Government of **Western Australia**
Department of **Water**

Groundwater pumping to prevent salinity at Bodallin

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Salinity and land use impacts series

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by

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Department of Water

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Cover photograph: Windmill at the project production bore at Bodallin
Photographer: S Dogramaci

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Summary

In this project groundwater was pumped from a production bore into a nearby evaporation basin where the water mostly evaporated and the salt leaked through the basin floor. Three power sources – solar panels, an electrical generator and a windmill – were serially used to drive the pump. The project purpose was to compare the effectiveness, costs and practicality of these power sources to control groundwater levels in farmland areas at risk of becoming salt affected. This approach for watertable control appears to be feasible but would require multiple production bores not just one.

Rising groundwater levels and salinity have affected large areas of the Wheatbelt in Western Australia resulting in loss of agricultural productivity and biodiversity. Efforts to lower high watertables have involved biological (trees or deep-rooted perennials) and engineering (drains or groundwater pumping) approaches. These are generally started only after salinity and associated crop failure or vegetation decline become evident.

By 2000 rising saline watertables within the valley floor of the Bodallin catchment were approaching 2 m below ground surface. To prevent salinity affecting their farms landowners in the Bodallin Catchment Group began groundwater pumping to control further rise. This report presents the results of pumping over a two-year period during 2005–06 and assesses its effectiveness as a practical method for controlling rising watertables at the paddock, farm and even catchment scale.

The practicalities of pumping are strongly influenced by the efficiency and reliability of available pumps and power supplies. Pumping schemes are often remote from the state electricity grid so may be dependent upon other ‘local’ sources of energy to lift water from a bore or well. At Bodallin, the efficiency and cost-effectiveness of solar panels and a windmill were compared with an electrical generator as local power supply options for pumping.

Saline groundwater, pumped from a 12 m deep bore drilled into the surficial aquifer, was discharged into a nearby evaporation basin. Groundwater hydrograph analysis indicated pumping resulted in a drawdown that extended at least 100 m from the production bore and suggested a watertable control benefit beneath some 3–20 ha. After about 18 months of pumping the watertable remained at around 2 m below ground despite heavy summer rains that caused interim groundwater rises.

The efficiencies of the power supply options were compared by their areas of watertable control. The areas were calculated from modelling pump discharge volumes over an extended period. The generator-powered option produced a potential watertable control beneath about 52 ha, given average recharge of 24 mm/yr (8% of average rainfall). This was followed by wind, 32 ha, then solar, 20 ha. The daily running time of the pump had the greatest effect on discharge and so watertable control. Solar had the most limited time of about eight hours a day. Higher groundwater recharge rates also caused corresponding reductions in watertable control.

In most cases, the area of watertable control needed to prevent salinity is greater than that achievable with a single production bore. To control the watertable over larger areas a bore-field approach would be needed. For this scenario the distances between bores was estimated by extrapolating the results from the three pumping options at Bodallin.

In the extrapolated bore-field the wind-powered pumping option was the most cost-effective and reliable energy source at $156/ha/yr calculated over the first 10 years. Solar-powered pumping was almost twice as costly at $255/ha/yr and the electrical generator pumping nearly four times at $565/ha/yr. Fuel, maintenance and replacement costs for the generator made this energy source the most expensive option.

A water and salt balance was used to demonstrate that an on-site evaporation basin was a suitable means for disposing of the saline groundwater discharge. Of the 14 800 kL of water pumped into the basin, 75% evaporated and the remainder leaked back into the underlying groundwater at an average rate of about 1.5 mm/d. All of the 590 t of salt pumped into the basin was lost with the leakage through the basin floor. Basin leakage caused no significant measured changes in either levels or salinities of the surrounding groundwater during the term of this project.

Computer modelling confirmed that the existing basin with its 0.9 ha surface area was large enough for the disposal of 4900 kL/yr and 7711 kL/yr from the solar and wind powered pumps, respectively. If continuous pumping with the generator were employed a basin surface area of at least 1.2 ha would be needed to evaporate the 12 410 kL/yr of expected discharge.

1 Introduction

Replacing native deep-rooted perennial vegetation with annual crops has changed the hydrologic cycle over large areas of the Wheatbelt in south-western Australia. Increased groundwater recharge has raised watertables, particularly around drainage lines and in many low-lying valley floors, so that the land is under threat of salinity and declining agricultural production.

For most Wheatbelt soils and landscapes reliable dryland crop growth begins to fail when the watertable rises above about 2 metres below the ground surface (Nulsen 1981). In some areas where high watertables and salinity have affected crop production, engineering solutions such as drainage and groundwater pumping have been used on a limited scale to lower watertables. These are generally reactive and remedial measures used to contain the spread of salinity or to recover agriculture land for cropping. Where the watertable is predicted to rise but is not yet near the surface, groundwater pumping can also be used to keep the watertable below 2 m to prevent salinity. This is a proactive approach to salinity prevention yet to be adopted by the wider farming community.

The effectiveness of groundwater pumping depends largely on the permeability of the aquifer, the amount of recharge and pumping rate. More groundwater can be pumped from an aquifer with higher permeability, such as sand, than one with lower permeability, such as clay. The geology of the Wheatbelt consists of granite and gneiss basement as the parent material of the low-yielding mainly clays with minor quartz that form its weathered regolith aquifers. Bore yields range from about 0.03 to 3 L/s, with median value of 0.8 L/s (George 1991; Allen et al. 1999), limiting the potential to develop high yielding production bores. Conversely, recharge rates at Bodallin are only in the order of tens of millimetres a year (De Broekert & Coles 2004) reducing the need to pump large volumes to control the watertable.

The Western Australian government's Engineering Evaluation Initiative (EEI) was established in 2002 to trial and evaluate various engineering solutions to Wheatbelt salinity (Dogramaci & Degens 2003). The focus was on increasing understanding of the appropriate use of engineering options to manage dryland salinity for economic, social and environmental benefits. The main scope of EEI consisted of three programs:

1. Improved siting and design of engineering options to maximise performance at the farm and catchment scale
2. Safe disposal of discharge waters
3. Implementation of options within a planned regional drainage context

Groundwater pumping was one engineering option trialled under EEI. The project was undertaken by the Department of Water in partnership with the Bodallin Catchment Group in 2005–07.

The pumping trial took place near Bodallin, about 300 km east of Perth in the eastern agricultural region of the Western Australian Wheatbelt. The aim of the project was to investigate the cost-effectiveness of groundwater pumping as an option to prevent or reverse further watertable rise. Part of the assessment included the practicalities of pumping in remote locations and the disposal of the saline and acidic discharge. To address these issues the project included both the evaluation of three energy sources to lift groundwater from the bore and the use of an evaporation basin to dispose of the discharge. The project objectives were:

1. Compare the cost-effectiveness and practicality of using an electrical generator, solar panels and windmill as power sources for the pump.
2. Calculate the area of land protected from a rising watertable when using an electrical generator, solar panels and a windmill to drive the production bore pump.
3. Evaluate the performance of the evaporation basin as a receiving environment for the discharge by using a water and salt balance approach.
4. Determine if pumping can prevent or reverse groundwater rise at a farm scale.

2 Site characteristics

2.1 Location

The Bodallin project site is in the eastern agricultural region of the Western Australian Wheatbelt about half way between the towns of Merredin and Southern Cross. It is located approximately 300 km east of Perth and 10 km north of the Bodallin townsite in the shire of Yilgarn (Fig. 1). The map reference for the site is Yilgarn Location 1365 and the project's production bore has the approximate MGA map coordinates of 678 200 mE, 6 532 200 mN (Zone 50).

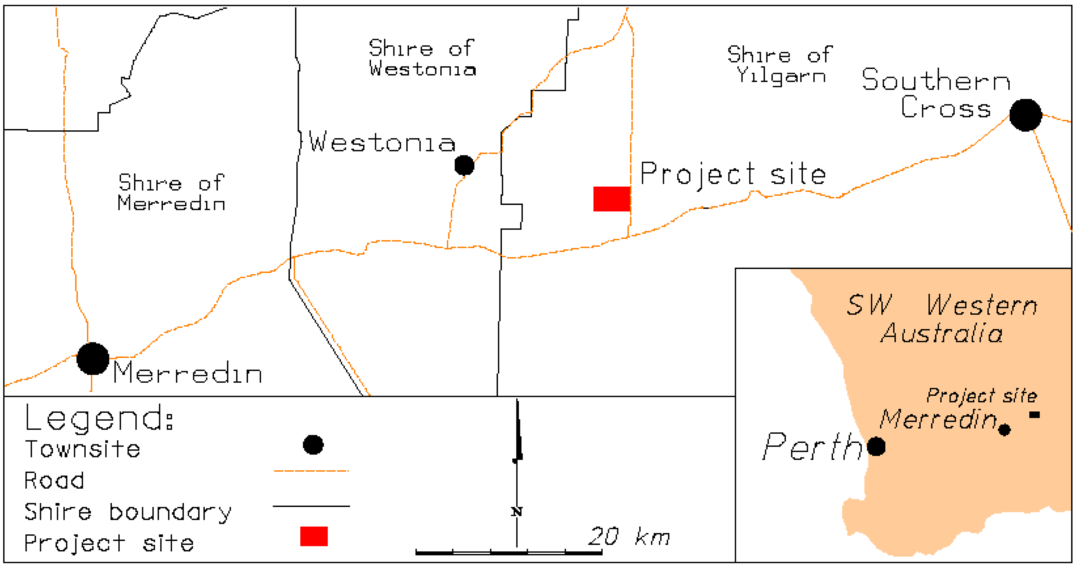

Figure 1 Location of the Bodallin groundwater pumping site

2.2 Climate

Bodallin has warm to hot summers and mild, moderately wet winters. The mean maximum daily temperature ranges from 16 °C in July to 34 °C in January. The average annual rainfall for Bodallin (1970–2007) is 310 mm (Bureau of Meteorology 2010). Approximately 60% of the total annual rain falls during the winter months (May–October). Winter rainfall is delivered by cold fronts that originate in the Southern Indian Ocean and regularly pass over south-west Australia. Summer rainfall is sporadic and associated with north-west tropical thunderstorms.

An automated rain gauge and Class-A pan evaporimeter were operated at the site from January 2005 to January 2007. Below-average rainfall was recorded in 2005 (247 mm) and above-average in 2006 (355 mm). A rain event of 67 mm on 4 January 2006 contributed to the above-average falls and uncharacteristically nearly 70% of total annual rainfall fell during the summer months (January–April) of that year. Class-A pan evaporation at the site totalled 2574 mm in 2005 (10 times rainfall) and 2596 mm in 2006 (Fig. 2).

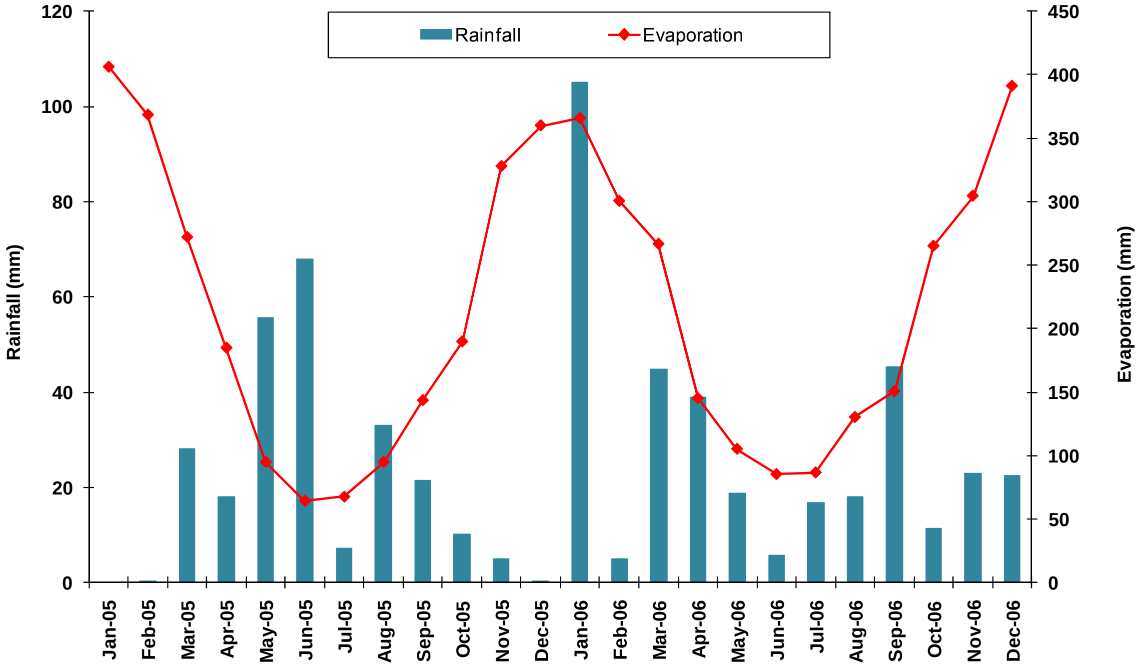

Figure 2 Monthly totals for rainfall and evaporation at the Bodallin project site

Solar radiation intensity and wind speed were not recorded at Bodallin. The values used in this report were obtained by averaging records for Merredin (60 km west) and Southern Cross (50 km east) for 2005–06 (Bureau of Meteorology 2010). This gave a mean daily solar radiation intensity for Bodallin of 29 MJ/m^2 in December which is three times the exposure (10 MJ/m^2) in June (Fig. 3). Average daily wind speeds ranged from 8 km/h in May to 12 km/h in February; the slightly higher speeds being the result of easterly winds generated by summer weather patterns.

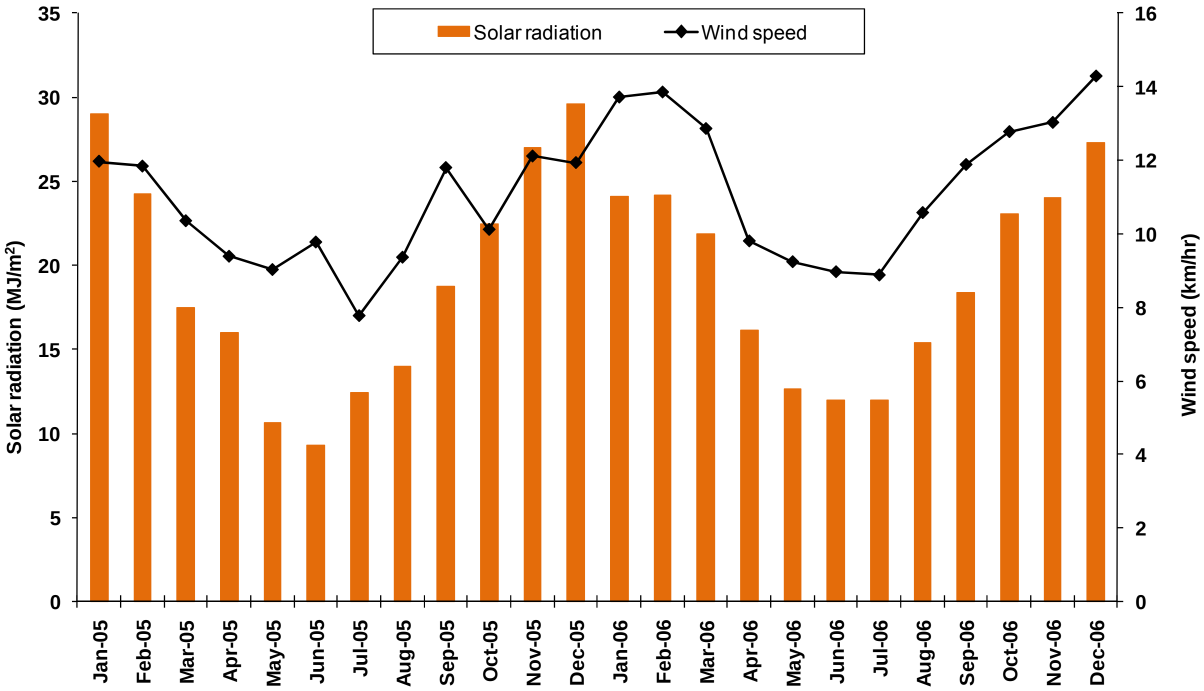

Figure 3 Average daily solar radiation and wind speed for each month at Bodallin (from Merredin and Southern Cross data)

2.3 Land use

The Bodallin region supports broad-acre dryland rotational cereal (mainly wheat) and legume cropping, with some livestock grazing. Land is often fallow between harvest in November and seeding in May. To enable agricultural production, the surrounding landscape has been largely cleared of native vegetation except for small remnant patches.

2.4 Topography and surface drainage

The Bodallin catchment is about 75 km long and 20 km wide with an area of 1324 km^2 (De Broekert & Coles 2004). The catchment encompasses a central southern tributary of the Yilgarn River. The Yilgarn River drains the upper north-east of the Swan-Avon drainage basin. Due to the semi-arid climate streamflow in the Yilgarn and its tributaries is ephemeral, with flow only after heavy or prolonged rainfall events.

The project site is roughly centrally located within the valley floor of the Bodallin catchment at an elevation of about 357 m AHD. From this point, the catchment rises to a maximum elevation of 455 m AHD 36 km to the south and falls to 310 m AHD 38 km to the north. The average slope along the valley floor is about 1 m/km (0.001 m/m) between the project site and catchment outlet.

The expansive flat valley floor varies in width from about 1 to 5 km in the lower two thirds of the catchment. At the project site the width of the valley floor is about 3 km and western footslopes start to rise about 500 m SW of the site. The long and gently inclined (1–5%) valley flanks rise to hilltops at about 80 m above the valley floor.

The main stream channel that drains the catchment passes 50 m to the east of the evaporation basin at the project site (Fig. 8 in Section 3.2). Other than this, drainage across the valley floor is poorly defined. Runoff from the valley flanks often results in sheet flows and ponding across the valley floor. Wetlands and clay pans are common in the catchment but are poorly integrated within the natural drainage network.

2.5 Soils

Regional surveys show that valley floor soils are mostly duplex alkaline red loamy sands to a depth of 1 m over grey clay subsoil (Schoknecht 1997). From drilling results (Dogramaci 2005) these were further described as red-brown or yellow-brown loams or loamy sands ranging from 0.6 to 1.2 m. Subsoils described from the excavated evaporation basin are medium to heavy grey sandy clays with red-brown mottles. In some instances the mottled material is extensive and cemented so as to form hardpans at about 2 m below the surface.

Lateritic loams and sands formed on most valley flanks are gradational and duplex over pale grey medium sandy clay or clay. Deep sand and deep sandy duplex soils are also present, commonly associated with minor drainage depressions.

2.6 Geology and hydrogeology

The Bodallin catchment is within the west Yilgarn tectonic terrane of the Yilgarn Craton. Basement is predominantly composed of Archaean granite, adamellite and gneiss and is locally intruded by mafic dykes (Chin & Smith 1983). Deep weathering of the basement is widespread, reaching a maximum regolith depth of 30–40 m of saprolite and saprock formation. Rocky outcrops are more common on hilltops and valley flanks than on the valley floors.

Weathered granite regolith underlies valleys and hillsides with clay minerals and some angular quartz being deepest in the valleys. Valley floors consist of surficial sediments of Cenozoic gravel, sands, and clays and Quaternary colluvium, aeolian sands and clays. These vary in depth and composition over weathered regolith.

A 40 m bore (bore 6d) was drilled at the project site to investigate the underlying hydrogeology. Sedimentary deposits identifiable by rounded and angular quartz grains in the drill cuttings were present from 0 to 16 m. Beneath the sedimentary layer was a 15–20 m thick clay-rich weathered profile that could act as a confining layer between the upper sediments and any underlying saprock aquifer. Drilling did not reach basement rock.

Hydraulic connection between shallow and deep groundwaters is uncertain because there are no adjacent shallow and deep piezometers to measure for comparison. However, the similarity in the groundwater hydrographs of bore 6d and nearby shallow and intermediate bores (bores 7–9) tends to indicate groundwaters are at least moderately well connected to 30–40 m.

Airlifting tests from the 12 project bores produced estimated hydraulic conductivity values of 0.8 m/d for the deepest bore (40 m), 0.5 m/d for the 12 m bores, and about 1 m/d for those 8 m or less (Dogramaci 2005). However, this data provided by the driller is somewhat subjective as airlifting is only a preliminary method of assessing aquifer permeability.

The production bore was drilled in 2001 before this project was started, but not equipped. Landowners reported that it was initially drilled to 40 m and then backfilled and established at its present 12 m depth. The decision to do this was made by the driller on the basis that aquifer permeability below 12 m was very low and the assumption that a deeper bore would be less effective than a shallower one. Although the drill logs for the production bore were not kept, this appeared to be an appropriate assumption given the results of the subsequent hydrologeological investigation undertaken with bore 6d.

2.7 Groundwaters and salinity

Groundwater measurements across the region showed some deeper watertables (> 8 m below ground) have been rising by up to 0.5 m/yr since the mid 1980s (Ghauri 2004). While most of the shallow watertable rise is in the order of centimetres per year, a flood event in January 2000 caused a rapid and much larger rise. Consequently, downward trends towards pre-flood levels were observed during 2000–04. Most of the falling levels were confined to valley floors where, although lateral flow within the aquifer is limited, the shallow watertables are close enough to the land surface for evaporation to occur.

In the lower reaches of the Bodallin catchment high watertables had already prompted some landowners to construct groundwater drains to protect and recover their land from salinity. While the project site and surrounding middle reaches of the catchment showed no evidence of land salinisation – with fairly uniform 2–3 m deep groundwater – some farms in the area had been experiencing increased waterlogging and inundation and were at risk from further watertable rise.

The groundwater at Bodallin is saline and acidic, which is common in the upper Avon catchment and the Wheatbelt in general (Shand & Degens 2008). The process of dryland salinisation is well documented and often caused by groundwater salinities equal to or higher than seawater (35 000 mg/L). The process of groundwater acidification is less well understood. The low pH is mainly due to the oxygen in infiltrating waters reacting with high concentrations of dissolved iron (Shand & Degens 2008). In aquifers with no neutralising minerals such as carbonates pH remains low and the groundwater acidic.

3 Project design

3.1 Project works

The groundwater pumping project at Bodallin consisted of a production bore and an evaporation basin to receive the discharge. The bore and basin had been constructed in 2001 as part of an earlier project by the Bodallin Catchment Group. Additional works undertaken in 2005 included installing the pump and power supplies, drilling 12 groundwater monitoring bores and installing a rain gauge, a Class-A pan evaporimeter and various other monitoring equipment.

Production bore

The production bore drilled in 2001 was unused until the start of this project. The bore was originally test drilled to 40 m, backfilled to 12 m and fitted with a 150 mm diameter bore casing. The inlet screen was placed at 6–12 m depth; that is, in the more permeable part of the aquifer (Section 2.6).

Pumping commenced on 30 June 2005 and the discharge was conveyed via a 50 mm pipe to the evaporation basin 200 m away.

Solar panels

Solar panels were used to power the groundwater pump from 1 July 2005 to 9 June 2006 (Fig. 4). The panels produced a maximum of 400 watts and powered a 60 volt electrical motor positioned above the bore. The motor drove a 75 mm (3 inch) piston pump that was set at 9 m down the bore hole. The solar panels and pump (Sun Mill) were installed by Solar Energy Systems Ltd and the pump was a poly-piston design chosen for its durability and corrosion resistance to the acidic, saline and iron-rich groundwater.

Figure 4 Solar panels powering an electric motor above the production bore at the Bodallin site

Electrical generator

A small single cylinder diesel fuelled generator was used to power the pump from 10 June to 31 October 2006 (Fig. 5). It produced 1.6 kilowatts and was connected via a transformer to the 60 volt electric motor and pump used during the solar-powered pumping phase. A 205 L auxiliary fuel tank was provided so the generator could run for about a week between refuelling.

Figure 5 Electrical generator at the Bodallin site

Windmill

A windmill with a 3.6 m (12 foot) diameter fan on a 6.0 m (20 foot) tower was used to drive the pump from 1 November 2006 to 14 April 2007 (Fig. 6). The Yellow Tail brand windmill was installed over the production bore by WD Moore and Co. The original 75 mm piston pump used by the solar and generator power options was replaced with a 108 mm (4 inch) piston pump better suited to the windmill.

Figure 6 Windmill at the Bodallin site

Evaporation basin

The evaporation basin was constructed using a bulldozer to first strip about 0.8 m off the sandy and loamy gravel upper soil profile to form the walls of the basin and expose the clay subsoil. About 0.5 m more of the clay subsoil was stripped from the basin floor area and pushed over the material in the walls to create a clay blanket of lower permeability. No compaction other than track rolling by the bulldozer was used.

The completed basin is about 160 m long and 65 m wide with a floor and overflow elevation of 361.7 m and 364 m AHD respectively, making it about 2 m deep. The floor is approximately 4000 m^2 and the inside batters are about 1:4 (Fig. 7). At its maximum capacity of 13 700 m^3 (13 700 kL), the evaporative surface area is 8905 m^2 (0.89 ha).

The basin is 200 m east of the project production bore (Fig. 8). Since April 2001 it had been receiving the discharge from two other production bores situated 300 m and 900 m to the east of the basin. From July 2005 the basin began receiving additional discharge from the project production bore.

Figure 7 Evaporation basin at Bodallin

3.2 Project monitoring

Monitoring bores

Twelve groundwater monitoring bores were drilled at the site in September 2004 (Fig. 8). Descriptions of the lithology are set out in the drilling logs (Table 1; Dogramaci 2005). (Although the codes assigned to the bores by Dogramaci (2005) are BD001–009 in the drill logs, in this report they are referred to as bores 1 to 9). The relative depth of the bore is indicated by a letter so that ‘d’ represents a deep bore (e.g. bore 6d) and ‘i’ represents an intermediate depth bore (e.g. 7i) when paired with a shallower bore.

Bores 1–5 formed a 400 m transect north-west of the production bore (Fig. 8) to measure the watertable response to the pumping. They were drilled to 12 m deep and screened at 9–12 m below ground level (bgl; Table 1).

Three sets of paired shallow and intermediate depth bores (bores 7, 7i, 8, 8i, 9 and 9i) were aligned in an 80 m transect at the north-east corner of the basin (Fig. 8). These bores were used to monitor water level changes caused by leakage from the basin. The shallow bores were drilled to 4 m and screened at 1–4 m bgl while their paired intermediate bores were drilled to 8 m and screened at 5–8 m.

Bore 6d is located at the north-west corner of the basin. It was drilled to 40 m to investigate the lithology and aquifer parameters of the site (Section 2.6).

Table 1 Bore information

Bore	Depth (m)	Screen (m bgl)	Distance from production bore (m)	Depth to water (m bgl)[1]	Salinity (mg/L)
Production	12	6–12	0	2.07	40 390
1	12	9–12	20	2.09	42 050
2	12	9–12	50	2.29	41 700
3	12	9–12	100	2.44	39 040
4	12	9–12	250	2.50	37 050
5	12	9–12	400	2.52	38 000
6d	40	34–40		1.94	50 150
7	4	1–4		1.88	6 650
7i	8	5–8		1.83	16 350
8	4	1-4		1.87	4 800
8i	8	5-8		1.93	21 000
9	4	1–4		1.82	6 250
9i	8	5–8		1.83	21 100

[1]Measured 24/02/2005

The water levels in bores 1–9 were measured in-situ approximately every two weeks from February 2005 to April 2007. In addition, bores 1, 2, 3, 5, 7 and 7i were equipped with automated water level sensors to measure and record at 2 or 4 hour frequencies between 19 May 2005 and 18 April 2007.

In-situ salinity and pH were measured in all bores at least once in 2005 and in 2006.

Comparison bores

Existing monitoring bores in similar landscapes and soils but 2–4 km from the project site were used to provide comparison water level measurements. The 14 bores were beyond the influence of any pumping or earthworks so changes in their groundwater levels represented the natural fluctuations caused by rain-fed recharge, evaporation and barometric pressure changes. Of the bores measured, three (SB1, NB1a and NB4) provided the comparative monthly water levels used in this report.

Pump discharge

The volume of groundwater lifted from the project production bore was measured by an automated flow meter. Continuous discharge was measured at the pipe's outlet at the western side of the basin (Fig. 8) and the volume automatically recorded every ten minutes from July 2005 to January 2007.

Discharges from the two existing production bores (Section 3.1) were measured by a dial flow meter at the SE corner of the basin (Fig. 8) and the cumulative volume was read periodically between December 2004 and May 2006.

The salinity and pH of the discharges were routinely measured throughout 2005–07 at their respective pipe outlets and before mixing with basin waters.

Evaporation basin

The basin water level was recorded daily from 8 July 2005 to 26 November 2006 by an automated water level sensor placed in the basin. In addition, in-situ water level measurements were read from a staff gauge at 1–3 monthly intervals between December 2004 and April 2007.

Basin water salinity and pH were periodically measured between 22 March 2005 and 18 April 2007 at the same times as the pump discharges. The measurements were collected as far as possible away from the pump discharges.

Climate station

Rainfall and evaporation were recorded daily between 1 January 2005 and 10 January 2007 by an automated weather station located at the rim of the evaporation basin (Fig. 8). Daily rainfall was measured by a tipping bucket rain gauge and evaporation by a Class-A pan evaporimeter.

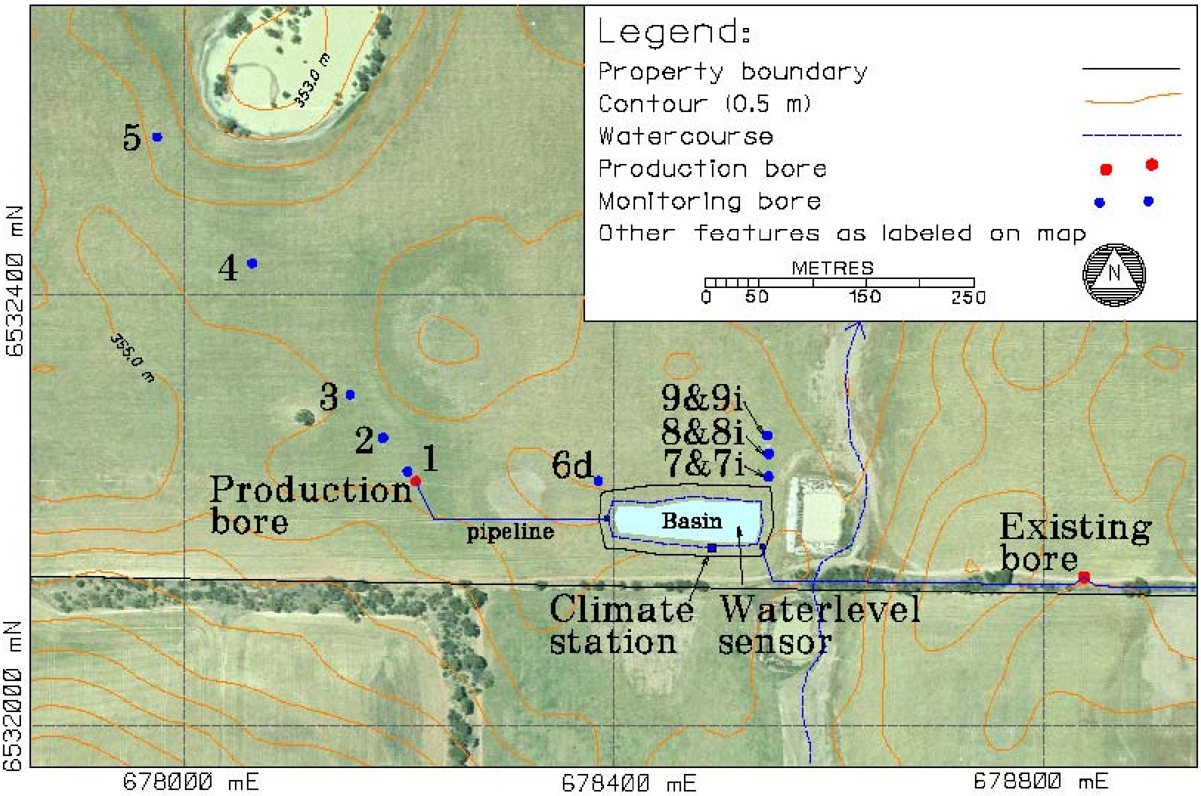

Figure 8 Layout of project site at Bodallin

4 Results

4.1 Comparison bores

Groundwater levels

Water levels measured in the comparison bores were 2–3 m bgl throughout the monitoring period (Fig. 9). In early 2006 recharge from heavy rains drove the water levels up about 0.5 m (NB4). After peaking at the end of March 2006 they receded but remained up to 0.3 m above 2005 levels.

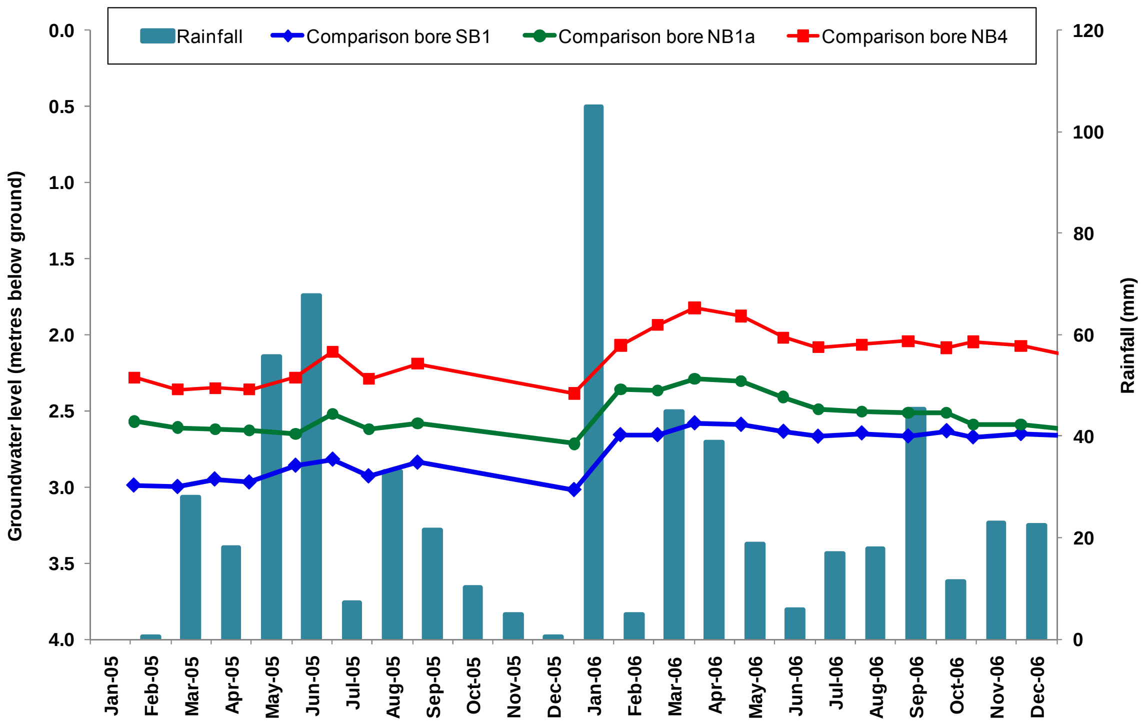

Figure 9 Groundwater levels of the comparison bores at Bodallin

4.2 Production bore drawdown

Groundwater levels

Before pumping started, the watertable along the transect of bores 1–5 was more than 2 m bgl and gradually falling from February to July 2005, possibly in response to high summer evaporation rates (Fig. 10). The water levels in bore 1 remained consistently higher than in the other bores. Levels in bores 2 and 3 were almost the same and in bores 4 and 5 about 0.2 m and 0.5 m respectively, lower. The pre-pumping levels showed a hydraulic gradient away from the production bore on 5 June 2005 (Fig. 11).

When pumping started on 1 July 2005 the water level in bore 1 fell instantaneously by 0.5 m to below the level in bore 5 (Fig. 10). When pumping stopped it rapidly recovered to close to its original level. This cycling was most evident during the period of solar-powered pumping when the pump operated only during daylight.

The response to pumping decreased with distance from the production bore and the water level changes measured in bores 2 to 5 were much smaller than in bore 1. While the pump was operating, groundwater drawdown gradually reorientated the hydraulic gradient towards the production bore from at least 100 m (bores 1–3; Fig. 11).

The effects of pumping on the water levels in bores 2 and 3 are reflected in the relative positions of their hydrographs. From 1 July 2005 the hydrograph of bore 2 fell below the level of bore 3. The hydrograph of bore 3 fell slightly but remained above bore 4 (Fig. 10). Continuous pumping driven by the electrical generator increased the drawdown between bores 1–3 to a maximum in September 2006. Each time the pump was shut down (4 December 2005, 29 October 2006 and 6 March 2007) the water levels in bores 1–3 rose to about their pre-pumping positions (Fig. 10).

Beyond 250 m (bores 4 and 5) any watertable response to pumping is less clear. Although a small increase in their water levels occurred during some pump shut down times it was much less than in bores 1–3 (Fig. 10). The relative positions of their hydrographs were similar with and without pumping and the water level changes were generally within the range of natural groundwater level variability.

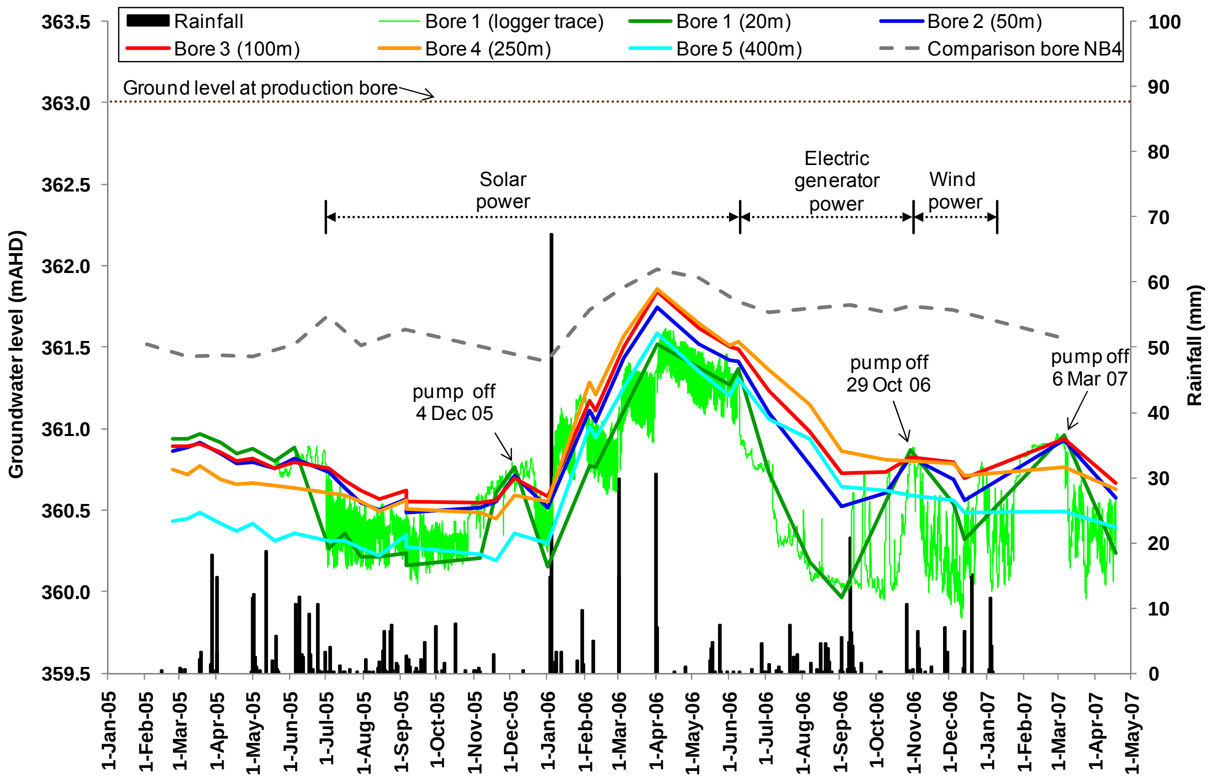

Figure 10 Groundwater levels in bores 1–5 and comparison bore

Recharge from rainfall events of 30 mm or more in January, March and April 2006 raised water levels in bores 1–5 by about one metre despite ongoing solar-powered groundwater pumping (Fig. 10). After peaking in April 2006, water levels gradually receded over about five months. By this time levels in bores 1–3 were back to 2005 levels, as measured when the pump was shut down on 29 October 2006, but levels in bores 4 and 5 were still above 2005 levels.

The pumping characteristics of the three power sources are reflected in the groundwater hydrographs produced by the automatic water level sensor in bore 1 (Fig. 10). The daily stop-start characteristics of solar power are seen from 1 July to 9 June 2006. The continuous power of the electrical generator produced a comparatively smooth falling hydrograph from 10 June to 31 October 2006 and from 1 November 2006 to 10 January 2007 the water levels fluctuated widely in response to the strength and duration of the wind.

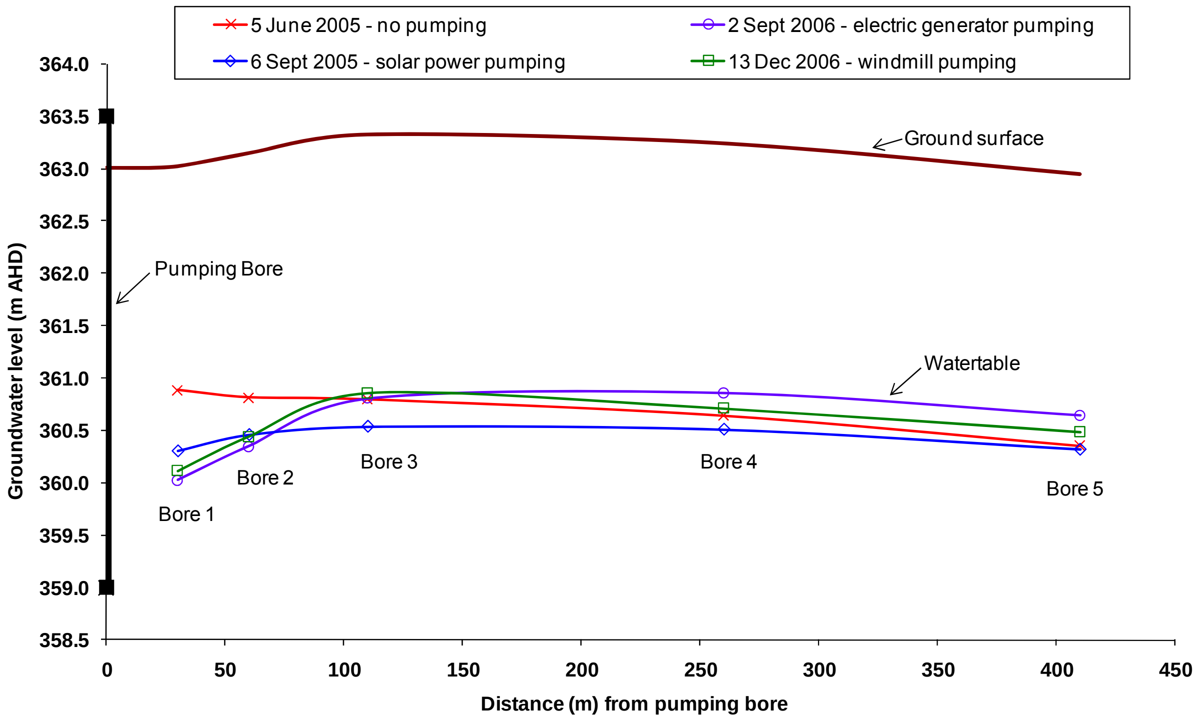

Figure 11 Watertable profiles of transect bores 1–5 during solar, electric and wind powered pumping

Groundwater quality

During 2005 and 2006 salinities in the project production bore and bores 1–5 were 36 000–43 000 mg/L (average 40 000 mg/L; Fig. 12). Some dilution of saline groundwater after the heavy summer rainfall in early 2006 was possibly responsible for the generally lower salinity in 2006 compared to 2005.

Groundwater was very acidic (pH 3.2–4.4) between the production bore and bore 4 at 300 m (Fig. 12). At 425 m (bore 5) from the production bore it was less acidic with average pH 6.3. Pumping from the production bore did not appear to affect groundwater salinity or pH.

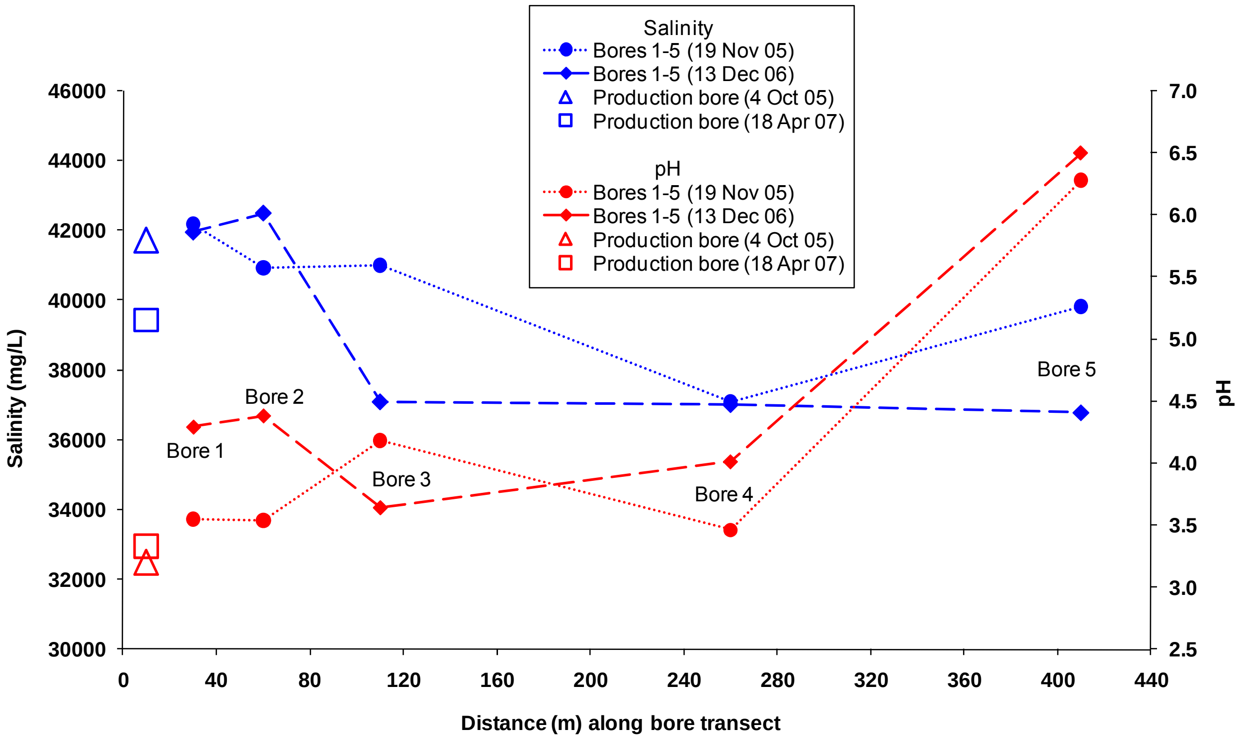

Figure 12 *Groundwater quality profiles for production bore and transect bores 1–5*

4.3 Basin monitoring bores

Groundwater levels

The water levels in bores 7–9, more than 300 m from the production bore (Fig. 8), appeared to be unaffected by pumping. The levels in the intermediate depth bores 7i–9i were the same as in their paired shallow bores throughout the monitoring period and are not presented here.

The hydrographs of bores 7–9 and 6d were similar to bore 5 (400 m from production bore) until June 2006 (Fig. 13). After June, water levels in the basin bores rose until October 2006. This was probably in response to basin leakage because at the same time the level in bore 5 fell and in the comparison bore NB4 was relatively stable.

In the period before pumping (February and April 2005), water levels in bores 7–9 were the same (Fig. 13) so the watertable adjacent to the basin was flat (18 March 2005; Fig. 14). During this time the basin contained the discharge from the two existing production bores and, although not measured, the basin water level and volume were low. Between January and May 2006 the watertable adjacent to the basin was again flat largely because rain-fed recharge raised the water levels in bores 7–9 by 0.8 m (similar to bores 1–5) obscuring any possible level changes due to basin leakage (2 April 2006; Fig. 14).

From June to December in both 2005 and 2006 the water level in bore 7 closest to the basin was higher than in bore 9 (Fig. 13) resulting in a hydraulic gradient sloping away from the basin (Fig. 14). This occurred during the periods of solar, electric and windmill pumping and suggests leakage from the basin. The steepest hydraulic gradient (0.7%) was measured on 9 October 2006 when the water in bore 7 was 0.3 m higher than in bore 9 approximately

40 m away. This coincided with the highest recorded basin water level with associated greatest hydraulic head and potential for leakage. Conversely, the highest (flat) watertable recorded on 2 April 2006 coincided with a relatively low basin level and indicates the dominant influence of rain-fed recharge.

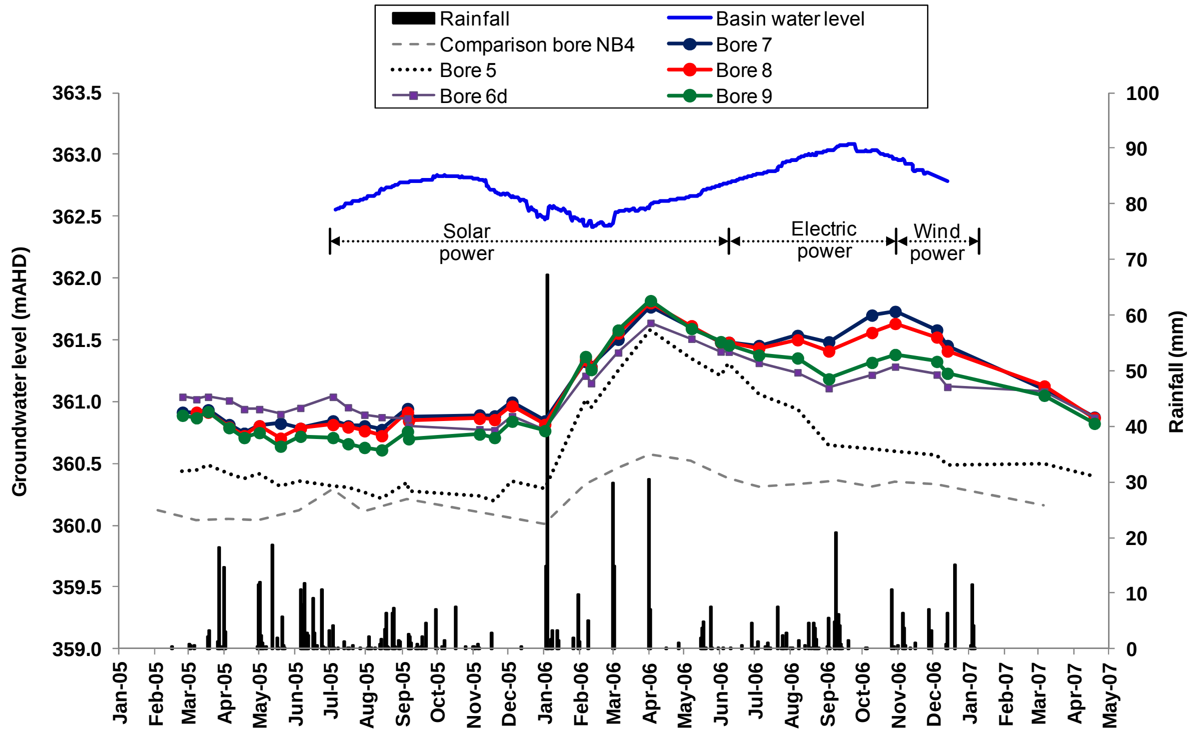

Figure 13 Groundwater levels in basin bores 7–9 compared to bore 5 and comparison bore

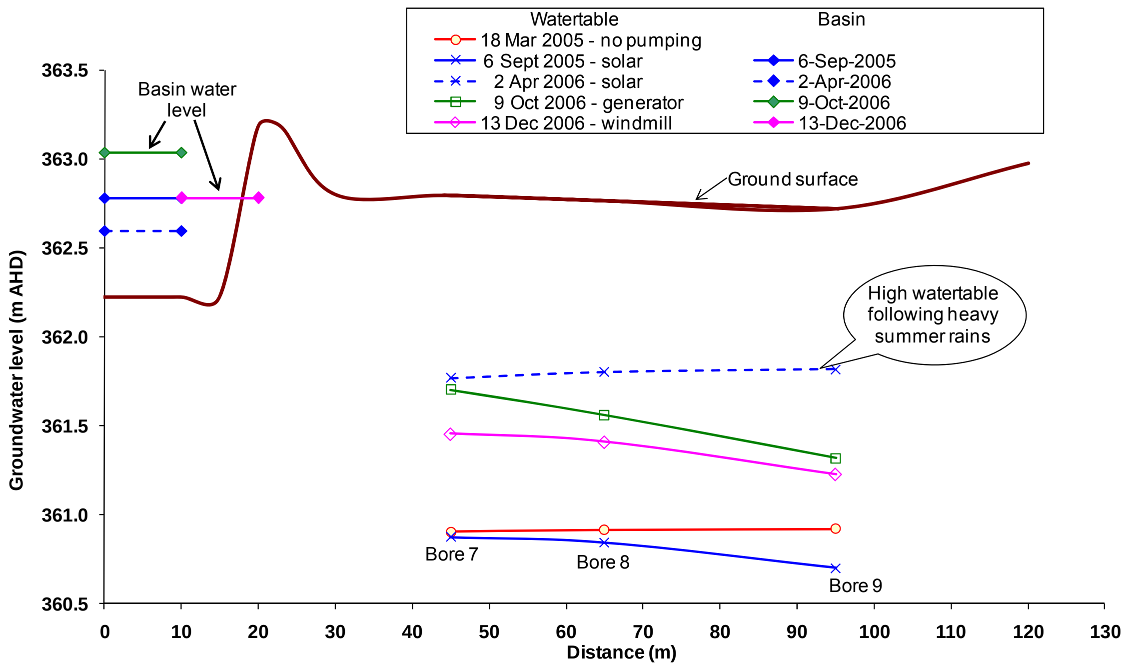

Figure 14 Basin water levels and adjacent watertable

Groundwater quality

The salinities in bores 7–9 varied from around 2000 to 12 000 mg/L (Fig. 15) while their paired deeper bores 7i to 9i had salinities 17 000–33 000 mg/L. The exception was bore 7i, nearest to the basin, which recorded 3000 mg/L in 2006. The highest salinities (around 50 000 mg/L) were found in bore 6d. Basin leakage did not appear to affect salinities in the shallow bores close to the basin during the term of the project.

All basin bores had lower salinities in 2006 than in 2005 possibly because of the dilution by heavy summer rainfall in early 2006. The large variation in measurements in some bores could be attributed to fresh water leaking from the adjacent watercourse (Fig. 8) into the shallow aquifer.

The pH in bores 6–9 was 3.5–7 (Fig.16). The deeper bores generally had more acidic water than their paired shallow bores. All shallow bores and bore 7i became less acidic in 2006. A change in salinity in bore 7i from about 30 000 mg/L in 2005 to 3000 mg/L in 2006 (Fig. 15) corresponded with a rise in pH from 3.5 to pH 7 (Fig.16).

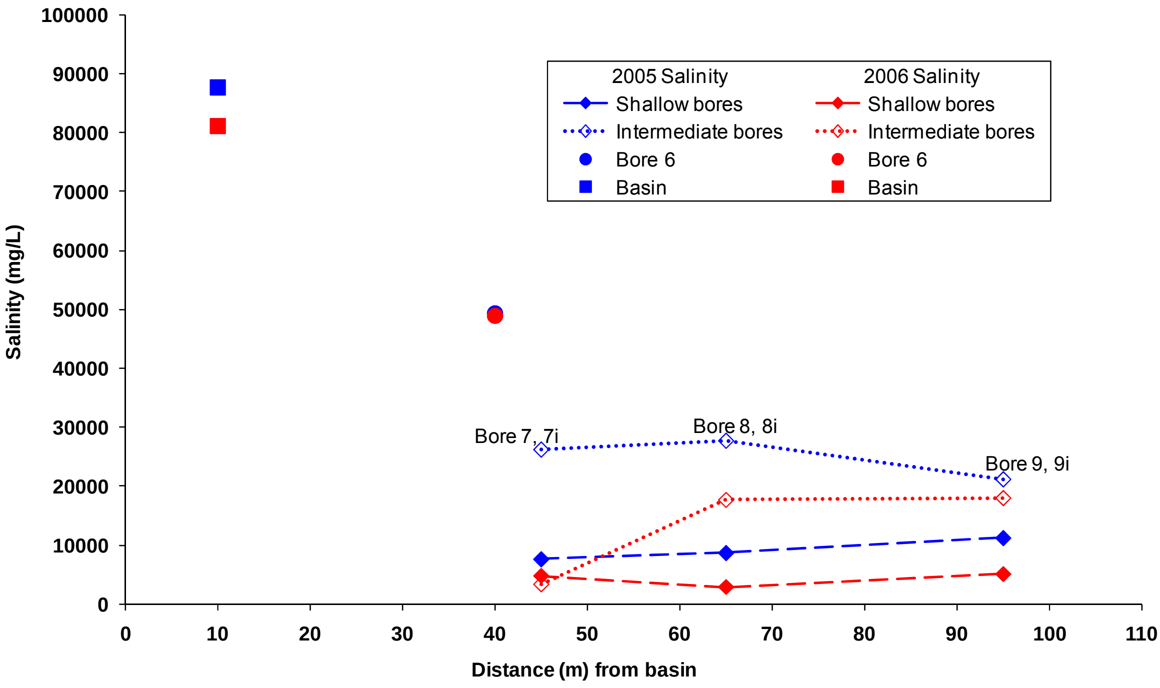

Figure 15 Groundwater salinity along basin bore transect

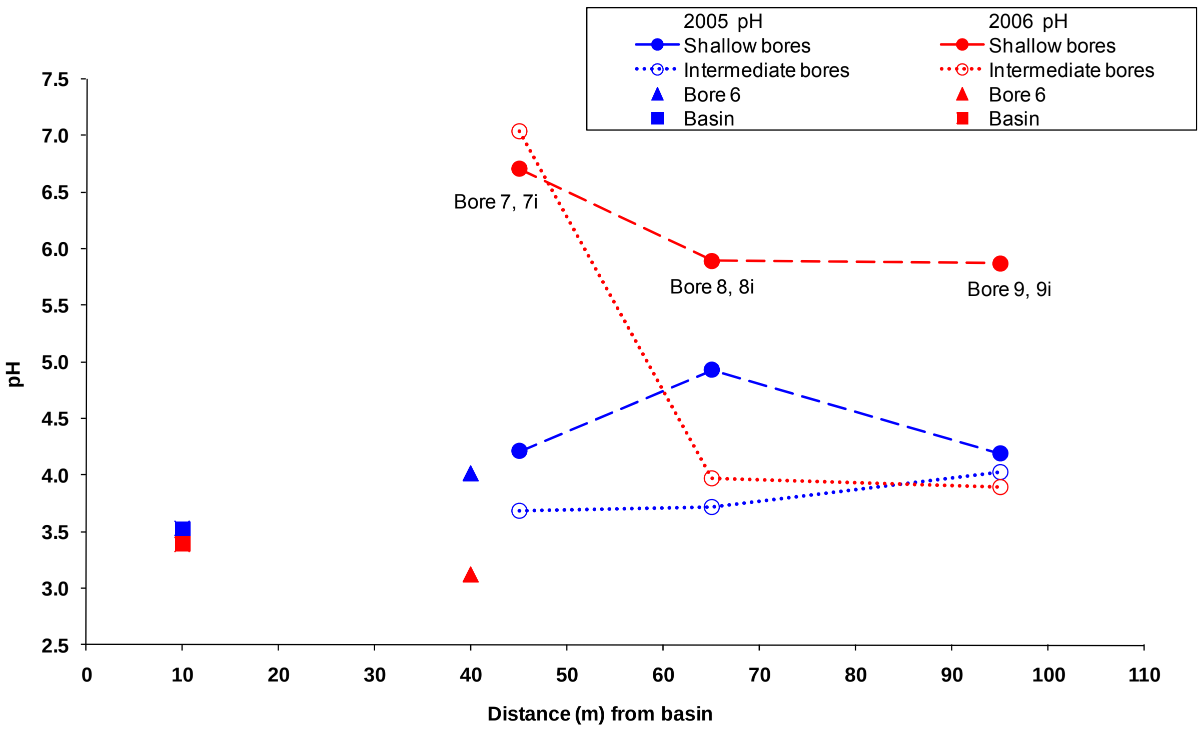

Figure 16 Groundwater pH along basin bore transect

4.4 Pump discharges

A total of 10 030 kL of groundwater was lifted from the production bore between 1 July 2005 and 10 January 2007. The average salinity of the discharge was 40 500 mg/L, from approximately 406 tonnes (t) of dissolved salt. Groundwater inflow to the bore exceeded the pumping rates so the bore never ran dry. Discharge results from the three different power sources are detailed below.

Solar-powered pumping

In total, 3821 kL of groundwater and 155 t of salt were lifted using the solar-powered pumping option (Table 2). As the solar panels only produced power in sunlight the pumping rates were partly limited by the number of daylight hours and cloud cover. Discharge was 4–25 kL/d and averaged 15 kL/d over the 287 days of operation (Fig. 17).

Due to maintenance problems the pump was non-operational for 57 days during which no discharge was recorded. This included a period of 41 days (10 November–22 December 2005) when the production bore had to be re-drilled after its casing had failed and collapsed. The bore failure was not caused by this pumping option.

Generator-powered pumping

Overall, 4474 kL of groundwater and 181 t of salt were lifted from the bore using the generator (Table 2). Discharge was about 30–45 kL/d and averaged 34 kL/d over 136 days of operation (Fig. 17). Although the generator supplied continuous power, the fluctuations in the pumping rate appeared to correlate with the water levels adjacent to the production bore.

Restarting the pump following shut down generally produced higher pumping rates which declined during subsequent days of uninterrupted pumping as groundwater levels around the bore fell.

The pump experienced 8 days of shut down mainly caused by interruptions of the power supply when the generator ran out of fuel or needed routine maintenance.

Wind-powered pumping

Discharge from the windmill pump was measured from 1 November 2006 to 10 January 2007 although the windmill remained pumping until 14 April 2007. Over the 71 days of measurement 1736 kL of groundwater and 70 t of salt were lifted from the bore (Table 2). Pumping rates varied widely depending on the wind strength and duration: 0–74 kL/d and an average 24 kL/d (Fig. 17). The eight days with no flow recorded were mostly due to lack of wind rather than mechanical or recording problems.

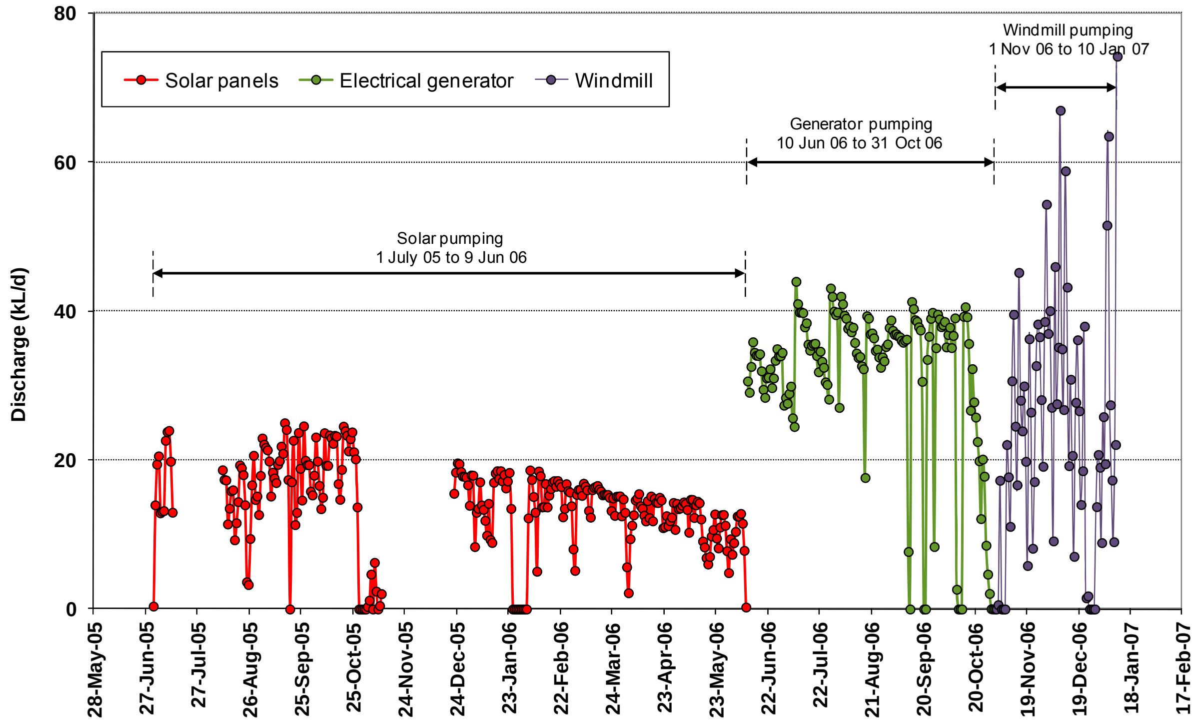

Figure 17 Pumping rates produced by solar, generator, and wind power

Table 2 Results of the pumping options

Pump power source	Total operating days	Total volume pumped (kL)	Average volume per day (kL)	Total salt load (t)	Average salt load per day (t/d)
Solar	287	3821	15	155	0.6
Electric generator	136	4474	34	181	1.3
Wind	71	1736	24	70	1.0

4.5 Evaporation basin

Water level and salinity

The basin water level was less than half its maximum possible depth during 2005–06 while receiving discharge from all pumping sources (Fig. 18). In total, 21 340 kL of discharge and 846 t of salt were pumped into the basin from the three production bores between December 2004 and January 2007. This included 11 310 kL and 440 t of salt from the two existing bores (Section 3.1) and 10 030 kL with 406 t of salt from the project production bore.

Evaporation and leakage to the underlying groundwater kept basin levels at their lowest during summer (January) and corresponding salinities at their highest. The highest salinity (162 000 mg/L) was measured in March 2005 but no corresponding water level was recorded at the time. The lowest salinities (about 70 000 mg/L) were measured during winter (August–September 2006) when basin water levels were at their highest.

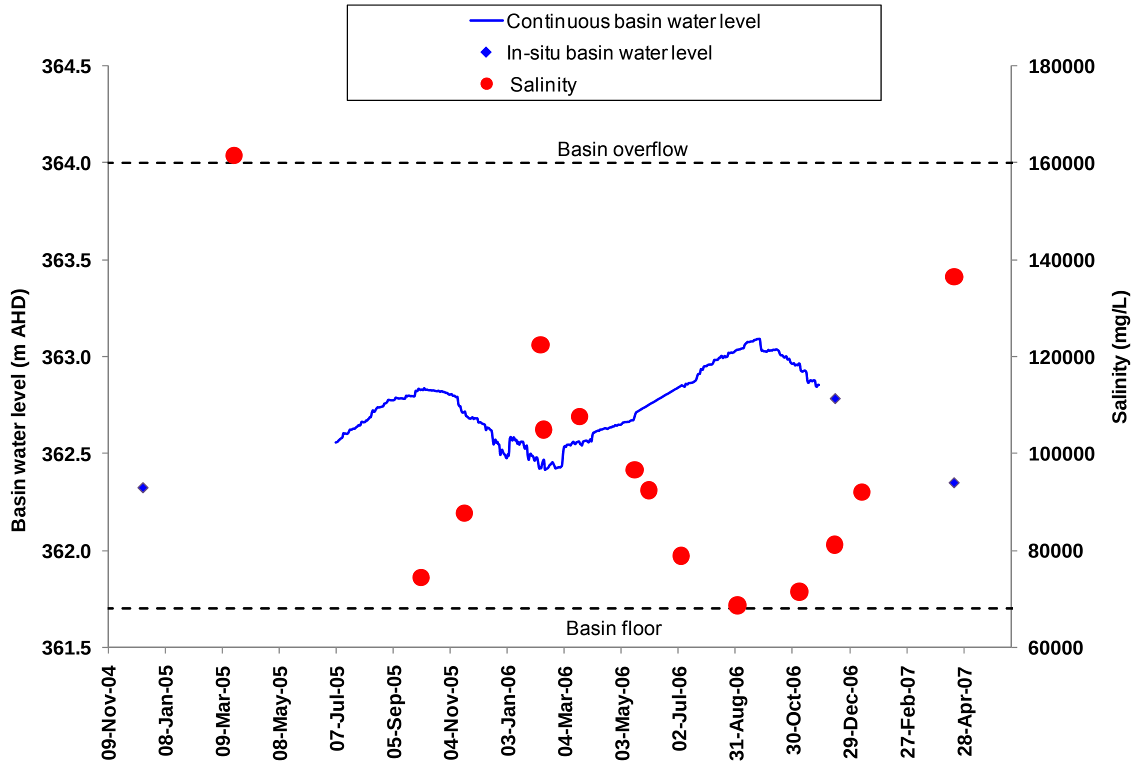

Figure 18 Evaporation basin water levels and salinities

Volume and salt load

The basin water volume was calculated from the water level measurements using a depth-to-volume rating table developed from a basin bathymetric survey. The rating table relates changes in water depth to changes in storage volume. The amount of salt in the basin (salt load) is the product of the water volume in storage and its corresponding salinity. Basin salt loads were calculated periodically between 4 October 2005 and 18 April 2007 when water level measurements coincided with salinity measurements (Fig. 19).

The basin was at less than half its maximum capacity of 13 700 m^3 in 2005–06. The volume fluctuated seasonally from a minimum at the end of summer to a maximum by the end of September (Fig. 19). The volume declined from about September despite continued discharge into the basin. Water loss appeared to be caused by both evaporation and leakage, with evaporation apparently the dominant process. Evaporation rates in summer are up to four times higher than in winter (Section 2.2). The salt load also fell and as the basin did not overflow the only way salt could have been be lost was through the basin floor with leakage water.

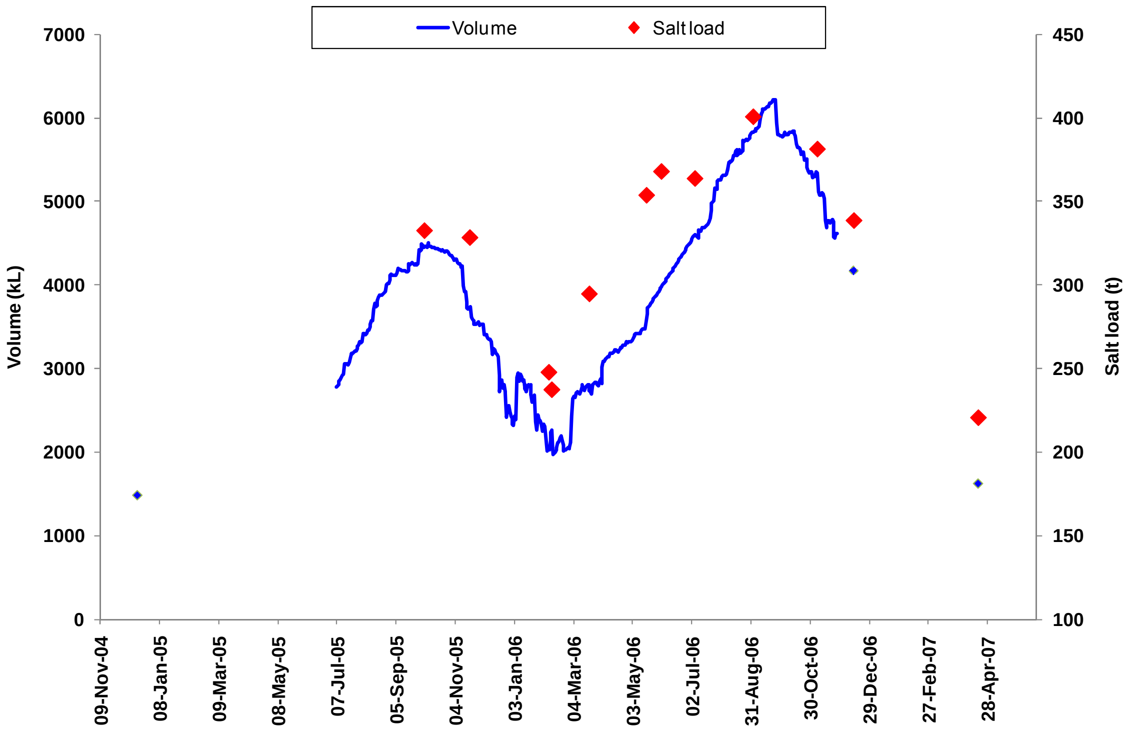

Figure 19 Evaporation basin volumes and salt loads

5 Discussion

The single bore and pump used at Bodallin produced a volume and drawdown that was small in relation to the size of the aquifer and its recharge. Between July 2005 and January 2007 10 030 kL of groundwater was pumped, causing watertable drawdown extending to at least 100 m and possibly somewhere between 100 and 250 m from the single production bore (Section 4.2). The exact drawdown distance was uncertain because there were no monitoring bores between 100 and 250 m. If these distances are extrapolated as radii from the bore, drawdown controlled the watertable beneath somewhere between 3–20 hectares of the valley floor that covers hundreds of hectares.

It was not possible to select the most effective of the three power source options by their measured discharge volumes because they were trialled in succession for different periods and operated under varying weather conditions. Instead, computer simulated discharges of the three options during 2005–06 were compared (Section 5.1).

Comparing the simulated discharges under various rain-fed recharge scenarios produced a range of watertable areas that could theoretically be controlled using each of the power sources. The results confirmed that more than one pumping bore would be needed to control the watertable across a paddock or farm irrespective of the power source used (Section 5.2).

The cost effectiveness of pumping at Bodallin was calculated from the respective watertable control areas and the associated installation and running costs of each option and the evaporation basin over 10 years (Sections 5.3 & 5.4). The performance of the evaporation basin was further assessed in terms of water and salt balances and the impacts on the surrounding watertable (Section 5.5).

5.1 Simulated discharges

The discharge volumes produced using the solar, wind and electrical generator power sources could be directly compared if they were trialled at the same time and under the same conditions. As this set-up was beyond the physical scope of this project, the available discharge data was used to create mathematical models to simulate the discharge for each power source/production bore unit for 2005 and 2006 (Fig. 20).

As the electrical generator operated independently of weather conditions the average discharge of 34 kL/d (Table 2, Section 4.4) was used; this produced a simulated annual discharge volume of 12 410 kL (Table 3).

For the solar and wind power options, regression analysis was used to develop mathematical relationships between the measured daily discharges and the corresponding daily solar intensity or wind speed. The relationship was linear between discharge and wind speed (pumping rate = 3.1031*(wind speed) – 13.25) and logarithmic between discharge and solar intensity (pumping rate = 8.0543*Ln(solar intensity) – 9.7378). Using daily solar intensity and wind speed for 2005 and 2006 (Section 2.2) as input data the equations generated daily simulated discharges. The simulated average annual discharge using solar power was 4900 kL (average 14 kL/d) and 7711 kL (average 21 kL/d) using wind power (Table 3).

The simulated discharges using solar and wind power showed annual cycles corresponding to seasonal changes in solar intensity and wind (Fig. 20). Both power sources yielded minimum discharges during the winter months of June and July. The effects of prevailing easterly winds during summer (Section 2.2) maintained higher discharges from the windmill than from the solar panel powered pump.

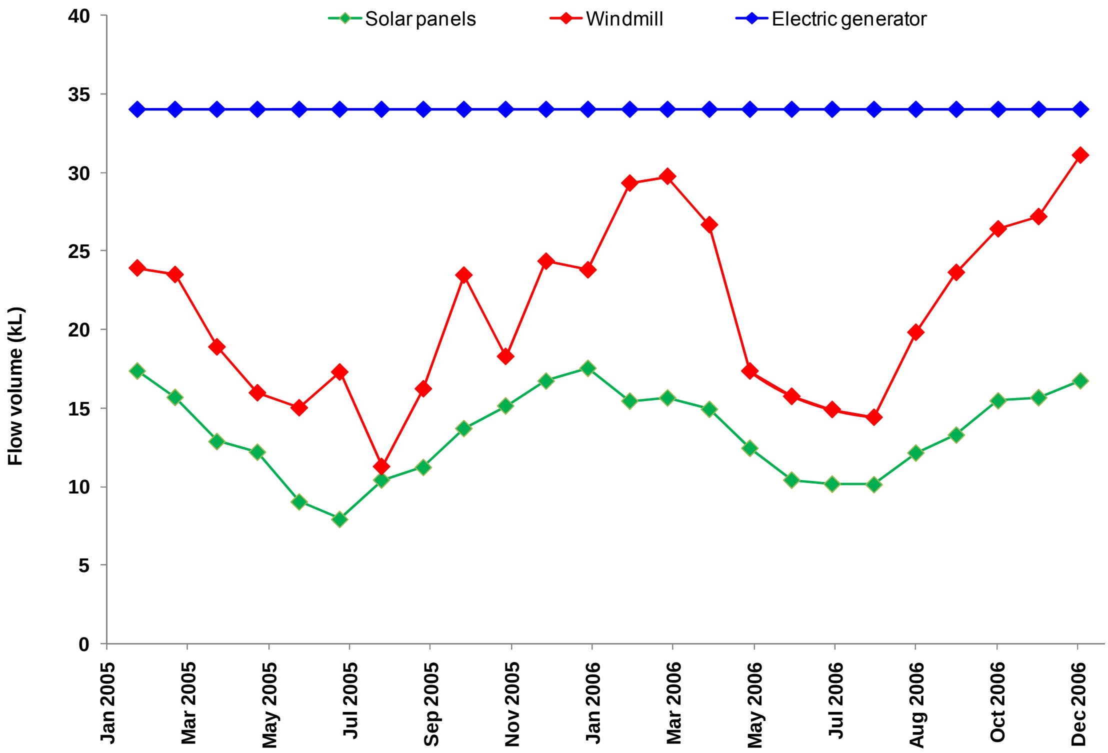

Figure 20 Simulated average daily discharge for each month of 2005 and 2006 for solar, wind and generator powered pumping

Table 3 Simulated average discharges for solar, wind and generator powered pumping

	Average discharge	
	(kL/yr)	(kL/d)
Solar panels	4900	14
Windmill	7711	21
Electric generator	12 410	34

5.2 Watertable control area

To calculate the area of watertable controlled by pumping, a steady-state groundwater system was assumed. Rainfall was the only source of recharge, and no groundwater was lost by either evaporation or flow within the aquifer. The latter assumptions are believed to be representative of the site because the watertable was 2 m or more below the ground surface with a negligible hydraulic gradient.

To maintain the watertable at a steady-state level, the volume of groundwater pumped in any one year must equal the volume or depth of recharge that would otherwise cause the watertable to rise. For example, if recharge was 8% of annual rainfall (Ali et al. 2004) this would equal 24 mm/yr based on the 2005 and 2006 average rainfall at Bodallin (301 mm/yr for 2005/06). To offset any watertable rise 240 kL/ha/yr would need to be pumped.

The area of groundwater control was calculated by dividing the annual discharge for each power source option (Table 3) by the average recharge per hectare per year (Equation 1):

$$A = V / U \qquad \textit{Equation 1}$$

Where:

A = area of groundwater control (ha)

V = volume pumped (kL/yr)

U = rainfall recharge (kL/ha/yr)

As expected from the equation, higher recharge rates caused corresponding reductions in the areas of watertable control (Table 4). In addition, if an evaporation basin was located within the groundwater capture area of the bore the recapturing of leakage would reduce the watertable control area. This could be avoided in the planning phase by siting basins well away or downgradient from the pumping sites.

These results show that a single production bore is unlikely to control the watertable across a Wheatbelt paddock or farm irrespective of the power source. To achieve watertable control over larger areas a network of production bores is required. A similar strategy was initiated by the Bodallin Catchment Group with the installation of eight groundwater pumps across five farms in the lower catchment by 2000 (Carew Hopkins no date).

The distance between production bores in a network or grid was estimated by doubling the radius of the watertable control area of a single pump. The areas were assumed to be circles with production bores at their centres. For example, to remove 24 mm/yr recharge (240 kL/ha/yr) using the solar pumping option the bores could be 510 m apart, using windmills, 640 m, and generator 811 m (Table 4; Fig. 21). The generator-powered option achieved the largest area of watertable control and largest distance between bores for given recharge rates as a result of having the highest pumping rate of the three options (Table 3).

Table 4 The area (A) of groundwater controlled per pump and distance (D) between pumps if in a bore field and with the different power sources and recharge rates

% recharge of 300 mm/yr rainfall (%)	Recharge/pumping rate to offset watertable rise (kL/ha/yr)	Solar		Wind		Generator	
		A (ha)	D (m)	A (ha)	D (m)	A (ha)	D (m)
5	150	33	645	51	809	83	1026
8	240	20	510	32	640	52	811
10	300	16	456	26	572	41	726
15	450	11	372	17	467	28	593
20	600	8	322	13	405	21	513

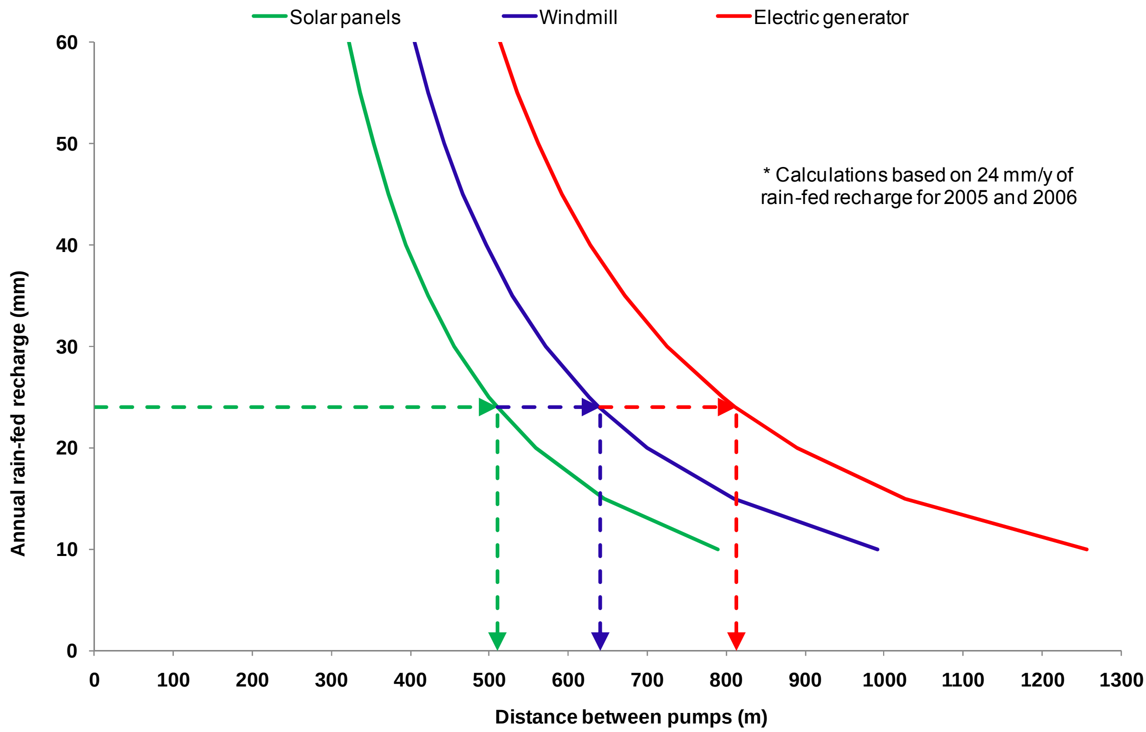

Figure 21 Bore spacing needed to control watertable rise using the three power sources

5.3 Costs and cost-effectiveness

The cost of establishing the production bore was $10 000 and building the evaporation basin was $20 000, totalling $30 000. The costs for the bore and basin were considered the same fixed cost for each power supply option (Table 5). Specific or variable costs for each option are detailed below.

The set-up cost for the electrical generator option included the pump ($2000) and diesel generator ($5000) totalling $7000. The estimated annual running costs were for fuel and oil to run the electrical generator continually over one year ($20 000) and maintenance ($1000). The generator would need to be replaced or re-built each year at a cost of $5000 resulting in an annual running cost of $26 000. Over 10 years, the total cost is estimated at $292 000, giving an average annual cost of $29 200 including $3000/yr fixed cost for the bore and basin (Table 5).

The set-up cost for the solar-powered pump included the pump ($2000) and solar panels ($10 000) totalling $12 000. The cost to maintain and run the solar-powered pump was estimated at $1000 per year. For the first 10 years the total cost including fixed costs would be $52 000, giving an average annual cost of $5200 (Table 5).

The set-up cost for the wind-powered pump included the windmill and pump at $10 000. The cost to maintain and run the mill was estimated at $1000 per year. The total 10 year cost of this option was expected to be $50 000 giving an average annual cost of $5000 (Table 5).

For each power source/production bore and basin unit, the average annual cost over 10 years (Table 5) divided by the area of groundwater control at varying recharge rates (Table 4) was used as a measure of the cost-effectiveness of the options (Fig. 22). For a recharge rate of 24 mm/yr (240 kL/ha/yr) at Bodallin, pumping using wind-power was the most cost-effective at $156/ha/yr, then solar power at $255/ha/yr. The electrical generator was the least cost-effective at $565/ha/yr (Table 5 & Fig. 22).

If recharge increases the watertable area controlled by one pump decreases. More pumps will be needed (at closer spacing) and the cost per hectare to control the watertable beneath an equivalent area rises (Fig. 22).

Table 5 Comparing costs of power sources

Item	Solar $	Wind $	Generator $
Unit set-up cost of production bore and evaporation basin	30 000	30 000	30 000
Unit set-up cost of power supply and pump	12 000	10 000	7 000
Running/maintenance cost for first year	1 000	1 000	21 000
Total cost for first year	**43 000**	**41 000**	**58 000**
Annual running/maintenance cost subsequent years	1 000	1 000	26 000
Total cost (including set up) for first 10 years	52 000	50 000	292 000
Average annual costs spread over first 10 years	**5 200**	**5 000**	**29 200**
Annual cost per hectare over 10 years (@ 24 mm recharge)	**255**	**156**	**565**

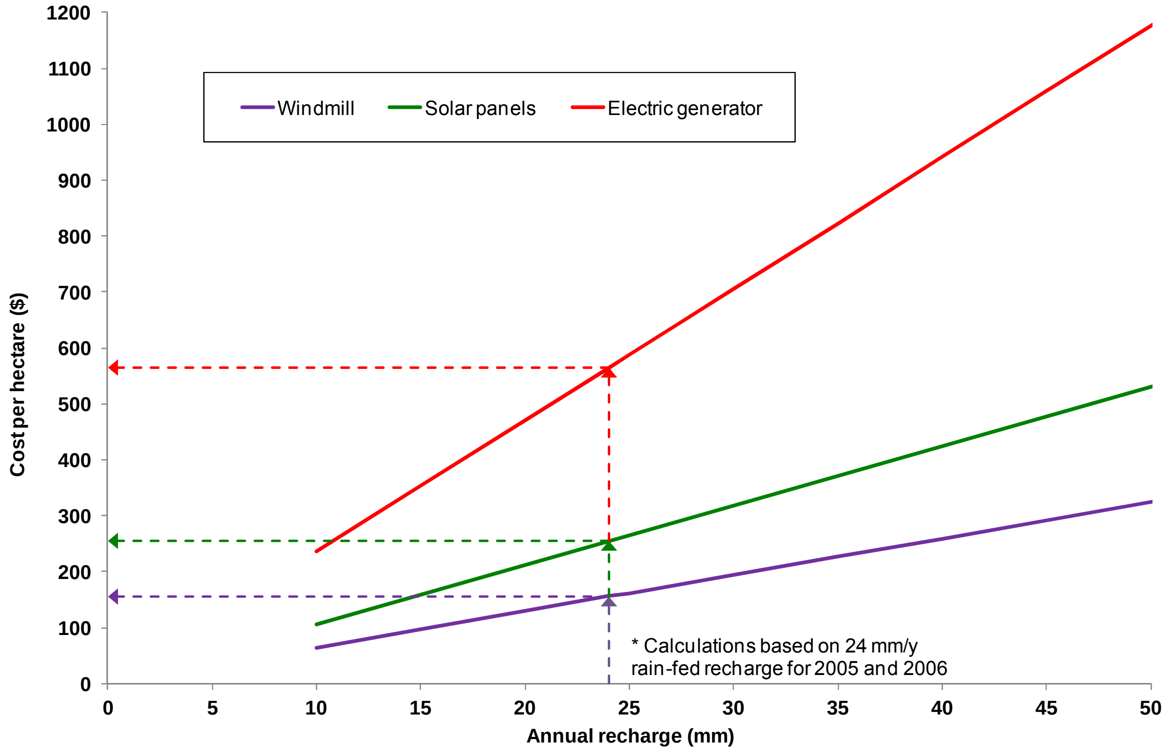

Figure 22 Annual cost per hectare over first 10 years of pumping to control recharge

5.4 Comparing power sources

Electrical-generator

The electrical generator allowed continuous pumping at a constant volume and so enabled more groundwater to be pumped than the other options. In this project, pumping with a small single cylinder electrical generator removed the greatest volume with an average 34 kL/d.

Although the generator-powered pump produced the greatest discharges it was the most expensive and required the most maintenance. The projected annual cost of $29 200 over the first 10 years of operation was nearly six times higher than for solar or wind power. On a per hectare basis it was also the most expensive option (Fig. 22).

Generator maintenance required more man-hours than the solar or wind powered systems. The small single cylinder generator used in this study required daily checking to keep the motor running and avoid potentially expensive engine failure. The time required by the land manager to keep the motor in working order was a hidden cost not considered here.

Labour and maintenance could be reduced by using a larger (continuous rated) generator and fuel tank with warning systems or mechanisms such as a low oil level automatic shut down switch. Although more expensive initially in set-up and in replacement costs, larger generators driving several pumps could be more cost-effective than multiple small machines. Where possible, connection to the mains grid would alleviate the need and time to maintain generators. However, in remote situations such as at Bodallin connection to the electricity grid may be prohibitively costly.

Solar panels

Solar panels delivered an interrupted power supply to the pump and a variable flow rate dependent on solar intensity. There was no pumping during the night and pumping rates declined on cloudy days. The solar-powered pump had the lowest discharge with an average of 14 kL/d. Although night-time pumping could be achieved with batteries the need for these and the extra solar panels to recharge them during the day would have greatly increased the cost of this option.

The annual expenditure of $5200 spread over the first 10 year period is slightly more than for wind power but much less than generator power and the cost per hectare is half that of the generator (Fig. 22).

Maintenance of the solar pump was not as intensive or costly as for the generator, requiring only weekly inspections to ensure working order. As a relatively new technology, breakdowns for this option often required expertise to be brought in from distant locations at high cost.

Windmill

The windmill delivered a variable power supply and pumping depended on wind speed and duration, with an average discharge of 21 kL/d. This was less than for the generator but compensated for by lower costs and maintenance. Annual expenses over 10 years were the lowest of the three options. On a per hectare basis, it was the least expensive (Fig. 22).

Maintaining the windmill system was the least labour-intensive of the three options requiring less than weekly inspections to ensure working order of the gear box and piston pump. In addition, spare parts for a windmill are generally readily available and breakdowns are usually easily repaired by local service providers and land managers themselves.

5.5 Evaporation basin

Evaporation basins allow on-farm containment and disposal of saline and acidic groundwater, alleviating concerns about its downstream effects on waterways and properties (Leaney & Christen 2000). Basins are broadly classified as ‘sealed’ or ‘leaky’ (George & Nott 2004) and operate by using the natural process of evaporation to dispose of water.

The evaporation basin at Bodallin is a ‘leaky’ basin constructed in clay soils with low permeability so that leakage is at manageable rates. Low rates of leakage are desirable to regulate the basin’s salt accumulation which, if excessive, will reduce evaporative losses. High leakage rates can result in rising watertables causing waterlogging and salinisation around the basin (Cox 2011). Suggested leakage rates of 0.5–1 mm/d are acceptable, with rates greater than 3 mm/d considered undesirable (George & Nott 2004).

Basin water balance

The water balance approach was used to assess the performance of the evaporation basin by quantifying the inflow and outflow component volumes. The main elements of the Bodallin basin water balance are inflows from pump discharge and rainfall, and outflows from evaporation and leakage. When expressed in combination with the water volumes stored in the basin at the start and end of the water balance period, the water balance equation is:

$$V_S + PD + P = E + L + V_E \qquad \textit{Equation 2}$$

Where:

V_S = starting volume of water in the basin

PD = pumped discharge into basin

P = precipitation or rainfall added to basin water

E = evaporation from the water surface areas

L = leakage of water through the basin floor

V_E = final volume of water in the basin

On 4 October 2005 the volume in the basin was 4500 kL and on 31 December 2006 it was 3700 kL (Table 6). As discharge measurements from the two existing production bores ceased in May 2006 they were estimated at 17.25 k/d from 18 May to 31 December 2006. A total 14 800 kL was pumped into the basin from the two existing bores and the project production bore from October 2005 to December 2006.

Rainfall contributed about 2600 kL to basin storage by falling directly onto the water surface and as runoff from the inside batters. It was assumed that all rainfall onto the water surface contributed to storage while some was lost by infiltration into and evaporation from the exposed batters. Infiltration losses from the batters were simulated using a 10 mm, 24 hour runoff threshold value. Only rainfalls heavier than 10 mm/d generated runoff and contributed to storage within the basin equivalent to the amount in excess of 10 mm/d multiplied by the batter area. Changes in both the water surface and batter areas in response to changing water levels were accounted for in the calculations. Of the 371 mm of rainfall onto the 8905 m^2 basin area (Section 3.1) 290 mm contributed to storage.

Potential evaporation of 3474 mm removed 13 600 kL (Table 6) from the changing basin water surface area. This volume was equivalent to 2143 mm (62% of pan) of evaporation from the 6350 m^2 average water surface. The daily evaporative losses were calculated from daily Class-A pan evaporation measurements (Section 3.2) multiplied by a lake factor of 0.65 (De Broekert & Coles 2004) and salinity factor of 0.97 (Turk 1970).

Leakage from the basin could not be measured but was estimated by the residual value required to balance inputs with outputs. The leakage of 4600 kL (10 kL/d) was equivalent to the loss of 724 mm from the average water surface of 6350 m^2 or 517 mm from the 8905 m^2 water surface area when the basin is at maximum capacity. The former value produces an average leakage rate of 1.5 mm/d and the latter, 1.4 mm/d. The water balance shows approximately 17 000 kL of water moved through the basin during 4 October 2005–31 December 2006 (454 days).

Table 6 Evaporation basin water balance (Equation 2) for the period 4/10/05 to 31/12/06

	Water in		Water out
Volume in basin on 4/10/05 (V_S)	4 500 kL	Volume in basin on 31/12/06 (V_E)	3 700 kL
Precipitation (P)	2 600 kL	Evaporation (E)	13 600 kL
Pump discharge (PD)	14 800 kL	***Leakage (L)***	***4 600 kL***
	21 900 kL		21 900 kL

Basin salt balance

A basin salt balance was undertaken as a means of cross checking the validity of basin leakage volume estimated from the water balance. The salt balance took into account the factors contributing to the changing basin salt loads allowing the loss of dissolved salt to be used as an indicator of leakage. Like the water balance, these factors include the initial and final salt loads and the inputs and outputs of salt.

The salt balance equation for the evaporation basin is:

$$L_S + PD_S = L + L_E$$ *Equation 3*

Where:

L_S = starting salt load of basin

PD_S = salt load of discharge pumped into basin

L = leakage salt load

L_E = final salt load of basin

For the purpose of this salt balance the contribution from rainfall was assumed to be zero as in reality this value would be extremely small. This leaves pumped discharge as the only source of additional salt into the basin. The only pathway by which salt can leave the basin is through leakage because evaporation does not remove salt. If salt was not lost through leakage the basin salt load would have continuously increased with ongoing pumping rather than fluctuated as measured (Fig. 19).

On 4 October 2005 the salt load in the basin was 332 t and on 31 December 2006 it was 340 t. Of the 591 t of salt pumped into the basin, 583 t dissolved in leakage water was lost through the basin floor (Table 7). Given the leakage of 4600 kL of water (Table 6) its average salinity would have been about 128 000 mg/L to transport this salt mass from the basin. However, basin salinities only rose to these levels in response to high rates of evapoconcentration during summer (Fig. 18).

Table 7 Evaporation basin salt balance (Equation 3) for the period 4/10/05 to 31/12/06

	Salt in		Salt out
Salt load in basin on 4/10/05 (L_S)	332 t	Salt load in basin on 31/12/06 (L_E)	340 t
Salt load of groundwater in (PD_S)	591 t	***Salt load of leakage (L)***	***583 t***
	923 t		923 t

If the average salinity of the basin water was 93 000 mg/L rather than 128 000 mg/L, a leakage of 6300 kL (14 kL/d) would be needed to remove the 583 t of salt. In the water balance, this would reduce evaporative loss to 11 900 kL in order to provide for the increased leakage. This scenario is entirely plausible within the context of the accuracy of the water balance and with leakage rates remaining within acceptable levels.

Effects of leakage

The estimated leakage rate of 10–14 kL/d caused no significant change in the surrounding groundwater levels within the short life of this project. The greatest response was the development of a 0.7% watertable gradient away from the basin on 9 October 2006 (Fig. 14). This occurred when the basin water level was at its maximum and groundwater rose close to 1 m below ground adjacent to the basin (Section 4.3).

The inability to ‘see’ the basin leakage in the watertable responses is thought to be a result of the comparatively low basin leakage rate compared to relatively high aquifer transmissivity. This concept can be demonstrated by rearranging the Darcy groundwater flow equation to solve for hydraulic gradient:

$$I = Q/KA$$ *Equation 4* (Darcy’s Law)

Where:

I = hydraulic gradient (m/m)

Q = leakage rate (kL/d)

K = hydraulic conductivity (permeability; m/d)

A = cross-sectional area of the aquifer (m^2)

The 450 m basin perimeter was substituted for the width of the aquifer, then multiplied by the 40 m aquifer thickness (Section 2.6). The resultant 18 000 m^2 is the cross sectional area through which leakage had to flow from inside the basin to the outside surrounding aquifer.

Substituting the values for leakage rate (Q) = 10 kL/d, hydraulic conductivity (K) 0.5 m/d (Section 2.6; De Broekert & Coles 2004) and cross-sectional area above into Equation 4 yields a gradient of 0.0011 m/m (0.11%). The aquifer only needs to develop a hydraulic gradient of 0.11% sloping away from the basin to convey the leakage. If the aquifer were thinner, permeability lower or leakage higher, the gradient would be steeper.

To develop a 0.7% hydraulic gradient as on 9 October 2006, the basin leakage would have theoretically been as high as about 63 kL/d calculated using the above aquifer characteristics. Given that leakage rates are related to the difference between the water levels in the basin and surrounding watertable it is not unexpected that the highest basin leakage was associated with its highest water level.

There was no indication that the saline water leaking from the basin was contributing to the salinity of the underlying or surrounding groundwaters. Salinities of around 50 000 mg/L measured in the deep bore at the NE corner of the basin (bore 6d; Fig. 15) were commensurate with the 40 000 mg/L from the production bore (Fig. 12) given this is considerably shallower. The shallow groundwaters at the NW corner of the basin (bores 7–9) were within the range 5000–30 000 mg/L and generally decreased from 2005 to 2006.

There is no doubt that ongoing leakage of saline water will increase groundwater salinity beneath the basin. To date, given its short period of use and the relatively small volumes leaked it is unlikely the salt had moved far enough from beneath the basin to be measured in surrounding bores. Any leakage of salt should however be viewed in the context of the already saline groundwater and massive salt stores that naturally underlie the basin, compared with the discharge management advantages it provides.

Basin performance

Basin performance over the period of this study 2005–06 was assessed by measured variables and a water balance approach (see above). During this time the volume of water in the basin did not reach the basin’s capacity.

To see how the basin would perform over a much longer period its volume was simulated by a monthly time-step spreadsheet model using the basin parameters of 13 700 m^3 capacity, 0.89 ha maximum surface area (Section 3.1) and 1.4 mm/d leakage rate based on the value derived from the water balance. Input data included 1970–2010 rainfall and evaporation for the Merredin townsite, and the averages of the 2005–06 simulated discharge results for the three power sources (Section 5.1). The model simulated monthly discharges into the basin for 1970–2010.

Over the 40 years the basin was big enough to cater for the disposal of discharge from the solar and wind powered pumping options but too small to manage the discharge from the generator pumping option.

In the solar-powered pumping simulation the water stored in the basin rose to a maximum of approximately 2600 kL and its salt load to about 100 t. The model produced fluctuations in the salt load, confirming the loss of salt through the basin floor in leakage water. In the wind-powered simulation basin storage rose to a maximum of about 3500 kL and salt load to nearly 180 t. In both scenarios the basin dried out during about 10 summers.

The modelling showed that the current basin dimensions are too small to contain the discharge from electric-powered pumping over the 40 years. After starting empty in 1970 the basin overflowed by 1974 and its salt load reached about 1000 t. Re-running the simulation using a bigger basin surface area of 1.2 ha prevented the stored volume from rising much above 8000 kL and its salt load to above 600 t.

6 Conclusion

The Bodallin groundwater pumping project operated a 12 m deep production bore in farmland over two years and trialled three power sources to drive the pump: solar panels, an electrical generator and a windmill. The groundwater lifted from the bore was discharged into a nearby evaporation basin. The volume pumped, the area of watertable control, the set-up and maintenance costs and the cost-effectiveness of each power source/production bore unit were evaluated.

Measurements showed that the watertable drawdown extended for at least 100 m from the bore during pumping. In an unseasonal heavy rain event in early 2006 the watertable rose by up to one metre even though pumping continued. However, within six months the watertable had dropped to pre-rain levels only within the drawdown area of the production bore while water levels in bores further away and in the control bores remained above the 2005 levels.

Of the three power sources the electric generator produced the best results. It could operate continuously independent of the weather conditions, produced the highest pumping rate and had the potential to control the watertable over a larger area than the other options. However, it was the least cost-effective at $565/ha/yr (Table 8). It was the most expensive to set-up and the ongoing fuel and higher maintenance costs made it six times more expensive to run per year than the solar or wind options.

The pumping rate delivered by solar panels depended on the hours and intensity of sunlight and the windmill rate depended on wind speed and so neither could achieve the efficiency of the generator. However, the windmill option proved to be the most cost-effective at $156/ha/yr (Table 8). The set-up and maintenance costs were similar to the solar panel option but its longer average running time per day resulted in more water pumped, greater watertable control area and so lower cost per hectare.

Table 8 Power source comparisons for one production bore for 24 mm/yr recharge

Power source	Av. pumping rate (kL/d)	Watertable control area (ha)	Annual cost/ha/yr
Solar panels	14	20	$255
Electric generator	34	52	$565
Windmill	21	32	$156

The windmill appeared to be the most practical of the three power options trialled. Windmills encompass technology that is simple, reliable and already familiar to many rural land managers. Repairs can often be made using improvised methods which reduce the need for parts from often distant locations.

Solar panels are also a reliable power source but in this project they were rated second to the windmill because the pumping rate was 2/3 of the windmill rate and its annual cost 2/3 more. If local experience with solar technology is limited there may be significant downtime associated with this option while waiting for repair.

Using a small electric generator to power a production bore pump is considered impractical due to ongoing and likely increasing fuel costs and the need for intensive supervision by the land manager. The viability of this option may improve if one large continuously rated generator was used to power multiple pumps.

The evaporation basin provided a satisfactory means of disposing of the discharge. Pumped discharge accounted for 85% of water into the basin and rainfall the remaining 15%. Of the 14 800 kL of groundwater pumped in about 75% evaporated and 25% leaked back into the underlying aquifer.

The 13 700 m^3 basin adequately contained the discharge over a two year period. Computer models used to simulate performance over a 40 year period showed the basin was big enough to accommodate discharge from the solar and wind-powered options, but would need to be enlarged for generator-powered pumping.

The basin leakage rates were within acceptable levels for a 'leaky' basin. Although the equivalent of nearly all the salt in the groundwater pumped into the basin leaked through the basin floor to the underlying groundwater, no increase in groundwater salinity around the basin was detected during the study. However, with ongoing use salinity would most likely increase.

This project showed that, in theory, groundwater pumping can be used in remote locations as a proactive strategy to control watertable rise and prevent land salinisation. The volumes pumped from a single bore at Bodallin were small in relation to the size of the groundwater aquifer and produced a relatively small area of watertable control. To control the watertable over a paddock, farm or even catchment scale a network of bores and pumps would be required to offset rain-fed recharge, the main cause of watertable rise in Wheatbelt valley floors.

In designing a network of pumping bores or bore-field, the results from this study demonstrated that the watertable control area per pump and so the spacing between pumps ultimately depended on the individual bore yield and rainfall recharge rate. The volume extracted from the bore, in turn, depended at least partly on the power source used to drive the pump. Where an evaporation basin is used to dispose of the discharge, interactions between basin leakage and pumping need to be considered as they will affect the scheme's overall efficiency.

Glossary and shortened forms

Aquifer	A water-bearing regolith layer that can store and transmit extractable volumes of water
bgl	below ground level
Class-A pan	A pan of known dimensions used to hold water to determine the quantity of evaporation at a given location
Cross sectional area	(CSA) The area of a truncated end or section of a structure such as a drain channel (m^2)
Discharge	The total volume of all water that flows from the outlet of a drain or drain section (kL)
Drawdown	A reduction in watertable height caused by the drainage of groundwater by a groundwater drain or pumping bore
Drawdown profile	The drawdown measured along a transect perpendicular to a drain or production bore
EEI	Engineering Evaluation Initiative
Evaporation basin	A shallow basin built for the purpose of maximising evaporative loss of the stored water
Groundwater	Water within an aquifer and below the watertable
Groundwater discharge	The groundwater component of discharge from the drain or pump outlet
Hectare	An area of 10 000 m^2 (ha)
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
Hydraulic gradient	The slope of the watertable (m/m)
Kilolitre (kL)	1000 L or 1 m^3 (approx.) of water (kL)
Kilometre	1000 metres distance (km)
L/s	Litres per second; the units for flow rate

m AHD	Height in metres above the Australian Height Datum taken as 0.026 m above Mean Sea Level at Fremantle
mE, mN	Metres East, metres North
MGA	Map Grid of Australia
mg/L	Milligrams per litre; a unit of measurement for salinity; the mass of salts dissolved in one litre of water
MJ/m^2	Megajoules per square metre; a unit of measurement for daily incoming solar energy
Rain-fed recharge	Recharge from the percolation of rainfall and runoff to the groundwater system (mm)
Recharge	The addition of water to the groundwater system (mm)
Runoff	The volume or depth of water moved over the land surface (kL or mm)
Salinity (specific)	The concentration of total dissolved salts in water or soil (mg/L)
Salinity (gen)/salinisation	The reduction in the productivity or biodiversity of land or water due to an excess of salts within the environment
Salt load	The number of tonnes of salt dissolved in flowing water or standing water (t)
Sediment	Material (soil) that is or has been moved from its site of origin by erosion
Tonne	1000 kg mass (t)
Transect (bore)	An alignment of bores used to measure 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
Waterlogging	The accumulation of excess water in the root zone of the soil
Watertable	Surface of unconfined groundwater at which the pressure is equal to atmospheric pressure

References

Ali, R, Hatton, T, George, R, Byrne, J & Hodgson, G 2004, 'Evaluating the impacts of deep open drains on groundwater levels in the Wheatbelt of Western Australia', *Australian Journal of Agricultural Research*, vol. 55, pp. 1159–1171.

Allen, AD, Laws, AT & Commander, DP 1999, 'South West Australia' in JW Lloyd, (ed.) *Water resources of hard rock aquifers in arid and semi-arid zones,* UNESCO Studies and Reports in Hydrology 58, pp. 249–261.

Bureau of Meteorology 2010, http://www.bom.gov.au.

Carew Hopkins, D n.d., Notes on Bodallin pumping trial (unpub.).

Chin, RJ & Smith, RA 1983, *Jackson, Western Australia 1:250 000 Geological Map and Explanatory Notes*, Geological Survey of Western Australia, Perth, WA.

Cox, NM 2011, *The use of drains and basins to manage salinity at Morawa*, Salinity and land use impacts series, Report no. SLUI 48, Department of Water, Western Australia.

De Broekert, PP & Coles, NA 2004, *Wetland basins for saline drainage water disposal Bodallin and Elechbutting catchments*, *Eastern Wheatbelt, Western Australia*, Resource Management Technical Report 290, Department of Agriculture Western Australia.

Dogramaci, SS 2005, Piezometer drilling program Bodallin, WRC file 18453, Department of Water, Western Australia.

Dogramaci, SS & Degens, B 2003, *Review of engineering and safe disposal options*, Water and Rivers Commission, Salinity and land use impacts series, Report no. SLUI 20, 22p.

George, R 1991, 'Hydraulic properties of groundwater systems in the saprolite and sediments of the wheatbelt, Western Australia', *Journal of Hydrology*, vol. 130, pp. 252–278.

George, R & Nott, R 2004, *Evaporation basins for salinity management*, Farmnote 53/204, Department of Agriculture Western Australia.

Ghauri, S 2004, *Groundwater trends in the Central Agricultural Region*, Resource Management Technical Report 269, Department of Agriculture Western Australia.

Leaney, F & Christen, E 2000, 'Basin leakage: site studies at Girgarre, Victoria and Griffith, NSW'; in *On-farm and community-scale salt disposal basins on the Riverine Plain*, CSIRO Land and Water Technical Report 16/00, 71p.

Nulsen, RA 1981, 'Critical depth to saline groundwater in non-irrigated situations', *Australian Journal of Soil Research*, vol. 19, pp. 83–86.

Schoknecht, N 1997, *Soil groups of Western Australia*, Resource Mapping Technical Report 171, Natural Resource Assessment Group, Agriculture Western Australia, South Perth.

Shand, P & Degens, B 2008, *Avon catchment acid ground-water: geochemical risk assessment,* CRC–LEME Open File Report 191, CSIRO Exploration and Mining, Bentley, WA.

Turk, LJ 1970, 'Evaporation of brine: a field study on the Bonneville salt flats, Utah', *Water Resources*, vol. 6, no. 4, pp.1209–1215.

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