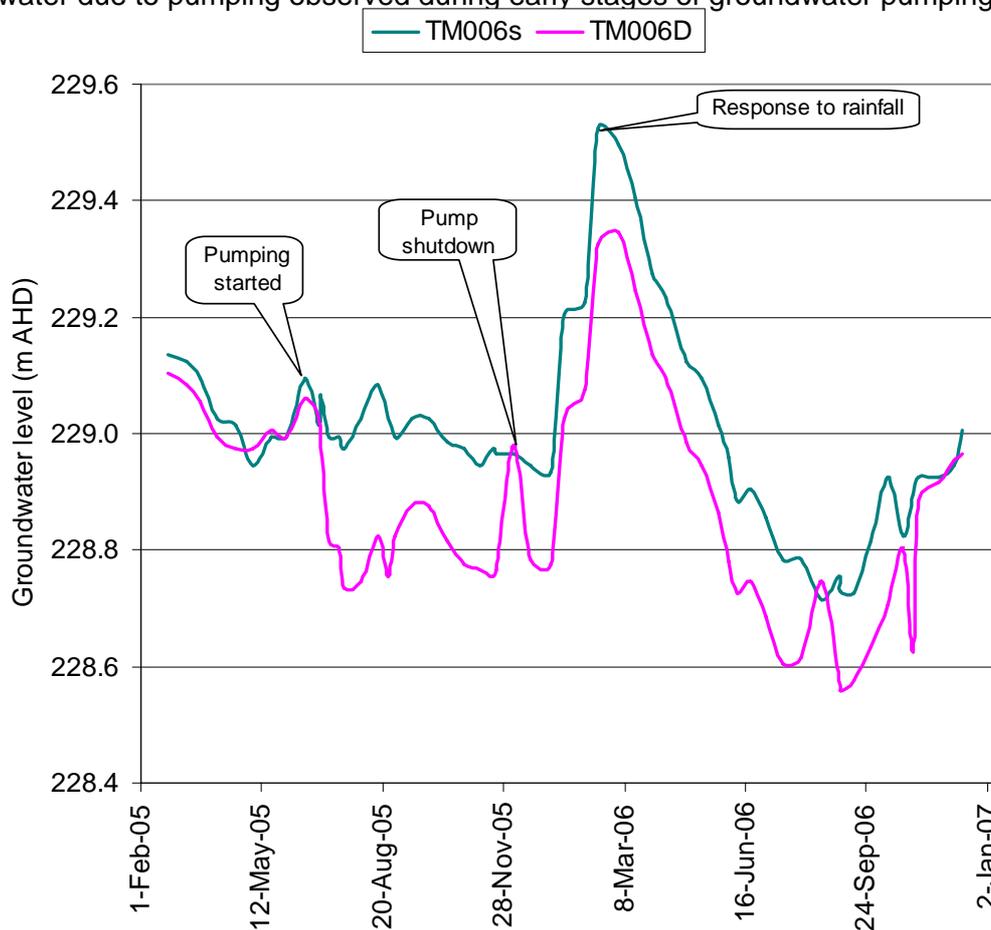


Figure 22 Groundwater levels TM006s and TM006D (450 m) upstream of the production bore

Table 3 Responses of shallow monitoring bores to 71 mm of rainfall in Jan. 2006

Bore ID	From production bore (m)	Depth to watertable (m)		Shallow-deep head difference (m)	Response to rainfall (m)
		Pre-pumping	After rain		
TM001s	50	1.76	1.75	2.19	0.50
TM002s	100	1.14	1.10	0.90	0.66
TM003s	300	1.65	1.48	0.17	0.43
TM004s	900	1.76	0.67	0.05	0.88
TM005s	105	1.71	1.66	0.95	0.48
TM006s	450	1.95	1.49	0.16	0.59
TM007s	150	1.42	1.30	NA	0.60
TM008s	300	1.89	1.35	NA	0.63

4.5 Cone of depression and capture zone

The responses of the deep (TM001D) and shallow (TM001s) monitoring bores to the pumping test suggest that the palaeochannel at the Tammin site is semi confined. This was highlighted by non-responsiveness of the shallow observation bore and the fall in head in the palaeochannel observation bores (Fig. 10). However, six weeks of continuous pumping resulted in gradual drawdown of the watertable in the shallow bore by ~ 0.5 m (Fig. 21).

The extent of the cone of depression for the palaeochannel aquifer is calculated using data from the monitoring bores. The drawdowns in the production bore and TM001 are 22 m and 3.8 m respectively. The area of this relatively small cone of depression around the production bore with drawdown > 3 m is ~ 7850 m². The cone of depression is likely enlarge asymmetrically because of channel boundaries and on a longitudinal north-west trending axis along the palaeochannel. The progression from circular to oval cone beyond the 100 m mark is expected because the impact of groundwater pumping is restricted by the width of the palaeochannel (~250 m). The calculated area for the oval cone of depression that extends to 450 m from the production bore with a minimum drawdown of 0.25 m is 212 000 m². The total area of the cone of depression is divided into categories depending on minimum and maximum head drawdowns (Table 4).

Table 4 The calculated area of the cone of depression for the palaeochannel aquifer

Bore ID	Depth (m)	Distance from production bore (m)	Head below ground level (m)	Drawdown (m)	Max–min drawdown (m)	Area of drawdown (m ²)
TM001PROD	54	–	1.06	22		
TM001D	51	50	1.85	3.8	22–3.8	~7 800
TM002D	51	100	1.34	2.1	3.8–2.1	~23 000
TM003D	48	300	1.76	0.4	2.1–0.4	~110 000
TM004D	48	900	1.84	0		
TM005D	50	105	1.74	2		
TM006D	49	450	1.89	0.26	0.4–0.26	~71 200
TM007	15	150	1.42	0.29		
TM008	15	300	1.89	0		0
Area of oval cone of depression (900 m x 300 m) with 0.25 m drawdown						~210 000 m²

The constant enlargement of the cone of depression in the deep aquifer resulted in a head difference between the deep and shallow aquifers. The difference between the watertable and the hydraulic head before groundwater pumping was quite small (~ 0.1 m) and the pressure gradient was downward (Fig. 22). After pumping, the head difference increased, inducing vertical leakage into the deep aquifer and drawdown of the shallow watertable. The loss of water from the shallow aquifer has resulted in the decline in watertable observed in monitoring bores 50, 100, 300 downgradient and 150 m NE of the production bore. The monitoring bores 900 m downgradient and 300 m NE of the production bore did not respond during the pumping trial (Figs 15 & 21). The monitoring bore TM 008 (300 m NE of the production bore), located outside the palaeochannel, is drilled into the weathered granite aquifer: this may explain why the watertable did not respond to pumping.

The minimum decline of shallow watertable by 0.15 m was observed in TM006 (450 m upgradient of the production bore). The watertable fell by > 0.6 m in a circular cone with a diameter of 100 m around the production bore. Beyond this point and up to 300 m the decline was 0.6–0.3 m. Smaller declines of 0.35–0.15 m were observed between 300 and 450 m. The maximum decline was noticed up to 100 m around the production bore. The calculated area of the watertable decline is shown in Table 5.

Table 5 The calculated area of the cone of depression for the watertable aquifer

Bore ID	Depth (m)	From production bore (m)	Watertable below ground level (m)	Drawdown (m)	Min. drawdown (m)	Area of drawdown (m ²)
TM001s	6	50	1.85	0.6	Min 0.6	~7 800
TM002s	6	100	1.24	0.6	0.51–0.6	~23 000
TM003s	6	300	1.85	0.35	0.51–0.35	~12 000
TM004s	6	900	1.84	0		
TM005s	6	105	1.67	0.51		
TM006s	6	450	1.89	0.15	0.35–0.15	~11 200
TM007	15	150	0.9	0.51		
Total area of watertable decline						~54 000 m²

The volume of groundwater discharged from the production bore was ~ 32 000 m³ — 19 000 m³ pumped between June and December 2005, the remainder during 2006. As the pressure head of the deep aquifer was lowered to about 22 m at the production bore and 0.26 m at bore TM06 (450 m up-gradient of the production bore), the shallow watertable declined by 0.15 m. To produce this cone of depression in the deep aquifer requires only ~ 2500 m³ of water, assuming the cone of depression is ellipsoidal in shape with length, width and height of 450, 150 and 5 m respectively, and a storage coefficient of 0.0018.

Thus, the bulk of water, about 29 500 m³, may have come from the overlying unconfined shallow aquifer through vertical leakage to the confining layer. Assuming an average 0.5 m drawdown in the watertable of the unconfined aquifer over the same area as the cone of depression of the deep aquifer, the estimated leakage is 16 000 m³. The difference between the discharge volume of 32 000 m³ and calculated groundwater volume (2500 m³+16 000 m³) of the cone of depression in both aquifers is the volume of water recharged to the aquifers during the ~ 16 months pumping trial (13 000 m³). Although watertable fall is restricted to 0.15 m at 450 m from the production bore, the unconfined aquifer can be considered to have released a relatively large volume of water to stop the expansion of the cone of depression. This is attributed to the specific yield of the unconfined aquifer of ~ 0.1 compared with the storage coefficient of the confined aquifer (0.0018).

4.6 Modelling the cone of depression

The area of the cone of depression calculated from previous sections is the steady-state condition that provides an assessment of the water-level response to the pumping. It assumes that the water balance has reached equilibrium and the volume of water discharged

by pumping will eventually equal the volume of recharge to the aquifer. For insight into the daily response of the watertable to the recharge–discharge mechanism, a model is needed to evaluate the impacts of water-balance changes, such as episodic recharge or pump stoppage, on the water level and the area of the cone of depression.

An adaptable spreadsheet model to evaluate daily water balances using water-level records from TM001 and the hydraulic properties of the aquifer was constructed and the responses of the daily water levels to pumping and recharge calculated by converting the volume of the water to drawdown in TM001.

Figure 23 shows that the model mimics the recorded daily data and that the daily expansion and contraction of the cone of depression depends on the water balance. The model suggests that the area of the cone of depression is maintained during the initial phase of pumping where the groundwater discharge is sourced from the storage. At this stage, the water level is characterised by a relatively steep slope and the area of the cone does not expand during drawdown. After the initial phase, the area of the cone increases substantially while the drawdown stabilises and the slope of the receding curve flattens. During the next three-week period, the area increases from ~ 10 000 to ~ 200 000 m² (Fig. 23). This agrees with the area of the cone of depression calculated from aquifer hydraulic parameters and from monitoring bore data (Tables 4 & 5).

The area of the cone of depression in the shallow aquifer contracts to pre-pumping values in response to recharge after the January 2006 rainfall. The water level then starts to recede and the area of the cone increases steadily until the pumping stops at the end of the project when the cone of depression contracts again to its pre-pumping area.

The expansion of the cone of depression is related to the head differences between the aquifers. The water level in the shallow aquifer declined a further 0.5 m after the January rainfall compared with the water level in the early stage of pumping. This is explained by depicting the differences in hydraulic head between the two aquifers to show the potential for leakage from the shallow aquifer that result in water level decline. The head difference between the deep and shallow aquifer in the early stage is ~ 5 m and decreases with continuous pumping to ~ 3.5 m. Once the water level stabilises the cone of depression starts to expand (Fig. 24).

After the January 2006 recharge event, this scenario is reversed and the head difference between the two aquifers increases by the addition of ~ 0.5 m of recharge directly from rainfall. The pumping and natural recession of groundwater creates a downward trend for the water level while the head difference maintains the upward trend. The large difference in head means a high potential for leakage from the shallow to the deep aquifer. Unlike the previous phase, where the water level stabilised, at this phase the water level does not stabilise but rises again in response to the additional recharge. This results in a much smaller cone of depression than the previous phase (Fig. 23).

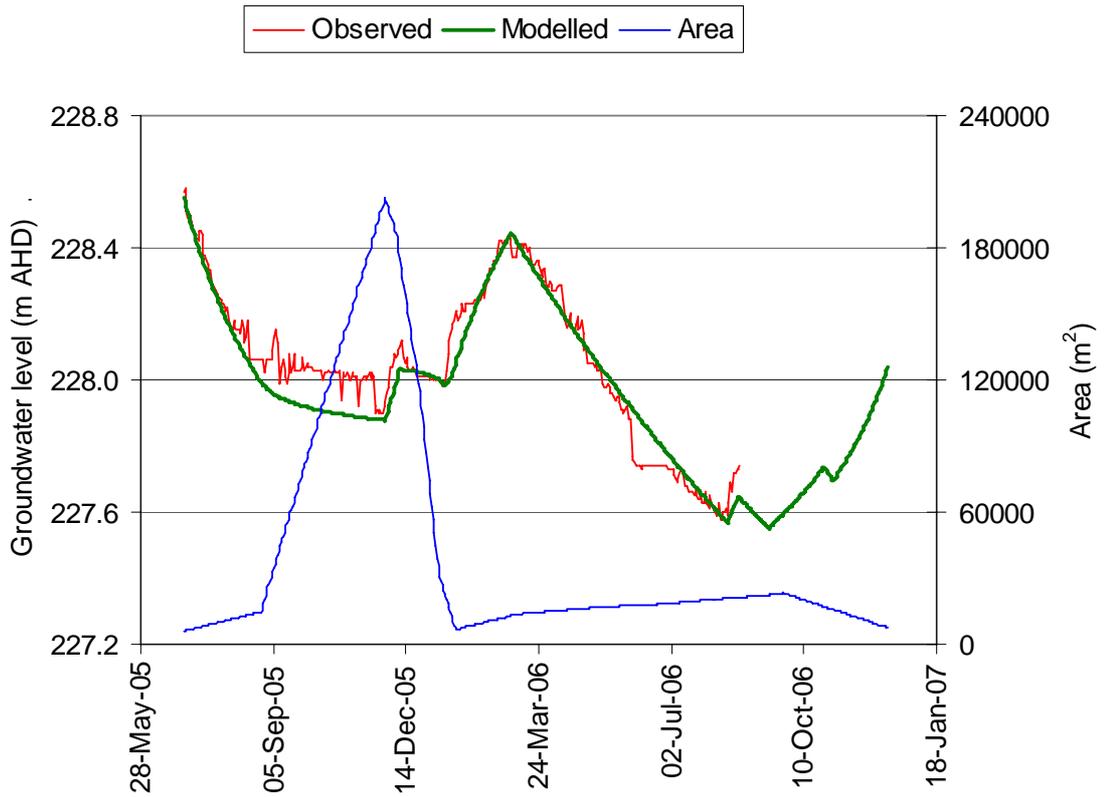


Figure 23 The model of the water level and cone of depression responses to water balance changes

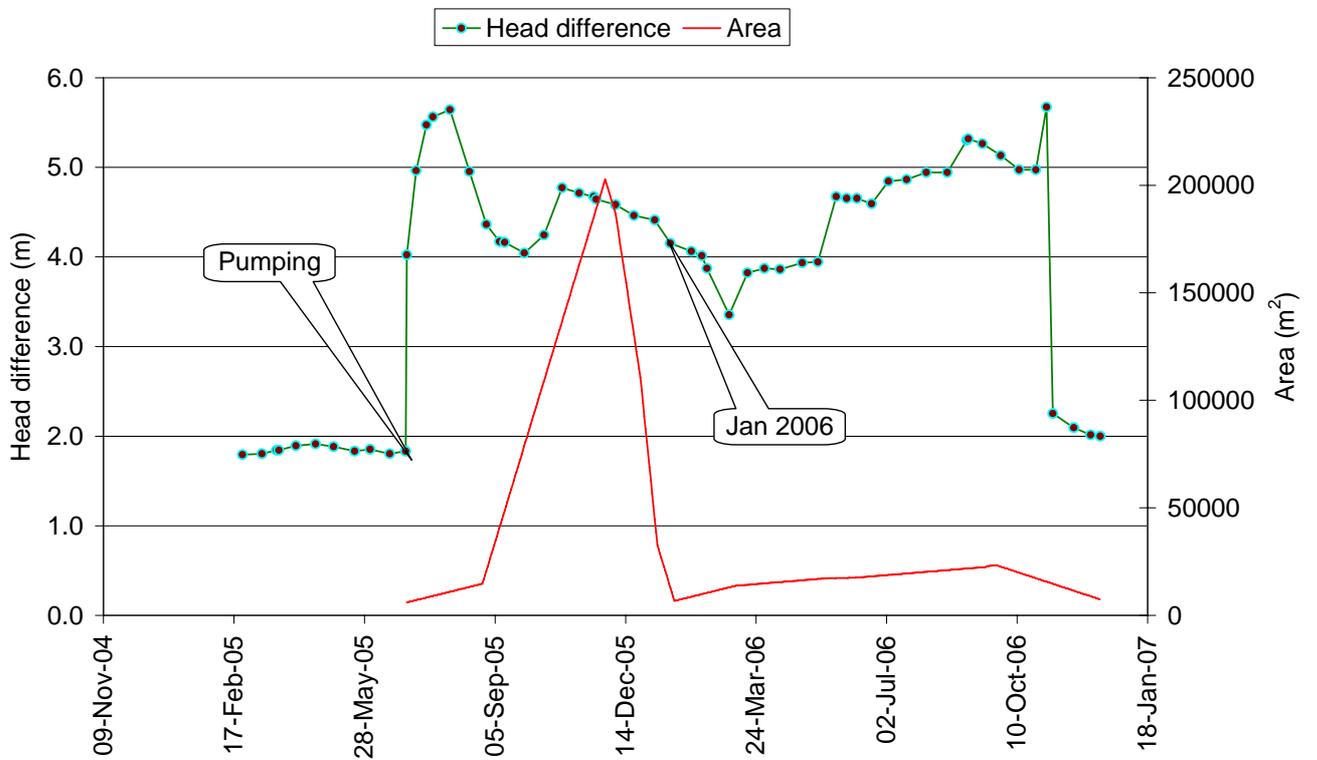


Figure 24 Head differences between the shallow and deep aquifers

To demonstrate that the cone of depression does not expand substantially unless the slope of the water-level drawdown stabilises, it is assumed that the water level remains at 227.7 m AHD. The modelled area of the cone of depression expansion is calculated and shown in Figure 25. Assuming continuous pumping and no recharge, the area increases by more than one order of magnitude in two months.

The spreadsheet model can also be used to evaluate whether the unforeseen pump stoppage affected the size of the cone of depression. Figure 25 shows the water level for continuous pumping, with a discharge of 90 m³/d for the entire period. The results of the model and the size of the cone of depression are identical to the results from using the measured discharge, suggesting that the slightly faster pumping and pump stoppage do not affect the size of the cone of depression. The most important factors deciding the responses of the water level to the pumping at Tammin are the volume of recharge to the shallow aquifer and the head difference between the shallow and deep aquifers. In addition, the model shows that the cone of depression is dynamic, expanding and contracting in response to changes in the water balance.

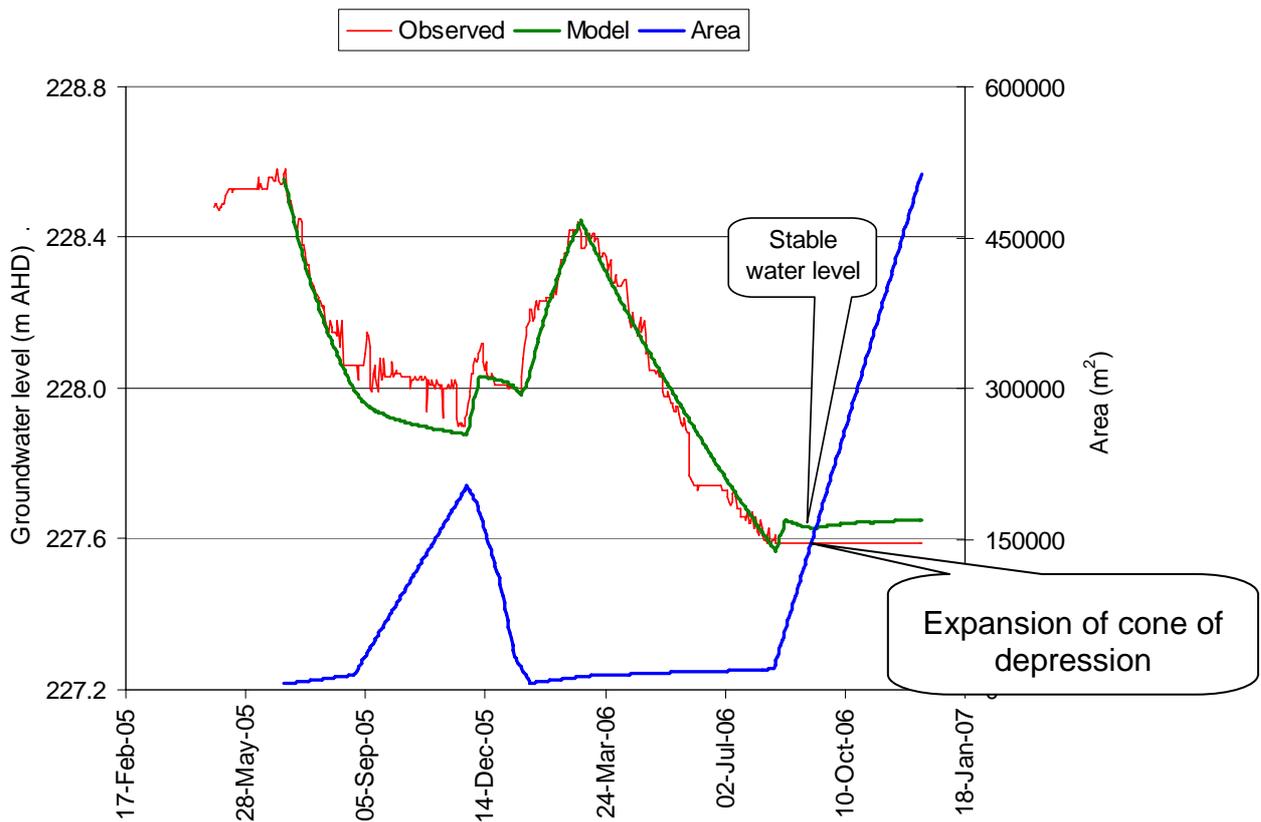


Figure 25 The model of the cone of depression response to stabilising water level

5 Groundwater chemistry

5.1 Salinity

The conductivity of the pumped groundwater was measured both continuously and manually at the discharge point of the production bore and then converted to salinity (mg/L TDS total dissolved salts), using a conversion equation that compensates for temperature. The salinity of deep groundwater ranges from 46 000 to 61 000 mg/L (Fig. 26). The lower than expected salinity measured by the logger corresponds to periods when the pump was off. There are also two erroneous manually measured salinities (> 60 000 mg/L), where water samples were collected from a discharge outlet to the creek line that might have been affected by evaporation.

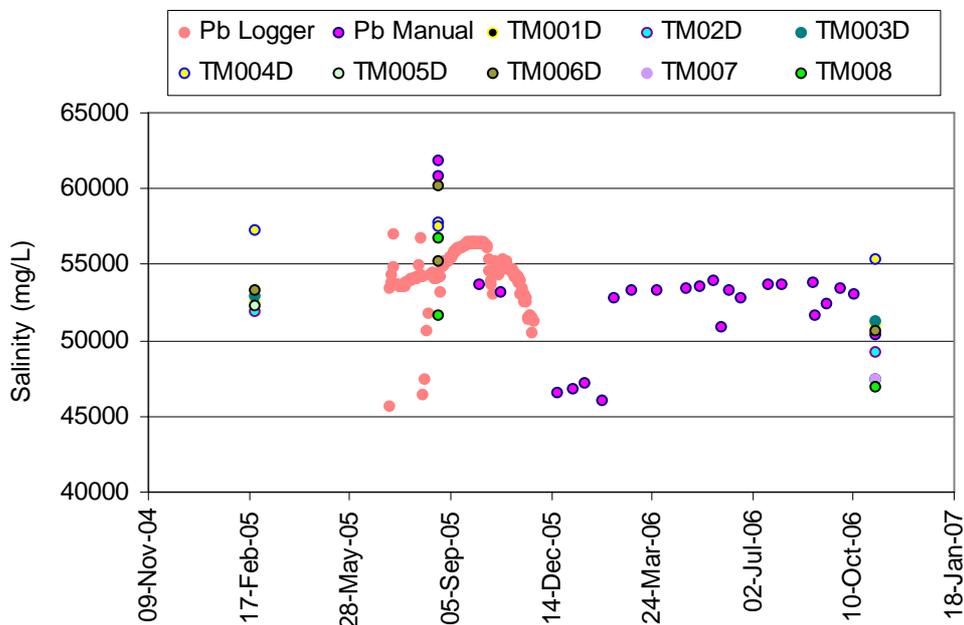


Figure 26 Salinity of groundwater in the deep aquifer

The salinity of the shallow groundwater varies. In general, with salinity 28 000–55 000 mg/L, it is slightly less saline than the deep groundwater. The salinity in TM001s increased from 28 000 mg/L in August 2005 to 32 000 mg/L in November 2006. By contrast, salinity of 40 000 mg/L in TM002 in August 2005 decreased slightly to 35 000 mg/L by November 2006. Unlike these two bores, the groundwater from TM004 increased from 35 000 mg/L in August 2005 to 45 000 mg/L in May 2006 and then decreased to 34 000 mg/L in November 2006. The variations in shallow aquifer salinity are due to the dilution with fresh recharge from rainfall depending on the location of the bores in the landscape. The salinity in the deep bores is consistently higher because the volume of shallow groundwater added by leakage is small compared with the volume of water in the deep aquifer.

The major ion compositions of deep and shallow groundwaters are similar to that of seawater with Na and Cl ions constituting approximately 80% of cations and anions. There is a slight depletion of Ca and SO₄ and enrichment of Mg relative to seawater by geochemical processes such as ion adsorption and cation exchange on clay minerals during the evolution of recharge from rainfall to saline groundwater in the aquifers. The composition of the major ions suggests that the majority of the total dissolved salts in groundwater are derived from marine aerosols from sea spray and deposited on the site via rainfall. (McArthur et al. 1989; Dogramaci & Yesertener 2001; Dogramaci & Herczeg 2002)

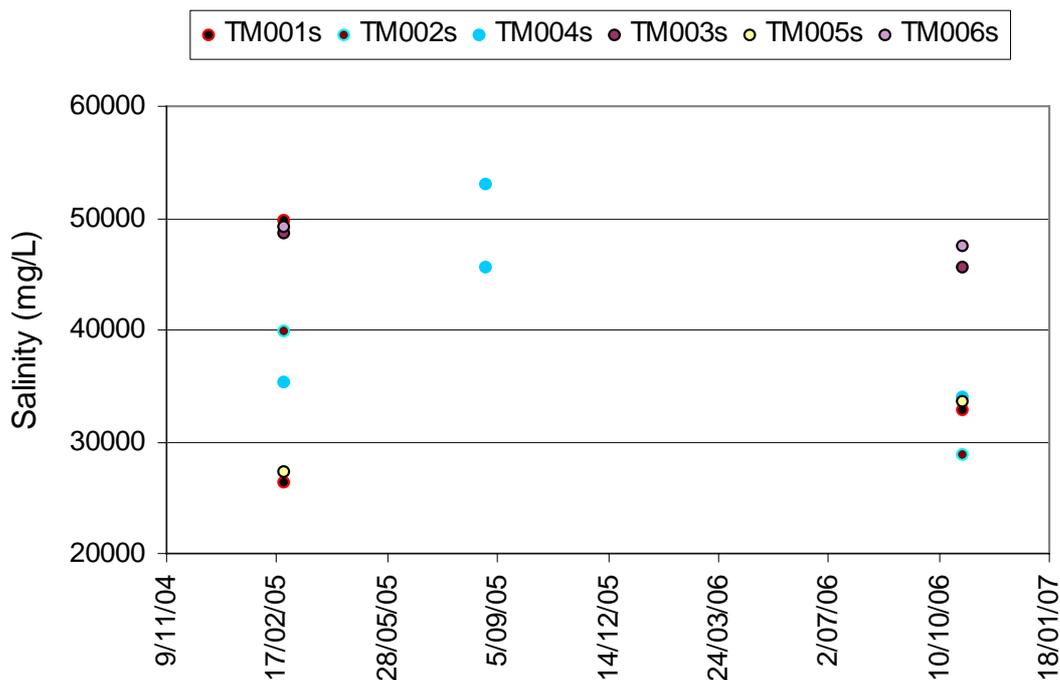


Figure 27 Groundwater salinity of the shallow aquifer

5.2 pH

The development of groundwater acidity in some parts of the Wheatbelt has been recognised and documented in previous studies (Bettenay et al. 1964; Mann 1983). High iron and aluminium concentrations and acidic groundwater seepage are common features of the Darling Ranges and in some of the drains installed in the eastern Wheatbelt. The acidity of groundwater results in increased solubility of metals such as iron and aluminium. The reduced condition of the deep palaeochannel aquifer enhances the mobility of these metals. Once the groundwater is discharged and exposed to the atmosphere the mobile metals in groundwater oxidise and precipitate in the creek bed.

The low pH and high concentrations of iron and aluminium are observed in both deep and shallow aquifers at Tammin. The total Al concentration range is 9.4–110 mg/L and total Fe concentration range is 27–670 mg/L.

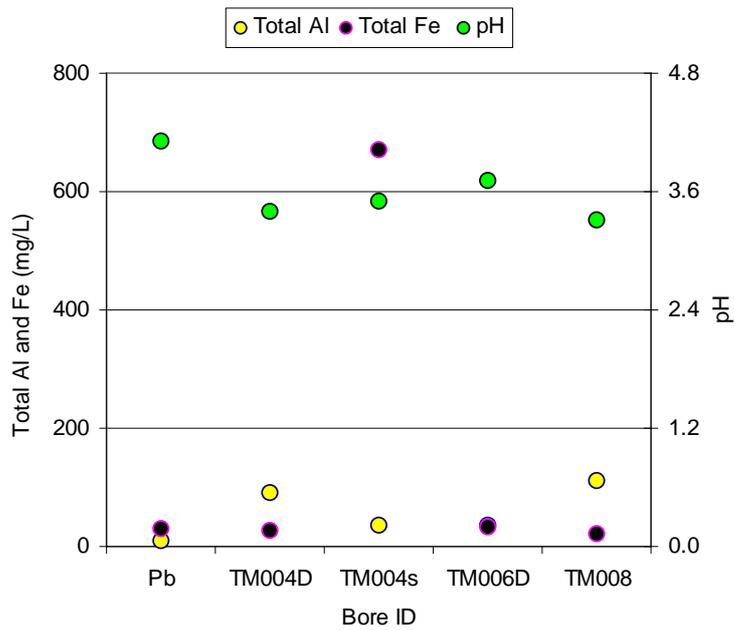


Figure 28 Dissolved Fe, Al and H (pH) in palaeochannel groundwater

Both deep and shallow aquifers have groundwater with pH 3–6.8. For the majority of the samples pH is around 4, except for two samples from the production bore with pH 6.7 and 6.8. Because most samples from the production bore have pH 4, these two outliers may be due to a faulty pH probe. The effects of this aluminium- and iron-rich and very acidic groundwater on receiving environments are documented in a separate report of the Engineering Evaluation Initiative (Silberstein et al. 2008).

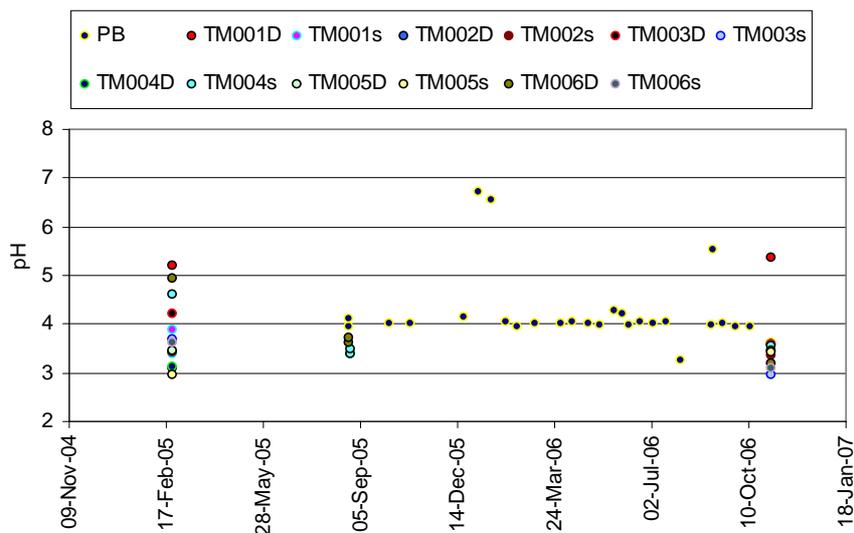


Figure 29 pH of groundwater in the deep and shallow aquifer

6 Groundwater modelling

The Tammin groundwater flow model represents the three hydrogeological layers and the palaeochannel sediments encountered during the drilling program. The layer overlying the sand at the bottom of the channel representing aquitards separates the surficial sandy clay and deep sand aquifers.

The buried palaeochannel aquifer is treated as a channel of higher hydraulic conductivity embedded in the weathered granite (Fig. 30). The weathered granite represents a regional aquifer of lower conductivity throughout the model domain. Groundwater recharge occurs at the top of this layer through infiltration. Water losses from deep aquifers occur through leakage to the overlying aquitard. The base elevation of this aquifer is set to 220 m AHD and thickness to 30 m. The hydraulic conductivities of the weathered granite and palaeochannel aquifers are 0.03 m/d and 0.46 m/d respectively.

The aquitard layer separates the deep and the-shallow aquifers with the vertical hydraulic resistance resulting in a semi-confined condition for the deep aquifer as it was observed from pumping test data. The aquitard has a thickness of 11 m throughout the model domain with a hydraulic conductivity of 0.005 m/d.

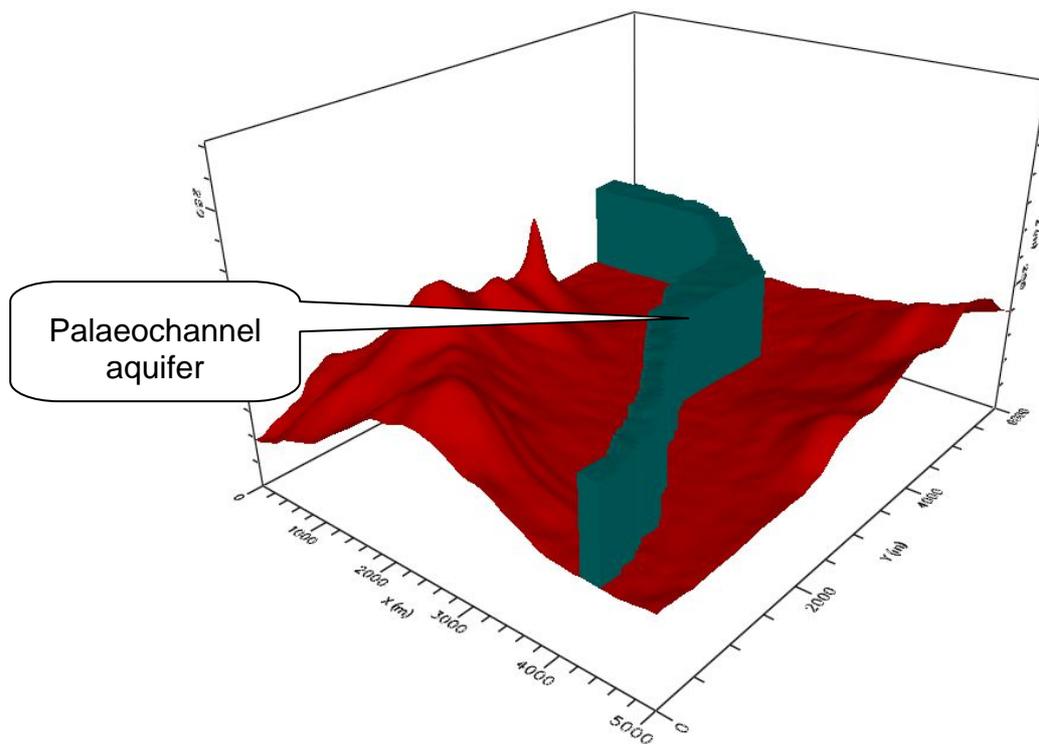


Figure 30 Three-dimensional view of the Tammin palaeochannel aquifer

The model is constructed using MODFLOW, and the aquifers are treated as extending over the entire model domain (Fig. 30). The only boundary imposed on the system is a general head boundary for the groundwater elevation (0.8 m below ground surface) at the discharge point at the north-western corner. The main waterway acts as hydrologic boundaries to the system. The model uses groundwater recharge, evapotranspiration and groundwater flow to maintain the water balance for inter-aquifer flow. This allows the model to respond properly to inter-aquifer stresses, like pumping, imposed on the system water balance.

The model covers the 5000 X 6000 m of the Tammin site. The production bore is located in the middle of the model domain so the effects of pumping can be detected along the palaeochannel in equal measures. The model domain incorporates all the observation bores on the site. Each cell is 50 m², resulting in 120 rows and 100 columns. The topographical data were taken from digital elevation maps of the catchment and geostatistical krigging was used to obtain a value for each node within the model area.

6.1 Recharge estimation from trend analysis

Various methods have been used to estimate recharge rates in the Wheatbelt of Western Australia (Johnston 1987; Nulsen 1998). Hydrograph analyses over the last 20 years suggest that the rate of recharge in the Wheatbelt after clearing is 5–12% of the annual rainfall, depending on the climate and catchment location (Nulsen 1998). In this study, the recharge rates were calculated using trend analysis of the controlled bores (bores not affected by pumping), with data then extrapolated for each cell based on its hydrogeological properties and the type of vegetation cover.

In the 1960s local farmers at Tammin observed the effects of a shallow saline watertable on the landscape at around 225 m AHD elevation (Tony York, pers. com. 2006). Within two years of establishing the paddock, the crops failed. A recent study by the Department of Agriculture and Food in the Central Agricultural region indicates that the watertables at South Tammin are rising at 10 cm per year (Heath & George 2007). The observed watertable for TM004s, 900 m from the production bore, rose 10 cm during 2004–06 confirming the upward trend. In addition, CSIRO bores located about 2 km to the north in a saltbush experimental site also recorded 10–20 cm per year rises in watertable for the period 2002–04.

The average annual rise in watertable (15 cm) only forms a part of groundwater recharge that goes into groundwater storage. Despite an episodic summer rainfall event in January 2006 and winter–spring rainfall later that year, data from TM004s indicates that only 10 cm was added to the groundwater storage in 2006 (Fig. 21). Most of the groundwater recharge was discharged into creek beds as baseflow.

The groundwater recharge rate in 2006 as estimated in Table 6 is higher than the average and is about 31% of annual rainfall. Two-thirds of the recharge was gained through the episodic rainfall event and some other small events between January and February 2006. Although there has been a significant amount of recharge, only a small volume was added to storage. Between December 2005 and December 2006 the watertable rose by only 70 mm

— equivalent to adding 7 mm of recharge to storage for 2006. In another words, for every mm of recharge adding to storage, a little over 17 mm was discharging from the site.

Table 6 Groundwater recharge in 2006 (based on TM004s)

Recharge event	Rain (mm)	Watertable response (mm)	Recharge (mm)	Recharge rate (% of rainfall)	Recession (mm)	Added to storage (mm)
Summer — episodic	197	880	73	37	63	10
Winter–spring	157.5	440	36	23	26	10
Total (annual)	354.5	1320	109	30.75	99	10

Based on the numbers in Table 6 a daily transient recharge model was constructed as an input for MODFLOW and the results compared with rates from hydrograph analysis in other parts of the Wheatbelt. The average recharge calculated from groundwater balance represents 12% of the average rainfall in the area — consistent with recharge values for other parts of the Wheatbelt (Johnston 1987; Nulsen 1998).

6.2 Recharge and discharge zones

Groundwater recharge to the top layer from infiltration of rainfall occurs throughout the model domain. Evapotranspiration is set, based on a previous investigation in the Collie catchment. Groundwater discharges from Layers 1 and 2 via leakage to the underlying units, discharge to surface waters, and discharge from seepage faces where the formation is truncated by the low-lying waterway. Water discharges from Layer 3 through upward leakage due to the potential head difference between the deep layer and the overlying two layers.

6.3 Calibration

The water levels in the shallow and deep aquifers were calibrated primarily by adjusting the input vertical and horizontal hydraulic conductivities for the aquitard layer and evapotranspiration and the extinction depth from which evaporation occurs in the shallow aquifer. The steady-state model was calibrated using the observed heads in the observation bores. The observed versus modelled depths to the watertable (Fig. 31) suggest that the standard error of estimates is 0.041 m, with a correlation coefficient of 0.962. The maximum and minimum differences in observed versus modelled data are 0.2 m (TM008) and 0.009 m (TM006D) respectively.

The optimisation of the model was carried out using the WinPEST package to test the impact of the hydraulic parameters on the correlation between observed and calculated groundwater heads. The values of hydraulic parameters from WinPEST were similar to values used in the model. Only small variations of 0.02 m/d in vertical hydraulic conductivity values were required to optimise the output of the model.

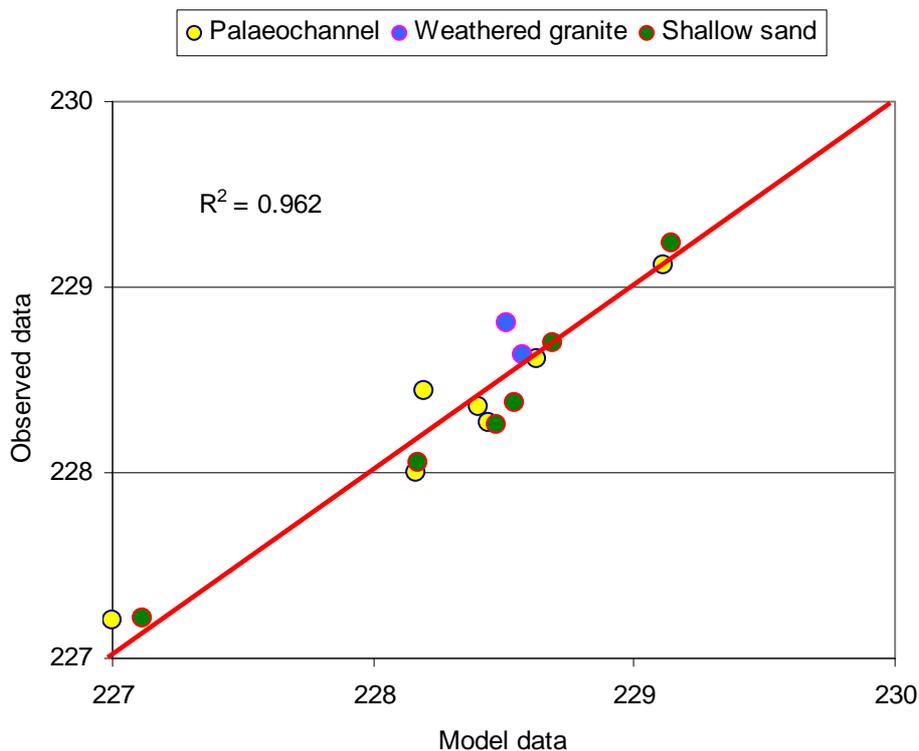
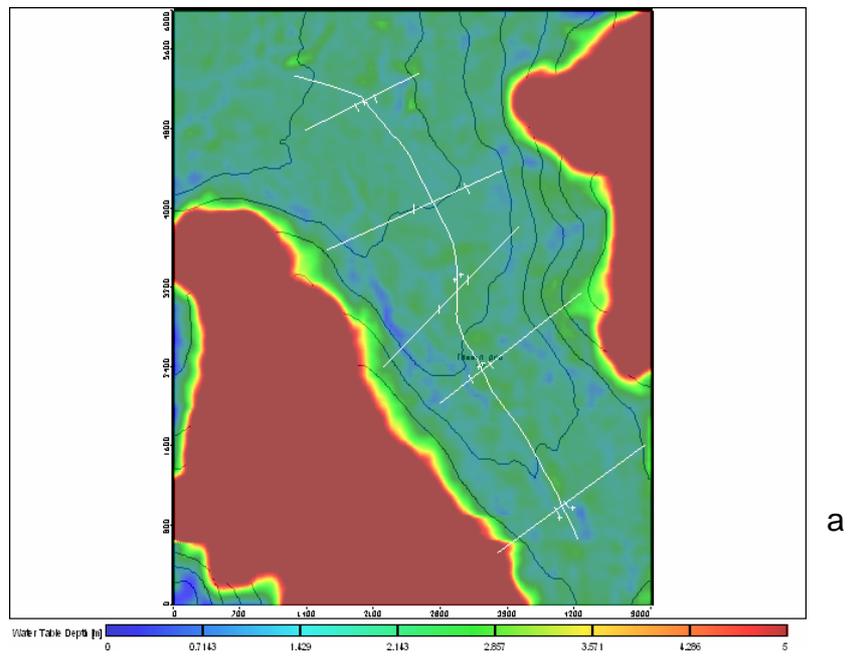


Figure 31 Calibration data for the groundwater model in Tammin

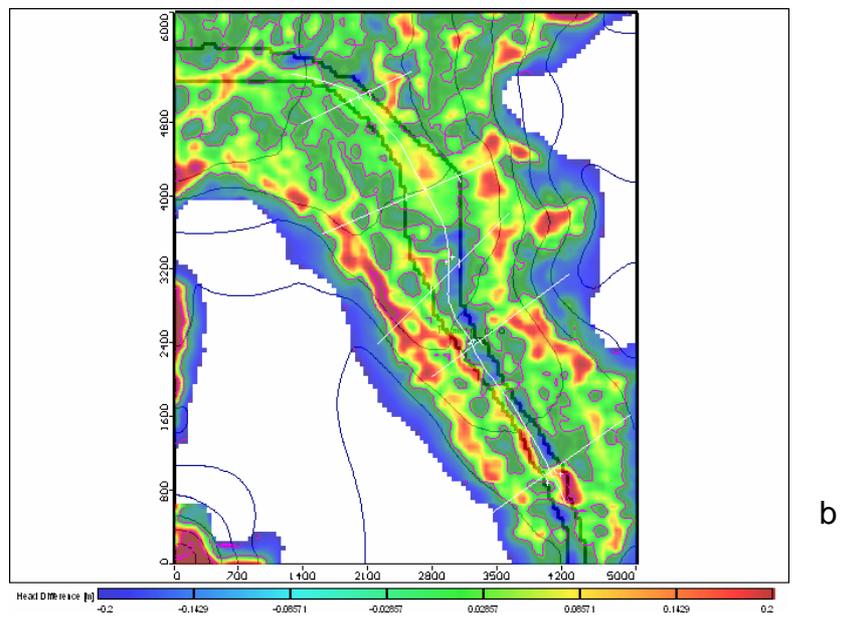
The steady-state watertable depth in the shallow aquifer is shown in Figure 32a. Generally, the watertable ranges from 0–2 m below the valley floor with differences in the depth mainly due to changes in micro topography; for example, the watertable depth along the main waterway (blue) ranges from ~0–1 m and along the palaeochannel (bright green) is ~2 m.

The creek bed is approximately 1.5 m below the main valley floor, so the watertable is closer to the surface.

The head differences between the palaeochannel aquifer and shallow aquifer depicted in Figure 32b indicate a potential for upward groundwater seepage into the main waterway (shown in red and yellow). The difference between the deep aquifer head and shallow watertable at the pumping site is -0.2 (blue) suggesting downward leakage from the shallow aquifer. These results were confirmed by measured data from the monitoring bore prior to pumping. The seepage of saline water from the deep and shallow aquifers along the waterway is confirmed by surface flow salinity measurements at the site.



a



b

Figure 32 (a) Watertable in the shallow aquifer and (b) the difference between deep aquifer head and shallow watertable (Palaeochannel aquifer superimposed as a black line)

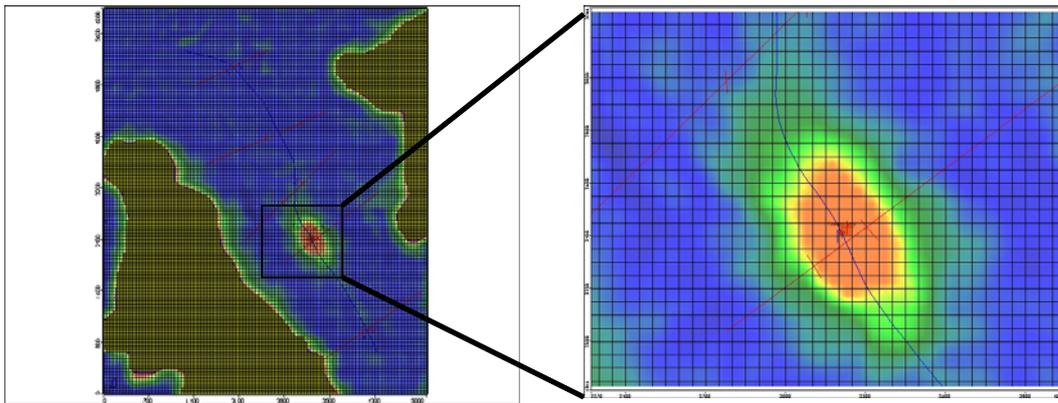


Figure 33 (a) Deep aquifer head and (b) extent of the cone of depression drawn from deep aquifer head

Steady-state model views for the pumping operation are shown in Figure 33. The downward cone of depression shows that the pumping has affected the deep aquifer immediately in the vicinity of the production bore pumping. The cone of depression is shown expanding in an ellipsoidal shape along the palaeochannel as expected from the measured groundwaters. Each cell in Figure 33 is 50 m wide, so the cone of depression is about 300 m wide and 900 m long — as confirmed by previous modelling.

6.4 Transient model

The steady-state simulation provided the spatial distribution of the depth to groundwater and head in the deep aquifers in Tammin while the transient simulation shows the impacts of long-term pumping on lowering the deep groundwater head and the seepage from the shallow aquifer once the head is below the base of the shallow aquifer. The comparison of the various steps of the transient model in terms of watertable depth in consecutive time-steps will provide information on the dynamic nature of the cone of depression. The transient model is constructed to run on daily steps, each representing a stress period for the 521 days of the recorded watertable, head and discharge data.

The modelled and measured heads in observation bore TM001 (50 m downgradient of the production bore) are shown in Figure 34. Although the modelled transient data mimics measured data, the calculated responses to various stress periods are markedly lower. For example, after 4 weeks of pumping, groundwater discharge stops and the head responds rapidly to the stoppage: the calculated recovery is 2 m less than the measured recovery. This is repeated in the latter part of the record.

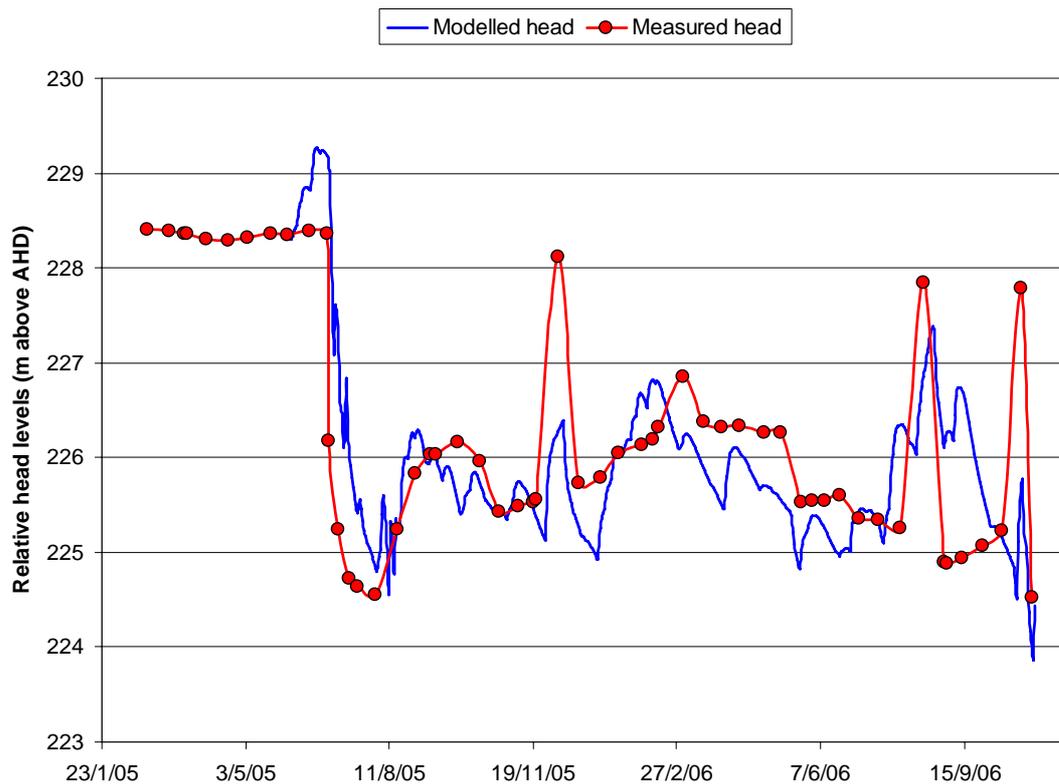


Figure 34 The measured and calculated model heads for the observation bore

The model also responds to recharge events faster than that observed in the field. For example, the calculated aquifer head rises immediately after the January rainfall events while the records show delay period of about two weeks. The explanation for these differences is that the model domain is treated as uniform in terms of hydraulic properties, and the aquifer layers have identical thicknesses throughout the model domain. Despite these shortcomings, it is remarkable how the model accurately responds to changes in water balance for each stress period despite the simple conceptualisation of the study area.

The results confirm the previous finding that the maximum size of the cone of depression in the 512-day record occurred 35 days after pumping started when the head dropped by about four metres and stayed there for five weeks before recovery. The calculated area for this period is similar to that calculated in previous sections (i.e. a 300-m wide and 900 m long ellipsoid with drawdown > 5 m in the middle and 0.1 m around the rim).

The transient model can also be run to simulate the impacts of various climatic scenarios (like decline in rainfall and more episodic recharge), pump capacity, pumping from multiple bores and to estimate the lateral extension of the head drawdown and watertable decline. In addition, this study has shown that simple conceptualisation of a large agricultural area can be carried out to construct numerical models that produce similar results to long-term field measurements.

7 Discussion

7.1 Costs of pumping

The cost of the geophysical survey and infrastructure for the pumping was \$76 000 and the running costs of the generator and the pump were an additional \$15 000 per year (Table 7).

The volume of water pumped from the site was ~ 32 000 m³ over 16 months. The cone of depression had an area of about 21 hectares, though measurements and modelling indicated that the watertable in the outer parts was only lowered by 0.2 m. The area where the water level was lowered by more than 0.5 m was only 250 m from the production bore and covered only 11 hectares.

The dynamic responses of the watertable and the head in the deep aquifer to the rainfall negated the benefits of the pumping in lowering the watertable. This study showed that the lateral extent of the cone of depression was not static and changed according to the water balance at the site. Even if we assumed that the whole area above the cone of depression were returned to production, and the head remained at the same level after the project was decommissioned, the cost of recovering the 21 hectares was \$90 000. While this is not a cost:benefit analysis, the numbers in Table 7 might provide a useful guide to the costs of similar future projects.

Table 7 Costs of the Tammin pumping trial

Item	Cost \$	Running costs/year
Geophysical survey	15 000	
Drilling	36 000	
Pump testing	2 000	
Submersible pump	6 000	
Diesel generator	12 000	
Installation and shed	5 000	
Fuel and oil (generator)		15 000
Total	76 000	15 000

7.2 Is palaeochannel pumping the best way to lower the watertable?

The Tammin groundwater pumping trial provides an example where a (semi) confined aquifer was pumped for more than 16 months to allow seepage from an overlying shallow aquifer. The aquitard obstructing saline (~ 40 000 mg/L) groundwater seepage from the deep aquifer is 11 m thick at the production bore site. The aquitard thins out downgradient resulting in a higher potential for leakage from the deep aquifer.

The groundwater data and modelling suggest that the heads and the watertable here may already be at steady-state equilibrium; in which case, salinity is not expected to worsen.

Long-term groundwater pumping at the site did not change the water balance: the deep aquifer head and watertable responded to short-term changes in rainfall and pumping. An overall decline due to the pumping is not anticipated because recharge in winter generally and episodic recharge in summer more than counterbalance the volume of water discharged by pumping.

In assessing the benefits of palaeochannel pumping, it is important to consider that the semi-confined aquifers rapidly respond to and recover from pumping for minimal removal of groundwater while unconfined aquifers are slower to respond to the same rate of groundwater removal and are slower to recover once dewatered to certain level. The recovery of the land might be the same whether the pumping was directly from the shallow aquifer or by pumping from the deep palaeochannel aquifer to enhance seepage because ultimately the only important factor in lowering the watertable is mining the storage in the shallow aquifer.

If the shallow aquifer is more than 10 m thick, installing multiple shallow bores might prove more useful than pumping a deep aquifer. In many cases however, the shallow aquifer is not thick enough (< 10 m) to install a pumping bore, so pumping the deep aquifer will be the only way to lower the watertable over a large area.

The success or otherwise of groundwater pumping schemes (from confined or unconfined aquifers) depends on the drainability and the leaching of the accumulated salt in the soil profiles.

8 Conclusions and recommendations

The conclusions and recommendations refer to the project's four objectives (Section 1.1).

Better understand the lateral and vertical extents of the palaeochannel aquifer.

The palaeochannel aquifer at Tammin is about 35 m thick overlain by ~ 11 m thick aquitard and a shallow aquifer. A 5 m thick sandy clay shallow aquifer overlies the aquitard and is connected to the deep aquifer. Potential flow from the shallow aquifer is by diffusion and preferential pathways through the silcrete layers interbedded with the aquitard. The palaeochannel aquifer is 300 m wide and offset by 200 m in a north-westerly direction from the main waterway. The channel is embedded in the weathered granite profile that occurs throughout the study area.

Define aquifer characteristics.

The hydraulic properties of the palaeochannel estimated from this study are lower than that estimated for other palaeochannels in the Wheatbelt. The transmissivity and storage coefficients range from ~ 11–18 m²/d and 0.0018–0.0020 respectively. Hydraulic conductivity as high as 0.35 m/d.

The groundwater in the palaeochannel (46 000–64 000 mg/L) is more saline than in the shallow aquifer (28 000–52 000 mg/L) possibly because shallow groundwater mixes with relatively fresh recharge. The pH of groundwater in both deep and shallow aquifers is similar, with a range 3–6.8, and the majority of samples around 4.

Investigate the potential of lowering the watertable by depressurising the deep palaeochannel aquifer.

The objective was to lower the pressure head of the deep palaeochannel aquifer to create an environment where there is a large head difference between shallow and palaeochannel aquifers to promote seepage and consequently lower the shallow watertable.

Pumping from the palaeochannel has resulted in lowering shallow watertable by > 0.5 m at the production bore site due to loss by seepage from the shallow aquifer. The total volume pumped from the palaeochannel sediments was 32 600 m³, more than 80% of which may have come from the unconfined aquifer as vertical leakage to the confined aquifer.

Natural conditions, including heavy rain, swamped the effects of pumping. Very large volumes of water recharge the aquifer compared with the rate of discharge from the production bore. The watertable in all the piezometers within the cone of depression rose above pre-pumping levels in response to heavy rainfall in January 2006 with the relative rises (0.4–0.6 m) directly proportional to their distances from the production bore.

Review the costs, benefits and the practicality of such pumping to control the watertable.

This study has shown that the high annual maintenance cost (~ \$15 000) of palaeochannel pumping to lower the shallow watertable by 0.5 m on 21 ha of agricultural land might be too high even if the costs of disposal were ignored.

This study shows that palaeochannel pumping is not a viable option control the watertable and alternatives should be sought and analysed when dealing with similar systems in the Wheatbelt.

If the objective is to lower the shallow watertable, a better option would be to install a few shallow bores equipped with windmill-driven pumps with the groundwater discharged into an evaporation basin. This option will also have shortcomings such as the loss of additional land and the costs of constructing the evaporation basin. Seepage from an evaporation basin is an issue, particularly in areas of relatively fresh groundwater.

Glossary

aquifer	A water-bearing soil layer that can store and transmit extractable volumes of water.
aquitard	A geological formation of low permeability that can store groundwater and transmit it slowly from one aquifer to another.
cone of depression	Drawdown of water within an aquifer during pumping from a bore as water is removed faster than the surrounding materials can replenish it.
drawdown	A reduction in watertable height caused by the drainage of groundwater by a groundwater drain (see watertable zone of influence)
groundwater	Water within an aquifer below the watertable
hectare	(ha) An area of 10 000 m ²
hydraulic conductivity	(K or K _{sat})A constant of proportionality in Darcy's Law defined as the volume of water that will move through the soil in unit time and unit hydraulic gradient through a unit area measured at right angles to the direction of flow (Ritzema 1994)
hydraulic head	A measurement of water pressure above a geodetic datum; usually measured as a water surface elevation, expressed in units of length, at the entrance (or bottom) of a piezometer. In an aquifer, it can be calculated from the depth to water in a piezometer (a specialised bore).
kilolitre	1000 L or 1 m ³ (approx.) of water (kL)
kilometre	1000 metres distance
m AHD	Height in metres above the Australian Height datum taken as 0.026 m above Mean Sea Level at Fremantle
mg/L	measure of salinity, expression of the mass of salts dissolved in one litre of water
palaeochannel	ancient drainages with deposits of unconsolidated sediments of sands, gravels and clays; separate from the modern drainage
recharge	The addition of water to the groundwater system (mm)
salinity (specific)	The concentration of total dissolved salts in water or soil (mg/L)

salinity (general)/salinisation	The reduction in the productivity or biodiversity of land or water due to an excess of salts within the environment.
sediment	Material (soil) that is or has been moved from its site of origin by erosion.
transect (bore)	An alignment of bores used to measure a locus/line of points of the watertable.
unconfined aquifer	A permeable bed partly filled with groundwater the surface boundary of which is the watertable. The groundwater is in direct contact with the atmosphere through the open pore spaces of the overlying soil or rock, the upper boundary is the watertable.
water balance	An equation of all of the inputs and outputs of water for a volume of soil or hydrological area over a given period of time.
watertable	Surface of unconfined groundwater at which the pressure is equal to atmospheric pressure.

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