Global Groundwater

Australian Bore Consultants Pty Ltd. Hydrogeological Division
ACN 077 734 153 ABN 66 077 734 153

PO Box 174
Bassendean
Western Australia
6054

Lake Nowergup

Factors in declining lake and groundwater levels

for

Department of Water

Government of Western Australia

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Australian Bore Consultants Pty Ltd
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ACN 077 734 153 ABN 66 077 734 153

PO Box 174 Bassendean, Western Australia 6054

Telephone: 61 8 9386 4725 Facsimile: 61 8 9386 1080 E-mail: office@globalgw.com.au

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Executive Summary

Lake Nowergup is positioned upon the Swan Coastal Plain at the western margin of the Gnangara Mound, in the northern metropolitan area east of Pinjar Lake, about 37 km north of the Perth CBD (Figure 1). When full, water levels within the lake reach a peak level of 17.5 mAHD (equivalent to about 4 m depth) and cover an area of about 40 Ha. Lake water levels have been falling since the 1970's in response to the regionally declining watertable. In 1989, autumn minimum lake levels fell to about 16.3 mAHD, at which point the lake covered an area of approximately 28.5 Ha, but by 2014 the minimum lake water levels were below 15 mAHD and the open water body covered an area of about 10.1 Ha. Since 1973, the watertable in the Superficial aquifer below Lake Nowergup has declined by around 3.5 m.

Environmental criteria and lake supplementation

Lake Nowergup is a conservation category wetland and Ministerial criteria site under the *Environment Protection Act 1986*. It is also a registered site of significance for Aboriginal heritage (McDonald, et al., 2005). The lake is within the Nowergup Groundwater Sub-area, which is part of the Wanneroo groundwater management area.

Environmental Water Requirements (EWR) criteria for the absolute minimum and preferred minimum for water levels in Lake Nowergup at the end of summer were first set in 1988 by the Minister for Environment. These were based on an absolute minimum water level of 16.3 mAHD. Lake water level requirements were revised in 1996, which stipulated that the peak spring water level should reach a minimum of 16.8 mAHD.

Artificial lake supplementation to achieve EWR levels commenced in 1990. Supplementation was undertaken over winter and spring to meet the criteria, after which the supplementation ceased. Subsequently, the minimum water level criteria have been frequently breached. By 2008 almost continual supplementation was required to achieve the EWR levels. Without lake supplementation, lake water levels would have declined to approximately the level of groundwater levels in the underlying Superficial aquifer, and the lake would consist of a small open body of water only during winter – spring.

Factors contributing to watertable decline at Lake Nowergup

Factors contributing to the watertable decline include changes in rainfall (climatic), land-use, and groundwater pumping for private purposes (principally horticulture) and public water supplies (principally the Pinjar and Quinns borefields), and also the lake water supplementation bore. However, the relative importance of each factor is not obvious.

Rainfall patterns have varied over time, with cycles of stable, above average or below average rainfall. Dry periods with below average rainfall, which would have resulted in lower groundwater recharge rates and a fall in watertable, have occurred most recently over 1975 to 1978, and 2002 to 2011. Extensive pine plantations east of the lake have also reduced groundwater recharge rates, while more recent urbanisation west of the lake has increased the recharge rates.

The Nowergup and Carabooda groundwater Sub-areas were proclaimed in 1986, and as of 2014 the total allocations were 2699 ML and 7985 ML respectively. Since 1986 there has been significant uptake in the allocation entitlements with the development and expansion of

market gardening and lawn turf farms. Most market gardens were established by 2002, with additional lawn turf farms established by 2009 and during 2014 (although this last one extracts water from the deeper confined Yarragadee aquifer).

The Water Corporation pumps groundwater for public water supplies from three borefields within the general vicinity of Lake Nowergup. These are Pinjar, Wanneroo and Quinns borefields. Each of these borefields include production bores in the Superficial and Leederville aquifers, and for Pinjar borefield two bores in the Yarragadee aquifer. The Wanneroo borefield is the oldest, having commenced pumping around 1977, but is peripheral to this study due to its distance from the lake. Pinjar borefield was first commissioned in 1989. Additional production bores in the Superficial aquifer were added in 1992 and pumping from the Leederville aquifer increased incrementally as additional bores were commissioned over 1989 to 1996. Leederville aquifer production bores of the Quinns borefield commenced pumping in 1999, while the Superficial aquifer bores began pumping variously between 1999 and 2000.

A lake water supplementation bore constructed in the Leederville aquifer has a licensed allocation of 1200 ML per year, and has pumped an average annual quantity of 511 ML between 1997 and 2003, and 1232 ML since 2004 (there is little pumping data from before 1997).

Objectives of study

The main objective for this study was to define the relative contributing factors causing the declining watertable in the Superficial aquifer at Lake Nowergup in order to aid in the formulation of water management strategies leading to a recovery in water levels.

To achieve the objective, the study estimated levels of drawdown caused by each factor using several approaches, involving:

- Hydrograph analysis,
- Multiple linear regression analysis (HARTT),
- Analytical distance drawdown calculations,
- PRAMS verification scenarios,
- Schematic Modflow simulations.

To support the analysis and better define the hydraulic connection between the lake and groundwater, a geological and hydrogeological review and evaluation of available data about the lake was undertaken to derive a better understanding of the hydrogeology in the broader area centred on Lake Nowergup. The study area extends from just east of Lake Pinjar to the coast, and several kilometres north and south. Greater emphasis on analysis of data was given closer to Lake Nowergup.

Geology

Lake Nowergup is underlain by the Quaternary (Pleistocene) age Superficial formations that comprise the Tamala Limestone in the west and Bassendean Sand to the east, with a tapering and possibly interfingering contact beneath the lake between these two formations. These overlie the Pliocene age Ascot Formation which forms the base of the Superficial formations beneath this part of the coastal plain. Lake sediments consisting of organic mud, silt and clay make-up lake floor deposits that lie upon the Superficial formations. The Superficial formations unconformably overlie the Wanneroo member of the Leederville Formation, with the contact at around -30 mAHD (about 50 m depth).

The Tamala Limestone comprises two main lithological units referred to as facies. There is a limestone of calcareous arenite, herein termed the limestone facies, overlying a basal calcareous clayey sand, herein termed the clayey sand facies. The limestone facies is a predominantly well lithified calcarenite that is frequently karstic. It thickens and deepens toward the coast, reaching up to 50 m thick, but the limestone does not extend as far east as Lake Nowergup as a coherent unit. The clayey sand facies of the Tamala Limestone is up to about 13 m thick at the lake, thinning beneath the lake to the eastern side where it is shallow and only a few metres thick. Toward the coast from the lake, the facies progresses into a calcareous sand up to 40 m thick. A sandy clay layer is present in the upper part of the clayey sand facies covering an extensive area about the west side of the lake. This clay layer shallows and thickens toward the lake, and is probably present beneath the lake.

The Bassendean Sand present east of the lake is a predominantly grey, fine to medium and coarse grained quartz sand up to 41 m thick, with medium to very coarse grained sand with very fine pebbles in its lower portion.

The Ascot Formation at the base of the Superficial formations is a light grey to fawn calcarenite limestone bedded with medium to coarse grained sand frequently with abundant shell fragments. The lower portion is often clayey sand or clay, often with phosphate nodules at the formation base. It has a variable intersected thickness between 4 and 21 m about the lake. A clayey sand and clay unit 5 m thick is present in the lower portion. The formation appears to be mostly absent west of the lake.

The Leederville Formation is Cretaceous in age and comprises interbedded sandstone, siltstone and shale deposited in marine and non-marine environments. It is sub-divided into 3 member units; the Mariginiup Member, Wanneroo Member and Pinjar Member in ascending order. About Lake Nowergup the middle Wanneroo Member subcrops the Superficial formations, while the Pinjar Member is absent. The Wanneroo Member contains the thickest and coarsest sand beds of the formation which are separated by shale and siltstone beds.

Hydrogeology

That part of the Superficial formations lying below the watertable comprises the Superficial aquifer. Lake Nowergup is situated within the transition zone between the Bassendean Sand and Tamala Limestone components of the Superficial aquifer, which coincides with a north-south linear chain of lakes, including Lake Nowergup.

Lake deposits form a low permeability floor to the lake. An average value for vertical hydraulic conductivity of approximately 0.17 m/day has been determined from water flux calculations for the upper half of the Superficial aquifer, which includes the lake floor deposits and clayey sand facies of the Tamala Limestone probably overlying Bassendean Sand.

Bassendean Sand and Tamala Limestone form a laterally continuous hydrostratigraphic unit. The Bassendean Sand is more permeable than the clayey sand facies of the Tamala Limestone, with hydraulic conductivity for the Bassendean Sand typically between 10 m/day to more than 50 m/day, while the clayey sand facies has been assessed to probably be a few metres per day. The sandy clay layer underlying at least the western half of the lake within the upper portion of the clayey sand facies forms an aquitard between the lake and Superficial aquifer. The limestone facies of the Tamala Limestone is a highly permeable part of the Superficial aquifer over the western portion of the coastal plain due to karstic sections providing pathways for rapid groundwater movement where they extend below the watertable. However, the limestone lies above the watertable until about 1 km west of the lake, and therefore does not comprise part of the Superficial aquifer adjacent to the lake. The Tamala Limestone clayey sand facies therefore forms a zone of lower permeability between the Bassendean Sand and limestone of the Tamala Limestone.

The Ascot Formation can be a highly permeable unit with a hydraulic conductivity probably greater than 47 m/day. The extensive clay unit within the lower Ascot Formation may impede the hydraulic connection between the Superficial aquifer and underlying Leederville aquifer, and effectively make the lower portion of the Ascot Formation hydraulically part of the underlying Leederville aquifer.

Groundwater levels within the Superficial aquifer decline from around 15 mAHD on the eastern side of Lake Nowergup to about 5 mAHD west of the lake as of autumn 2014. A steep hydraulic gradient is evident vertically beneath the western portion of the lake and laterally west of the lake, across the area comprising the lower permeability Tamala Limestone clayey sand facies.

The Leederville aquifer underlies the Superficial aquifer in the Lake Nowergup area, where there is some degree of hydraulic connection between the two aquifers. The Wanneroo member is the upper most member of the Leederville Formation present at the lake and is the most permeable portion of the Leederville aquifer. Hydraulic conductivity of 43.5 m/day was determined over the screened sand bed in supplementation bore 2/00, but it possibly averages less than 10 m/day over the full Leederville Formation due to interbeds of finer grained units. Vertical hydraulic conductivity of 5×10^{-4} m/day was adopted in the Lake Nowergup area for PRAMS modelling, but it is suspected that the value is higher through the Wanneroo Member considering the dominant sand lithology and observed hydrograph responses to pumping. An extensive clay layer present in the lower Ascot Formation may reduce the hydraulic connection of the Leederville aquifer with the Superficial aquifer, particularly on the east side of the lake.

Watertable changes

The watertable elevation beneath the Swan Coastal Plain has changed over the years in response to factors affecting groundwater recharge and storage. Groundwater recharge rates change in response to changes in annual rainfall, particularly through extended wet and dry cycles, and in response to land-use changes. Clearing of vegetation and urbanisation are associated with increases in recharge, while the establishment of pine plantations results in lower groundwater recharge. Groundwater pumping directly affects groundwater storage, resulting in a drawdown of water levels.

Prior to 2002, Lake Nowergup behaved as a throughflow lake. A higher watertable than the lake level about the eastern margin allowed groundwater to discharge to the lake, and a lower watertable about the western end of the lake facilitated downward leakage of water from the lake. Following a period of approximate equilibrium between the lake water levels and the watertable about the eastern lake margin from 2002 to 2007, the lake water levels have been higher than the watertable upon the eastern margin. This indicates that the lake no longer receives inflow of groundwater and is sustained predominantly by supplementation.

Monitoring bore hydrographs within the Superficial aquifer show the watertable has been declining for most of the period since 1975, during which several distinctive phases of decline are evident. There was a rapid watertable decline of about 1 m over the coastal plain east of the Tamala Limestone, including Lake Nowergup, from about 1973 to 1978. As this is prior to significant groundwater pumping, the decline is considered to be a response mostly to reduced groundwater recharge from lower rainfall and the effect of maturing pine plantations east of the lake.

From 1979 to 1992 the watertable was largely stable or declined at relatively low rates. A gradual decline totalling about 0.9 m was recorded 1.3 km southeast of the lake over this time, while lake levels fell by about 0.2 m. Rainfall was relatively stable over the 1979-1992 period and probably did not contribute significantly to the watertable decline, suggesting the observed decline would be related mainly to groundwater pumping east of the lake, probably dominated by private pumping in the Nowergup and Carabooda Groundwater Sub-areas, with minor contribution from the Pinjar borefield commissioned for public water supply in 1989.

A relatively consistent increase in the rate of watertable decline is seen from 1993 to 1998, when the water level declined fairly uniformly by 0.7 to 0.8 m about the lake. Until 1999, the watertable decline becomes progressively less west of the lake and increases to the east, where it is in excess of 1.1 m within 300 m of the east side of the lake. The watertable decline in this period coincides with a significant increase in private groundwater pumping, particularly in the Carabooda Groundwater Sub-area, and increased pumping from the Pinjar borefield. Below average rainfall during 1993, 1994 and 1997 may also have contributed to the decline. Minimum lake water levels over this period were generally stable until 1996, but subsequently the minimum lake water levels dropped by up to 1 m between 1997 and 2002.

The rate of watertable decline slows from 1998 to 2002 in the immediate vicinity of Lake Nowergup coincident with lake supplementation, but only 300 to 500 m west of the lake the watertable fell rapidly by just over 1 m over this time and continued to fall rapidly east of the lake. The decline seen west of the lake coincides with the commencement of pumping from the Quinns borefield. This is also the start of a prolonged period of below average rainfall from the year 2000 to 2010.

A period of stable watertable is seen from 2002 until 2008 about the lake in response to lake supplementation, but the watertable continued to fall further from the lake. After 2008, watertable levels even adjacent to the lake have commenced to rapidly decline. From 2002 to 2014, the watertable has probably fallen by around 1.6 m beneath the central part of the lake, declining by slightly over 2 m about the southeast area of the lake and just over 1 m about its northwest side. Lake water levels that had largely been sustained by supplementation after the rapid fall in 1997 have again fallen rapidly since 2010 with minimum summer-autumn water levels declining to around 14.5 to 15 mAHD by 2014. Most of the observed drawdown is most likely the result of increased private pumping in the Nowergup and Carabooda Groundwater Sub-areas, combined with below average rainfall until 2010. Drawdown impacts resulting from the Quinns Superficial (Tamala Limestone) production bores probably reached near equilibrium condition soon after 2002, and are unlikely to have contributed significantly to the subsequent watertable decline.

Pumping of groundwater for public water supplies from the Leederville aquifer by the Pinjar and Quinns borefields has resulted in depressurisation of the aquifer forming a drawdown cone in potentiometric heads beneath the Superficial aquifer in the Gnangara Mound area. The drawdown cone from these borefields has not been well defined between the borefields and Lake Nowergup due to the limited number of monitoring bores in the aquifer through this area. However, based on the decline seen at monitoring bores to the east at the Pinjar borefield and west of the lake, it is concluded that the potentiometric head within the Leederville aquifer beneath the lake has probably declined by around 10 m, and is now about 7 mAHD. Recent water levels measured in the supplementation bore in the Leederville aquifer confirm this assessment. Whereas an upward hydraulic gradient previously existed between the Leederville and Superficial aquifers about the western margin of the lake, a downward gradient now exists beneath the entire lake area, increasing the potential for downward leakage of groundwater from the Superficial aquifer to the Leederville aquifer.

Increasing rate of lake supplementation required

As the watertable at the lake declines, the rate of supplementation will need to increase to maintain the criteria lake water levels. This is a result of the increased downward hydraulic gradient between the lake water body and the watertable causing an increased rate of downward leakage from the lake. Failure to increase supplementation as the watertable falls results in a declining lake water level and a contraction of the lake water area until the lake water balance matches downward leakage from the lake. At the current watertable elevation of 13.5 to 14.5 mAHD, it is estimated that an average annual rate of lake supplementation of 1900 to 2700 ML will be required to maintain a lake area similar to that in 1989 of 28.5 Ha.

Evaluation of the causes for declining water levels

The watertable decline at Lake Nowergup attributed to each of the factors identified as contributing to the decline is presented by Table 1, and these have been derived from the various methods of analysis employed in this study. These findings are presented for each of the main observed phases of decline. A relative ranking is given for pumping impacts on the lake, from ‘1’ for the largest impact to ‘6’ for the least.

Groundwater pumping from the various areas has resulted in between 2.5 and 3.8 m of watertable decline at Lake Nowergup. Private pumping of groundwater in the Nowergup and Carabooda Groundwater Sub-areas is assessed as having the largest historical impact on the watertable, where it is responsible for 1.4 to 2.4 m of decline. A total decline of 0.5 to 0.65 m is attributed to the Pinjar borefield and 0.55 to 0.7 m to the Quinns borefield (both Superficial and Leederville aquifer production bores). Changes in rainfall patterns is considered to have resulted in 1.05 to 1.45 m of the watertable decline, but this may have also included some influence from maturing pine plantations to the east, particularly during Phase 1. The total resulting decline from pumping and climate effects is therefore between 3.5 and 5.2 m, which is partially off-set by supplementation water that raised the watertable by 0.6 m to 0.8 m.

Table 1. Summary of watertable change (m) and relative ranking of contribution from groundwater pumping.

Period	Phase 1	Phase 2	Phase 3			*Total*	Ranking
	1973 – 1978	1979 – 1992	1993 – 1998	1999 – 2002	2003 – 2014		

Rainfall	0.5	0.05	0.1	0.1	0.3 – 0.7	1.05 – 1.45	
Nowergup & Carabooda	0	0.3	0.3 – 0.5	0.2 – 0.4	0.6 – 1.2	1.4 – 2.4	1
Pinjar – Superficial	-	0	0 – 0.1	0.1	0.1	0.2 – 0.3	5
Pinjar – Leederville	-	0	0.1	0.1	0.1 – 0.15	0.3 – 0.35	3
Quinns – Superficial	-	-	-	0.2	0.05 – 0.1	0.25 – 0.3	4
Quinns – Leederville	-	-	-	0.2 – 0.3	0.1	0.3 – 0.4	2
Supp. Bore	-	-	-	0.01	0.03 – 0.04	0.04 – 0.05	6
Lake supp.	-	-	-	+0.2	+0.4 - +0.6	+0.6 – +0.8	
Total	*0.5*	*0.35*	*0.5 – 0.8*	*0.71 – 1.01*	*0.68 – 1.99*	*2.74 – 4.65*	

The future long-term watertable at Lake Nowergup is projected to remain relatively stable in response to on-going groundwater pumping. Recent reductions in pumping rates of the Water Corporation borefields has decreased the ultimate drawdown by between about 0.8 m and 1.2 m at the lake. There should be a recovery in levels of about 0.25 m from pumping from the Pinjar borefield, while additional drawdown from the Quinns borefield Leederville production bores of just over 0.1 m is anticipated. Water levels about the lake could take around 10 years to fully respond to the reduced pumping. There should be minimal additional impact from the supplementation bore and Quinns Superficial borefield under current pumping rates. Most of the long-term decline caused by private groundwater pumping in the Nowergup and Carabooda Groundwater Sub-areas has already occurred, where any additional drawdown from current private pumping should not exceed about 0.3 m.

Recommendations

- Lake supplementation should be increased to maintain lake water levels as the watertable continues to decline.
- Further hydrogeological characterisation of the Tamala Limestone clayey sand facies and Ascot Formation clay layer should be undertaken. This would be incorporated in subsequent revisions to the conceptual hydrogeological model and Local Area Model.
- Monitoring bores should be established in the Leederville aquifer, and watertable monitoring at selected bores about the lake re-established.
- Modifications are required to the Lake Nowergup Local Area Model for it to be suitable as a predictive groundwater model. Parameter values and zonations of the Superficial aquifer need to be revised to include the more detailed hydrogeology identified by this study, and boundary conditions improved. Calibration deficiencies in the Leederville aquifer will need to be resolved.
- Strategies for consideration to achieve watertable recovery:
    - Shifting of private pumping from the Superficial aquifer to the Leederville or Yarragadee aquifers in the Nowergup and Carabooda Groundwater Sub-areas,

- Allow water efficient and environmentally sensitive urbanisation up-gradient of the lake to significantly increase groundwater recharge rates,
- Replace the supplementation bore with a bore constructed into the deeper Yarragadee aquifer.

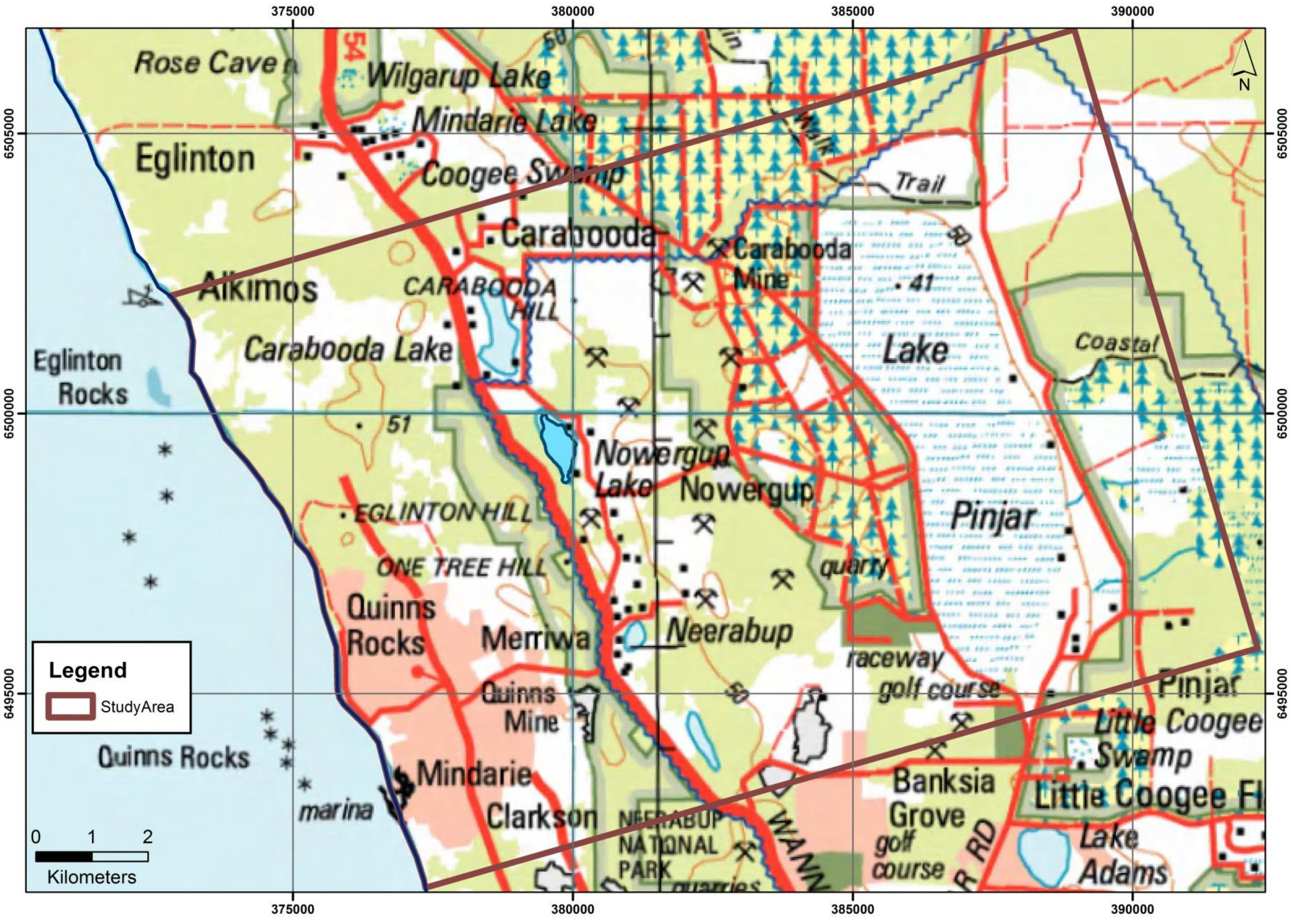

Figure 1. Lake Nowergup locality.

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1 Introduction

Lake Nowergup is positioned upon the western margin of the Gnangara Mound, about 37 km north of the Perth CBD and just over 2 km east of the northern suburb of Butler (Figure 1-1). Regional groundwater levels and lake water levels have been falling since the 1970's. In response to the declining lake water levels, supplementation of the lake by groundwater pumped from the Leederville aquifer has been undertaken since 1989 in an attempt to maintain the water level above defined environmentally important levels (Water Authority of Western Australia, 1992; Searle et al., 2011).

The Department of Water (DoW) engaged Global Groundwater to provide an improved understanding of the relative influence of factors contributing to declining lake and groundwater levels at the lake where possible from available data.

1.1 Environmental importance and regulatory management

Lake Nowergup is a conservation category wetland and Ministerial criteria site under the *Environment Protection Act 1986*. It is also a registered site of significance for Aboriginal heritage (McDonald, et al., 2005). Water Authority of Western Australia (Water Authority) (1995) lists the lake's most important attributes of environmental importance as:

- A permanent deep-water wetland,
- A drought refuge for waterbirds, and a habitat supporting aquatic invertebrates, fish and turtles,
- Sustaining sedges about the lake margins.

The lake is within the Nowergup Groundwater Sub-area, which is part of the Wanneroo Groundwater Management area. Management of these water resources is the responsibility of the Department of Water (DoW), and is undertaken in accordance of the *Gnangara groundwater areas allocation plan* (2009). The DoW is committed under conditions of the Minister for the Environment to maintain the ecological values of the lake.

Environmental criteria for the absolute minimum and preferred minimum end of summer water levels in Lake Nowergup were set in 1988 by the Minister for Environment (Water Authority, 1992; Searle et al., 2011). These levels included an absolute minimum water level of 16.3 mAHD and preferred minimum of 16.5 mAHD. Until 1996 the preferred minimum lake water level was regularly breached, but the absolute minimum water level was not. Spring peaks remained above 16.8 mAHD, and averaged 17 mAHD until 1997 (Department of Water, 2008a, b).

Lake water level requirements were revised in 1996 based on a *Section 46 review of Environmental Conditions across the Gnangara Mound* and improved knowledge of the ecological and social values of wetlands. These revised criteria stated that each spring a peak water level should reach a minimum of 16.8 mAHD, but with a preferred spring minimum peak of 17.0 mAHD. Each year supplementation was undertaken over winter and spring to meet these criteria, after which the supplementation ceased. However, under this regime minimum water levels were frequently breached. Between 1997 and 2001 minimum levels were not reached 2 out of the 5 years and the spring peak has been reached only once (in 2007) since 2001 during which time the spring peak levels have averaged around 16.5 mAHD.

Ecological values of the lake were reassessed in 2004 and new Environmental Water Requirements (EWR) proposed (Froend et al., 2004 a, b). Although the recommendations have not been adopted as Ministerial criteria, they are used by the DoW for impact assessments. The proposed EWR included:

- An autumn minimum Superficial aquifer watertable level of 15.22 mAHD to support groundwater dependent vegetation,
- Minimum lake water level of 16.35 mAHD to prevent oxidation of acid sulphate soils,
- A lake water level of 17.0 mAHD to be reached for two months in at least four out of six years to support waterbirds,
- A lake water level of 16.85 mAHD required for two months in at least four out of six years to support macroinvertebrates.

As part of the shallow groundwater systems investigation it was conceded that the continued artificial maintenance of Lake Nowergup would not meet the existing Ministerial criteria, and that these water levels were no longer appropriate (Searle et al., 2011). It was recommended that a spring peak lake water level of 16.2 mAHD be adopted with a gradual reduction from the 16.5 mAHD level. However, spring peak lake water levels have not exceeded 16 mAHD since 2011. Evidence for some acidification at the lake has been recently noted resulting from the lower lake water levels (Judd and Horwitz, 2015), with a pH range of 7.98 – 8.03 recorded for lake water compared to a previous typical range of 7.95 – 9.21.

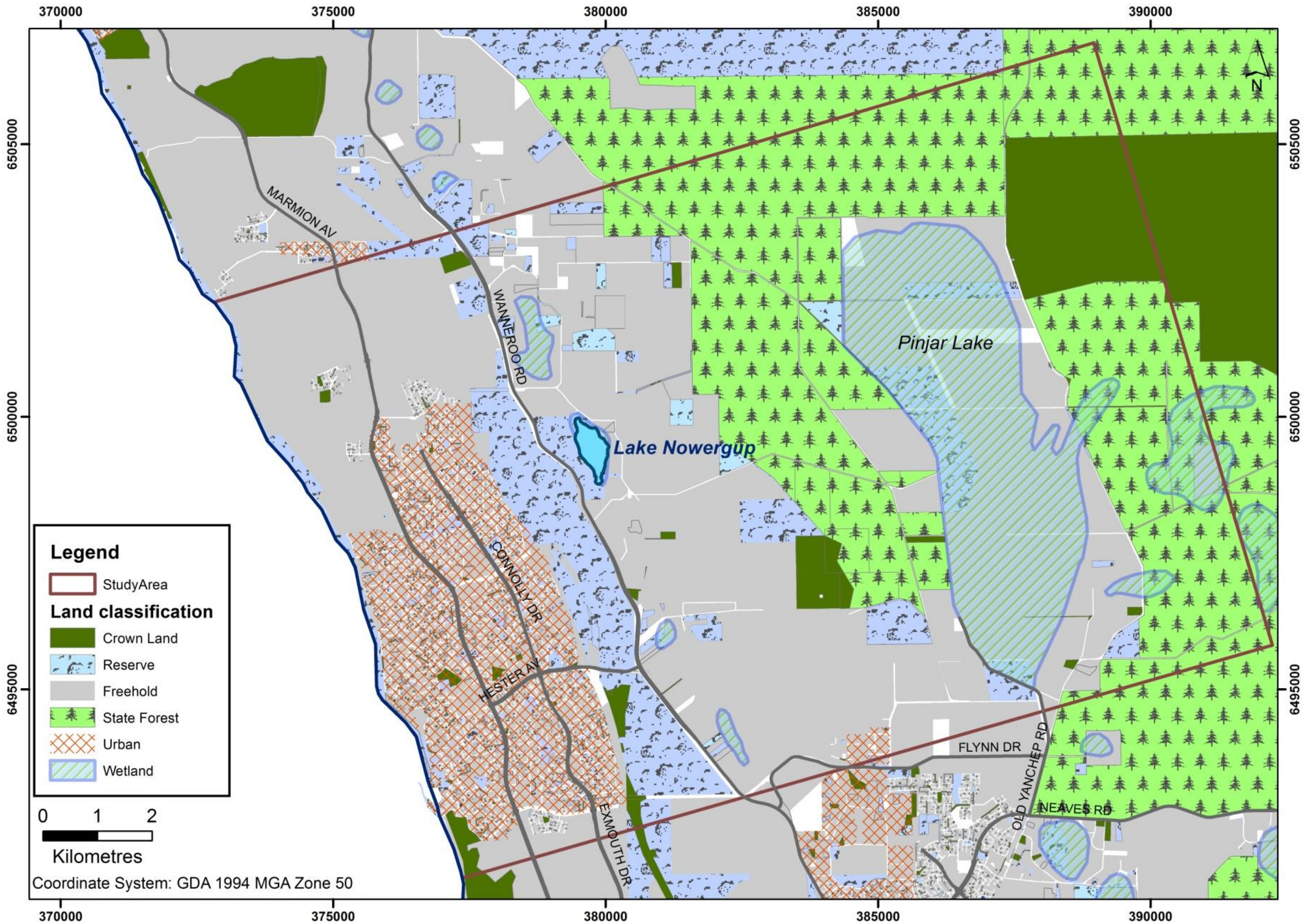


Figure 1-1 Lake Nowergup – Locality and land-use.

1.2 Previous investigations

Lake Nowergup has been the subject of a series of studies since the 1980's. During 1989 a comprehensive investigation was undertaken at Lake Nowergup by the then Water Authority of Western Australia. Details of that program are provided in Water Authority (1995).

The program saw 39 monitoring bores (LN1 to LN39) drilled at 23 sites to depths of between 5 and 65.5 m. Shallow bores were drilled to about 3 m below the watertable, and intermediate and deep bores were drilled along northeast to southwest transects in the approximate direction of groundwater flow. Monitoring bore locations are given on Figure 1-2. A pumping test was undertaken on bore JP17 over 49 days. Bore JP17 is part of the Joondalup monitoring bore network and is screened in the Superficial aquifer over 21.4 m to 39 m depth.

As part of the 1989 program, CSIRO drilled 12 additional shallow monitoring bores at the northern and southern extremities of the lake to investigate lake-aquifer interaction. Seepage meters were installed on the upgradient shore of the lake and these recorded seepage volumes over a three week period (Water Authority, 1992).

In 1990, production bore 2/90 was drilled into the upper Leederville aquifer as a source of water for lake supplementation. This bore was completed with 150 mm ID casing and screened between 57.77 and 75.95 m depth. A 24-hour constant rate pumping test at a flow rate of 4000 kL/day was undertaken, which resulted in a total drawdown of 12.35 m. The supplementation water source was shifted in 2000 to bore 2/00, which was screened deeper in the Leederville aquifer (between 72 m and 92 m depth) to provide a higher rate of supply for supplementation. Step and constant rate pumping tests were carried out to determine the sustainable yield and bore efficiency. The constant rate test was conducted at 9000 kL/day for 24 hours for total drawdown of 17.22 m.

Hydrogeological investigations and the establishment of monitoring bores have been undertaken over the larger area of the coastal plain. Locations of these monitoring bores are shown by Figure 1-3. These programs have included the Artesian Monitoring Network, which principally established monitoring bores into the deeper confined aquifers, and Superficial aquifer monitoring bores of the Pinjar Observation (P), Pinjar Monitoring (PM), Joondalup Monitoring (JP) and North West Coastal (E & Q) networks.

Lake Nowergup was part of the Perth shallow groundwater systems investigation undertaken over 2007 to 2010 (Searle et al., 2011). Objectives of this investigation included: assessment of the interactions and connectivity of surface water and groundwater; evaluation of the wetland chemistry and associated sediments, and how this may influence the quality of lake water and groundwater.

A number of numerical groundwater models have been developed that include Lake Nowergup. The Pinjar Model developed by the Water Authority in 1987 to simulate aquifer systems in the Superficial formations demonstrated the need for artificial lake maintenance to conform to EPA lake level criteria for Lake Nowergup (Water Authority, 1992). This model was superseded by the Perth Regional Aquifer Modelling System (PRAMS), a regional groundwater model with grid size resolution of 500 x 500 m which was too large to assess specific conditions at the lake. A Local Area Model was prepared for Lake Nowergup in 2009 as part of the Gnangara Sustainability Strategy (SKM, 2009a) in order to provide a more detailed representation of the local hydrogeological processes about the lake. The model utilised Modflow and was based on the PRAMS model, but with model grid and layers modified to provide more detail for the Superficial aquifer and to better represent the lake. Predictive scenarios run using the Local Area Model indicated that the planned harvesting of the pine plantations would result in the largest recovery in groundwater levels, but also showed that despite that recovery, lake water levels would not meet the Ministerial water level criteria of 16.8 mAHD by 2020 under any of the scenarios run.

1.3 Groundwater pumping

Allocations to pump groundwater are managed by Department of Water in accordance of the *Gnangara groundwater areas allocation plan* (2009). The Water Corporation pumps groundwater for public water supplies from borefields exploiting both the Superficial and Leederville aquifers located in the Reserve and Quinns Groundwater Sub-areas respectively. Private pumping of groundwater is undertaken mainly for horticultural activities, and this is mostly in the Neerabup, Nowergup and Carabooda Groundwater Sub-areas. A summary of the current groundwater allocations as of 2014 are presented in Table 1-1 for production relevant to this study, and pumping locations for the Water Corporation and private bores are shown by Figure 1-4.

Table 1-1 Licensed groundwater allocations as of 2014.

Groundwater Sub-area	Licensed allocations (kL)		
	Private	Public Open Spaces	Water Corporation
Superficial aquifer			
Quinns	2,909,549	119,584	[a]11,000,000
Eglinton	1,425,290	1,193,708	
Neerabup	2,571,600		
Nowergup	2,699,365		
Carabooda	7,985,750		
Pinjar	611,045		
Reserve	1,421,742		[b]650,000
Leederville aquifer			
Perth North Confined	1,364,220		[a]6,000,000
Gnangara Confined			[b]3,000,000
Wanneroo Wellfield			[c]7,950,000
Yarragadee aquifer			
Gnangara Confined	600,000		[b]11,050,000

Notes: a – Quinns borefield b – Pinjar borefield c – Wanneroo borefield

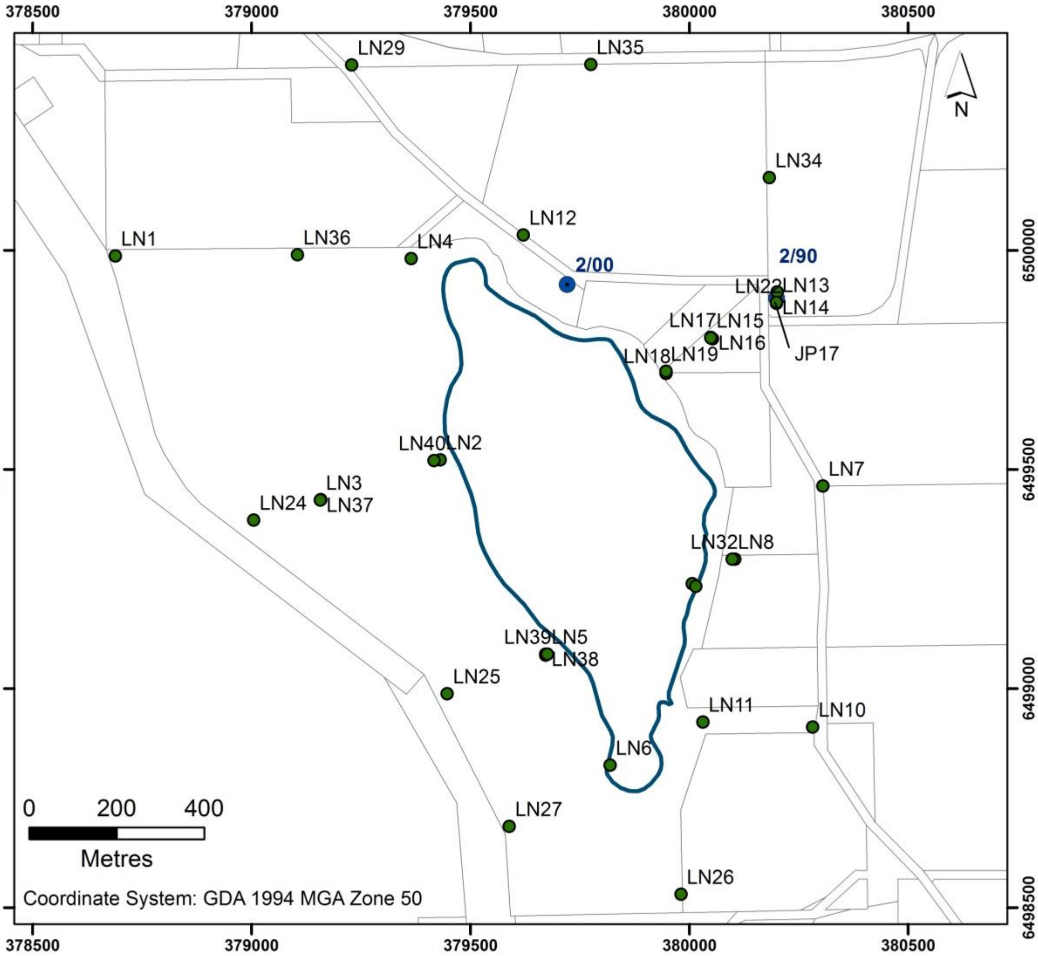


Figure 1-2 Monitoring and supplementation bores - Lake Nowergup.

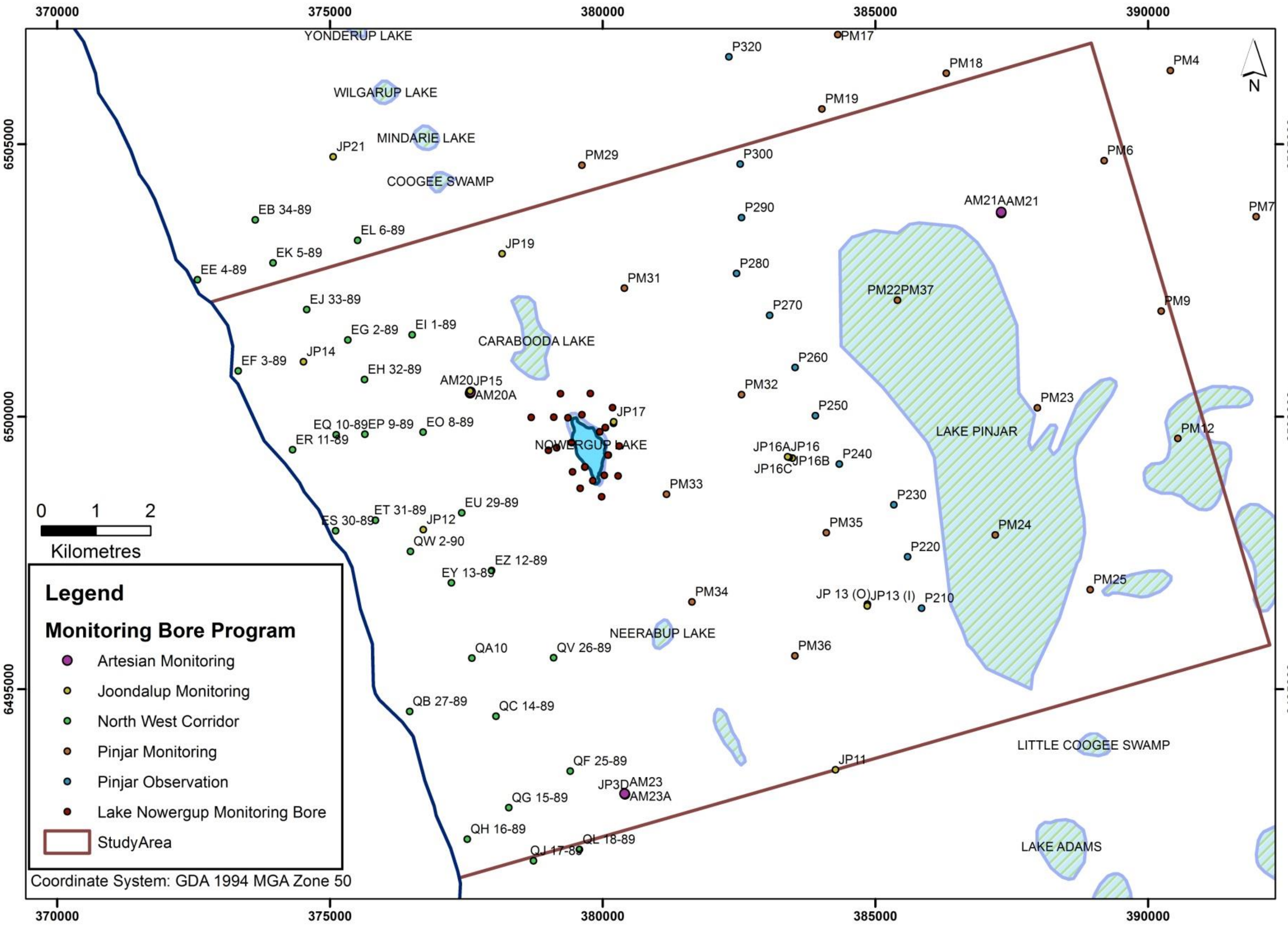


Figure 1-3 Regional groundwater monitoring bores.

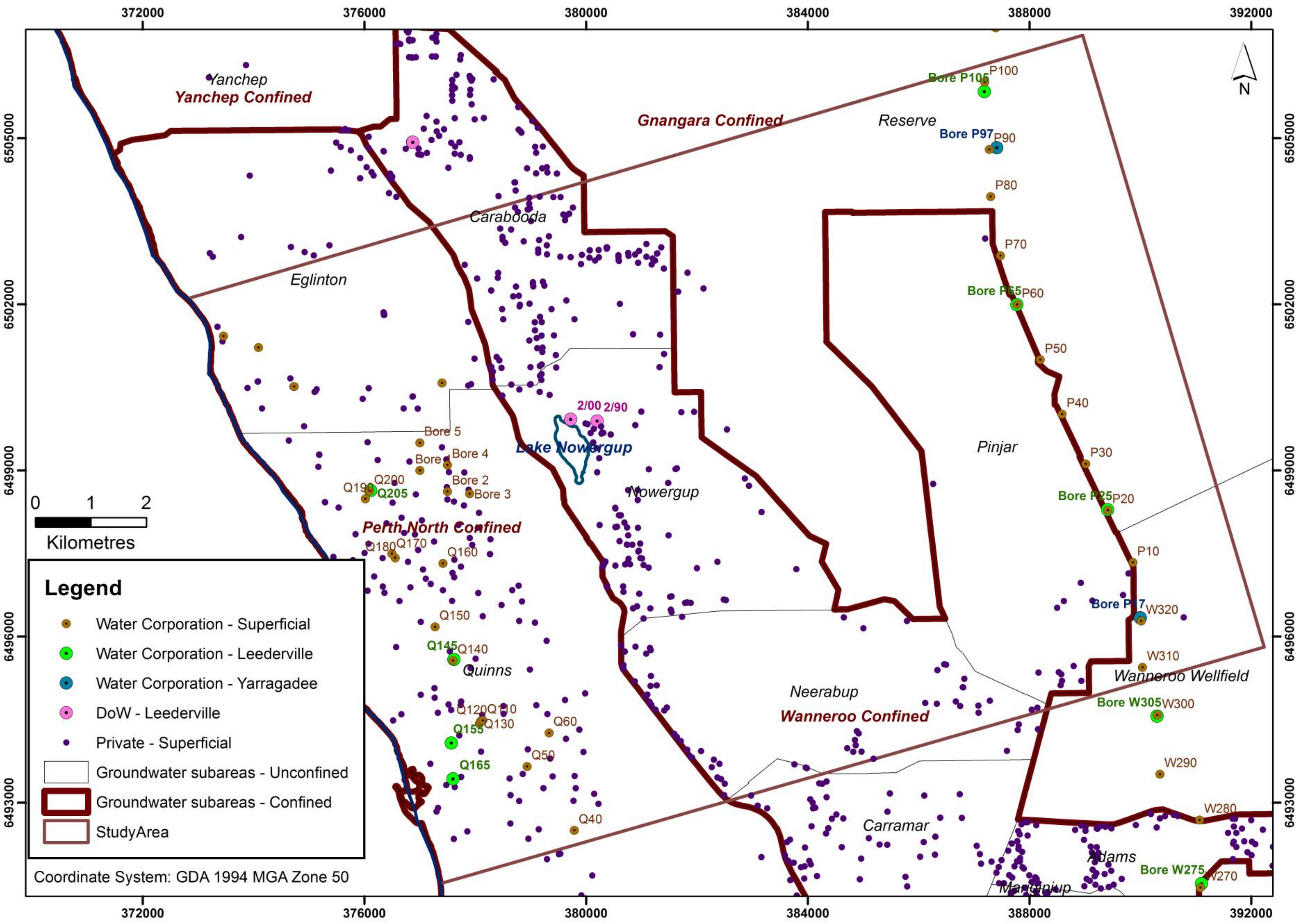


Figure 1-4 Water Corporation and private production bores.

1.3.1 Public water supplies

The Water Corporation's Pinjar, Wanneroo and Quinns borefields are located in the vicinity of Lake Nowergup. Each of these borefields include production bores in the Superficial and Leederville aquifers, and for Pinjar borefield two bores in the Yarragadee aquifer. The Wanneroo borefield is the oldest, having commenced pumping in about 1977. The Pinjar borefield was first commissioned in 1989, with additional production bores added in the Superficial aquifer during 1992. Pumping from the Leederville aquifer increased incrementally over the period 1989 to 1997 as additional bores drilled into that aquifer were commissioned in the Pinjar borefield. Pumping from both Leederville and Superficial aquifer production bores of the Quinns borefield commenced in 1999, although some Superficial aquifer bores did not begin pumping until 2000.

A summary of Water Corporation pumping for public supply from these borefields is given in Figure 1-5. This figure includes two (W310 and W320) of the northern-most Superficial aquifer production bores within the Wanneroo borefield with the Pinjar borefield pumping for consideration of potential impacts on watertable levels in the area of Lake Nowergup. These bores are included as they are within the study area, while the majority of the Wanneroo borefield lies outside. Production from Wanneroo borefield Leederville aquifer bores are shown due to the potential that this pumping could have an influence on water levels at Lake Nowergup, although they are distant from the lake. The Leederville aquifer bore within the Wanneroo borefield closest to the lake is 11.3 km to the east-southeast (W305), while the most distant is 19.5 km to the southeast (W25).

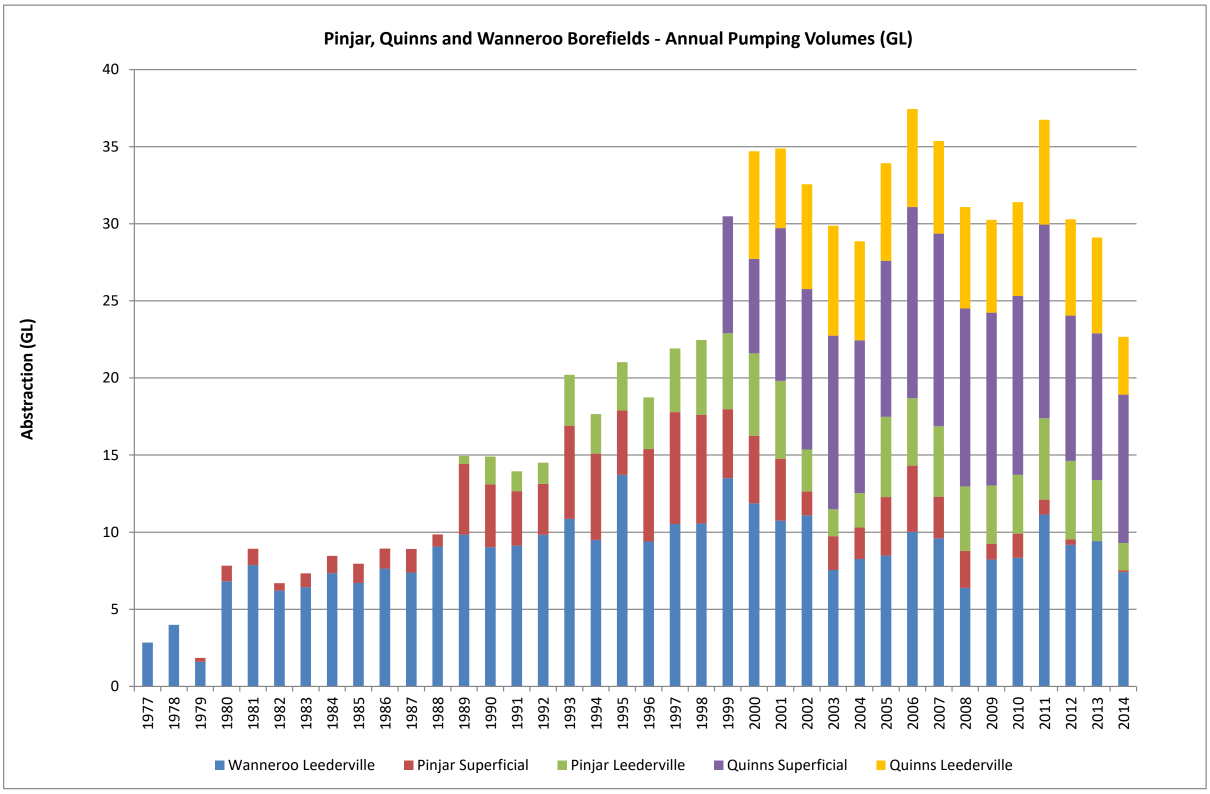


Figure 1-5 Annual groundwater pumping - Pinjar/Wanneroo and Quinns borefields.

1.3.2 Private allocations in the Nowergup and Carabooda Groundwater Sub-areas

The Nowergup and Carabooda Groundwater Sub-areas were proclaimed in 1986. Groundwater allocations were granted according to the existing activities with allowance for future expansion and consequently, the water resources in these areas were immediately fully allocated. As of 2014 the total allocations for the Nowergup and Carabooda Groundwater Sub-areas were 2699 ML and 7985 ML respectively. A chart showing licensed private allocations from the Superficial aquifer in each sub-area since 1986 is given by Figure 1-6 (note – Quinns allocations over 1997-2000 are an extension of 1996 data), and the location of the private allocation draw points is shown by Figure 1-7 (note – that single licenses may be represented by more than one draw point).

Prior to 1986 in the Nowergup Groundwater Sub-area, several market gardens and a turf farm were already established. This included a market garden 900 m south-southeast of the lake about the southeast corner of Nowergup and Gibbs Road, and a turf farm. Another turf farm was situated 1.6 km east of the lake. At this time in the Carabooda Groundwater Sub-area, a market garden is present along the southern part of Karoborup Road, about 800 m northwest of Lake Nowergup, and market gardens were established over the period 1981 to 1985 in the Karoborup Road and Carabooda Road areas, particularly about the southern, eastern and northern sides of Lake Carabooda. There is also significant development in the north about Safari Place and Bailey Road.

Subsequently, in the Nowergup Groundwater Sub-area, there was significant expansion of market gardening areas along Dayrell Road, about 3 km south-southeast of the lake by 1995. A further large market garden had developed by 2002 on the north side of Wesco Road, about 1 km east-southeast of the lake, and by 2005 another had been established 1.7 km east of the lake.

For the Carabooda Groundwater Sub-area, by 1995 further market gardens had been established along Carabooda Road and a large turf farm about 2 km north-northeast of the lake. There is also an avocado farm just south of the turf farm. Over the period 1995 to 2002, there has been increased development about Safari Place in the north of Carabooda, including Benara Nurseries. By 2002 most horticultural developments had been established. A second turf farm is established north of Kiln Road, 1.5 km north of the lake and this was operational by 2009. Additional centre pivots that are possibly an expansion to the turf farm appear to have been established just south of Kiln Road about 800 m from the lake during 2014, however, this operation is supplied by a bore established in the deeper confined Yarragadee aquifer.

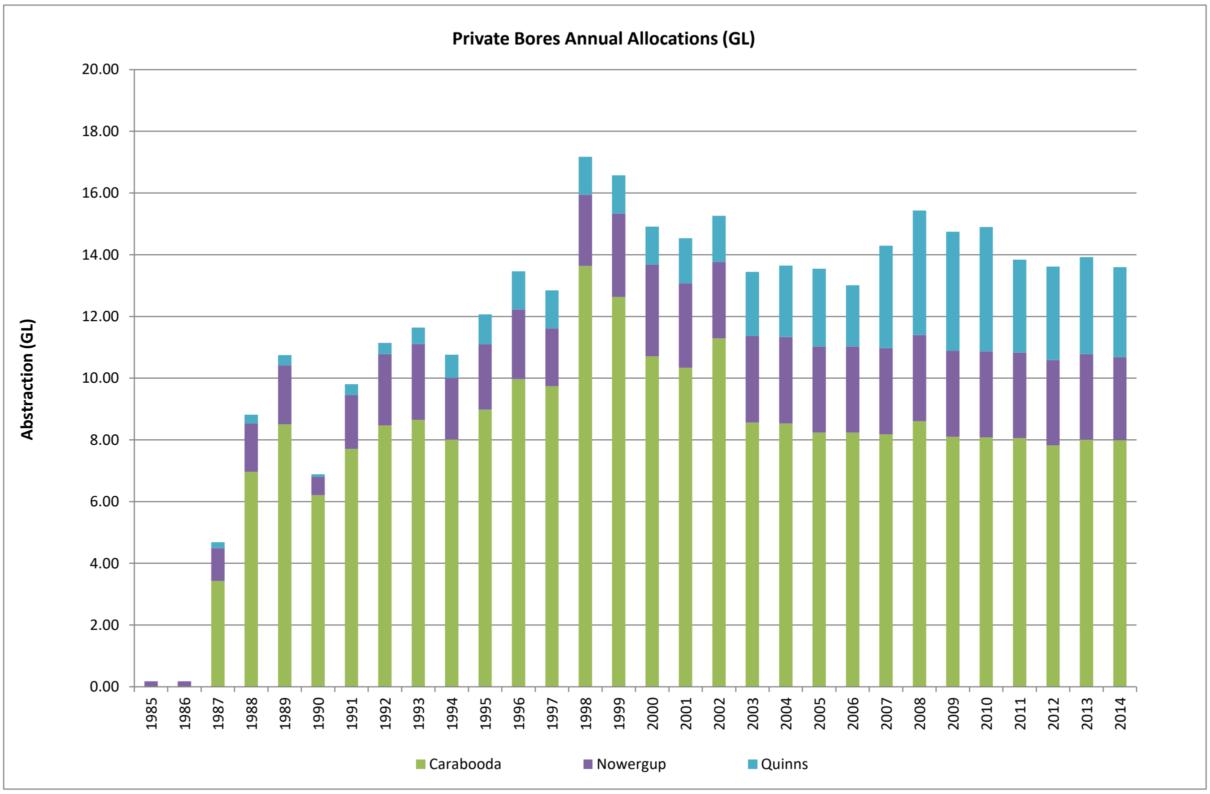


Figure 1-6 Private groundwater allocations (1985 – 2014) Carabooda, Nowergup and Quinns Groundwater Sub-areas.

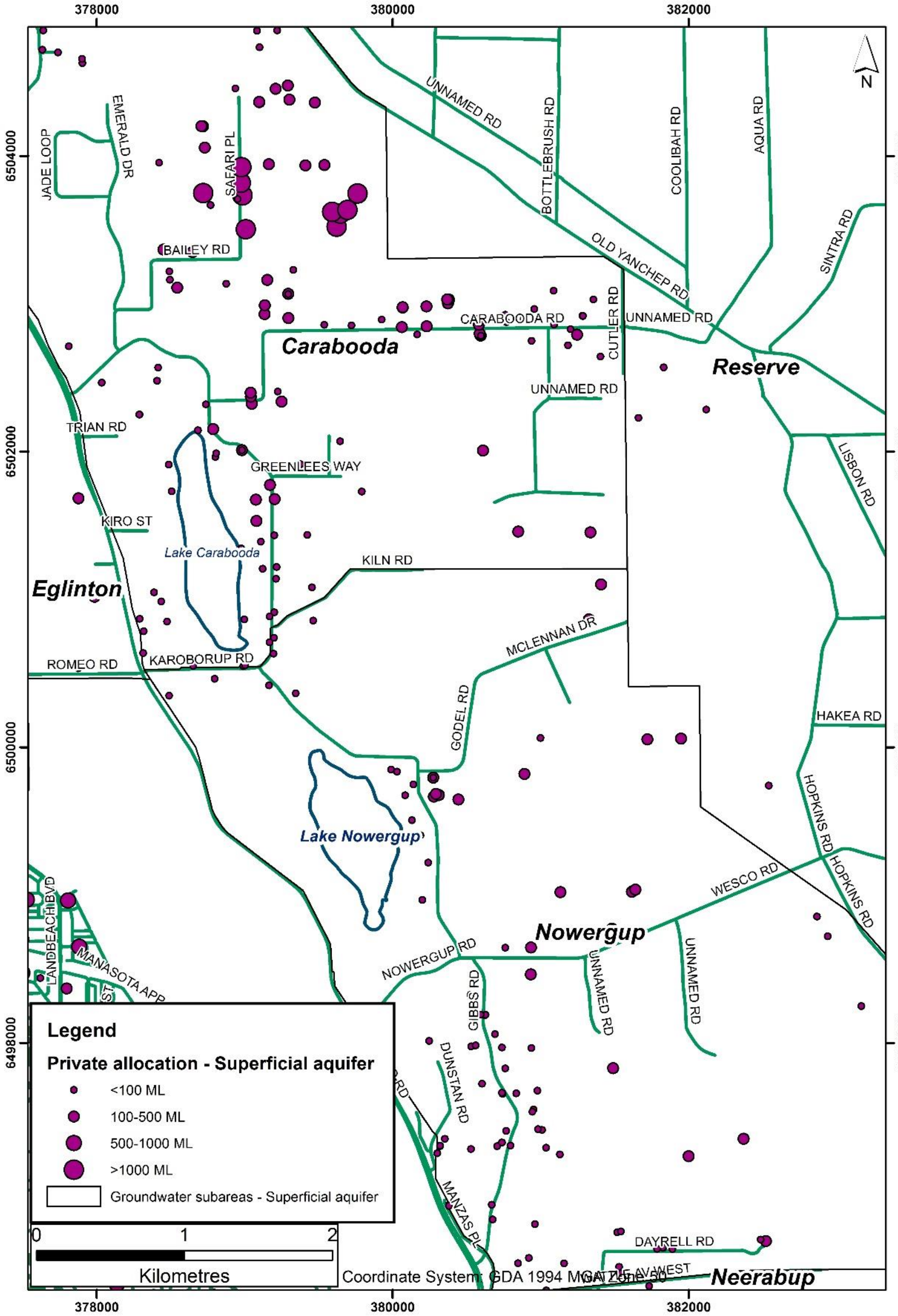


Figure 1-7 Private groundwater allocation draw points from the Superficial aquifer - Nowergup and Carabooda Groundwater Sub-areas.

1.4 Lake supplementation

The Department of Water is committed to maintaining the ecological values of Lake Nowergup, and to achieve lake levels required for EWP (Environmental Water Provisions) have undertaken artificial supplementation which commenced in 1990. By 2008, almost continual supplementation was required to achieve the EWP levels. A summary of past supplementation of Lake Nowergup is given in:

- *The artificial maintenance of Lake Nowergup – implications for current and future management (Department of Water, 2008a),*
- *Memorandum – Revised approach to the artificial maintenance of Lake Nowergup for 2008-9 and 2009-10 financial years (Department of Water, 2008b).*

An initial supplementation trial was performed in 1989 utilising Superficial aquifer bore JP17 to test the feasibility of pumping groundwater into the lake for maintaining a lake level above the EPA's minimum level criteria (Water Authority, 1992). Leederville aquifer bore 2/90 was drilled adjacent to bore JP17 to provide greater pumping capacity than bore JP17. Pumping into the lake commenced in March 1990 at a rate of 3000 kL/day as the lake water level dropped toward 16.3 mAHD, and continued until May 1990 over three separate periods of operation (Water Authority, 1992). A total of 107,717 kL was pumped into the lake over this period.

Higher capacity Leederville aquifer production bore 2/00 screened deeper within the aquifer and situated 480 m west of bore 2/90 was commissioned in 2001. Long-term, supplementation began in July 2001 and continued until October 2001 when the preferred minimum spring peak was achieved. However, after supplementation ceased in October 2001 the lake water level declined more than 1 m over 6 months, which was the lowest level in 30 years of monitoring. After this from 2002 to mid-2006, supplementation commenced each year in August/September and continued over summer until April/May in an attempt to maintain the summer minimum water level above 16.0 mAHD. Using this approach, the lake was more effectively artificially maintained, although water levels continued to decline. Reduced supplementation during October – November 2006 due to mechanical problems with the main bore resulted in a dramatic fall in lake water levels.

From 2007, pumping each year recommenced in March, earlier than the previous program, and continued through winter and spring so that the spring peak could be reached. High water levels were achieved over the following winter and spring, and resulted in flooding onto adjoining private property. To limit the rapid rate at which lake levels declined when the supplementation stopped, a new regime was implemented the following spring that aimed to achieve a rate of decline of 85 mm per month for a total of 360 mm by the end of June.

Figure 1-8 shows the annualised rate of lake water supplementation and lake water levels from 1989 to 2014. Increased supplementation from 2005 to 2011 resulted in the stabilisation of lake levels for most of this period. Despite continued lake supplementation at a lower rate averaging 573 ML from 2011 to 2014, water levels within the lake resumed declining. Reduced rates of supplementation are principally the result of declining bore yields and increased pumping costs, which has encouraged the department to shift pumping to mostly off-peak electricity supply periods to minimise power charges.

Department of Water holds a groundwater license for the Leederville aquifer to pump 1.2 GL per year for lake water supplementation, which has been exceeded during several water years.

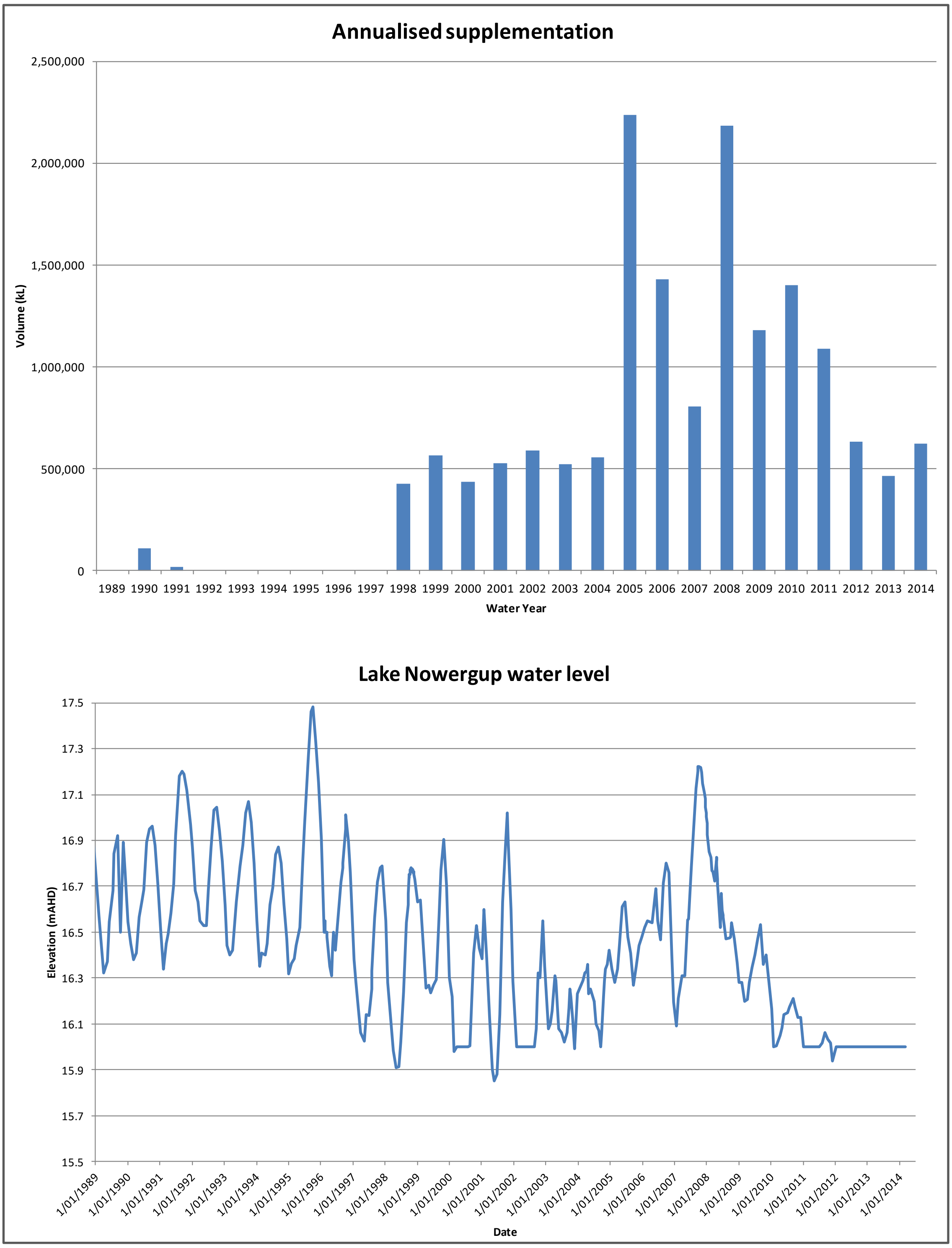


Figure 1-8 Lake Nowergup supplementation and lake water levels (1989 - 2014).

1.5 Scope and methodology

Factors thought most likely to influence lake and groundwater levels at Lake Nowergup are changes in climate (mostly rainfall patterns), land-use and groundwater pumping for private and public water supplies, although the relative influence of these is unclear. The main objective of this desk top study is to improve the understanding of the relative importance of the contributing factors to aid in the formulation of water management strategies allowing for a recovery in water levels.

To achieve the objective, this study has derived estimates of drawdown around the lake from each factor using hydrograph analysis, analytical methods and groundwater modelling; both as results from existing models and from numerical simulations developed in this study. To support the analysis and better define the hydraulic connection between the lake and groundwater, the interpretation of hydrogeology at Lake Nowergup has also been refined.

The study area extends from just east of Lake Pinjar to the coast, and several kilometres north and south, as shown by Figure 1-9. Greater emphasis has been placed on analysis of data closer to Lake Nowergup.

The study involved several stages, including:

- Literature review
- Compilation of data relevant to the study
    - Including borehole data (lithology and hydrographs), geological data, aquifer testing data, licensed allocations, public water supply production data and previous groundwater modelling.
- Review of the geology and hydrogeology of the Superficial and Leederville aquifers in the area
    - Analysis of borehole data about the lake to provide an improved hydrogeological understanding,
    - Review of hydraulic parameter data,
    - Assessment of the hydrogeological complexity of the Bassendean Sand and Tamala Limestone contact.
- Detailed analysis of water level hydrographs from the Superficial aquifer
    - Definition of the magnitude and rate of water level change,
    - Evaluation of temporal trends in water levels in relation to changes in rainfall patterns, groundwater pumping and land-use changes – including the application of Hydrograph Analysis and Rainfall Time Trends (HARTT).
- Evaluation of groundwater flow hydrodynamics
    - Consideration of changing hydrodynamics of the aquifers, such as groundwater throughflow based on previous studies and findings from this study,
    - Estimation of water fluxes between the lake and Superficial aquifer, and between the Superficial aquifer and underlying Leederville aquifer.
- Review of the existing groundwater models previously used for predictive planning scenarios in the Lake Nowergup area.

- Evaluation of the contribution to drawdown at the lake from each of the main groundwater pumping areas using findings from hydrograph analysis, regional modelling results (PRAMS) and analytical analysis and simulations using schematic groundwater modelling.

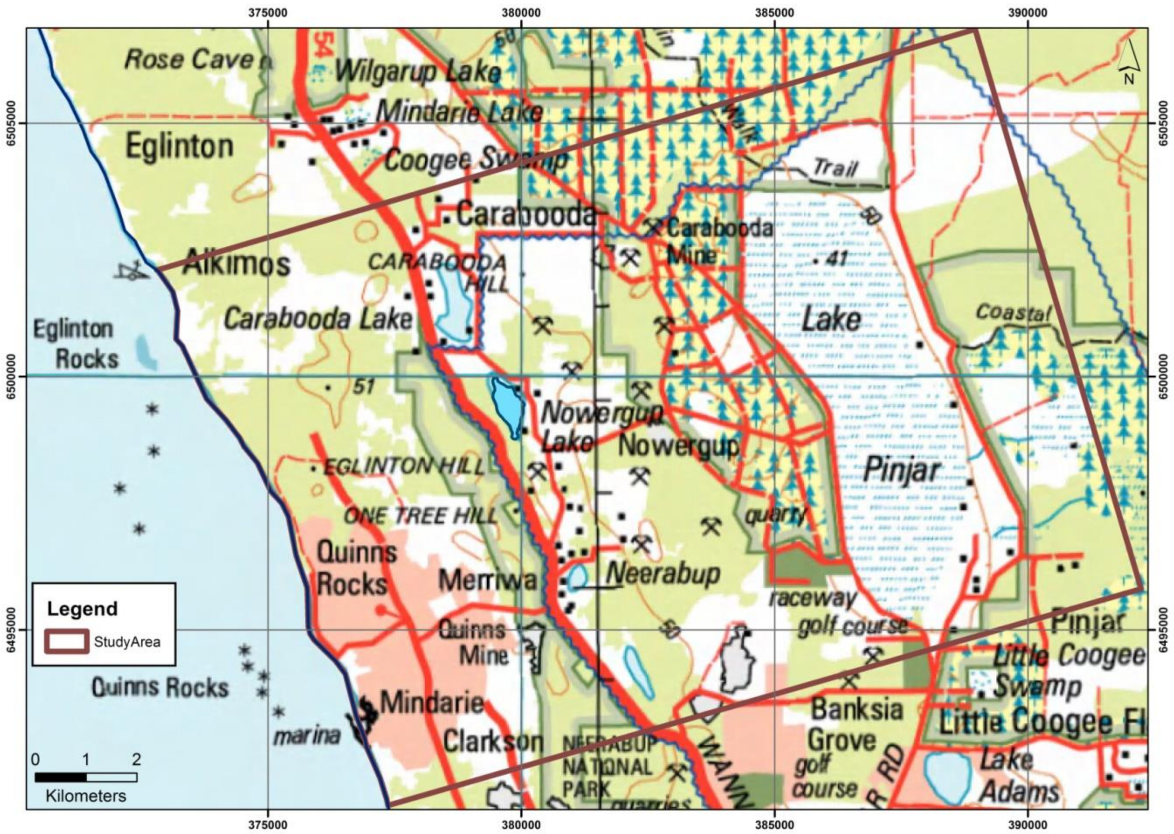


Figure 1-9 Study area.

2 Physiography

2.1 Climate

The region experiences a Mediterranean type climate, with hot, dry summers and mild, wet winters. SILO (Scientific Information for Land Owners) weather data for a point about 1 km south of the lake covering the years 1889 to July 2014 is used for the climatic analysis. The average monthly rainfall and maximum and minimum temperatures for the period 1889 to 2014 are presented in Figure 2-1. Average daily temperatures are highest in February with a maximum of 30.6°C and minimum of 17.5°C, and lowest in July with a maximum of 17.6°C and minimum of 8.7°C. The average annual rainfall since 1889 is 774 mm. The driest month is January with 7 mm. Most rainfall occurs in July with an average of 158 mm. Monthly potential evaporation is a maximum of 287 mm in January and a minimum of 59 mm in July. The long-term average annual potential evaporation is 1895 mm but the average has increased to 1969 mm since 1960. Average annual evaporation has been 1966 mm since 2000.

Rainfall patterns have varied over time, with cycles of stable, above average or below average rainfall. Accumulative Annual Residual Rainfall (AARR) is presented by Figure 2-2, and shows that several cyclical rainfall periods have occurred since 1907. The main wet periods occurred over 1917 to 1934, and 1963 to 1968. Dry periods occurred over 1936 to 1945, 1948 to 1952, 1975 to 1978, and 2002 to 2011.

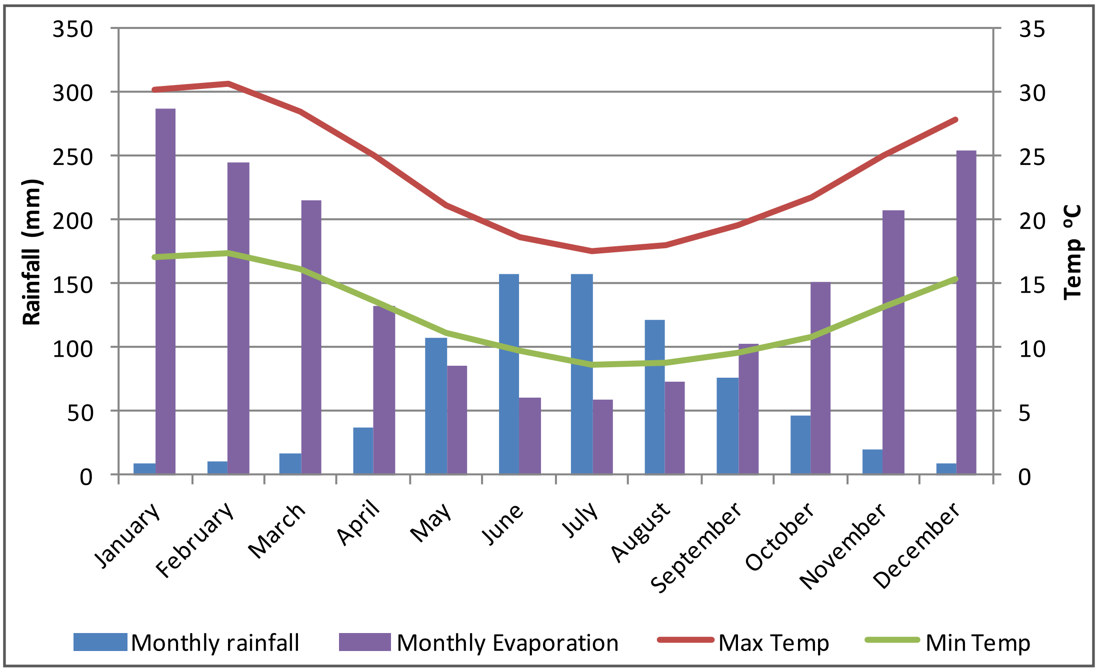


Figure 2-1 Temperature and rainfall - 1889 to 2014.

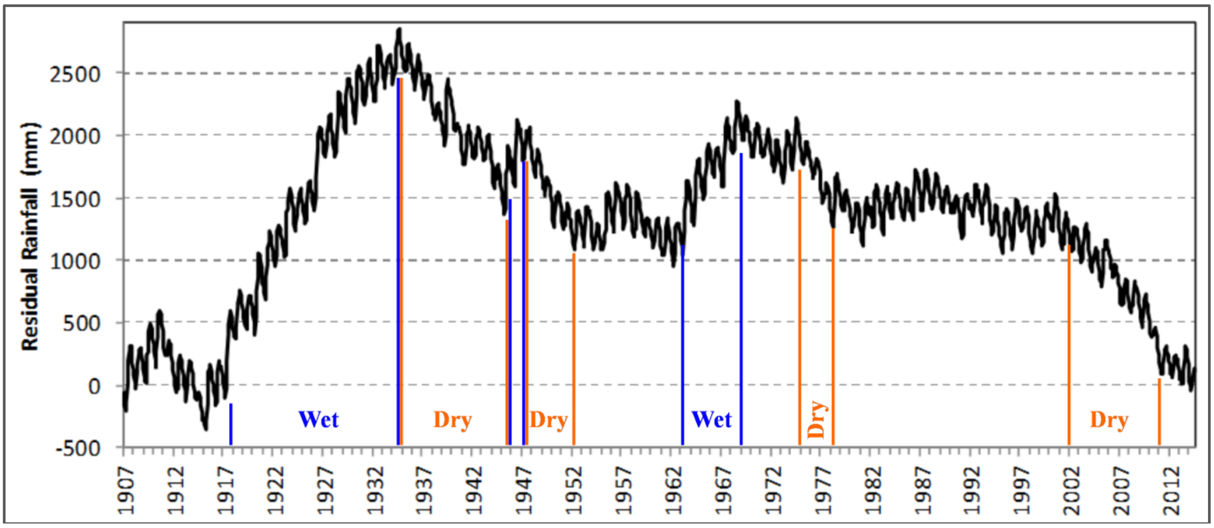


Figure 2-2 Accumulative Annual Residual Rainfall.

Annual rainfall received at Lake Nowergup since 1960 is shown by Figure 2-3. A maximum of 1062 mm was recorded in 1963 and minimum of 497 mm in 2010. Over the period rainfall has averaged 760 mm, compared to the long-term average of 774 mm. Since 2001 annual rainfall has averaged about 690 mm.

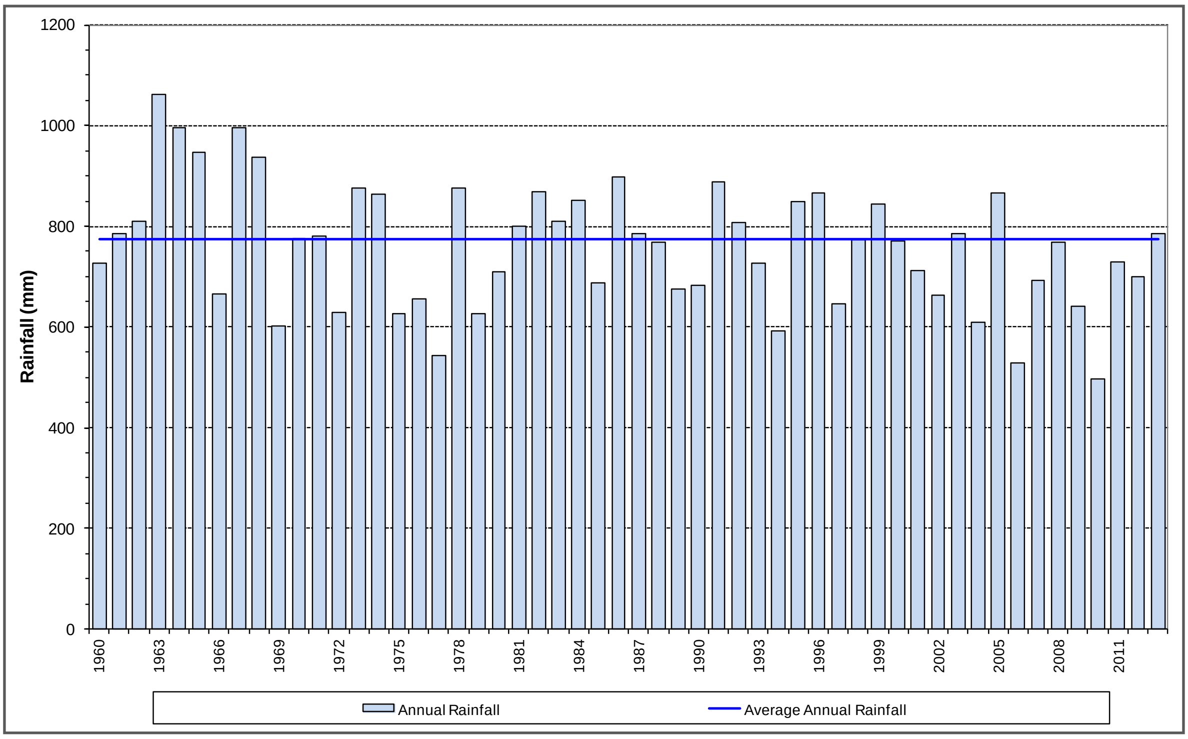


Figure 2-3 Annual rainfall - Lake Nowergup 1960 to 2013.

Recent and projected future decreases in annual rainfall have been related to large-scale changes to southern hemisphere circulation that has resulted in a reduction in the number and strength of low pressure systems and associated cold fronts (Frederiksen and Frederiksen, 2007). This effect is consistent with expected changes due to increased anthropogenic greenhouse forcing (Frederiksen and Frederiksen, 2007). Based on Global Climatic Modelling (GCM) under a range of warming scenarios, rainfall in the southwest of Western Australia is projected to decrease by up to 15% by 2030 relative to the 1990's, with greater decreases by around 2090 of 25% to 45% under various scenarios (Charles et al., 2010; Hope, 2015). The largest decrease in rainfall is seen in winter and spring, with increased periods of drought. Mean annual temperatures are also projected to rise, increasing by 1.1 to 4.2°C by 2090 under the various GCM (Hope, 2015).

2.2 Geomorphological setting

Lake Nowergup is situated upon the Swan Coastal Plain, which comprises a series of landforms roughly parallel with the coast (McArthur and Bettenay, 1960) between the coast and Darling/Gingin Scarps that is 32 km wide over this part of the plain. Topography over the western part of the coastal plain comprising the study area is shown by Figure 2-4.

Lake Nowergup is part of a chain of lakes forming the Wanneroo Linear Lakes occupying a north-northwest trending depression within the Spearwood Dune System. East of the coastal lake chain are the Bassendean Dunes that form a gently undulating aeolian sand plain with a surface elevation reaching around 100 mAHD in the study area. The Spearwood Dunes and Quindalup Dune System extend to the coast west of the lakes. These systems form dunes and ridges of slightly calcareous aeolian sand and wind-blown lime and quartz beach sand. The dunes reach a maximum elevation of about 40 mAHD on the western margin of Lake Nowergup.

Lake Nowergup can cover an area of 40 ha when full at which point water levels within the lake reach a peak level of 17.5 mAHD. The lake bed at its low point drops to an elevation of approximately 13.5 mAHD about the centre of the lake, so that when full, the lake depth can reach a maximum of about 4 m. Seasonal water level fluctuations occur with the lake retreating to the deeper central portion over summer. In 1989, the lake covered an area of approximately 285,060 m^2, but by 2014 the lake area has decreased to about 100,815 m^2 (Figure 2-5). Seasonal fluctuation in lake water levels were normally about 0.6 m from the 1970's to 1989, after which lake supplementation commenced. Subsequent to the supplementation the range of seasonal change has increased, now ranging from less than 0.4 m to more than 1 m.

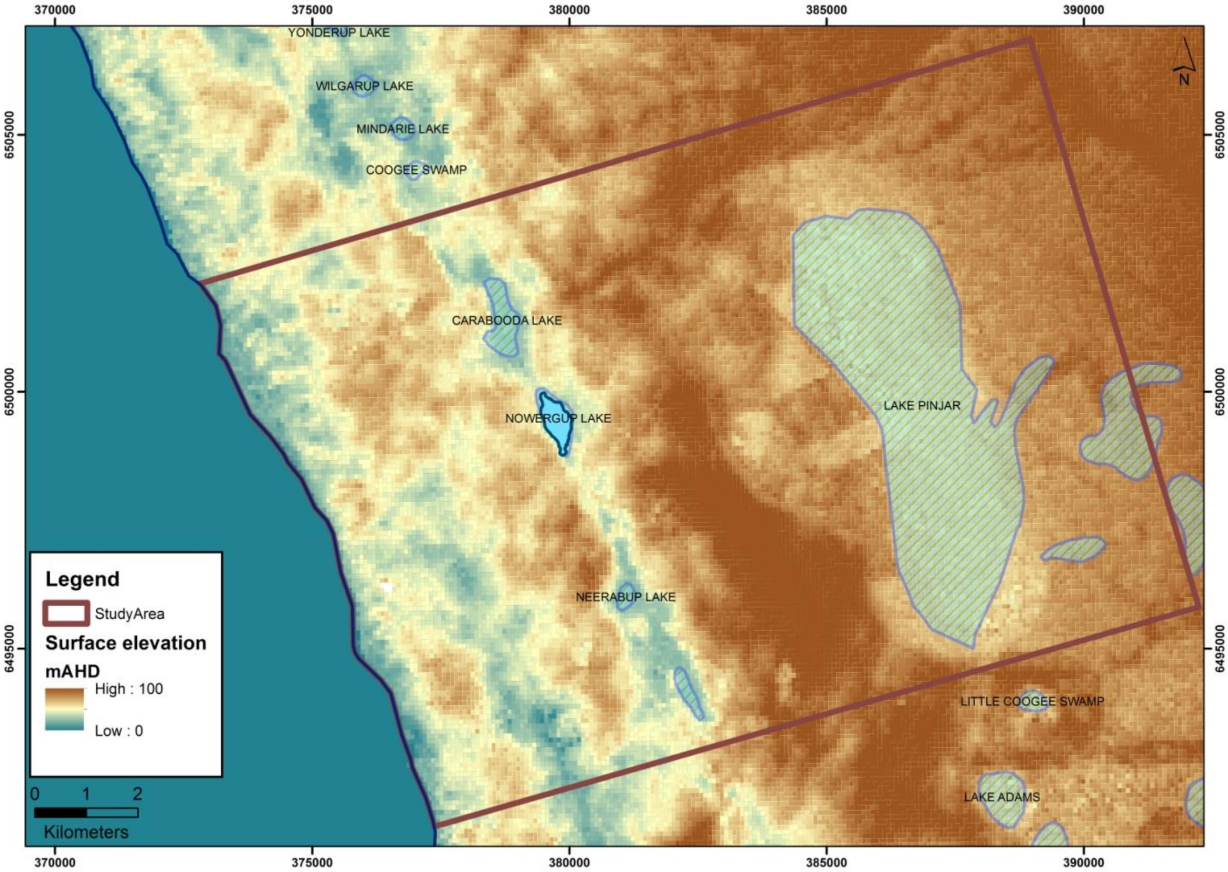


Figure 2-4 Geomorphology.

Figure 2-5 Aerial view of Lake Nowergup - February 2014.

2.3 Land-use

The main land-use in the study area as categorised by Landgate cadastre is freehold, State Forest, National Park/reserve and residential (see Figure 1-1). Freehold land extending east of Wanneroo Road to the east side of Lake Nowergup is used for irrigated horticulture and private rural holdings. Remnant bushland mostly of Banksia woodland and extensive areas of State Forest are located beyond about 2 km east of Lake Nowergup and are present both sides of Pinjar Lake. State forest is utilised for Pine plantations, but since about 2008 much of the Pine plantation has been harvested (evident in Google images).

The Neerabup National Park borders the western side of Lake Nowergup, and comprises native woodland extending for about 1500 m west of the lake. Residential suburbs of Butler, Ridgewood and Merriwa are situated between the national park and coast, and currently form the northern limit of the Perth Metropolitan area.

3 Geology

The geology of the Swan Coastal Plain has been previously described by Playford et al. (1976) and Davidson (1995). In the local area of Lake Nowergup additional geological descriptions have been presented by Water Authority (1995) and Searle et al. (2011), but there has been no previous reporting of detailed analysis of geological information for this area. Findings from the examination and interpretation of geological data by this study presented here represent the most detailed to date for the Lake Nowergup area.

In order of increasing depth, the near surface at Lake Nowergup is underlain by the Superficial formations overlying the Leederville Formation. Lake bed deposits consisting of organic mud, silt and clay make-up lake floor deposits lying upon the Superficial formations. The upper portion of Superficial formations at Lake Nowergup comprise the Tamala Limestone west of the lake and Bassendean Sand to the east, with a tapering and possibly interfingering contact between the two formations beneath the lake. These formations are of Quaternary (Pleistocene) age and overlie the Pliocene age Ascot Formation forming the base of the Superficial formations in the lake area.

Superficial formations lie unconformably upon the Wanneroo Member of the Leederville Formation. The basal contact between Superficial formations (Ascot Formation) and the Leederville Formation is around -30 mAHD at the lake. Geological relationships about the lake are shown by the east–west and northwest–southeast cross-sections in Figure 3-1 and Figure 3-2.

3.1 Lake bed deposits

Deposits comprising muds of silt, sand and organic clays cover the floor of Lake Nowergup. The precise lithology and thickness of these deposits is uncertain due to lack of drilling within the lake. At Loch McNess to the north, dredged lake bed sediments showed that they consisted of mainly silts and sands (Kretschmer and Kelsey, 2012). Davidson (1995) states that the lakes upon the coastal plain contain sediments of biogenic origin (peat, peaty sand, diatomite and calcareous clay), and marley limestone. He also noted that lacustrine sediments are generally more sandy on the up-gradient side (usually eastern) than the down-gradient side where they are commonly peaty.

3.2 Tamala Limestone

Orange brown to yellow brown fine to coarse and very coarse grained sub-angular to sub-rounded quartz sand forms the surface west of the lake. It is up to about 11 m thick (11 m in LN24; 5 m in LN37; 7 m in LN38), represents aeolian deposits and the leached upper surface of the Tamala Limestone corresponding with the Spearwood Dune System (McArthur and Bettenay, 1960). The Tamala Limestone beneath the surface sand comprises two main lithologies; a limestone of calcareous arenite overlying a basal calcareous clayey sand. These are referred to here as the limestone facies and clayey sand facies.

The limestone is a hard to crumbly calcarenite of mostly fine to coarse and up to very coarse grained, sub-angular to sub-rounded sand comprising quartz and shell fragments with calcareous cementation. It is coloured mostly creamy white and occasionally iron-stained to a fawn colour. There are intervals of loose, creamy orange, calcareous and often clayey sand through the limestone. In the area of Lake Nowergup, the limestone thins rapidly from the west toward the lake. The maximum thickness intersected by drilling is about 34 m in bore LN1 west of the lake, but it was absent in bores LN38, LN4 and LN6 adjacent to the western margin of the lake. Solution cavities and vugs were noted in the limestone intersected in bore LN37 at 12 to 16 m depth, which is roughly about the middle of the limestone section, and also in bore LN24 from 23 to 24 m depth. The lower portion of limestone is often described as rubbly, and may represent discontinuous thin limestone layers and nodules within calcareous sand.

The limestone facies sits upon the clayey sand facies comprising sand, clayey sand or sandy clay. This unit was referred to as Tamala Sand by Kretschmer and Kelsey (2012) at Loch McNess. It is orange brown to light brown, coarse to very coarse grained sand that is sub-rounded to rounded, calcareous with nodules of limestone, and typically contains a significant portion of clay in the matrix. It has a thickness of 12 to 13 m intersected in bores LN37 (29-42 m) and LN38 (20–32 m).

A sandy clay layer is present in the upper part of the clayey sand facies over an extensive area west of the lake. This layer shallows and thickens toward the lake. It is dark brown to light brown and orange brown and frequently contains limestone stringers. The sandy clay is present between 10 and 15 m depth in bore LN38 adjacent to the western lake shore. These depths correspond to about 6 and 11 mAHD suggesting the sandy clay may be present directly beneath the deeper parts of the lake floor. The sandy clay layer appears to be less developed beneath the northwest margin of the lake in bore LN4, and also the southwest margin of the lake in bore LN6.

Shallow and thin intervals of the Tamala Limestone overlying Bassendean Sand have been intersected in bores LN7 (5-6 m), LN10 (3-6 m) and LN11 (1-2 m) about the southeast side of the lake. At these sites it is an orange brown to yellow brown sand containing limestone fragments and calcareous clayey sand that is only a few metres thick. Presence of the clayey sand facies southeast of the lake suggests continuity beneath the lake from the west to the east shore.

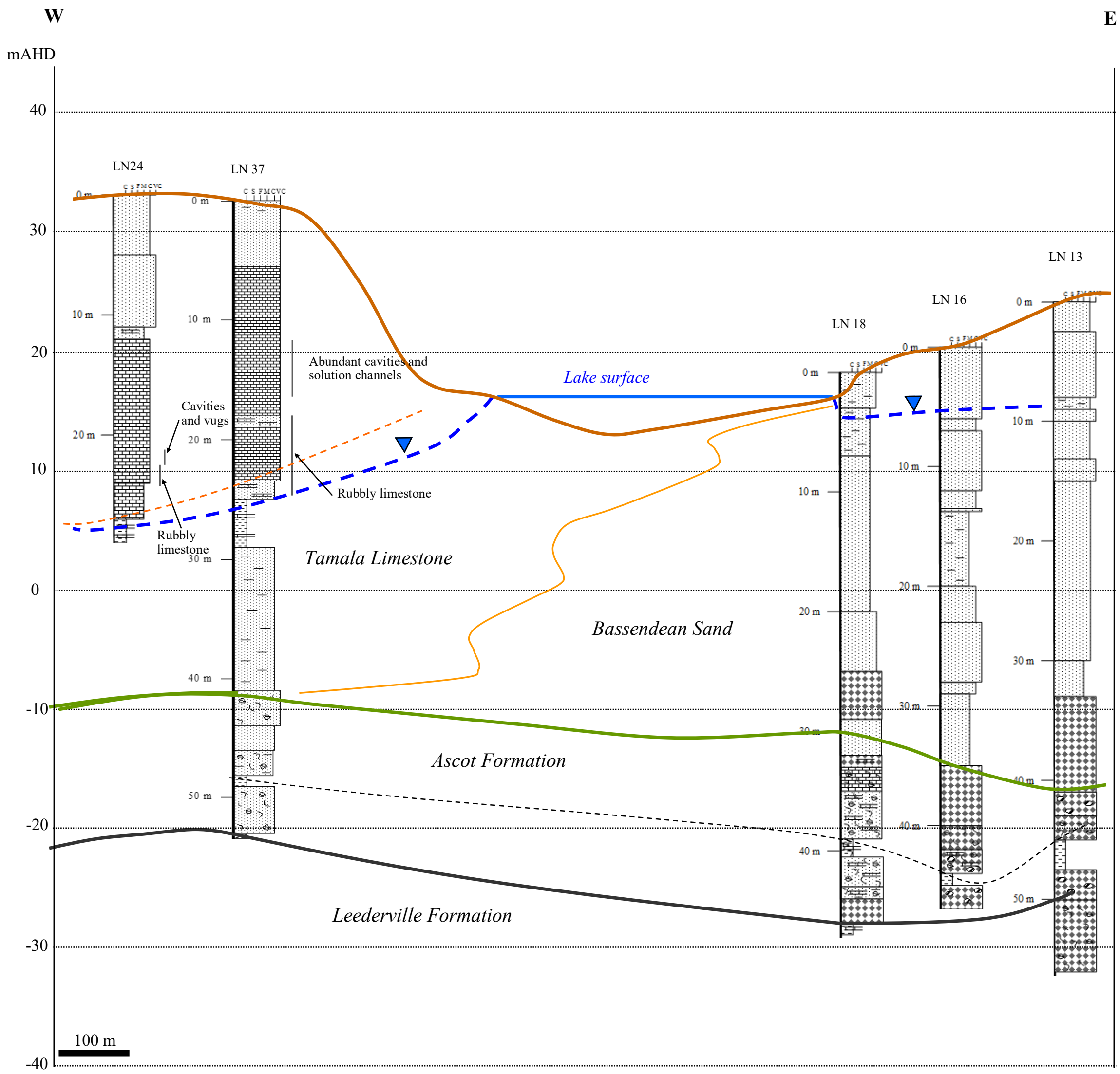
3.3 Bassendean Sand

The Bassendean Sand is present east of the lake and forms a tapering wedge sloping westward beneath the Tamala Limestone below Lake Nowergup. It comprises fluvial, dune and shoreline deposits with estuarine and shallow-marine intercalations present at the base (Playford et al., 1976). Between 30 m and 41 m of Bassendean Sand has been intersected in bores LN18, LN16 and LN13 on the eastern side of the lake. In these bores it is a predominantly grey, fine to medium and coarse grained quartz sand that is sub-angular to sub-rounded. The lower portion of Bassendean Sand is medium to very coarse grained sand with very fine pebbles, with the larger grains well rounded. This lower portion increases in thickness toward the east, from a few metres in bore LN18 to 8 m in bore LN13 and possibly represents a shoreline deposit. It may represent the Gnangara Sand (Davidson, 1995), although this formation has been grouped with the Bassendean Sand by Department of Water in the Northern Perth Basin Groundwater Bulletin (Department of Water, in prep.).

3.4 Ascot Formation

The Ascot Formation occurs at the base of Superficial formations in the Lake Nowergup area. It is a shallow-water open-marine deposit comprising light grey to fawn calcarenite limestone bedded with medium to coarse grained sub-angular to rounded sand. Shell fragments are frequently abundant. Clayey sand or clay is common through the lower portion and phosphate nodules are often found at the base of the formation. The Ascot Formation has a variable thickness of between 4 and 21 m where fully penetrated by drilling about the lake and unconformably overlies the Leederville Formation.

A dark grey, pyritic sandy clay bed up to 5 m thick was encountered within the lower portion of the formation in all bores drilled to sufficient depth about Lake Nowergup. It was intersected in bores LN13, 16, 18 and 38, suggesting that this may be an extensive unit about the lake, although it is better developed about the eastern side. It is uncertain whether this constitutes a continuous clay layer or an interval containing clay layers of limited extent.



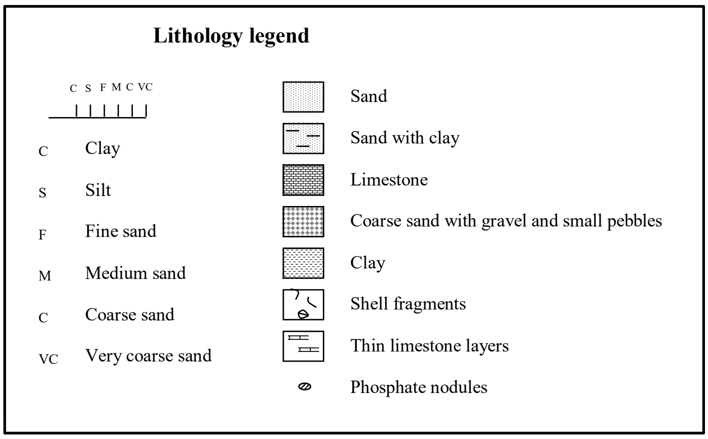


Figure 3-1 East - west geological cross-section, Lake Nowergup.

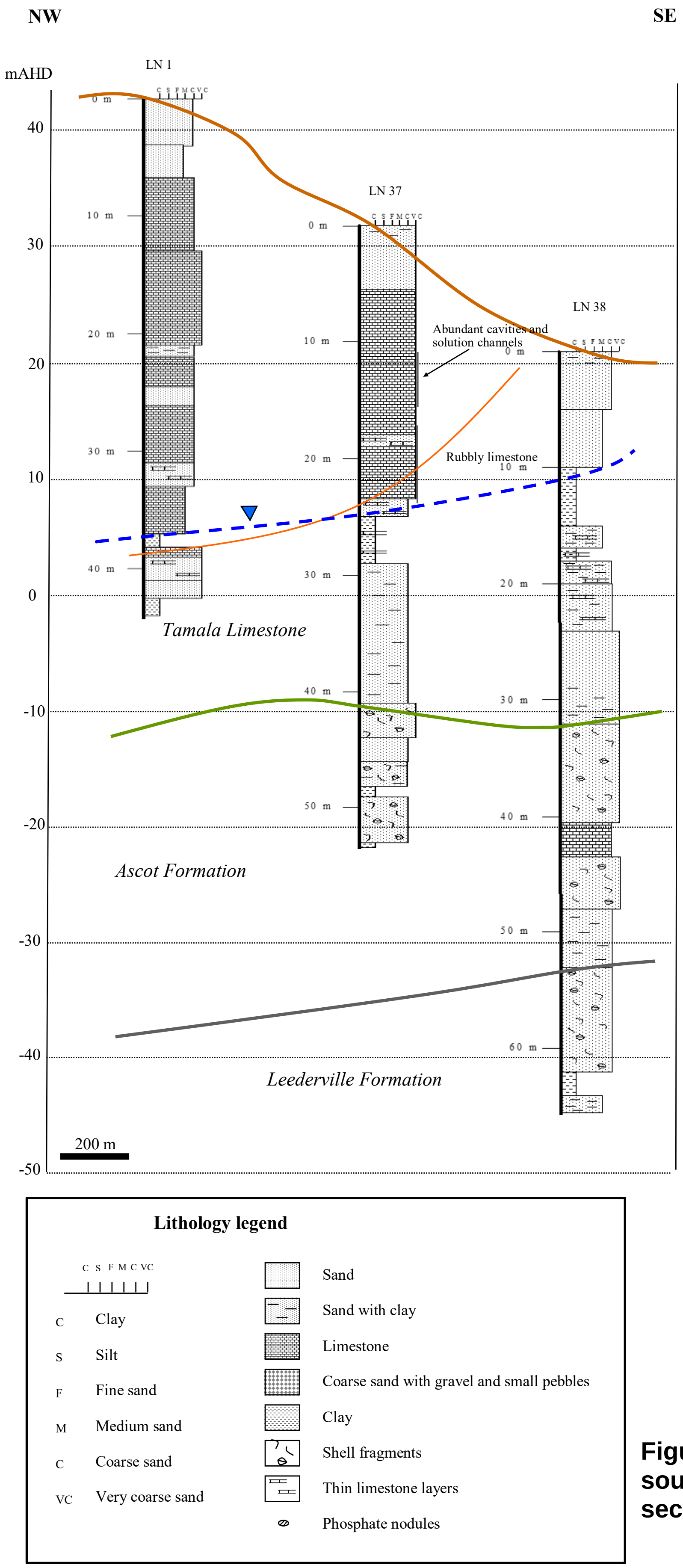


Figure 3-2 Northwest - southeast geological cross-section, Lake Nowergup.

3.5 Leederville Formation

The Leederville Formation is a Cretaceous age sequence that comprises interbedded sandstone, siltstone and shale deposited in marine and non-marine environments. It is sub-divided into 3 member units, which are in ascending order the Mariginiup Member, Wanneroo Member and Pinjar Member (Davidson, 1995). In the Lake Nowergup area the middle Wanneroo Member subcrops the Superficial formations, while the Pinjar Member is absent. The Wanneroo Member contains the thickest and coarsest sand beds of the formation with intervening shale and siltstone beds. Based on mapping by Davidson (1995) the Leederville Formation is interpreted to be around 180 m thick, overlying the South Perth Shale.

The Leederville Formation has been intersected by bore LN38 on the west side of the lake and by bores LN13 and LN18 on the east side, in addition to production bores 2/90 and 2/00. Production bore 2/90 which was used for supplementation of the lake until 2000 is constructed into the top of the Leederville Formation, having been drilled to 77 m depth and intersecting Leederville Formation sediments from 52 m depth. These consisted of fine to coarse grained sands, black shale, coal and pyrite. A downhole gamma-ray log is available for bore 2/00, which is shown by Figure 3-3. This log shows Leederville Formation present from 47 m depth consisting of interbedded siltstone, shale and sandstone. A thick sandstone unit occurs between 75 m and 91 m. However, based on a comparison with the gamma ray log from bore AM20, it may be that the base of the Wanneroo Member is at only 91 m depth at this site, which is considerably shallower than interpreted by Davidson (1995) of around 160 m depth (about -140 mAHD).

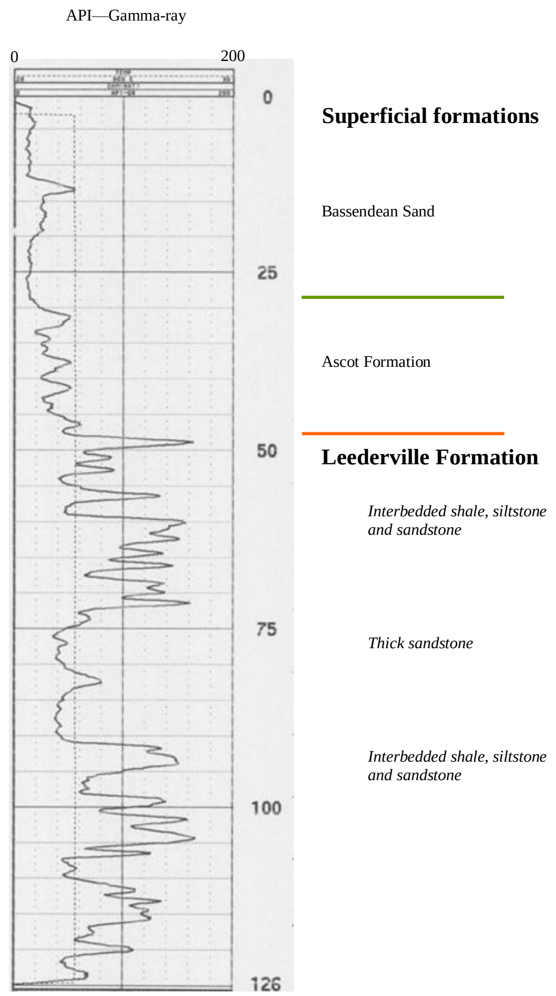


Figure 3-3 Downhole gamma-ray log bore 2/00.

3.6 Variability of formations across the coastal plain

The Superficial formations gradually slope upward inland upon an unconformity over Cretaceous age sediments. It is at its lowest along the coast where the basal elevation of the Superficial formations is below -35 mAHD, and rises inland, reaching between about -20 and -30 mAHD at Lake Nowergup, and approximately -10 mAHD at Lake Pinjar 5 km east of Lake Nowergup and 10 km inland. Within the Superficial formations, the limestone facies of the Tamala Limestone also rises in elevation inland, where it has a base elevation that reaches below -10 mAHD at the coast and climbs to almost +10 mAHD at LN37 situated 4.4 km in from the coast, and just west of the lake. A geological section extending between the coast and LN1 west of Lake Nowergup is presented in Figure 3-4. Cretaceous age formations subcropping the Superficial formations through the study are shown in Figure 3-5, which is reproduced from previous work by Davidson and Yu (2008).

The limestone facies in the upper Tamala Limestone is up to 50 m thick and described as being vuggy west of the lake. Clayey sand facies of the lower Tamala Limestone at Lake Nowergup progresses to a calcareous sand unit west of the lake, where it is between about 20 m and 40 m thick containing sand and limestone, and is referred to here as the sand facies to distinguish it from the clayey sand facies at Lake Nowergup. The sand is cream coloured, calcareous and contains limestone nodules, with limestone intervals of up to several metres thick. The Ascot Formation does not appear to extend far west of the lake, except for an area about EQ 10-89 where clay and sand containing phosphate nodules was encountered which may be part of the formation.

The Bassendean Sand extends east of Lake Nowergup, where it is a relatively clean, grey to white, fine to coarse grained sand containing intervals of coarse sand to granule sized grains, mostly through the middle and lower portion of the unit. About Lake Pinjar and east of the lake, clay is present through intervals in the upper to middle portion of the sand. This clay is normally white, and probably represents kaolin clay weathered from feldspar sands.

About Lake Nowergup the Superficial formations directly overly Wanneroo Member sediments of the Leederville Formation. However, the Pinjar Member is present at the top of the Leederville Formation just northwest of the lake, but does not occur to the east until the other side of Lake Pinjar, a distance of about 10 km from the lake (see Figure 3-5). A short section of Pinjar Member sediments were intersected between 56 m and 68 m depth in AM20, situated 2 km northwest of Lake Nowergup, while intervals were also intersected in Water Corporation Quinns borefield Leederville production bores Q145 (originally QA25) and Q205 (originally QZ35) below the Superficial formations. The Pinjar Member is a finer grained deposit that comprises predominantly shale, siltstone and fine grained sandstone, with some occasional coarse grained sandstone. In AM20 the Wanneroo Member extends beneath the Pinjar Member to 192 m depth, and is dominated by fine to coarse grained sand with intervals of gravel. Previously the Kardinya Shale consisting of interbedded siltstone and shale was interpreted as overlying the Leederville Formation approximately 2 km west of the lake, separating the Superficial formations from the Leederville Formation (Davidson, 1995; Davidson and Yu, 2008), however reanalysis using later borehole data from Q145 and Q205 found that the Kardinya Shale was absent through this area and that the Superficial formations were underlain by Pinjar Member sediments of the Leederville Formation.

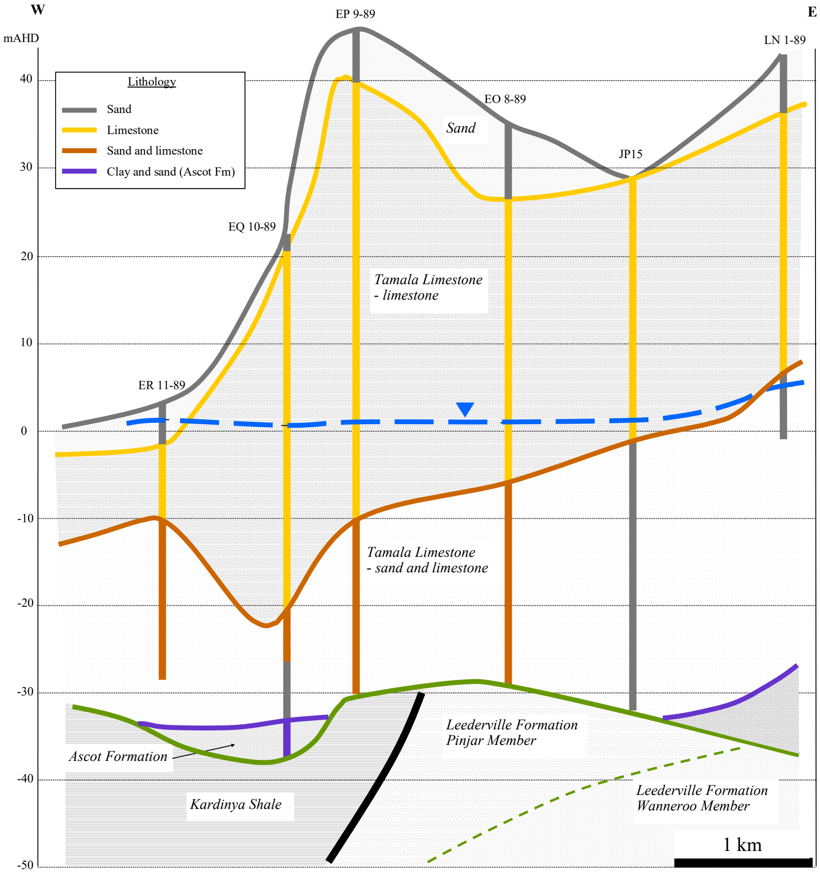


Figure 3-4 East - west geological cross-section west of Lake Nowergup.

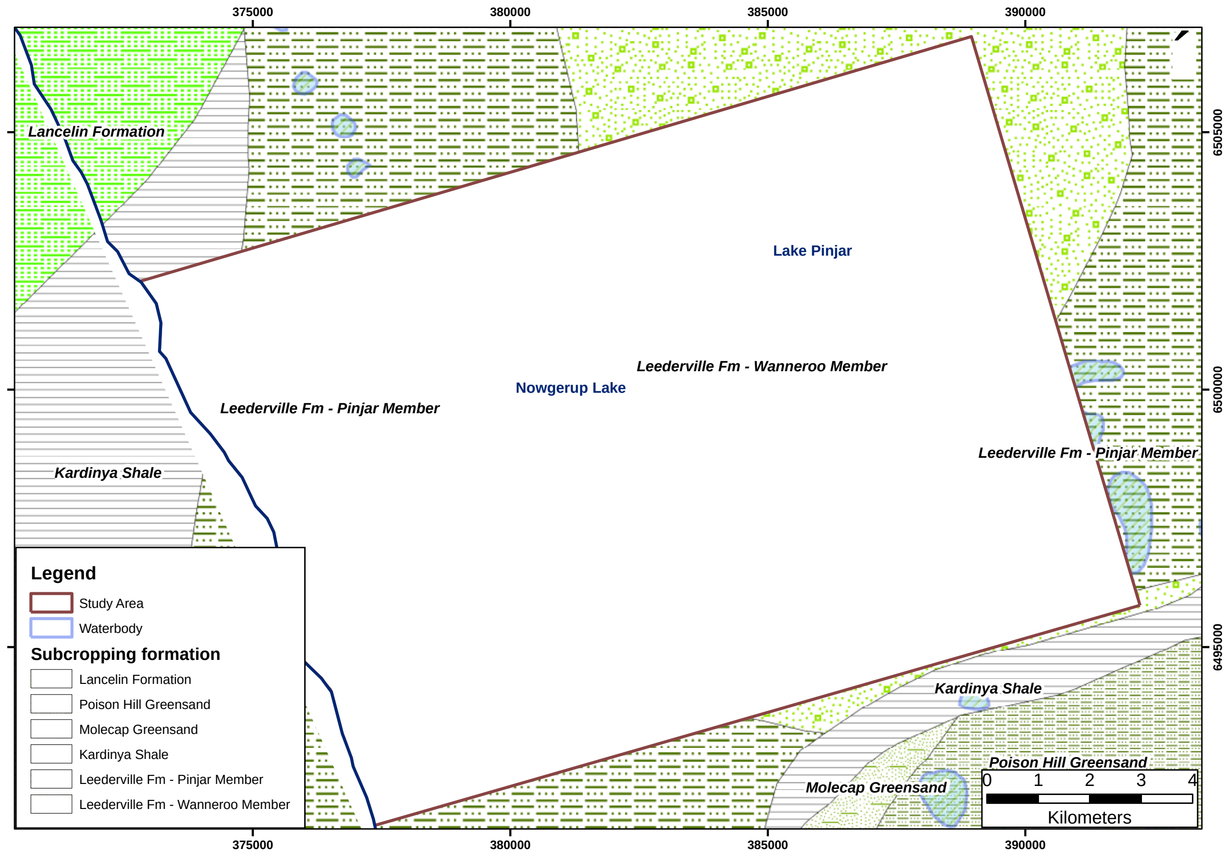


Figure 3-5 Geological formations subcropping Superficial formations (adapted from Davidson and Yu, 2008; Layland, 2012).

4 Hydrogeology

The regional hydrogeology is defined by Davidson (1995) and this section is given largely within the context of that work. The Superficial aquifer is defined by the saturated sections of the Superficial formations. It is an unconfined aquifer with the watertable forming its upper surface. Lake Nowergup is situated upon the western margin of the Gnangara Mound within the Superficial aquifer. The lake is situated within the transition zone between the Bassendean Sand and Tamala Limestone components of the aquifer. Groundwater within the Superficial aquifer flows away from the crest of the Gnangara Mound under the influence of gravity, and in the area of Lake Nowergup the flow is to the west.

The Leederville aquifer is a multi-layered regional aquifer that underlies the Superficial aquifer. It is formed principally by groundwater within the Leederville Formation, but groundwater within the basal portion of the Ascot Formation is included as Leederville aquifer herein due to apparent hydraulic continuity between the units in the area of Lake Nowergup. Groundwater within the Leederville aquifer is largely confined by shale and siltstone within the Leederville Formation or clay in the Ascot Formation.

4.1 Superficial aquifer

The Superficial aquifer comprises several hydrostratigraphic sub-units that chiefly correspond with the component geological formations. These hydrostratigraphic units comprising the Superficial aquifer present in the Lake Nowergup area are:

- Lake bed deposits,
- Tamala Limestone limestone facies,
- Tamala Limestone clayey sand facies,
- Bassendean Sand,
- Ascot Formation.

Lake bed deposits of silty organic sand form a low permeability floor to the lake, although there has been limited testing of its hydraulic properties. The lake bed sediments provide an interval that is resistive to groundwater flow. Higher levels of the lake floor about the lake margins are probably more permeable allowing greater hydraulic connection between the lake and adjacent aquifer. This allows the lateral movement of groundwater into the lake as part of a throughflow when watertable levels are sufficiently high. The east lake side may also be more sandy, and therefore more permeable, relative to the west side. Davidson (1995) found that lacustrine sediments on the groundwater inflow side of a lake were generally more sandy than those on the outflow side. Lake floor deposits in deeper parts of the lake are likely to comprise thicker mud (silt, clay and peat) with a lower permeability, which will impede lateral and vertical movement of water between the lake and aquifer.

The Tamala Limestone clayey sand facies and Bassendean Sand are interpreted to form a laterally continuous hydrostratigraphic unit below the lake, although the permeability will likely be greater in the Bassendean Sand relative to the Tamala Limestone clayey sand facies based on the sediment lithology. The sandy clay layer at the top of the clayey sand facies that was intersected by bores on the western side of the lake (Figure 3-1 and Figure 3-2) will form a local aquitard. It reaches up to 10 m thick in bore LN38 and gradually deepens and thins westward away from the lake until it is only about 1 m thick at bore LN1 630 m west of the lake. Extrapolation of the clay layer eastward suggests it underlies at least the western half of the lake. Several of the shallow monitoring bores about the western margin of the lake (LN5, LN6 and LN36) are slotted within the sandy clay and show the watertable occurring within that layer.

The Tamala Limestone limestone facies consists of predominantly well lithified calcarenite which as a coherent unit does not extend as far east as Lake Nowergup, although elevated outliers do occur east of the lake. The limestone thickens and deepens toward the coast, extending below the watertable west of LN1. Frequently developed karst within the limestone provides very high permeability through preferred pathways for groundwater movement where the limestone exists below the watertable.

The Ascot Formation, at the base of the Superficial aquifer, is a medium to coarse grained sand with calcarenite limestone that forms a permeable unit mostly between about 10 m and 20 m thick hydraulically connected with the overlying Tamala Limestone (sandy clay facies) or Bassendean Sand. There is often a low permeability horizon about 5 m thick in the lower portion of the unit formed by clayey sand and clay (Water Authority, 1992). If sufficiently extensive and continuous the clay unit may form an aquitard that could impede the hydraulic connection between the Superficial aquifer and underlying Leederville aquifer in the area about the lake, but does not extend far to the west.

4.1.1 Superficial aquifer groundwater head and movement

There is a relatively low hydraulic gradient through the Bassendean Sand, but the gradient increases and becomes much steeper about the eastern portion of the Tamala Limestone through the transition zone. West of this zone, the hydraulic gradient within the Tamala Limestone is very low due to the very high permeability of the limestone which is in hydraulic connection with the ocean.

Hydrographs from nested piezometers on the east and west margins of the lake are shown by Figure 4-1 and Figure 4-2 respectively. These reveal that the vertical hydraulic gradient through the Superficial aquifer is different on each side of the lake. On the east side, each site with monitoring bores slotted at various depths in the Superficial aquifer show practically identical water levels, indicating no vertical gradient through the aquifer in this area and implying good vertical hydraulic continuity. The notable exception is bore LN13, which is slotted in the lower Ascot Formation below the confining clay and is probably hydraulically connected with the underlying Leederville aquifer (based on water level responses to pumping from the Leederville aquifer).

In contrast, nested piezometers on the west side of Lake Nowergup show a significant vertical hydraulic gradient at each site. A downward hydraulic gradient exists within the Superficial aquifer adjacent to the lake in piezometers LN5 and LN39. This also indicates relatively low vertical hydraulic conductivity through the Tamala Limestone clayey sand facies.

An east – west hydrogeological cross-section through Lake Nowergup is shown by Figure 4-3, which uses water level data recorded between April and July 2014. The section shows water levels through the Superficial aquifer that decline from around 15 mAHD on the east side of Lake Nowergup to about 5 mAHD west of the lake. A steep hydraulic gradient is evident laterally through the aquifer beneath the western portion of the lake and just west of the lake.

Water levels within the lake have mostly fallen below 16 mAHD since 2011 and are now around 15 mAHD, but lake supplementation appears to be maintaining a downward hydraulic gradient between the lake and underlying Superficial aquifer. Some back-flow of water eastward from the lake may also still be occurring, which has been the condition since 2002 in response to lake water supplementation and a falling watertable (Searle et al., 2011).

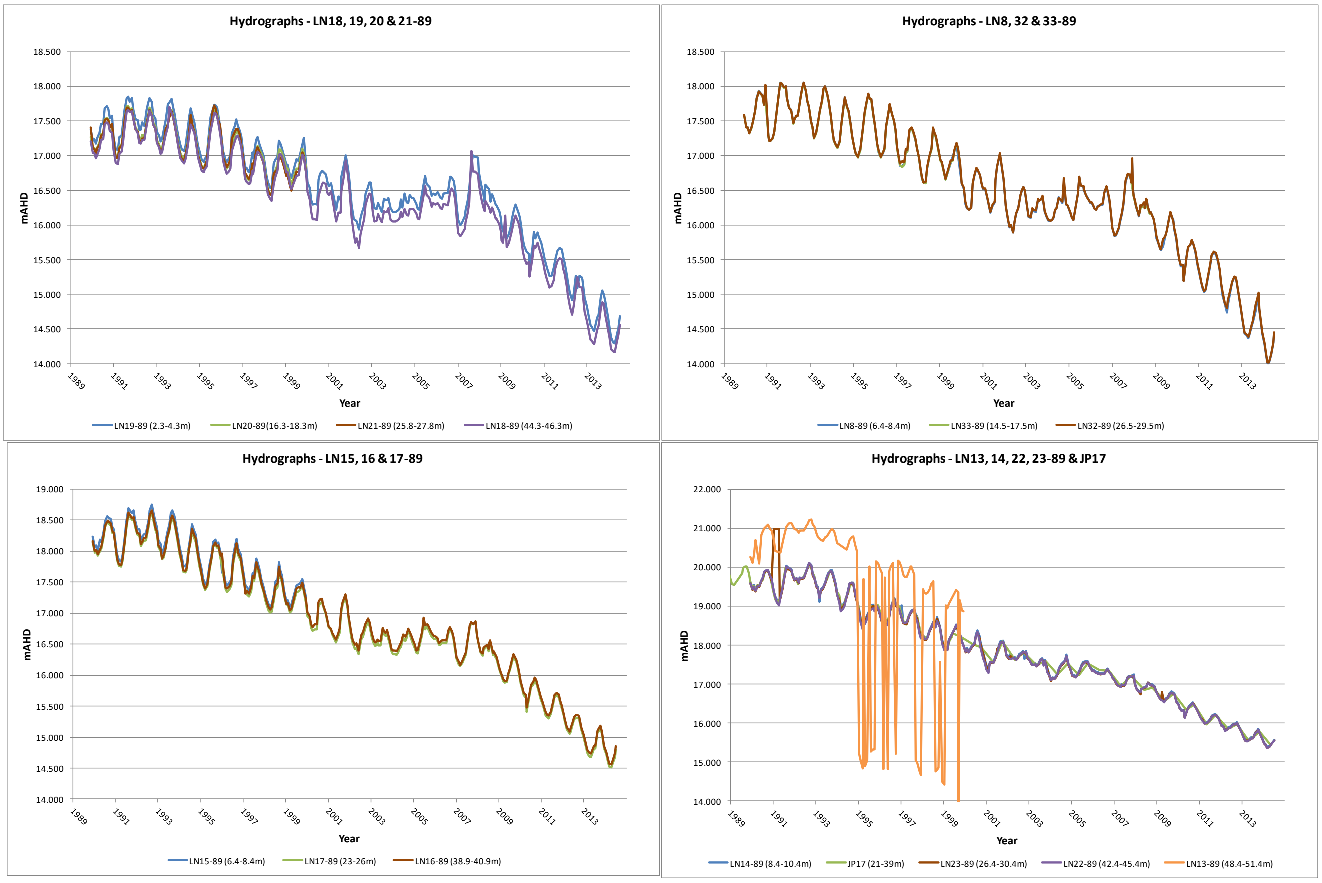


Figure 4-1 Hydrographs - East side of Lake Nowergup.

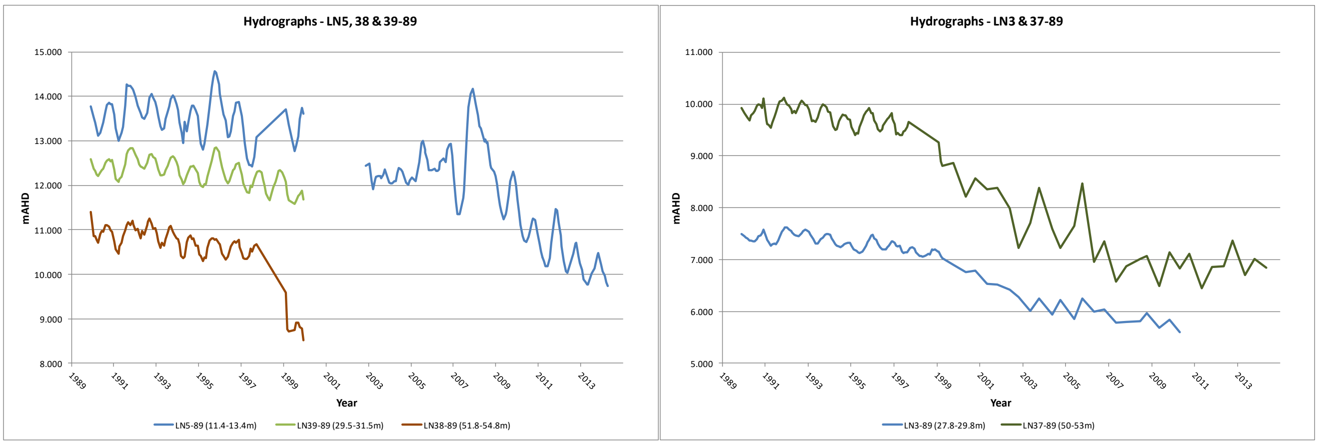


Figure 4-2 Hydrographs - West side of Lake Nowergup.

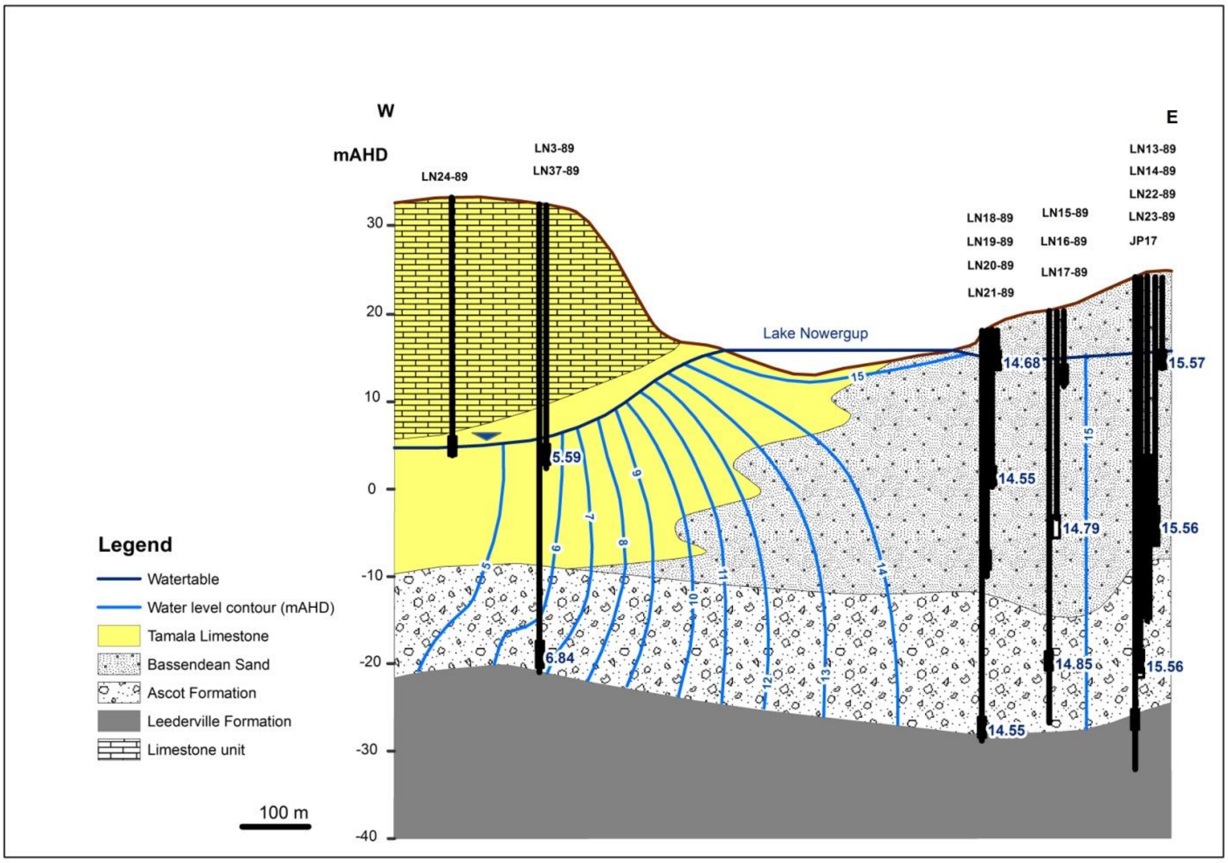


Figure 4-3 Hydrogeological cross-section - Lake Nowergup (2014).

4.1.2 Complexity of the sand – limestone contact

Tamala Limestone clayey sand facies forms a zone of lower permeability between the Bassendean Sand and limestone of the Tamala Limestone. A steep watertable gradient occurs across this zone. Within the Bassendean Sand behind the low permeability zone, the westward flow of groundwater is effectively partially impeded behind the Tamala Limestone clayey sand facies, resulting in a relatively low hydraulic gradient within the Bassendean Sand. Davidson (1995) noted that the relatively steep hydraulic gradient about the contact between the Bassendean Sand and Tamala Limestone was due largely to the marginally lower hydraulic conductivity of finer grained sand at the eastern margin of the Tamala Limestone. The effect of the lower permeability through the eastern margin of the Tamala Limestone, corresponding to the clayey sand facies, may be more pronounced than suggested by Davidson in the Lake Nowergup area due to the clayey nature of these sediments.

A review by Rockwater (2005) also identified a zone of lower hydraulic conductivity in the area of the chain of lakes was responsible for the steeper hydraulic gradient. Kretschmer and Kelsey (2012) considered that the steeper hydraulic gradients observed through the contact area was the result of lower conductivity of the Tamala clayey sand facies (referred to as Tamala sand) compared with the Bassendean Sand in the east, and the highly conductive karstic Tamala Limestone to the west.

4.1.3 Interaction between the lake and surrounding watertable

Figure 4-4 shows hydrographs of water levels in Lake Nowergup compared with groundwater levels recorded adjacent to the east and west sides of the lake. Prior to 2002, comparison of lake and watertable levels show typical lake throughflow characteristics, where the watertable is higher than the lake level on the east side (bores LN8 and LN19) and lower on the west side of the lake where there is a downward hydraulic gradient between the lake and Superficial aquifer. This indicates that groundwater can flow into the lake along the upgradient margin and discharge downgradient.

Monitoring bores immediately north and south of the lake (bores LN11 and LN12) closely mimicked lake water levels until 1999. This suggests that groundwater levels beneath the central portion of the lake were very similar to lake water levels, and that the eastern half of the lake was hydraulically well connected with the Superficial aquifer up to this time.

A period of approximate equilibrium between the lake water levels and watertable on the east side occurred from 2002 to 2007, while a downward hydraulic gradient developed between the central portion of the lake and underlying Superficial aquifer as demonstrated by bore LN12. Subsequently onward from 2007, lake water levels have been higher than the watertable on the east side of the lake, indicating that it no longer receives inflow of groundwater and thus the lake is sustained by supplementation. The watertable on the east side of the lake has progressively fallen deeper below the lake level and by 2014 was probably around 1 m deeper than the lake water level. The downward hydraulic gradient below the west side of the lake has also increased over the same period.

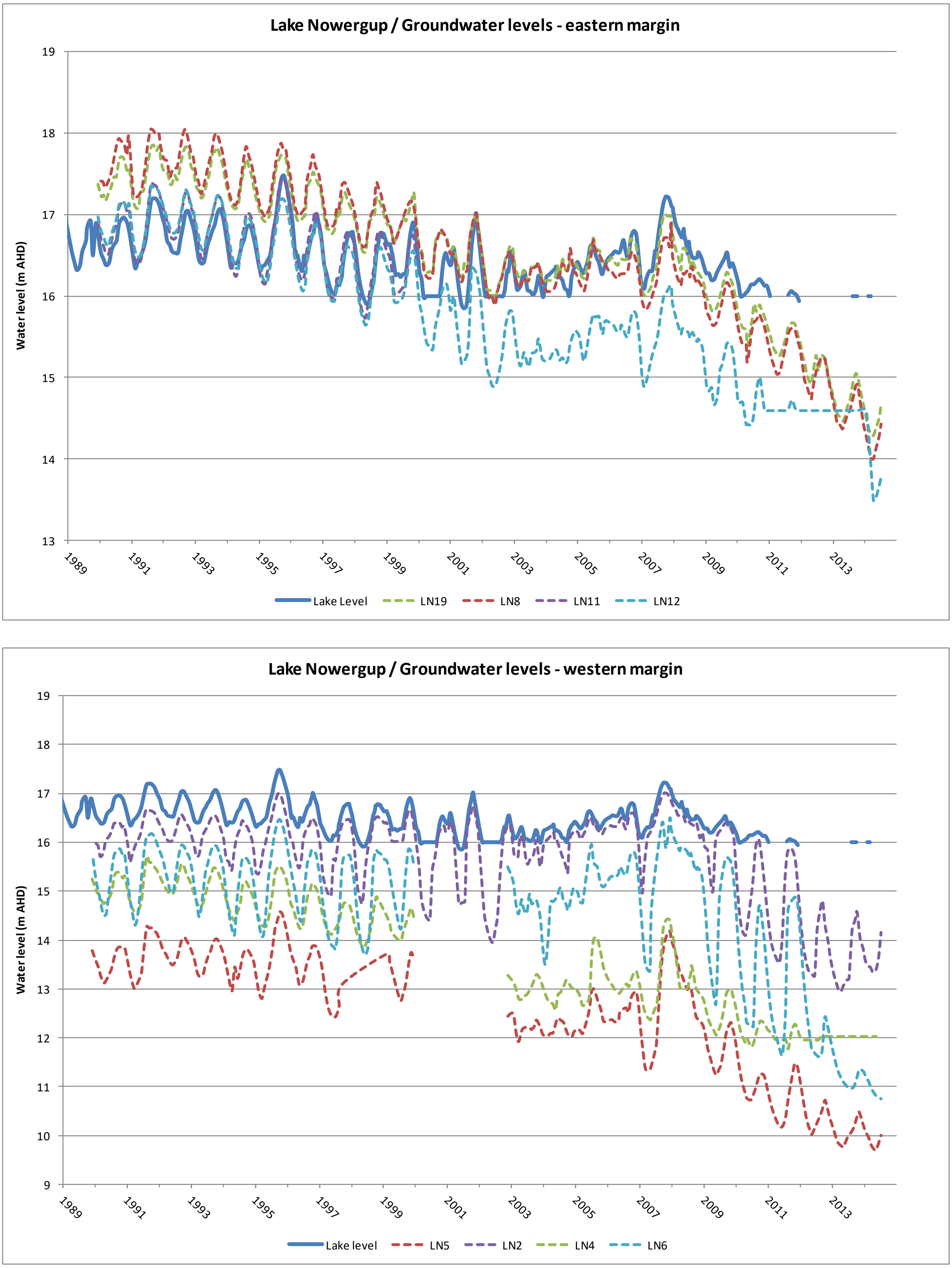


Figure 4-4 Hydrographs of lake and groundwater levels - Lake Nowergup.

4.1.4 Superficial aquifer hydraulic parameters

Superficial aquifer hydraulic parameters are available from pumping tests conducted at various sites over the coastal plain and reported in Bulletin 142 (Davidson, 1995). Hydraulic conductivity of the sandy Bassendean Sand over the central portion of the Gnangara Mound ranges from 10 m/day to more than 50 m/day, with an average of about 15 m/day. Toward the coast the Tamala Limestone has very high values of hydraulic conductivity in the range of 100 to 1000 m/day. A recent review of pumping test data from bores in the Quinns area concluded that average hydraulic conductivity values are around 130 m/day for the bores screened within the Superficial aquifer (Kretschmer and Degens, 2012), mainly comprising the Tamala Limestone. A subsequent study determined an average hydraulic conductivity of 370 m/day for the Tamala Limestone based on a flow net analysis using production from the Quinns borefield and changing hydraulic gradients during the period of 2000 to 2002 (Water Corporation, 2014). This same study also determined an inflow hydraulic conductivity for the Quinns Groundwater Sub-area of 32 m/day. This area broadly corresponds to the area up-gradient of the coastal lake chain.

In the study area, pumping tests have been undertaken upon numerous bores constructed into the Tamala Limestone for irrigation or public water supply purposes that variously include the sand facies (different to the clayey sand facies at Lake Nowergup – see Section 3.6) and limestone facies. Both the sand and limestone facies are highly permeable, with very high permeability associated with karstic features developed in the limestone.

Analysis of pumping test data for bores west of Lake Nowergup and screened in the sand facies underlying the limestone yielded values for transmissivity of between 250 and 1400 m^2/day (Hydroplan, 1992, 1994a, b, 1995), corresponding to hydraulic conductivity over the screened intervals of about 21 to 183 m/day. Lower values of 21.2 and 36.5 m/day from these tests probably best represent permeability of the sand, while higher values are probably influenced by leakage from overlying limestone. Bores screened in the sand facies where some limestone is present showed a higher permeability, with transmissivity values of 594 to 4610 m^2/day and averaging almost 1800 m^2/day (Hydroplan, 1993a, b, c, 1996a; Water Corporation, 1999a). These values are equivalent to hydraulic conductivity of 34.5 to 268 m/day over the screened intervals which averaged 144.5 m/day.

Bores screened within the limestone facies yielded very high values for transmissivity of 2000 to 11,000 m^2/day from pumping tests (Water Authority, 1990; Water Corporation, 1999a, b; Hydroplan, 1994c, 1996b), although analysis was difficult for these bores due to the low rate of drawdown through the test. These transmissivity values are equivalent to hydraulic conductivity values of 153 to 1320 m/day. The very high permeability is a result of the karstic nature of the limestone aquifer. Pumping tests undertaken on bores within the Quinns borefield screened in the Tamala Limestone yielded values for hydraulic conductivity between 32 and 383 m/day (Water Corporation, 2014), but many of the tests experienced the majority of drawdown in the first few minutes and could not be reliably analysed.

The Eglinton production bore (site EG10, located about 1.5km NW of Lake Carabooda) constructed about the eastern portion of the limestone was screened across the full saturated thickness of Tamala Limestone, including the limestone facies and medium to coarse sand considered part of the sand facies over the lower 13 m of the screened interval (Water Corporation, 2014). This bore yielded a value for hydraulic conductivity of between 100 and 150 m/day from a constant rate pumping test conducted at 4585 m^3/day.

No bores for aquifer testing have been constructed within the narrow strip (probably no more than about 1 km wide) of the Tamala Limestone clayey sand facies from which values for hydraulic conductivity can be derived. However, an estimate of 10.9 m/day for the full thickness of Superficial aquifer is made here (Equation 4-1) based on the calculated groundwater throughflow for 1989 (see Section 5.4.2) and the hydraulic gradient west of Lake Nowergup. However, this estimate includes the permeable Ascot Formation, suggesting that the hydraulic conductivity of the Tamala Limestone clayey sand facies will be significantly lower, probably in the order of a few metres per day.

Rearrangement of Darcy's Law for hydraulic conductivity: $K = v / i$

Where: K = hydraulic conductivity (m/day)
v = Darcy velocity or specific discharge (m/day) = 0.251 m/day
i = hydraulic gradient (m/m) = 0.023

$$K = 0.251 / 0.023$$

$$= 10.9 \text{ m/day}$$

Derivation of input parameters

Darcy velocity in 1989:

v = throughflow / (aquifer width x aquifer thickness)
= 13,395.2 / (1300 x 41)
= 0.251 m/day

Throughflow for 1989 = 13,395.2 m^3/day (see Section 5.4.2)
Aquifer width = 1300m
Aquifer thickness = 41m

Hydraulic gradient in 1989 calculated between the lake and LN3:

i = (h1 - h2) / L
= (16—7.5) / 370
= 0.023

Waterlevel at lake (h1) = 16 mAHD
Waterlevel at LN3 (h2) = 7.5 mAHD
Distance (L) = 370 m

Equation 4-1 Hydraulic conductivity calculation - Superficial aquifer down-gradient of Lake Nowergup.

The Ascot Formation appears to be mostly highly permeable. Re-evaluation of pumping test data from four irrigation water supply bores screened within the Ascot Formation at Carabooda (CB1, CB2, CB3 and CB4) give values for hydraulic conductivity between 47 and 140 m/day, with an average of 71 m/day. These bores were originally considered to be screened both over sand in the lower Tamala Limestone and the Leederville Formation (Rockwater, 1986; Water Corporation, 2014). However, based on the lithology described and correlation to the stratigraphy in the Lake Nowergup area about 2 km south-southwest of the bores, it is concluded that these bores are screened within the Ascot Formation. Pumping tests of Pinjar borefield bores P60, 70, 80 and 90 northeast of Lake Pinjar and screened within the Ascot Formation indicate transmissivity of between 1780 and 3930 m^2/day for bores. This is equivalent to hydraulic conductivity values over the screened intervals of 98.9 to 218 m/day, averaging 159 m/day.

There is no pumping test data available for the Bassendean Sand in the study area, but it is probably consistent with the values for hydraulic conductivity given by Davidson (1995) averaging 15 m/day.

The vertical hydraulic conductivity beneath Lake Nowergup is relatively low. Previous laboratory analysis of vertical permeability of samples taken from the lake floor sediments at 4 sites determined hydraulic conductivity values ranging from almost 0 to about 5 m/day, with most analysis between about 0.002 m/day and 0.5 m/day (Townley, et al., 1993). An estimate is also made in this study for vertical hydraulic conductivity beneath the lake using Darcy's Law with inputs of the water balance for the lake over 2013 and the hydraulic gradient determined from groundwater monitoring and lake water levels (Equation 4-2). This yields an average value of approximately 0.17 m/day for the upper half of the Superficial aquifer (about 20 m), which incorporates the lake floor sediments and clayey sand facies of the Tamala Limestone.

Rearrangement of Darcy's Law for hydraulic conductivity: K = v / i

Where: K = hydraulic conductivity (m/day)
v = vertical Darcy velocity or specific discharge (m/day) = 0.0.0127 m/day
i = hydraulic gradient (m/m) = 0.075

$$K = 0.0127 / 0.075$$
$$= 0.17 \text{ m/day}$$

Derivation of input parameters

Vertical Darcy velocity in 2013:
v = leakage / lake area
= 1284.5 / 100,815
= 0.0127 m/day
Leakage from lake 2013 = rainfall (0.7858 m x 100815 m^2) + supplementation (592,000 m^3) - evaporation (2.0074m x x100815m^2)
= 468844.4 m^3/year
= 1284.5 m^3/day
Lake area estimated from air-photography for Feb 2014 = 100,815 m^2

Vertical hydraulic gradient in 2013 over 20m below the lake floor:
i = (h1 - h2) / L
= (15 - 13.5) / 20
= 0.075
Lake waterlevel (h1) estimated from air photography and bathymetry mapping = 15 mAHD
Groundwater level (h2) from monitoring bore LN12 = 13.5 mAHD
Vertical distance (L) = 20 m

Equation 4-2 Vertical hydraulic conductivity calculation - upper Superficial aquifer beneath Lake Nowergup.

4.2 Leederville aquifer

The Leederville aquifer is a multi-layered sand and clay aquifer that in the Lake Nowergup area comprises the Wanneroo and Mariginiup Members of the Leederville Formation, and the basal portion of the Ascot Formation. The Wanneroo Member is the most permeable portion of the Leederville aquifer, and subcrops the Superficial aquifer at Lake Nowergup and the broader area east of the lake. There is likely to be a degree of hydraulic connection between the two aquifers in this area, but it will probably not be continuous due to areas of clay present within both the Leederville Formation and the lower portion of the Ascot Formation. Just north and west of the lake the lower permeability Pinjar Member of the Leederville Formation is present between the Wanneroo Member and Superficial aquifer (see Figure 3-5), and this will at least partially isolate groundwater in the Wanneroo Member of the Leederville Formation from groundwater in the Superficial aquifer.

4.2.1 Leederville aquifer groundwater head and movement

There appears to be hydraulic separation of the Leederville aquifer (including the lower portion of the Ascot Formation) over much of the area around Lake Nowergup. This is demonstrated by monitoring bores slotted in the lower Ascot Formation below the clay layer, which appear to reflect potentiometric heads within the upper Leederville aquifer. Effectiveness of the clay layer as an aquitard is seen at monitoring bore LN13 located east of the lake and slotted over 48.4 to 51.4 m, which is beneath the clay layer and against sands of the very lowest portion of Ascot Formation and the upper-most Leederville Formation. Monitoring from this bore shows an upward hydraulic head of about 1 m between the Leederville aquifer and Superficial aquifer across the clay layer (see Figure 4-1).

Adjacent to the west side of the lake, bore LN38 shows a downward hydraulic gradient between the Superficial and Leederville aquifers, but further west bore LN37 shows the hydraulic gradient between the aquifers has reversed and is upward at that site. The potentiometric head in the lower Ascot Formation at bore LN37 was about 2 m higher than the watertable at that site prior to 2000, but subsequently declined and is now only about 1 m higher. The relative westward decline in water levels in the Superficial and Leederville aquifers is responsible for this changing pattern between upward and downward hydraulic gradients between the aquifers.

Additional evidence for hydraulic separation of the Leederville aquifer from the Superficial aquifer is seen in the drawdown response observed in bore LN13 to pumping from the nearby supplementation bore 2/90 screened deeper in the Leederville aquifer (57.7-75.3 m depth) that was not seen in shallower nested monitoring bores slotted in the Superficial aquifer at the same site, including bore LN22 slotted over 42.4 to 45.4 m just above the Ascot Formation clay layer. However, greater hydraulic connection is evident between the Superficial aquifer and Leederville aquifer at monitoring bore LN18 (44.3-46.3 m) in the lower Ascot Formation adjacent to the eastern margin of the lake. The hydrograph from this bore is in-sync with water levels in the Superficial aquifer with a small downward hydraulic gradient.

More recently, a similar drawdown response is seen in monitoring bores LN37 and LN38 situated in the upper Leederville aquifer to pumping of supplementation bore 2/00 during May and June 2014 when data loggers were installed to monitor water levels at hourly intervals, which is shown by Figure 4-5. Water levels drew down by about 0.3 m in LN37 and up to almost 1 m in LN38, which are both west of the lake and situated about 750 m southwest and 850 m south of the bore respectively. These observations suggest confined aquifer type conditions with reasonable degree of hydraulic isolation between the Leederville aquifer and Superficial aquifer between these sites, particularly south of the supplementation bore. However, monitoring bores LN16 and LN18 located 350 m east-southeast and 300 m southeast of 2/00 respectively did not respond to the pumping. LN16 is within the lower portion of the Superficial aquifer, while LN18 is in the upper Leederville aquifer where good hydraulic connection with the overlying Superficial aquifer has been noted, and therefore unconfined aquifer conditions probably prevail for these bores.

Within the Leederville aquifer there is a good degree of vertical hydraulic connection between the pumping interval of bore 2/90 in the Wanneroo Member and monitoring interval of bore LN13 at the very top of the aquifer within the lower Ascot formation. This is demonstrated by the rapid response of water levels observed in bore LN13 in response to pumping of bore 2/90. Monitoring of bore LN13 ceased in 1999 when supplementation pumping shifted to bore 2/00.

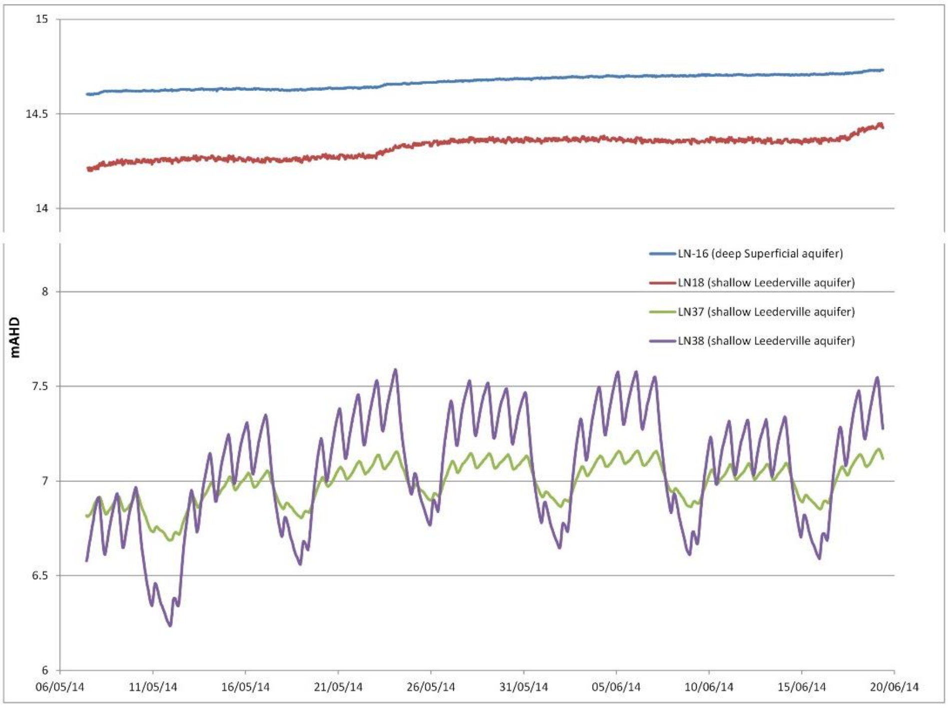


Figure 4-5 Data logger water levels for LN16, 18, 37 and 38 during May-June 2014.

4.2.2 Hydraulic properties

Values for horizontal hydraulic conductivity of sand beds in the Leederville Formation derived from pumping tests average about 10 m/day (Smith, 1979). As the sand typically comprises about 50% of the formation, the hydraulic conductivity for the entire aquifer will be proportionally less. If sand beds within the Leederville Formation are not laterally continuous, then the average value for hydraulic conductivity laterally through the aquifer would be even less. Davidson (1995) determined average hydraulic conductivity values using a flownet analysis to vary between 1 and 9 m/day for north of the Swan River.

A pumping test of the supplementation bore 2/00 yielded a transmissivity of 870 m^2/day (Varma, 2000), which over the screened interval of 20 m is equivalent to a hydraulic conductivity of 43.5 m/day. The screened interval is over a thick sand unit in the Leederville Formation, while the remainder of the formation intersected to 126 m depth comprises interbedded shale and sand, indicating that the average hydraulic conductivity over the Leederville Formation is probably much lower, and possibly less than 10 m/day. Evaluation of pumping test data from Water Corporation production bores yielded values for hydraulic conductivity over the screened intervals of 3.4 m/day and 3.2 m/day respectively for Pinjar borefield bores P105 and P145, and 9.3 m/day and 26.1 m/day respectively for Quinns borefield bores Q145 and Q205.

Vertical hydraulic conductivity through the Leederville aquifer varies depending on the lithology. The most sandy portions of the Wanneroo Member will have the greatest vertical permeability, while the more silt and shale dominated Pinjar and Mariginiup Members will have a lower vertical permeability. A value for vertical hydraulic conductivity of 5×10^{-4} m/day has been determined for the upper half of the aquifer using ^{14}C isotope dating (Thorpe and Davidson, 1991), while a value of 4×10^{-4} m/day was adopted at the site of bore AM20 based on shale intervals apparent from gamma-ray logging through the aquifer (Water Corporation, 2014). This site includes an interval of Pinjar Member. For the Wanneroo Member a higher value for the vertical hydraulic conductivity is likely considering the greater portion of sand and its coarser grained nature.

5 Changes in watertable levels and hydrodynamics

Watertable levels beneath the Swan Coastal Plain have changed over the years in response to processes and activities that lead to altered groundwater recharge rates and reduced groundwater storage. Groundwater recharge rates vary in response to changes in annual rainfall, increasing during periods of higher rainfall and decreasing when it is lower. Changes in the land-cover will also influence groundwater recharge rates. Removal of vegetation has been found to have the largest impact due to its effect of increasing groundwater recharge rates resulting in rising water levels (Yesertener, 2008). Recharge is enhanced in urbanised areas by runoff from roof and hard surfaces discharging into the ground via soaks and compensation basins. Under mature pine plantations there may be almost no groundwater recharge at all (Sharma and Pionke, 1984).

Pumping of groundwater from bores reduces the volume of water stored within aquifers. Where the pumping is from the unconfined Superficial aquifer or the drawdown from underlying confined aquifers propagates to the unconfined aquifer, the result is a declining watertable until a new equilibrium is reached in the water balance between recharge, throughflow and discharge of groundwater.

During the 1960’s a period of above average rainfall combined with on-going clearing of large areas of native vegetation for the planting of pine trees resulted in watertable levels rising and an increase in the depth and area of surface lakes over the Gnangara Mound. Subsequently, the watertable has declined during periods of below average rainfall, the maturing of pine plantations reducing groundwater recharge rates, and increased pumping of groundwater chiefly for horticultural and public water supply purposes. The relative importance of these factors in changing watertable levels varies between locations across the coastal plain.

5.1 Watertable changes 1977 to 2013

Plans showing watertable contours for the winter–spring periods of maximum water levels during 1977, 1989 and 2013 are shown by Figure 5-1, 5–2 and 5–3. This mapping is based on water level monitoring of bores within the Superficial aquifer of the Pinjar, North West Coastal and Lake Nowergup monitoring bore networks. Each period shows the watertable elevation declining from east to west toward the coast. There is a relatively constant hydraulic gradient in the watertable slope east of Lake Nowergup, but a steep gradient immediately west of the lake. A very flat hydraulic gradient is present beneath the western-most portion of the coastal plain within about 4 km of the coast, and this corresponds with the zone of karstic Tamala Limestone comprising much of the Superficial aquifer through this area.

East of Lake Nowergup to Pinjar Lake a hydraulic gradient of almost 0.004 has existed through the period, but immediately east of the lake there was a lower gradient of almost 0.003 (between monitoring bores PM32 and JP17). West from Lake Nowergup a hydraulic gradient of around 0.01 has remained stable between the western lake margin and the 4 mAHD groundwater contour, even though the watertable has declined at the western margin of the lake (16 mAHD to 14.6 mAHD).

The decline in watertable levels between each of the years of 1977, 1989 and 2013 is shown by Figure 5-4 and 5–5. Between 1977 and 1989, the biggest decline was observed east-southeast of Pinjar Lake in an area adjacent to pine plantations and close to the Wanneroo borefield located to the south, which commenced pumping in 1975, and the Pinjar borefield that commenced pumping in 1989. The watertable rose beneath the western portion of Pinjar Lake, and immediately west of the lake. Further west, between Pinjar Lake and the coastal chain of lakes (including Lake Nowergup) water levels declined by between about 0.5 and 1.3 m. The largest decline of over 1 m (bore P280) occurred close to extensive areas of pine plantations. There was little change in water levels west of the chain of lakes.

From 1989 to 2013, the watertable continued to decline east of Pinjar Lake. More notable was a decline in excess of 5 m in the Carabooda area where there is significant private pumping of groundwater forming a north-south elongate area of drawdown east of the coastal lake chain. The watertable declined by a smaller level of around 3 m about Lake Nowergup, where lake supplementation may be partly responsible for reducing the decline. Peak water levels in Lake Nowergup declined from 16.9 mAHD in 1989 to around 14.5 mAHD in 2014 (determined from air-photography and bathymetry).

Water levels since 1989 declined least at a little under 1 m beneath the southern portion of Pinjar Lake. There has been a general decline of around 0.5 m over the western portion of the plain, but there is considerable variation with declines up to 0.65 m evident.

5.1.1 Summary of watertable changes

Between 1977 and 1989:

- The biggest decline in the watertable was of several metres east-southeast of Pinjar Lake, where it was probably influenced by reduced groundwater recharge beneath pine plantations and groundwater pumping from the Wanneroo and Pinjar borefields;
- Between Pinjar Lake and the coastal chain of lakes (including Lake Nowergup) water levels declined by between about 0.5 and 1.3 m, and the decline was largest close to pine plantations;
- There was little change in water levels west of the chain of lakes.

From 1989 to 2013,

- The largest decline in the watertable forms a north-south elongate drawdown cone east of the coastal lake chain, reaching a maximum in excess of 5 m in the Carabooda area where there is significant private pumping of groundwater;
- Lake supplementation may have limited decline of the watertable to around 3 m about Lake Nowergup;
- East of Pinjar Lake the watertable continued to decline;
- There has been a general decline of around 0.5 m over the western portion of the plain.

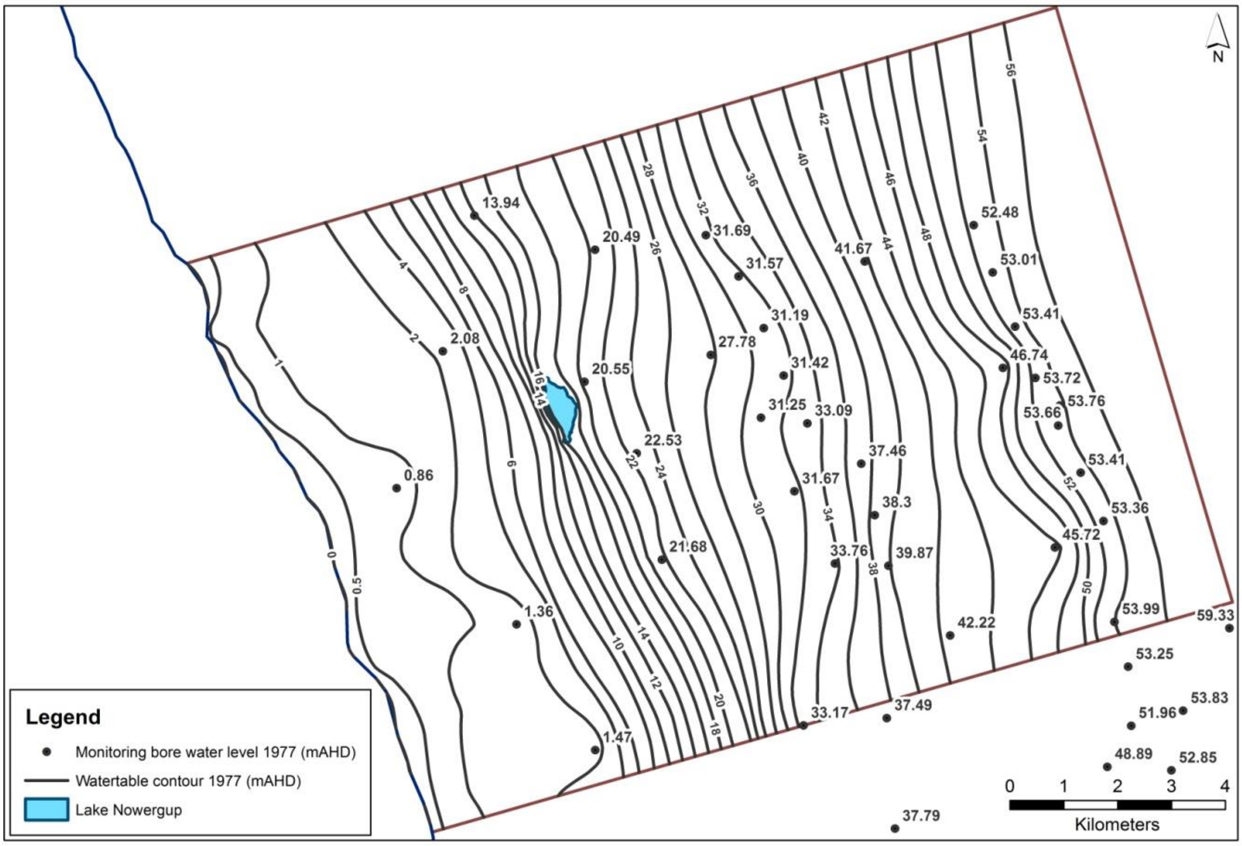


Figure 5-1 Watertable contours - Winter- spring maximum, 1977.

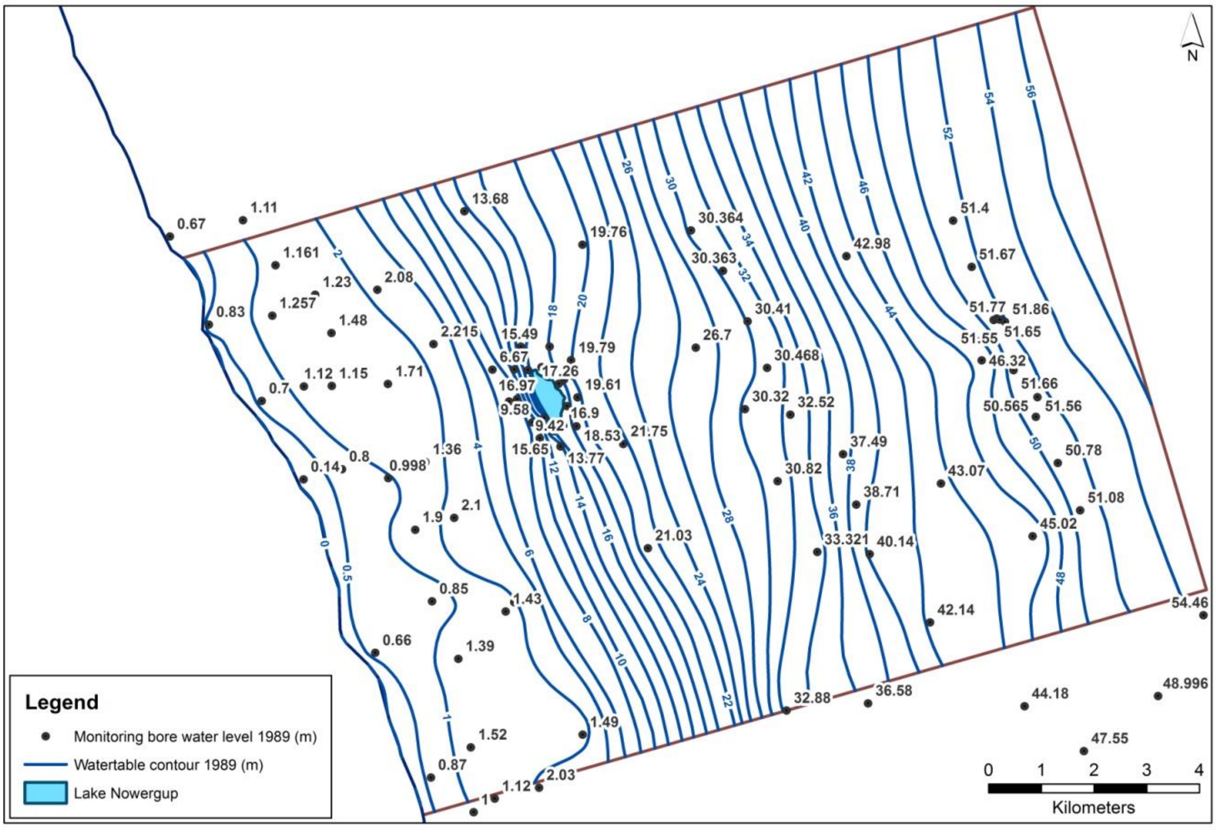


Figure 5-2 Watertable contours - Winter - spring maximum, 1989.

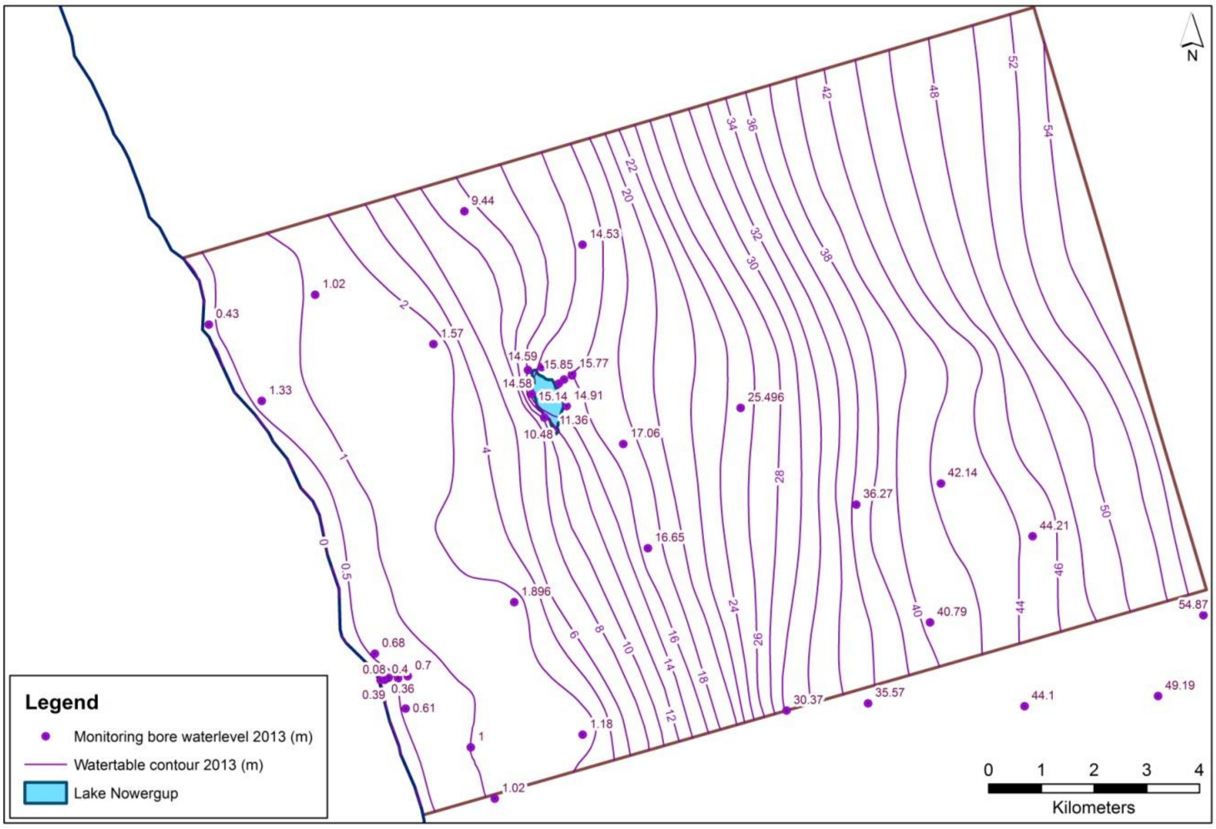


Figure 5-3 Watertable contours - Winter - spring maximum, 2013.

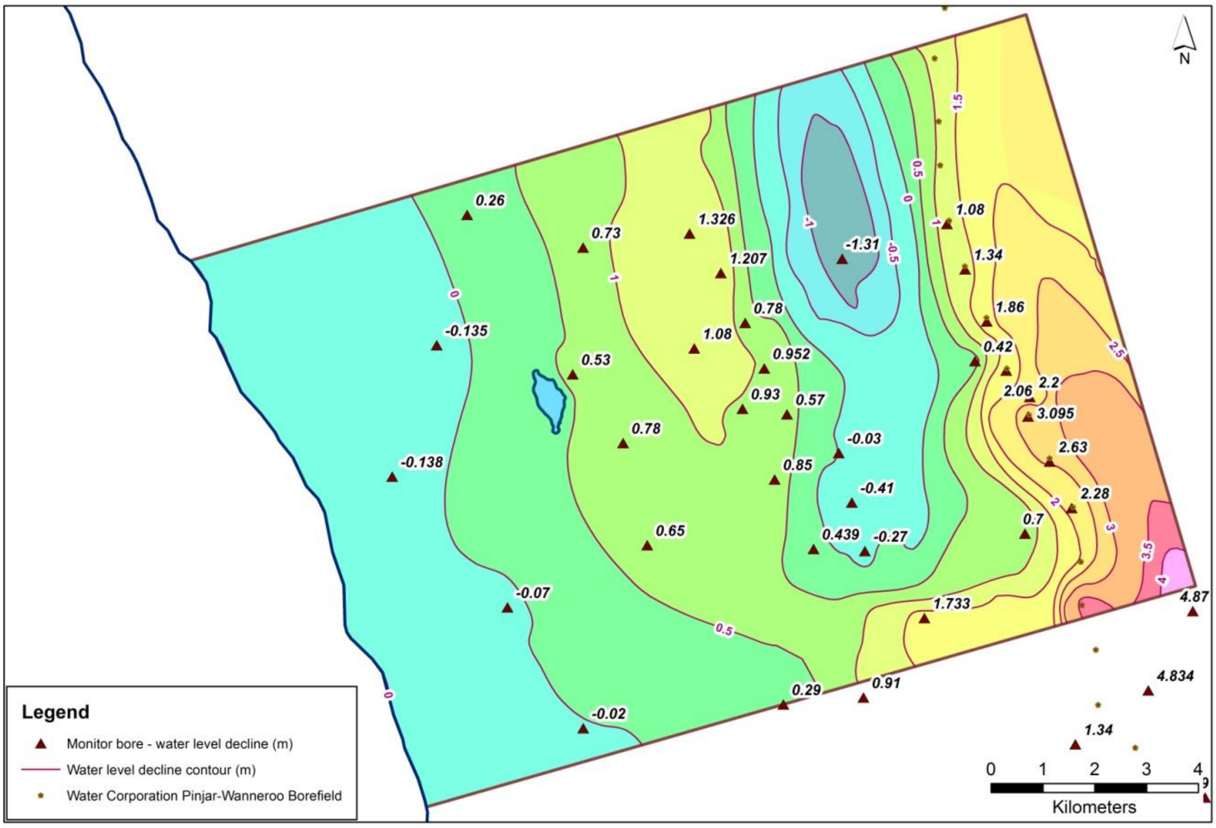


Figure 5-4 Measured and interpreted watertable decline - Superficial aquifer, 1977 to 1989.

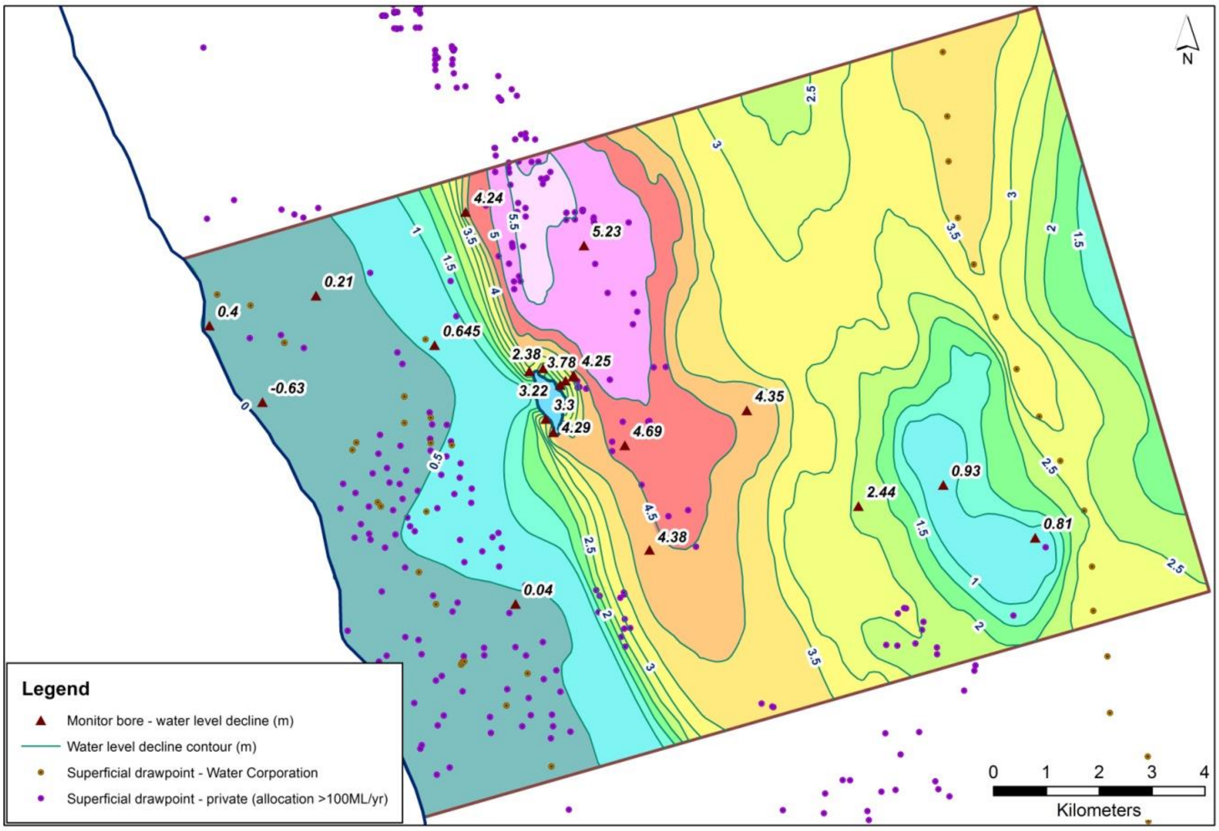


Figure 5-5 Measured and interpreted watertable decline - Superficial aquifer, 1989 to 2013.

5.2 Hydrograph analysis

5.2.1 Water level trends in the Superficial aquifer; Bassendean Sand – Ascot Formation

A review of hydrographs from monitoring bores within the Superficial aquifer east from the coastal chain of lakes show that the watertable has been declining for most of the period since 1975. Several distinct periods of decline are evident, and these are shown schematically by Figure 5-6. Between 1973 and 1979 there is a period of rapid watertable decline, followed by a period of gradual decline with relatively stable levels at times beneath some parts of the coastal plain. A significant increase in the rate of watertable decline commences over the area at various times between 1993 and 1997. There was a further increase in the rate of decline from the year 2000 that has continued to the present in most areas between Lake Nowergup and Pinjar Lake. A slight decrease in the rate of decline starting around 2009-2010 is seen in several monitoring bores (PM32, PM35, P250, P270) located within the pine plantations east of Lake Nowergup and this corresponds with extensive clearing of pines prior to 2009 that should have allowed a higher rate of groundwater recharge.

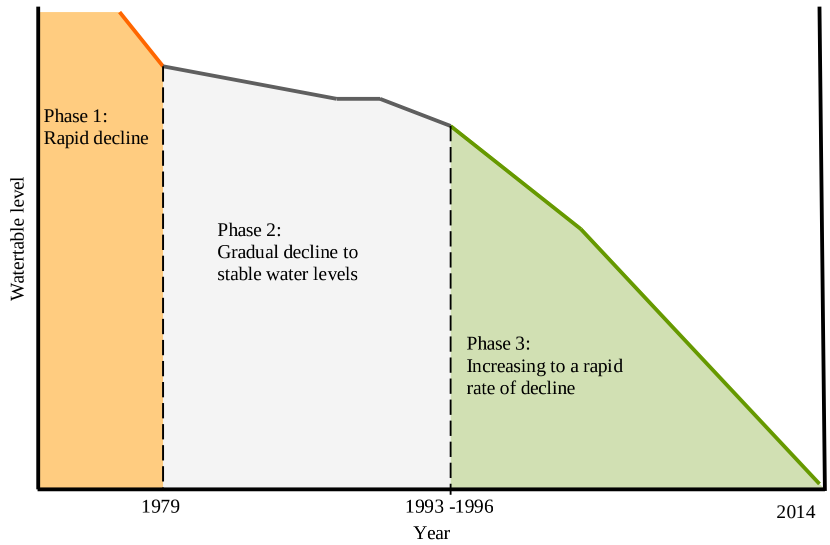


Figure 5-6 Relative rate of watertable decline, Superficial aquifer east of Lake Nowergup (schematic).

Figure 5-7 and 5–8 show several representative hydrographs for monitoring bores within the Bassendean Sand of the Superficial aquifer east of Lake Nowergup. A rapid decline of 0.23 to 0.52 m/year is evident during Phase 1 until 1979. The decline is also relatively evenly spread over the area, suggesting it was the result of an aerially extensive phenomena rather than local activities such as pumping. It corresponds with a period of well below average rainfall from 1975 to 1977 and precedes significant groundwater pumping. Consequently, the decline in levels is likely a response to reduced groundwater recharge rates from lower average annual rainfall and possibly the effect of maturing pine plantations.

An abrupt decrease in the rate of watertable decline occurs from 1978-79 at the start of Phase 2. This continues until 1993, but appears to extend up to 1996 at some sites in the east (e.g. bore P250). There is a period of stable water levels from 1986 extending into 1989 in the more eastern monitoring bores (Figure 5–7), but this is less evident further west (Figure 5–8), and may be due to a period of relatively stable rainfall and possibly near equilibrium conditions of recharge under the pine plantations. The seasonal amplitude of watertable fluctuation increases markedly from 1987 in bore PM31 and a greater rate of decline at 0.2 m/year is observed in bore P280 from 1988. Both these bores are located in the Carabooda area and may be responding to commencement of local private pumping. There is a pause in the watertable decline during 1991 to 1993 that is evident in all of the monitoring bores, and corresponds to a period of above average rainfall for 1991 and 1992.

In Phase 3, the watertable enters a period of more rapid decline after 1993, falling by an average of almost 0.15 m/year and up to 0.26 m/year at bore PM31 in the Carabooda area. Figure 5-9a shows the spatial distribution of general watertable decline from 1993 until 2000. The watertable declined at a rate of between about 0.16 and 0.19 m/year about the western portion of the Bassendean Sand, increasing to 0.26 m/year in the Carabooda area. The decline is least about southern Lake Pinjar area and an area just west of the northern part of Lake Pinjar, which may be the result of increased groundwater recharge from pine plantation thinning undertaken over the later part of this period.

During the latter part of Phase 3 from 2000, the rate of watertable decline increases markedly at many sites, accelerating to be mostly between 0.22 and 0.26 m/year. Figure 5-9b shows that the greatest rates of decline from the year 2000 were in the western portion of the area and the Carabooda area. A notable increase in rate occurs just west of Pinjar Lake and southeast of Lake Nowergup. The effect of lake supplementation in partially maintaining the watertable is seen about Lake Nowergup, where the watertable was relatively stable about the lake margins over 2002 to 2008.

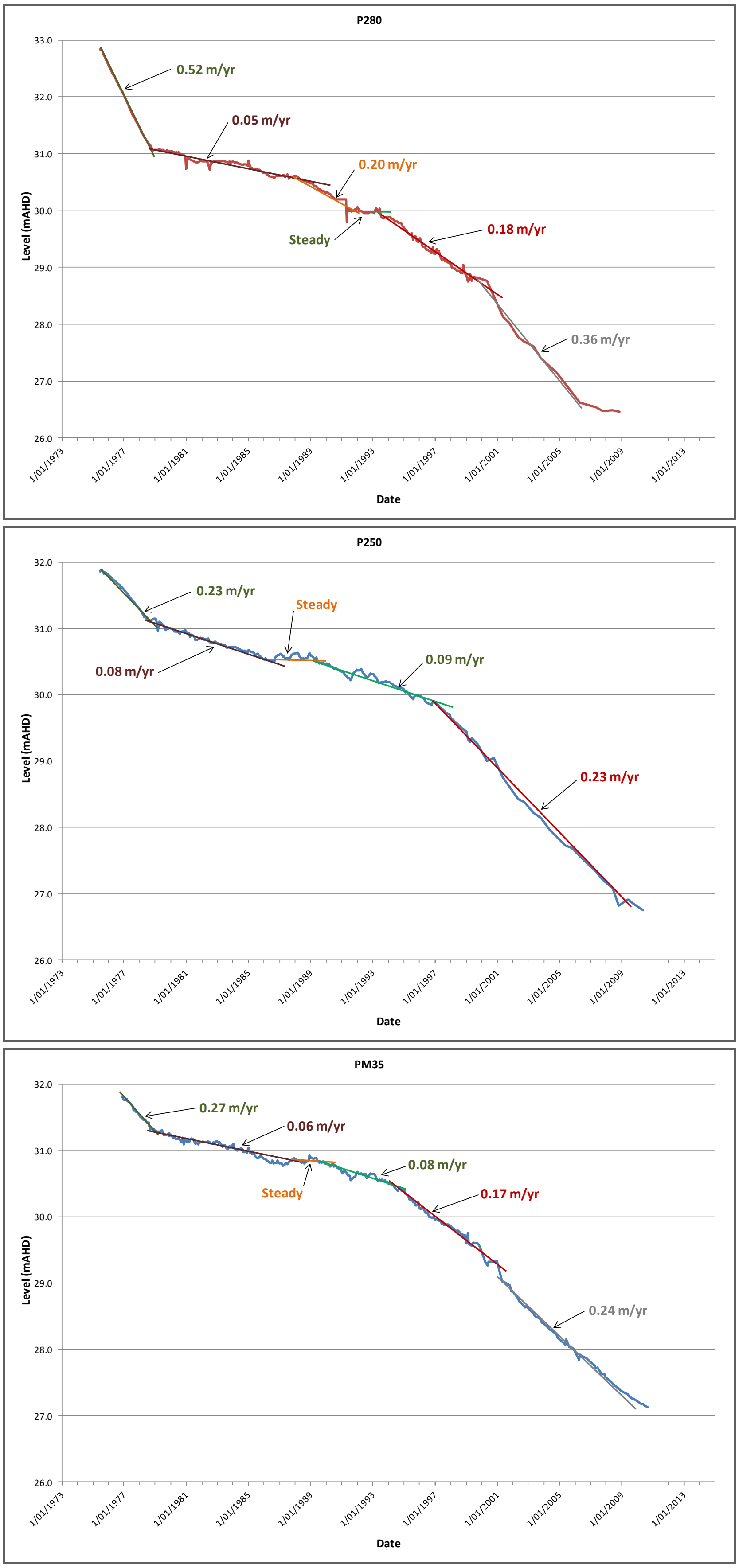


Figure 5-7 Watertable trends east of Lake Nowergup.

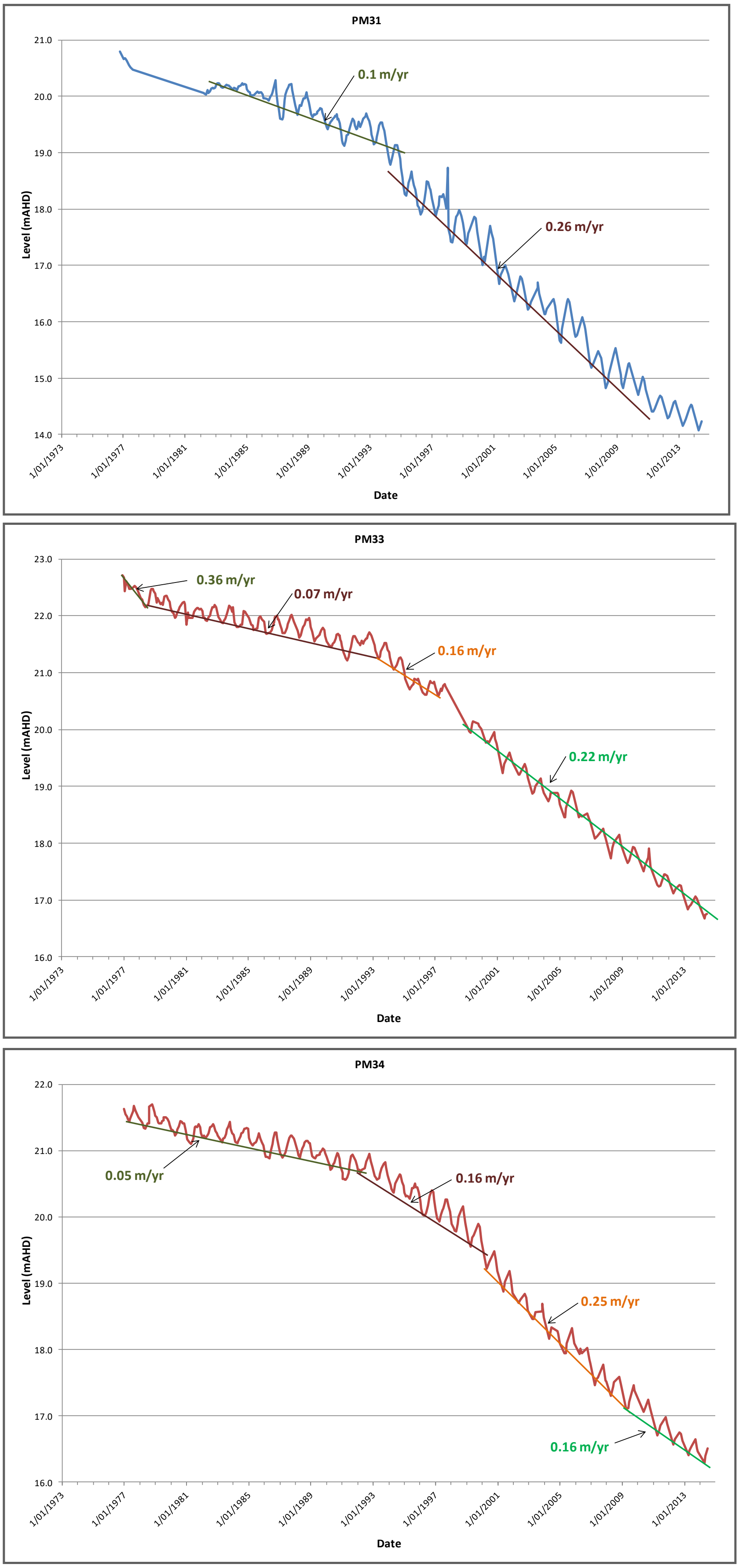


Figure 5-8 Watertable trends about the western limit of Bassendean Sand.

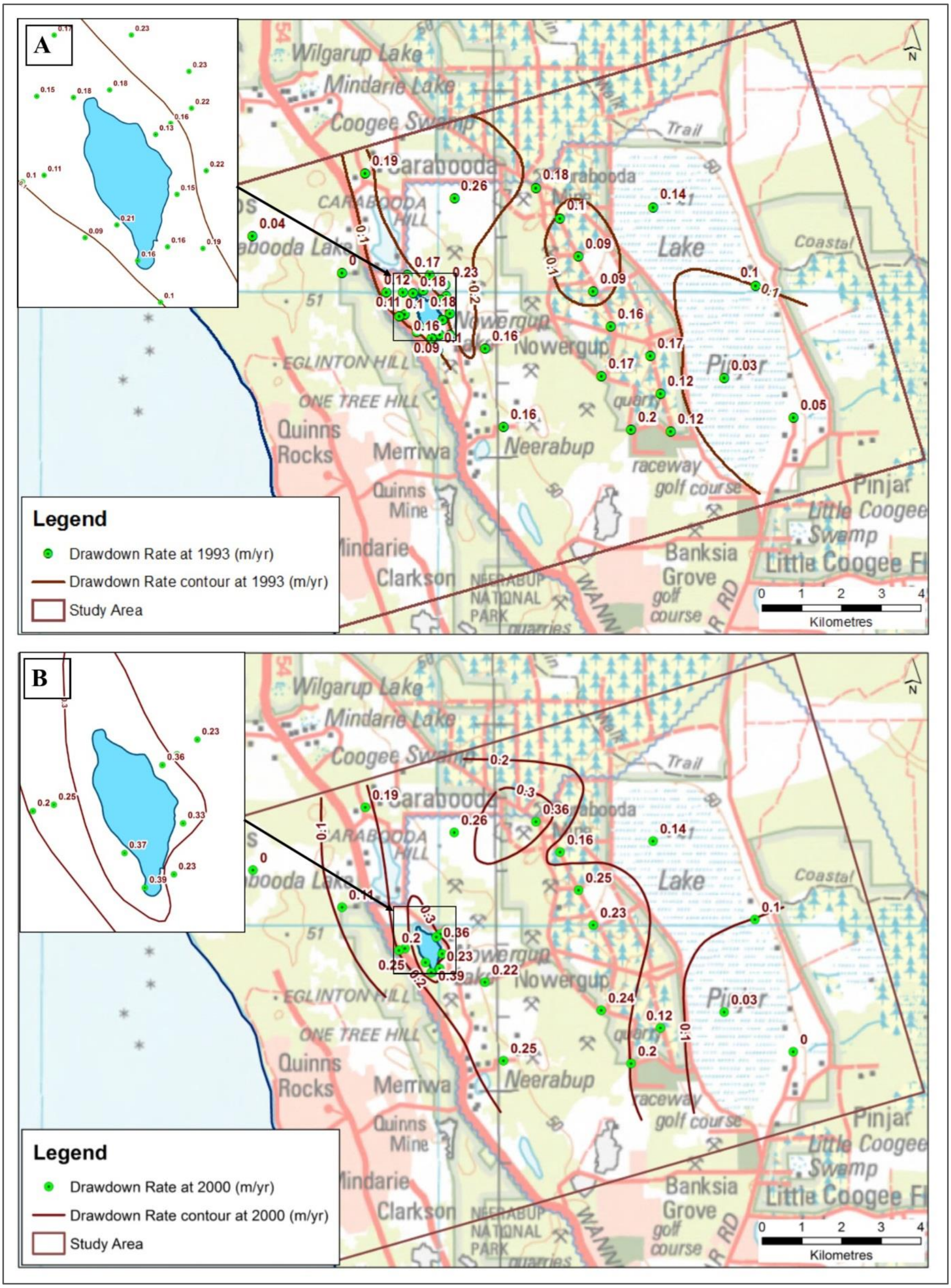
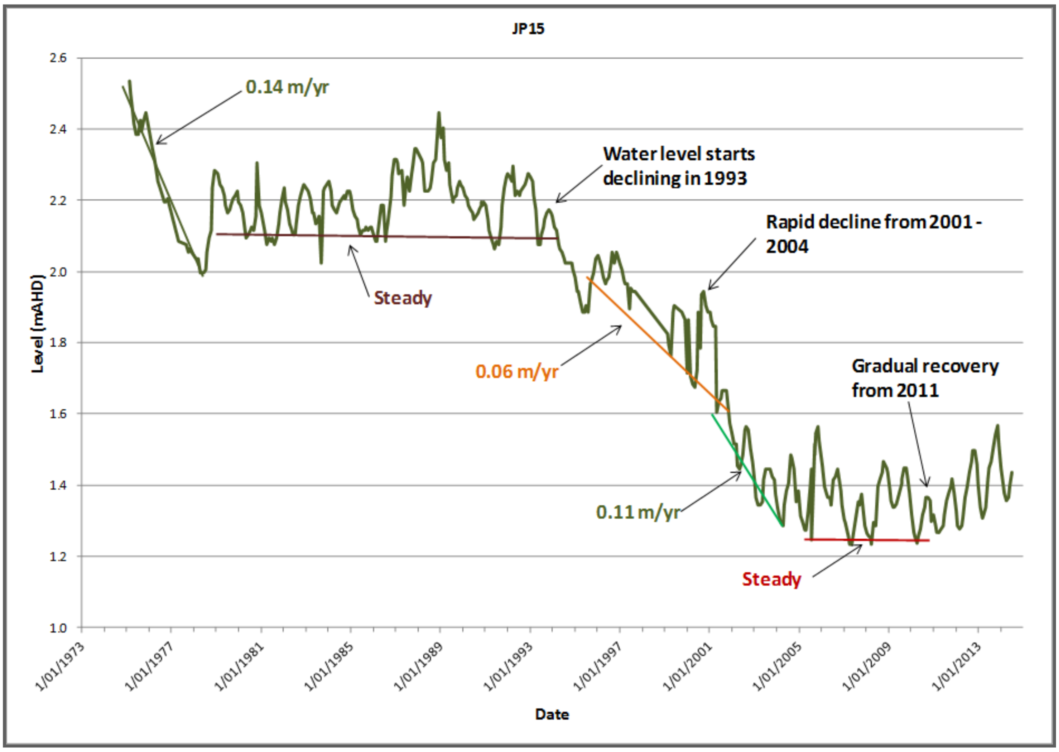


Figure 5-9 Rate of watertable decline; a) 1993 to 2000, b) 2000 to 2014.

5.2.2 Water level trends in the Superficial aquifer; Tamala Limestone

Monitoring bores within the Tamala Limestone show very low rates of decline in water levels until about the year 2001. Falling watertable levels that occurred in the Bassendean Sand to the east do not extend far west beyond the lake systems due to the very high aquifer transmissivity of the limestone. Monitoring bores situated within the eastern portion of Tamala Limestone close to the Carabooda area did show a progressive decline in the watertable commencing in 1994; falling 0.27 m by 1999 in bore EI 1-89 located 1.9 km west of Carabooda Lake and 0.31 m in bore JP15 situated 1.3 km west of the lake. This compares to a decline of 1.46 m in bore JP19 north of Carabooda Lake and 1.77 m in bore PM31 in the Carabooda horticultural area, both within the Bassendean Sand.

A rapid decline in the watertable is seen within the Tamala Limestone in all monitoring bores from 2001, with declines up to about 0.65 m over one or two years, but subsequently water levels have remained relatively stable. At most sites the watertable fell by around 0.2 to 0.3 m. Timing of the fall in watertable levels corresponds with commissioning of the Quinns borefield which commenced pumping for public supplies from the Superficial aquifer production bores over 1999 to 2000. Some sites show a recovery trend starting variously from between 2005 (bore QV 26-89) and 2011 (e.g. bores JP15, EH 32-89, EG 2-89) and continuing to the present. This may be related to the effect of increased groundwater recharge from urbanisation (including the initial clearing of native vegetation) and reduced pumping from the Quinns Superficial borefield on-ward from 2012, and helped by close to average rainfall since 2010. Representative hydrographs for monitoring bores within the Tamala Limestone are presented by Figure 5-10.



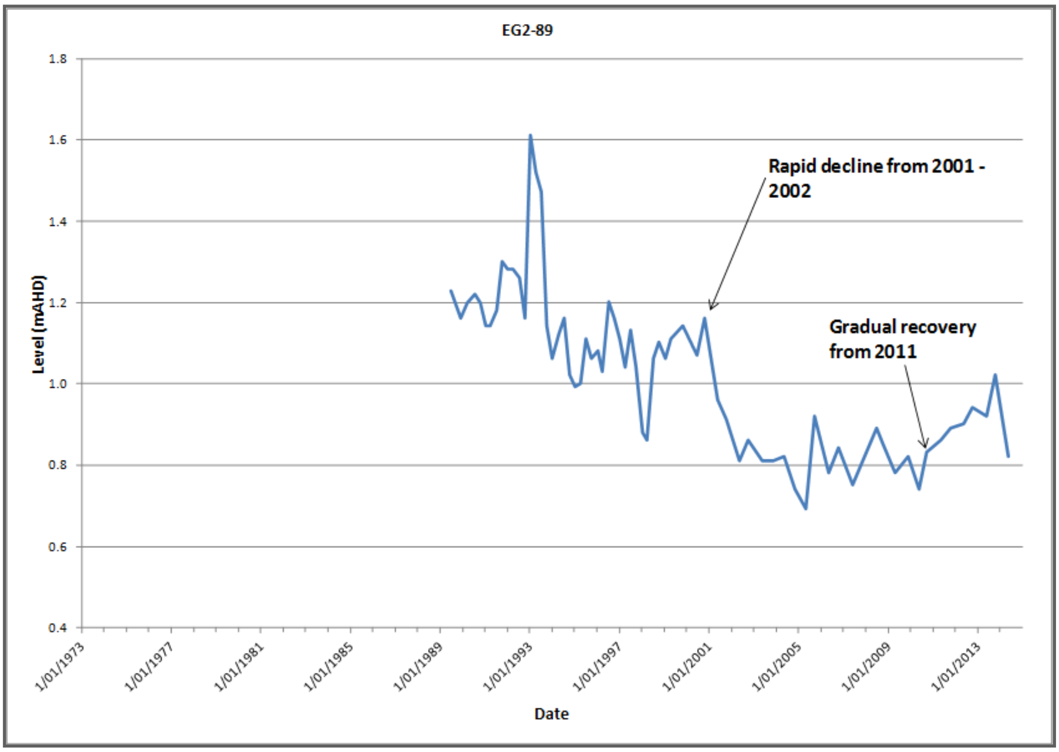


Figure 5-10 Watertable trends west of Lake Nowergup.

5.2.3 In proximity to Lake Nowergup

Hydrographs of monitoring bores about Lake Nowergup show similar trends as observed at the sites further from the lake. An exception is that the influence of lake supplementation is apparent in hydrographs of monitoring bores up to 400 m east of the lake where the watertable has been maintained or at least partially held up for the period 2002 to 2008. However, about the western side of the lake the influence of lake supplementation is apparent only near the lake margins. Figure 5-11 and 5–12 present hydrographs for monitoring bores LN32 and JP17 showing the changing watertable trends about the eastern side of Lake Nowergup. Representative hydrographs about the western side of Lake Nowergup are presented in Figure 5-13 and 5–14 for monitoring bores LN5 and LN3.

The pattern of decline about the eastern side of the lake is similar to that seen elsewhere along this part of the coastal plain. Prior to 2002, the rate of watertable decline was around 0.15 m/year (e.g. in LN32), which is less than observed in the Carabooda area. Groundwater levels stabilise between 2002 to 2008 as a result of lake supplementation, but subsequently the rate of watertable decline increases from 2009, exceeding 0.3 m/year about the lake and up to 0.36 m/year along the eastern lake shore in LN18. This is greater than seen elsewhere in this part of the coastal plain, which is about 0.25 m/year after 2009. Causes for the greater rate of decline may include local private pumping, impacts from pumping of the supplementation bore 2/00, or the reduction in lake supplementation that has averaged 897 ML/year since 2009 compared to 1188 ML/year between 2002 and 2008.

About the western side of Lake Nowergup, the watertable declined at rates of between 0.16 m/year (bore LN6) to 0.21 m/year (bore LN5) during the early part of Phase 3 between 1993 and 1999 (Figure 5–13 and 5–14). This is consistent with rates seen in the Bassendean Sand elsewhere along this part of the coastal plain. The rate of decline decreases westward away from the lake, with it being less than 0.1 m/year within about 500 m of the lake. Onward from 2009, a rapid decline has been observed in watertable levels about the western margin of the lake, declining by 0.37 m/year to 0.39 m/year at least until 2013. The rate decreases to 0.2 m/year within about 500 m west of the lake.

A more detailed review of changes in watertable levels about Lake Nowergup during the different phases follows.

Watertable changes 1973 – 1978 (Phase 1)

The period from about 1973 to 1978 experienced a rapid decline in water levels. The watertable declined by 0.74 m at about 0.25 m/year from 1975 to 1978 in bore JP17 situated around 380 m northeast of the lake. The watertable declined by 0.39 m at bore JP15, located about 2 km northwest of the lake. Lake water levels also declined over this period, with the seasonal minimum level declining by about 0.16 m, although in 1978 it declined by a further 0.31 m but subsequently recovered in 1979. This period precedes any watertable monitoring at the lake margin and it is expected that these changes in lake water levels are likely to be a good indication of the watertable change that would have occurred about the eastern side of the lake.

As this period is before any significant groundwater pumping, the decline in water levels is thought to be in response mostly to reduced groundwater recharge rates resulting from lower rainfall and the effect of maturing pine plantations east of the lake. Well below average rainfall was recorded during 1975 to 1977.

Watertable changes 1979 – 1992 (Phase 2)

During the period 1979 to 1992 the watertable beneath the coastal plain was largely stable, or declined at relatively low rates of less than 0.1 m/year. East of the lake, monitoring bores

JP17 and PM33 were operational through the entirety of this period. At bore JP17 the watertable was stable, but declined at 0.07 m/year for a total of about 0.9 m in bore PM33 over this time. Watertable levels were stable west of the lake, as observed at bore JP15 located 2 km northwest of the lake. Rises and falls of groundwater levels during this period are attributed to years of above or below average rainfall.

The seasonal low in lake water levels did show a gradual decline during Phase 2, when it fell up to 0.37 m by 1989, but partially recovered for an overall decline of about 0.2 m at the end of the period. Monitoring of the LN series of bores about Lake Nowergup commenced too late to observe the watertable decline through this period. Overall, this was a period of relatively stable rainfall and the observed decline is therefore thought to be related mainly to groundwater pumping east of the lake, although the pine plantations to the east may have also contributed to the decline by reducing groundwater recharge.

Watertable changes 1993 – 2002 (early Phase 3)

A relatively consistent gradual decline in the watertable is seen starting in 1993, continuing until 2002. The rate of decline slows from 1998 coincident with lake supplementation. The watertable declined fairly uniformly about the lake until 1998, falling by around 0.7 m (bore LN11) at the eastern margin and about 0.8 m (bores LN4, 0.82 m; LN2, 0.95 m; LN6, 0.78 m) at the western margin, with an average rate of decline of around 0.15 m/year to 0.21 m/year respectively for the east and west lake sides. The declines increase east of the lake. Declines in excess of 1.1 m occur within 300 m of the east side of the lake (bore JP17, LN7 and LN10) and increase to almost 1.7 m in bore LN34 situated around 520 m northeast of the lake.

Over the period 1993 to 1999 the water level decline became less to the west away from the lake (monitoring of many bores ceased in 1999). Declines of around 0.49 m to 0.58 m were observed (bores LN25, LN27 and LN36) about 300 m west of the lake, but was 0.25 m (bore LN24) about 480 m west of the lake. Very low rates of decline were observed within the Tamala Limestone further west. A rapid decline in watertable levels occurred from 1999 to 2003 at monitoring bores LN3 and LN24 of 1.02 m and 1.04 m respectively.

Seasonal minimum lake water levels from 1993 were generally stable until 1996, but subsequently over 1997 to 2002 dropped by up to 1 m, bringing the lake water level closer to the watertable. The decline in watertable coincides with a significant increase in groundwater pumping, particularly in the Carabooda area and commissioning of the Pinjar borefield for public supply in 1989. Below average rainfall during 1993, 1994 and 1997 may be partially responsible for the decline, although the decrease in the Accumulative Residual Annual Rainfall (see Figure 2-2) was only minor, suggesting that the effect on watertable levels should also be minor.

Watertable changes 2003 – 2014 (late Phase 3)

A period of stable watertable is seen from 2002 until 2008 about the lake, which is the result of regular lake supplementation that commenced in 1998 and increased significantly from 2005 to 2011. This also corresponds with the commissioning of the larger capacity supplementation bore 2/00 and a change in strategy for supplementation where water was pumped into the lake from spring through to autumn. This was a period of mostly below average rainfall, with the Accumulative Residual Annual Rainfall showing a rapid decline.

Further from the lake there has been a decline in the watertable since 2002, which was greater east of the lake. Just north of the lake watertable levels fell by 1.4 m at bore LN12, while adjacent to the east side of the lake watertable levels fell by 1.6 m (bore LN19) to 1.9 m (bore LN8), increasing further east to 2.2 m at bore JP17 and 2.5 m about 1 km southeast of the lake at PM33. Adjacent to the lake most of the decline has occurred since 2008, when the watertable declined by up to about 2.1 m (bore LN8).

Lake supplementation maintained watertable levels about the west side of the lake during the period from 2002 to 2008. However, from about 2008 to 2014 the seasonal minimum watertable level declined from previous minimum levels by between 2.2 m (bore LN5) and 2.6 m (bore LN6) about the western margin of the lake, similar to declines along the eastern margin of the lake. Seasonal maximum groundwater levels declined less than the seasonal minimum levels, falling by about 2 m from 2008 to 2014. This smaller decline is possibly the result of on-going lake supplementation. The seasonal maximum groundwater level collapsed in bore LN6 after 2011, falling over 2.5 m in one year, and by 2013 was almost 4.5 m lower than pre-2002 levels. The rapid fall in levels may reflect the position of the bore at the very southern end of the original lake extent that is now distant from the current lake water surface so that it is now less affected by lake supplementation.

Lake supplementation has had no apparent influence on the watertable west of the lake at the location of bores LN3 and LN24. The pattern of decline at these sites is similar to that observed in the Tamala Limestone further west following commissioning of the Quinns borefield. However, the decline commenced earlier (1999 instead of 2001) and has been greater in bores close to Lake Nowergup than that observed in the Tamala Limestone where the watertable fell generally by 0.2 to 0.3 m. This suggests an additional contribution to water level decline at the lake other than the Superficial production bores of the Quinns borefield. The initial period of rapid decline in water levels from 1999 was followed by a more gradual decline of 0.42 m and 0.2 m, respectively to 2010, when monitoring ceased at these sites. This subsequent gradual decline was not evident in the Tamala Limestone further west and may represent downward leakage into the Leederville aquifer near the lake in response to reduced potentiometric heads in the Leederville aquifer caused by pumping from the Quinns Leederville borefield.

Water levels within Lake Nowergup have been largely sustained by supplementation during this time following the rapid fall that occurred in 1997. Since 2010, lake water levels have fallen rapidly, with summer minimum levels falling from around 16.2 mAHD to possibly less than 15 mAHD in 2014. Near-average rainfall since 2010 has not resulted in any stabilisation in water levels.

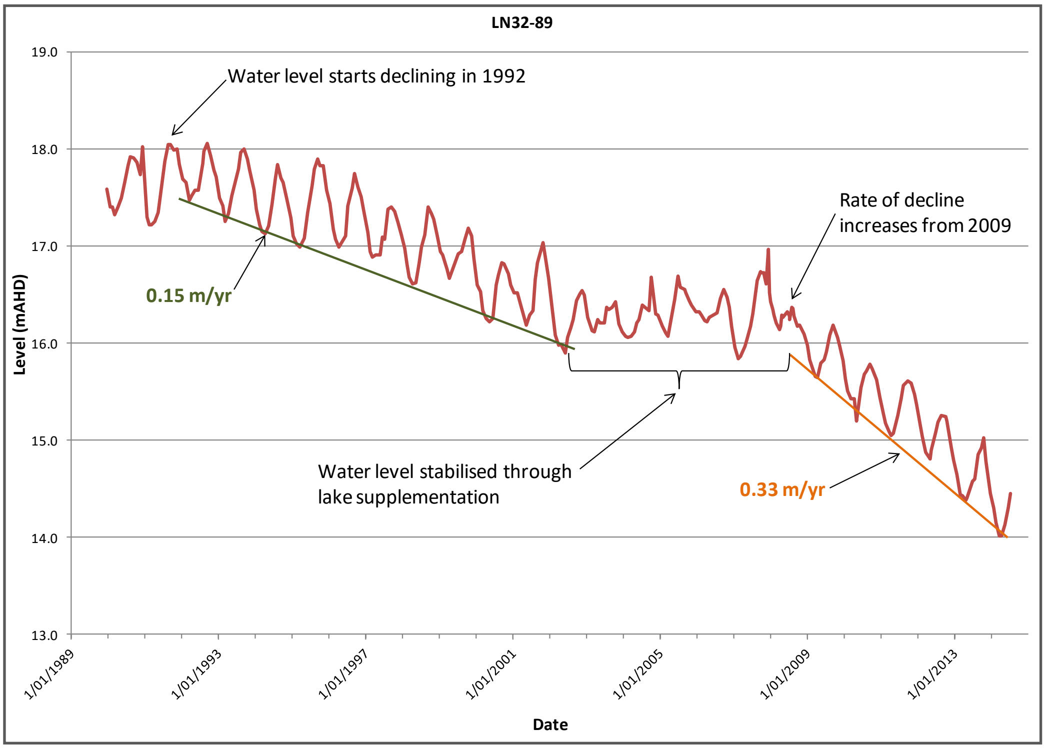


Figure 5-11 Hydrograph - eastern margin of Lake Nowergup.

Figure 5-12 Representative hydrograph, northeast margin of Lake Nowergup.

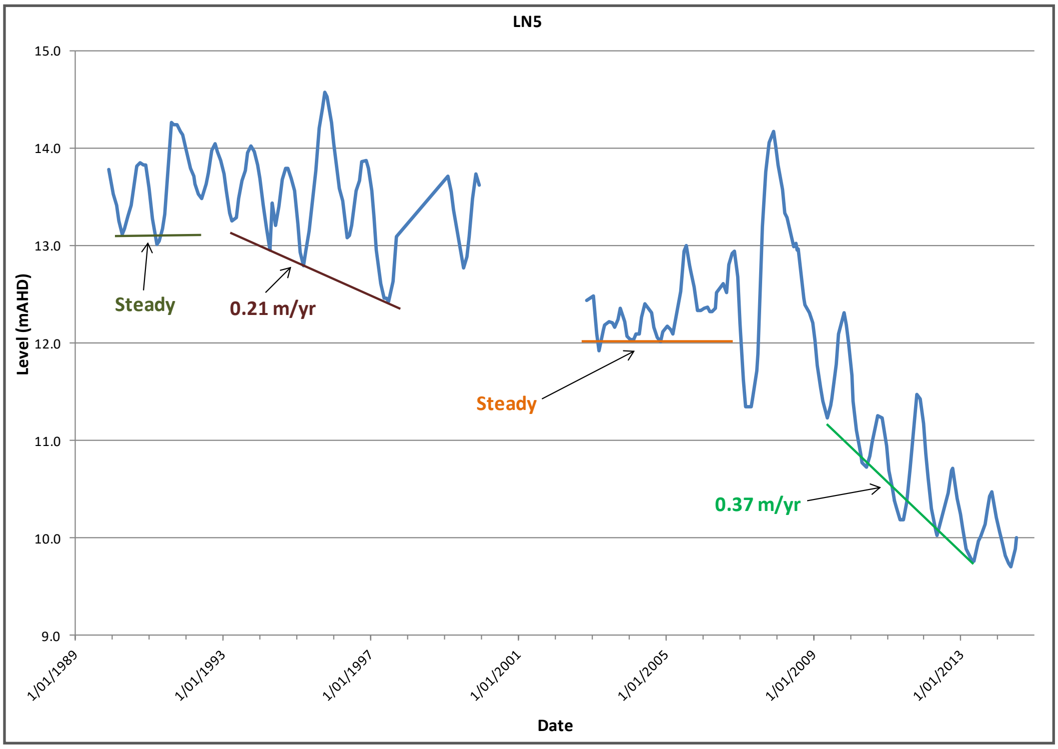


Figure 5-13 Representative hydrograph southwest margin of Lake Nowergup.

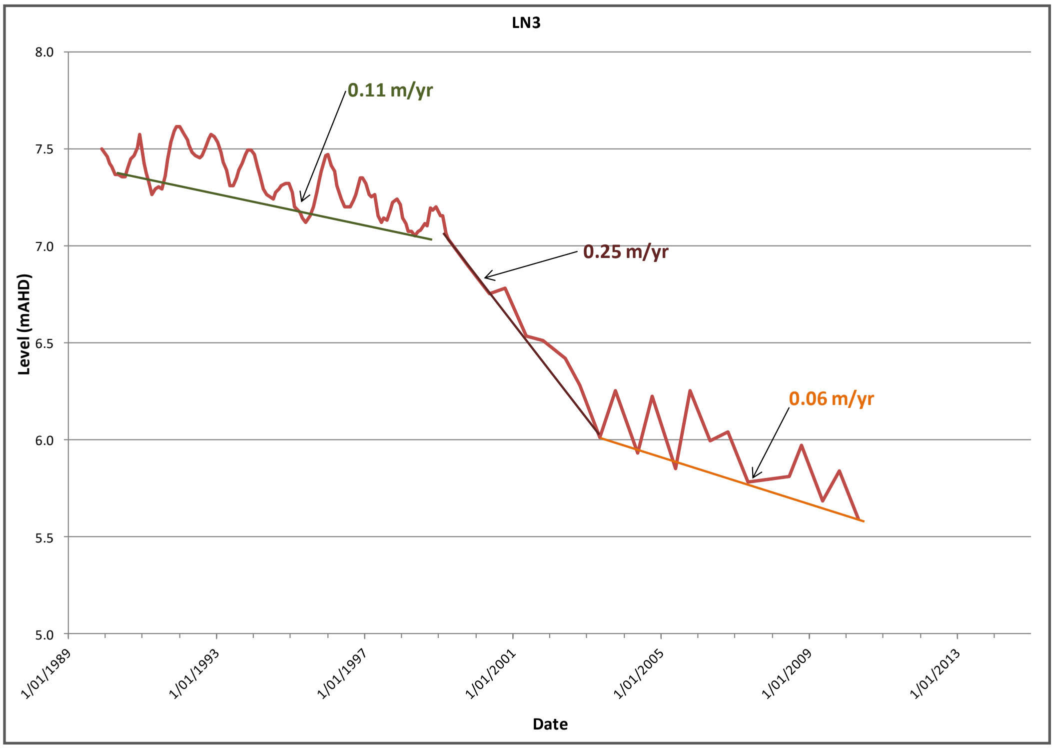


Figure 5-14 Representative hydrograph west of Lake Nowergup.

5.2.4 Within the Leederville aquifer

Pumping for public supply from the Pinjar and Quinns Leederville borefields, and possibly the more distant Wanneroo borefield, has resulted in depressurisation of potentiometric heads within the aquifer forming a drawdown cone beneath the Gnangara Mound (Kretschmer and Kelsey, 2012). The Pinjar Leederville borefield commenced pumping in 1989, increasing incrementally to 1997, and the Quinns Leederville borefield commenced pumping in 1999. Pumping from the Leederville aquifer in the Wanneroo borefield started in 1977.

The drawdown cone from pumping has not been well defined between the borefields and Lake Nowergup due to the small number of monitoring bores in the aquifer through this area. There are also only limited monitoring data for the Leederville aquifer in the vicinity of Lake Nowergup, and these are only from monitoring bores LN18 and LN37 bores within the very upper-most portion of the aquifer in the basal portion of the Ascot Formation, which may not fully represent changes in potentiometric heads occurring deeper in the aquifer. More distant Leederville aquifer monitoring bores are bores AM20A situated 2 km west-northwest of the lake, AM23A 5.8 km south, JP21 6.6 km northwest, and AM21A 8.4 km east-northeast of the lake.

Figure 5-15 shows the observed drawdown of potentiometric heads within the Leederville aquifer for the period of 1989 to 1998, 1999 to 2012, and for the total for 1989 to 2012. Based on the changes seen at the monitoring bore sites, the potentiometric head within the Leederville aquifer beneath Lake Nowergup has probably declined by around 10 m. Previous mapping of the Leederville aquifer potentiometric head for 1992 by Davidson (1995) had a level of around 16.5 to 17 mAHD in the Lake Nowergup area, but this is now probably about 7 mAHD. This is confirmed by a water level measurement taken in March 2015 at the supplementation bore 2/00 beside the lake where the potentiometric head level was found to be approximately 7.2 mAHD.

Hydrographs from monitoring bores within the Leederville aquifer in the study area are presented in Figure 5-16. Potentiometric head in monitoring bore AM21A, located along the Pinjar borefield east of Lake Pinjar and about 8 km east of Lake Nowergup is shown in Figure 5-17 along with the incremental increases in pumping from the Pinjar Leederville borefield. From 1989 to 1992, potentiometric heads declined by about 2.3 m coincident with pumping from bore P25 located 5850 m from monitoring bore AM21A. An additional decline of 4.8 m occurs after 1993 associated with the addition of pumping from bore P65 located 1854 m from monitoring bore AM21A. Pumping was further increased from 1997 with the commissioning of bores P105 and P145 (2089 m and 6050 m from monitoring bore AM21A, respectively) and this is coincident with a further decline of 8.9 m. The total maximum drawdown was 16 m from an initial seasonal minimum potentiometric level of about 32 mAHD.

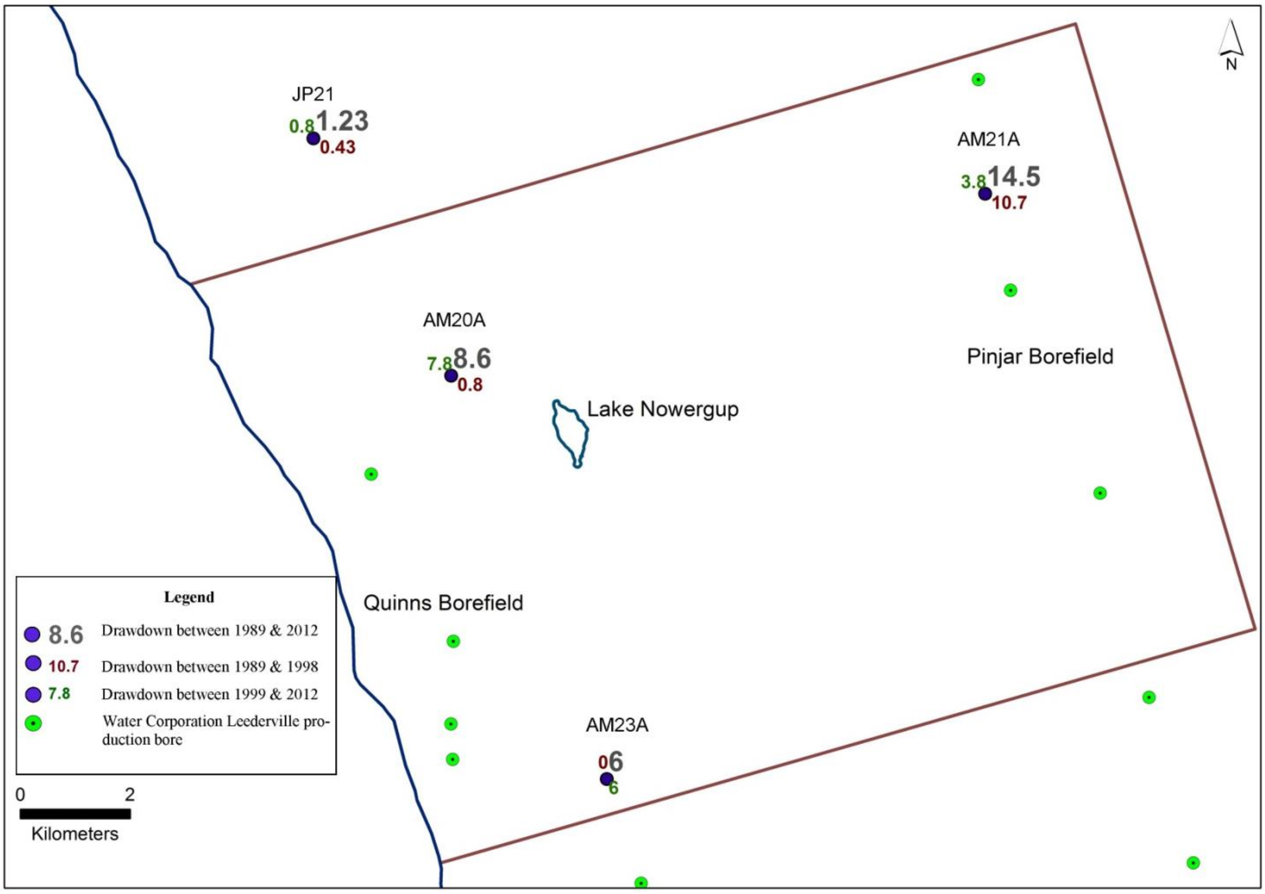


Figure 5-15 Potentiometric head drawdown - Leederville Formation observation bores, 1989 to 2012.

Monitoring bores AM20A and AM23A within the Leederville aquifer west of Lake Nowergup are near to the Quinns borefield area and screened in the deeper parts of the Leederville aquifer (156-161 m and 144-152 m bgl respectively). These bores show a distinct drop in potentiometric head coincident with the commencement of pumping from the Quinns borefield in 1999. Potentiometric heads declined by around 7 m in bore AM20A, which is 2.3 km from the closest production bore Q205. To the south, a similar decline is seen in bore AM23A, which is 2 km from the closest production bore Q35, but in this case potentiometric heads fully recovered between periods of obvious pumping, at least until 2014 when a downward trend is first seen. Prior to pumping from the Quinns borefield, a gradual decline of 0.8 m of potentiometric head in bore AM20A over 1990 to 1996 may be in response to pumping from the Pinjar Leederville borefield, although a gradual decline evident from 1986 may have other causes. These may include influence of declining water levels in the Superficial aquifer and pumping from the more distant Wanneroo borefield. A recovering trend is evident in the potentiometric head level in AM20A over 2013 and 2014, which may have resulted from a reduction in annual pumping rates from the Quinns borefield Superficial aquifer bores from 2012 and from the Leederville aquifer bores from 2014.

A decline in potentiometric head of 0.4 m from 1990 and 1998 occurred in monitoring bore JP21, located 6.6 km northwest of Lake Nowergup. This may have been due to pumping from the Pinjar Leederville borefield, although the closest Pinjar Leederville aquifer production bore is over 12 km to the east, or private pumping in the Yanchep area. There was a further 0.6 m decline between 1999 and 2010, which may be at least partly associated with the Quinns Leederville borefield pumping, with the closest Leederville aquifer production bore Q205 situated 6.2 km to the south of bore JP21. Water levels have been stable in the bore JP21 since about 2010.

The only monitoring bores within the Leederville aquifer adjacent to Lake Nowergup are bores LN18 near the eastern margin of the lake and LN37 just west of the lake. Both bores effectively monitor the upper-most portion of the Leederville aquifer, being screened in the basal Ascot Formation. Bore LN18 shows a very similar hydrograph to that from the shallow Superficial aquifer monitoring bore LN19 at the same location, suggesting hydraulic connection at this site between the upper-most Leederville aquifer and Superficial aquifer. A decline in water levels of around 0.5 m between 1990 and 1998 is coincident with groundwater pumping from the Pinjar Leederville borefield, but may also be a result of declining water levels in the Superficial aquifer. There is also possibly some contribution to drawdown from pumping of the supplementation bore screened deeper in the Leederville aquifer, although no immediate impact from this pumping is evident in the plot (i.e. a rapid fall and recovery in potentiometric heads in response to periods of pumping and non-pumping). Some amelioration of the drawdown as a result of lake supplementation via the Superficial aquifer is evident from 2003 to 2008. Due to the apparent good hydraulic connection between the Leederville and Superficial aquifers at this location, it is uncertain if water levels from bore LN18 are a good representation of potentiometric heads within the Leederville aquifer.

Potentiometric head in bore LN37 located west of Lake Nowergup declined by around 2.8 m at a fairly constant rate from 1999 until 2007, after which water levels have been relatively stable. The decline in head is coincident with pumping from the Quinns Leederville borefield, and may reflect this pumping with additional contributions caused by pumping from Superficial bores in the Quinns borefield, the supplementation bore 2/00 and private pumping (Superficial aquifer) east of the lake. Although there is no evidence in the hydrograph of bore LN37 of any drawdown associated with pumping from the Pinjar Leederville borefield that commenced in 1989, it is considered that the potentiometric head deeper in the aquifer may have declined by around 1 m based on the drawdown observed at bore AM20A further west.

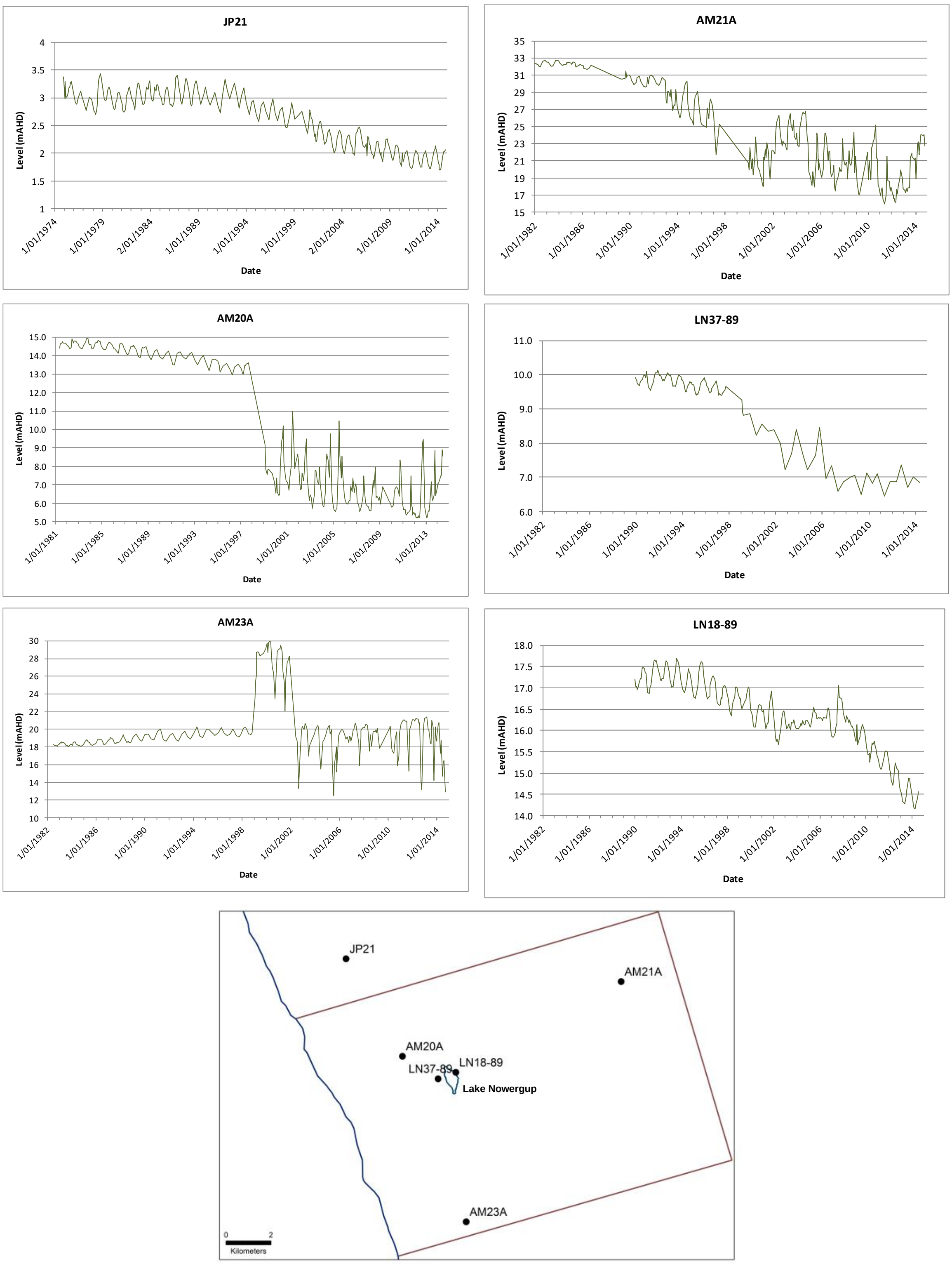


Figure 5-16 Leederville aquifer hydrographs.

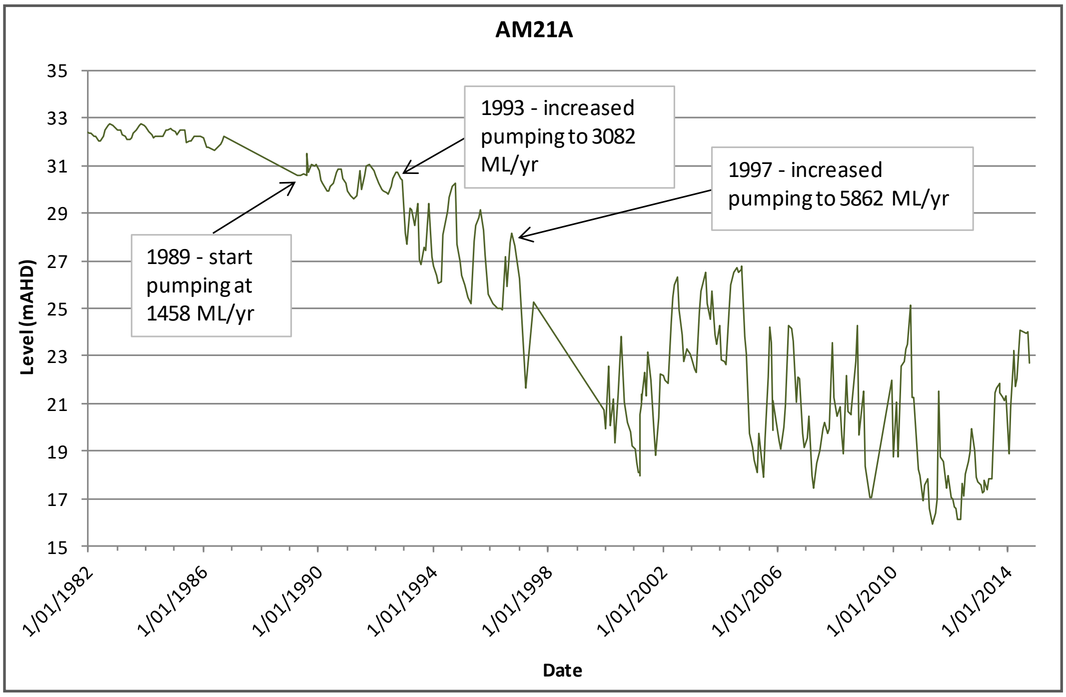


Figure 5-17 Leederville aquifer hydrograph - Pinjar Leederville borefield operation.

5.2.5 Hydraulic gradient between the Leederville and Superficial aquifers

The pattern of water levels and the direction of hydraulic gradients between the Leederville and Superficial aquifers are summarised in Figure 5-18 for the years 1990 and 2014. Prior to major Leederville aquifer pumping, potentiometric heads in the Leederville aquifer were approximately equal to water levels in the Superficial aquifer beneath the eastern margin of Lake Nowergup, so that there was no significant vertical hydraulic gradient and little flow between the two aquifers. About the western margin of the lake an upward hydraulic head probably slightly greater than 3 m existed between the main portion of the Leederville aquifer (comprising the Wanneroo Member) and the Superficial aquifer, creating the potential for groundwater to flow upward from the Leederville aquifer into the Superficial aquifer in this area.

Hydraulic gradients have changed significantly in response to the reduced potentiometric head within the Leederville aquifer. Downward hydraulic gradients now exist beneath the entire lake area, with head differences of about 3 m about the western lake margin to 7 m at the eastern side. This indicates that beneath the entire lake area the potential is now for downward leakage from the Superficial aquifer into the Leederville aquifer. There is a small upward hydraulic gradient west of the lake between bores LN37 and LN3 in the upper-most part of the Leederville aquifer comprising the lower Ascot Formation and Superficial aquifer. It is, however, possible that a downward gradient exists between the Ascot Formation and Wanneroo Member portions of the aquifer.

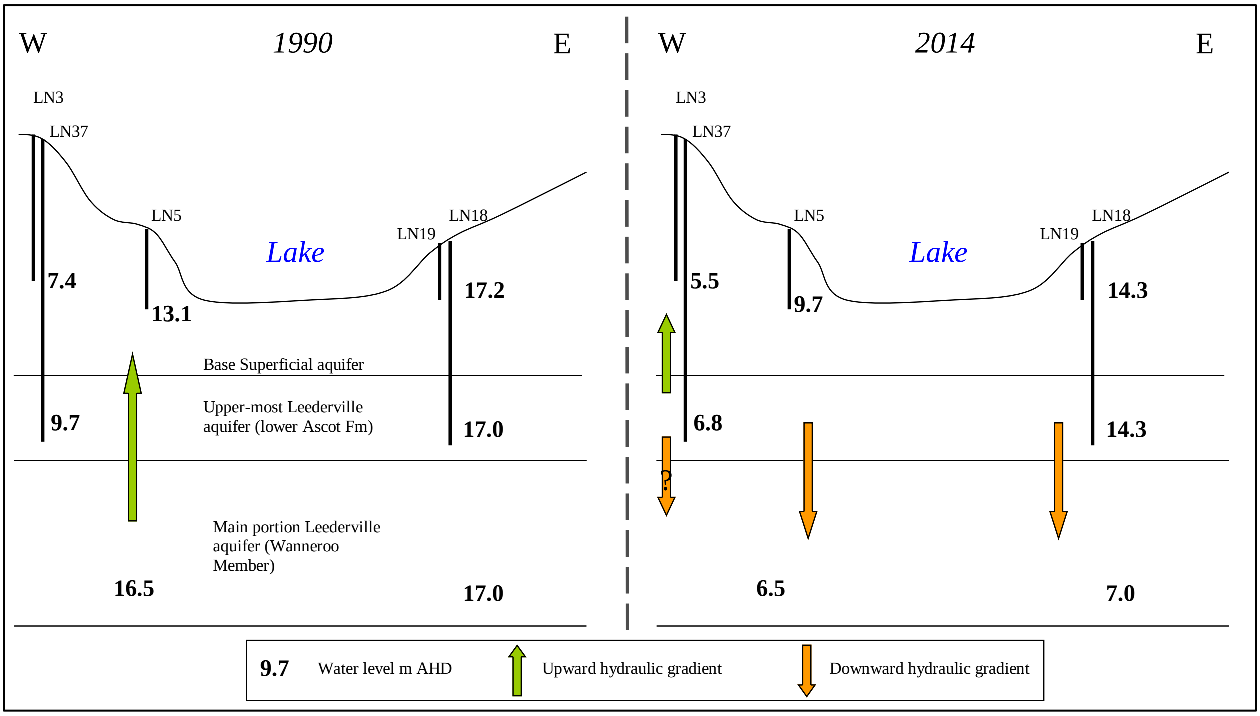


Figure 5-18 Water levels and hydraulic gradient beneath Lake Nowergup - 1990 and 2014.

5.2.6 Summary of hydrograph analysis

Watertable within the Bassendean Sand east of the coastal chain of lakes

- Has been declining for most of the period since 1975, during which several distinct phases of decline are evident;
- Periods of rapid decline occur between 1973 and 1979, and from 1993, with the rate of decline increasing from the year 2000 that has continued to the present;
- Until 1979 (Phase 1), the watertable decline is relatively evenly spread over the area, suggesting that it is in response to reduced groundwater recharge rates from lower average annual rainfall and possibly the effect of maturing pine plantations;
- An abrupt decrease in the rate of watertable decline occurs from 1978 which continues until 1993 (Phase 2), and may be in response to a period of relatively stable rainfall and possibly near equilibrium conditions of recharge under the pine plantations;
- The watertable enters a period of decline after 1993 (Phase 3), where the rate is greatest about the western portion of the Bassendean Sand, increasing to 0.26 m/year in the Carabooda area. This may be related to increased groundwater pumping in the area;
- From 2000 (latter part of Phase 3), the rate of watertable decline increases markedly at many sites, and corresponds with further increases in groundwater pumping and a period of lower annual rainfall that continued until 2010.

Watertable within the Tamala Limestone west of the coastal chain of lakes:

- There are very low rates of decline until about the year 2001;
- There is a progressive decline commencing in 1994 seen in the eastern portion of Tamala Limestone close to the Carabooda area, representing drawdown caused by groundwater pumping propagating from the Carabooda area;
- A rapid decline of up to about 0.65 m is seen within the Tamala Limestone from 2001 over one or two years, but subsequently water levels have remained relatively stable. Timing of the fall in watertable levels corresponds with commissioning of the Quinns borefield.

Watertable in proximity to Lake Nowergup:

- Show similar trends as observed at the sites further from the lake;
- A rapid decline in watertable levels from about 1973 to 1978 of possibly more than 0.74 m is observed (Phase 1), probably in response to lower rainfall and possibly the effect of pine plantations to the east. Lake water levels also declined over this period, with the seasonal minimum level declining by about 0.16 m;
- Watertable was generally stable over 1979 to 1992 (Phase 2), although there was a small rate of decline east of the lake. Lake water levels show a gradual decline totalling about 0.2 m at the end of the period.
- A relatively consistent gradual decline in the watertable is seen starting in 1993, continuing until 2002 (early Phase 3) where levels fell by around 0.8 m, although the rate of decline does slow from 1998 coincident with lake supplementation. Lake water levels from 1993 were generally stable until 1996, but subsequently over 1997 to 2002 dropped by up to 1 m;
- Lake supplementation maintained or at least partially held up the watertable about the lake for the period 2002 to 2008;
- Onward from 2009 (late Phase 3), the watertable has declined rapidly, falling by up to 2.6 m. Lake water levels have probably fallen by over 1.2 m over this period. Causes for the falling groundwater and lake levels may include local private pumping, impacts from pumping of the supplementation bore 2/00, or the reduction in lake supplementation.

Potentiometric head levels within the Leederville aquifer:

- Drawdown cone in the Leederville aquifer from pumping has not been well defined between the borefields and Lake Nowergup due to the small number of monitoring bores in the aquifer through this area;
- Potentiometric head within the Leederville aquifer beneath Lake Nowergup has probably declined by around 10 m from initial levels, and is now probably about 7 mAHD;
- A gradual decline evident from 1986 to 1990 in AM20A west of Lake Nowergup of about 0.36 m may include influence of declining water levels in the Superficial aquifer and pumping from the more distant Wanneroo borefield;
- A gradual potentiometric head decline of 0.8 m in bore AM20A over 1990 to 1996 may be in response to pumping from the Pinjar Leederville borefield;

- A distinct drop in potentiometric head of around 7 m over 1999 – 2000 observed in bore AM20A is coincident with the commencement of pumping from the Quinns borefield;
- A recovering trend is evident in AM20A over 2013 and 2014, which may have resulted from reduced pumping from the Quinns borefield from 2012;
- The only monitoring bores within the Leederville aquifer adjacent to Lake Nowergup are bores LN18 near the eastern margin of the lake and LN37 just west of the lake, and both are screened in the basal Ascot Formation forming in the upper-most portion of the Leederville aquifer. There is an apparent good hydraulic connection between the Leederville and Superficial aquifers at LN18, so it may not provide a good representation of potentiometric heads within the Leederville aquifer;
- Potentiometric head declined by around 2.8 m in bore LN37 from 1999 until 2007, which may be in response to pumping from the Quinns Leederville borefield with additional contributions caused by pumping from Superficial bores in the Quinns borefield, the supplementation bore 2/00 and private pumping (Superficial aquifer) east of the lake.

Hydraulic gradient between the Leederville and Superficial aquifers:

- Prior to commencement of pumping from the Leederville aquifer by the Water Corporation borefields, the potentiometric head was approximately equal to water levels in the Superficial aquifer beneath the eastern margin of Lake Nowergup and an upward hydraulic gradient existed about the western margin of the lake probably slightly greater than 3 m;
- Pumping from the Leederville aquifer has reduced the potentiometric head resulting in a downward hydraulic gradient now existing beneath the entire lake area and creating the potential for downward leakage of groundwater from the Superficial aquifer into the Leederville aquifer.

5.3 Impact on the watertable of reduced potentiometric head in the Leederville aquifer

In a regional context some degree of hydraulic connection between the Leederville and Superficial aquifers will exist. Therefore, a reduction in the potentiometric head within the Leederville aquifer will result in a decline in the watertable of the Superficial aquifer either from a reduction in upward flow from the Leederville aquifer to the Superficial aquifer where an upward hydraulic gradient exists, or from increased downward flow from the Superficial aquifer into the Leederville aquifer where the gradient is downward. In some areas the flow of groundwater between the two aquifers may reverse from upward to downward. It has been observed that watertable levels in the Superficial aquifer have fallen in response to decreased potentiometric heads in the Leederville aquifer (Kretschmer and Kelsey, 2012).

Simulations of groundwater flow using PRAMS has shown pumping drawdown impacts within the Leederville aquifer propagate rapidly through the aquifer (Water Corporation, 2008), which is typical for confined aquifers. Drawdown stabilises about 2 years after the commencement or increase in pumping, which is consistent with the observed drawdown seen in the Leederville aquifer following commencement of pumping from the Quinns Leederville aquifer borefield. However, the watertable within the Superficial aquifer responds slowly to pumping from underlying confined aquifers. Simulations also indicate that the drawdown impacts persist for a prolonged period within the Superficial aquifer after pumping from the Leederville aquifer ceases, with more than half of the drawdown impact remaining after 15 years.

The magnitude of watertable decline in the Superficial aquifer is much less than the reduced potentiometric head in the underlying Leederville aquifer. In the shorter term this is due to the much higher volumes of groundwater released from storage per unit decline in the watertable (specific yield) in the unconfined Superficial aquifer under gravity drainage relative to that released from storage per unit decline in the potentiometric surface (storativity) of the Leederville aquifer as elastic storage. Specific yield of the Bassendean Sand is in the order of 0.15 while storativity for the Leederville Formation is around 0.0001. This relationship is, however, complicated by the leaky character of the Leederville aquifer. In the longer-term, vertical hydraulic conductivity of the confining units between the aquifers for a given hydraulic gradient is the most significant parameter controlling the degree of leakage from the watertable. Analysis using generalised modflow modelling showed that for a vertical hydraulic conductivity value of 0.0005 m/day as used for the Wanneroo Member in the Lake Nowergup area by PRAMS, the watertable drawdown may represent only about 1% of the reduced potentiometric head in the Leederville aquifer. If, however, the vertical hydraulic conductivity is doubled to 0.001 m/day, the long-term drawdown in the overlying Superficial aquifer increases to over 6%, demonstrating how sensitive impacts at the watertable are to the vertical hydraulic conductivity of the Leederville aquifer.

5.3.1 Summary of watertable impacts from reduced potentiometric head in the Leederville aquifer

- Pumping drawdown impacts within the Leederville aquifer propagate rapidly through the aquifer, but typically stabilise about 2 years after the commencement or increase in pumping;
- The watertable within the Superficial aquifer responds slowly to pumping from the underlying Leederville confined aquifer;
- The magnitude of watertable decline in the Superficial aquifer is much less than the reduced potentiometric head in the underlying Leederville aquifer due to the much higher specific yield of the unconfined Superficial aquifer relative to the confined elastic storage of the Leederville aquifer, and the relatively low vertical hydraulic conductivity between the two aquifers;
- For a vertical hydraulic conductivity value of 0.0005 m/day as used for the Wanneroo Member in the Lake Nowergup area by PRAMS, the watertable drawdown may represent only about 1% of the reduced potentiometric head in the Leederville aquifer, but this increases to over 6% if the vertical hydraulic conductivity is doubled to 0.001 m/day.

5.4 Water budgets and groundwater fluxes

5.4.1 Historical calculations of groundwater throughflow

Throughflow calculations have previously been undertaken for the coastal area including Lake Nowergup using Darcy's Law, although they have not been specifically determined for Lake Nowergup. Flownet analysis by Davidson (1995, Figure 27 and Table 13) using watertable levels from 1992 included Lake Nowergup as part of the southern Gnangara Mound flow system, falling within flow channel 1. Throughflow calculations presented in that publication determined throughflow across the 10 mAHD contour to be 49,750 m^3/day over a channel width of 14.6 km, equivalent to 3407 m^3/day per km. Proportioned over the lake width of 1300 m, this gives throughflow of 4429.1 m^3/day, or 1617.7 ML/year.

Flownet analysis based on 2012 groundwater levels undertaken as part of a resource assessment of the North West Coastal area (Water Corporation, 2014) calculated the inflow to the Tamala Limestone from the 4 mAHD watertable contour, effectively representing groundwater outflow from the coastal lake chain area. The study found that the watertable had declined equally within the Tamala Limestone and Bassendean Sand contact area over the period 2000 to 2002, so that the hydraulic gradient had not changed to any significant degree. Groundwater inflow to the Quinns Groundwater Sub-area was calculated to be 26,500 ML/yr along 11 km, which over the approximately 1300 m width of Lake Nowergup is equivalent to throughflow of 3132 ML/yr. This throughflow calculation should, however, over-state throughflow from the lake as it is calculated from the 4 mAHD contour that is about 1 km downgradient of the lake, and would therefore include groundwater recharge received over the intervening area. Recharge between the lake and 4 mAHD contour is probably about 200 ML/year (21% rainfall recharge), therefore approximate groundwater throughflow from these calculations would be about 2930 ML/year.

5.4.2 Throughflow calculations for 1989 and 2013

Groundwater throughflow for Lake Nowergup in 1989 and 2013 has been estimated in this report using Darcy's Law and water balance calculations over an area covering the lake of 715,000 m^2, extending 1300 m perpendicular to flow direction and 550 m along flow. Results are shown in Figure 5-19 and Figure 5-20.

The throughflow estimate for 1989 used the following inputs –

- A saturated thickness of the Superficial aquifer of about 46 m east of the lake and 41 m in the west. The full saturated thickness incorporates the Ascot Formation in the west as it is only in the east where its basal section is interpreted to be within the Leederville aquifer.
- Average hydraulic conductivity through the Superficial formations of 32 m/day, consistent with the Water Corporation's (2014) assessment.
- Lake area covered by water in 1989 of 285,060 m^2 over which there was 675.4 mm of rainfall and evaporation of 1746.4 mm using data for the relevant years. Outside the area with surface water, the land surface is a mixture of open woodland, pasture and exposed lake bed, where a groundwater recharge rate from rainfall of around 40% is deemed appropriate based on previous studies (Silberstein et al., 2004; Davidson and Yu, 2008).

- Hydraulic gradient east of the lake of about 0.007 based on groundwater elevation contours. There is a steep hydraulic gradient immediately west of the lake, which shallows progressively with increasing distance west of the lake.

From the above, groundwater throughflow entering the lake area in 1989 is calculated to be 4892.6 ML as displayed by Equation 5-1. Groundwater throughflow leaving the lake area to the west cannot be easily be calculated using Darcy's Law due to the uncertainty of the appropriate hydraulic conductivity for the aquifer in that area and rapidly changing hydraulic gradient away from the lake. The net water balance over the lake surface in 1989 is taken as the difference between rainfall and evaporation of 190.4 ML and incorporating this, groundwater outflow is estimated to be 4700.1 ML.

$$Q = K \; i \; A$$

Where: K (hydraulic conductivity) = 32 m/day
i (hydraulic gradient) = 0.007
A (cross-sectional area) = 1300 x 46

$$Q = 32 \times 0.007 \times (1300 \times 46)$$

$$= 13{,}395.2 \text{ m}^3\text{/day}$$

$$\Rightarrow 4892.6 \text{ ML/year}$$

Equation 5-1 Groundwater throughflow entering Lake Nowergup area, 1989.

By 2013 the watertable had declined, lake supplementation had been implemented, and the lake water surface area had reduced. The throughflow estimate for 2013 used the following inputs –

- Saturated thickness of the Superficial aquifer of 40 m east of the lake and 37 m in the west. This represented almost a 10% decrease since 1989.
- Average hydraulic conductivity through the Superficial formations of 32 m/day.
- Lake area covered by water in 2013 of 100,815 m^2, over which there was 785.8 mm of rainfall and evaporation of 2007.4 mm. Outside the area with surface water a groundwater recharge rate of 40% of rainfall.
- Lake supplementation over the 2013 calendar year of about 652 ML.
- Hydraulic gradient east of the lake of about 0.003 based on groundwater elevation contours. This is a decrease of about 60% from the 1989 hydraulic gradient which may largely be a result of lake supplementation causing a degree of water mounding about the lake.

From the above, groundwater throughflow entering the lake area in 2013 is calculated to be 1823.3 ML as displayed by Equation 5-2. This represents about 37% of throughflow estimated for 1989 and results from the combination of the reduced saturated aquifer thickness and lower hydraulic gradient. Reduced head in the Leederville aquifer causes a greater than 10-fold increase in downward leakage from the Superficial aquifer to the Leederville aquifer over the area. Groundwater outflow from the lake area of 2530.6 ML during 2013 is derived from the water flux balance.

$$Q = K\ i\ A$$

Where: K (hydraulic conductivity) = 32 m/day
i (hydraulic gradient) = 0.003
A (cross-sectional area) = 1300 x 40

$$Q = 32 \times 0.003 \times (1300 \times 40)$$

$$= 4992\ m^3/day$$

$$\Rightarrow 1823.3\ ML/year$$

Equation 5-2 Groundwater throughflow entering Lake Nowergup area, 2013.

A comparison of the various calculations of throughflow west from Lake Nowergup are summarised in Table 5-1, which includes results derived from PRAMS (v3.5) water balances for 1990-91 and 2012-13 across the boundary between the Nowergup and Quinns Groundwater Sub-areas, proportioned over the lake area. There is general agreement between the throughflow calculations herein with previous throughflow estimates for this part of the Superficial aquifer, even though some parameter assumptions are different and the point where the throughflow is calculated vary somewhat. The exception is from Davidson (1995), where a much lower rate for throughflow in 1992 was calculated, and results from a lower value for hydraulic conductivity used for the Superficial aquifer. Davidson (1995) used a hydraulic conductivity of 25 m/day compared to 32 m/day used by Water Corporation (2014), with balance of the difference attributed to a lower hydraulic gradient used by Davidson (1995) (not given). Overall, the evaluation of the data shows that a general decrease in throughflow between 1989 and 2013 has occurred in the Lake Nowergup area.

Table 5-1 Groundwater throughflow comparisons exiting westward from the Lake Nowergup area.

Source	This Study	PRAMS (v3.5)	Davidson (1995)	Water Corp (2014)	PRAMS (v3.5)	This Study
Year	1989	1990-91	1992	2012	2012-13	2013
Throughflow (ML/yr)	4700.1	3676.5	1617.7	2930	2503.8	2530.6

Leakage of groundwater downward from the Superficial aquifer into the Leederville aquifer is a small component of the groundwater fluxes at Lake Nowergup. Calculations use a vertical hydraulic conductivity of 5×10^{-4} m/day through the Wanneroo Member of the Leederville Formation (same as in PRAMS), with the Wanneroo Member possibly about 50 m thick beneath Lake Nowergup. The average head difference (including both areas of upward and downward hydraulic gradients) between the Superficial and Leederville aquifers was downward in both 1989 and 2013, being 1.3 m and 5.6 m respectively. From the base of the Wanneroo Member, this is equivalent to a downward hydraulic gradient of 0.026 in 1989 and 0.112 in 2013. Over the Lake Nowergup area of 715,000 m^2 used in the water budget calculations, this implies downward leakage of 3.4 ML during 1989 and 14.6 ML for 2013 from Darcy's Law, which is a very small component of the water budget. If the actual vertical hydraulic conductivity beneath the lake area is greater or less than adopted in PRAMS, then the groundwater leakage rate will also differ by the same proportion as the difference in hydraulic conductivity.

Although downward leakage is relatively small compared to other water fluxes through the area, the corresponding decline in groundwater levels resulting from this loss can be significant. This is due to the downward leakage occurring over a large area, resulting in depletion of groundwater stored in the Superficial aquifer. Depleting 14.6 ML/year of groundwater from the Superficial aquifer in the lake area is equivalent to a decline in the watertable of about 0.1 m/year, assuming a specific yield of 0.2.

5.4.3 Changes in the water budget 1990 - 2013

A summary of groundwater flux balances for 1990-91 and 2012-13 based on PRAMS v3.5 simulations are presented in Table 5-2 for each of the groundwater sub-areas in the study area. The significant changes evident between the two periods is a large decrease in groundwater flow passing from the Carabooda and Nowergup Groundwater Sub-areas to the Eglinton and Quinns Groundwater Sub-areas, and also much less groundwater passing to the coast from these coastal sub-areas. Groundwater depletion has actually reduced significantly between the two periods, mostly due to the higher rainfall and associated groundwater recharge in 2012-13 compared to 1990-91.

Table 5-2 Water flux budgets (GL) from PRAMS v3.5.

	Groundwater Sub-area						
	Reserve	Pinjar	Neerabup	Nowergup	Quinns	Carabooda	Eglinton
1990-91							
Recharge	49.2	-2.3	1.3	2.2	7.0	3.5	3.4
Flow In	36.2	13.6	5.4	12.2	37.3	20.2	23.6
Wells	-2.3	-1.8	-1.9	-1.3	-1.7	-3.9	-0.8
Flow Out	-141.5	-13.3	-8.9	-17.7	-42.7	-25.9	-29.3
Storage Change	-58.3	-3.7	-3.5	-4.6	-7.3	-6.1	-3.3
2012-13							
Recharge	77.9	1.6	3.3	3.4	15.0	4.4	5.2
Flow In	39.3	12.6	6.2	11.4	26.6	20.1	16.1
Wells	-1.9	-0.7	-2.5	-2.7	-15.6	-7.4	-2.1
Flow Out	-142.8	-14.5	-7.7	-12.5	-26.4	-17.1	-19.3
Storage Change	-27.4	-1.0	-0.8	-0.4	-0.2	-0.1	-0.1

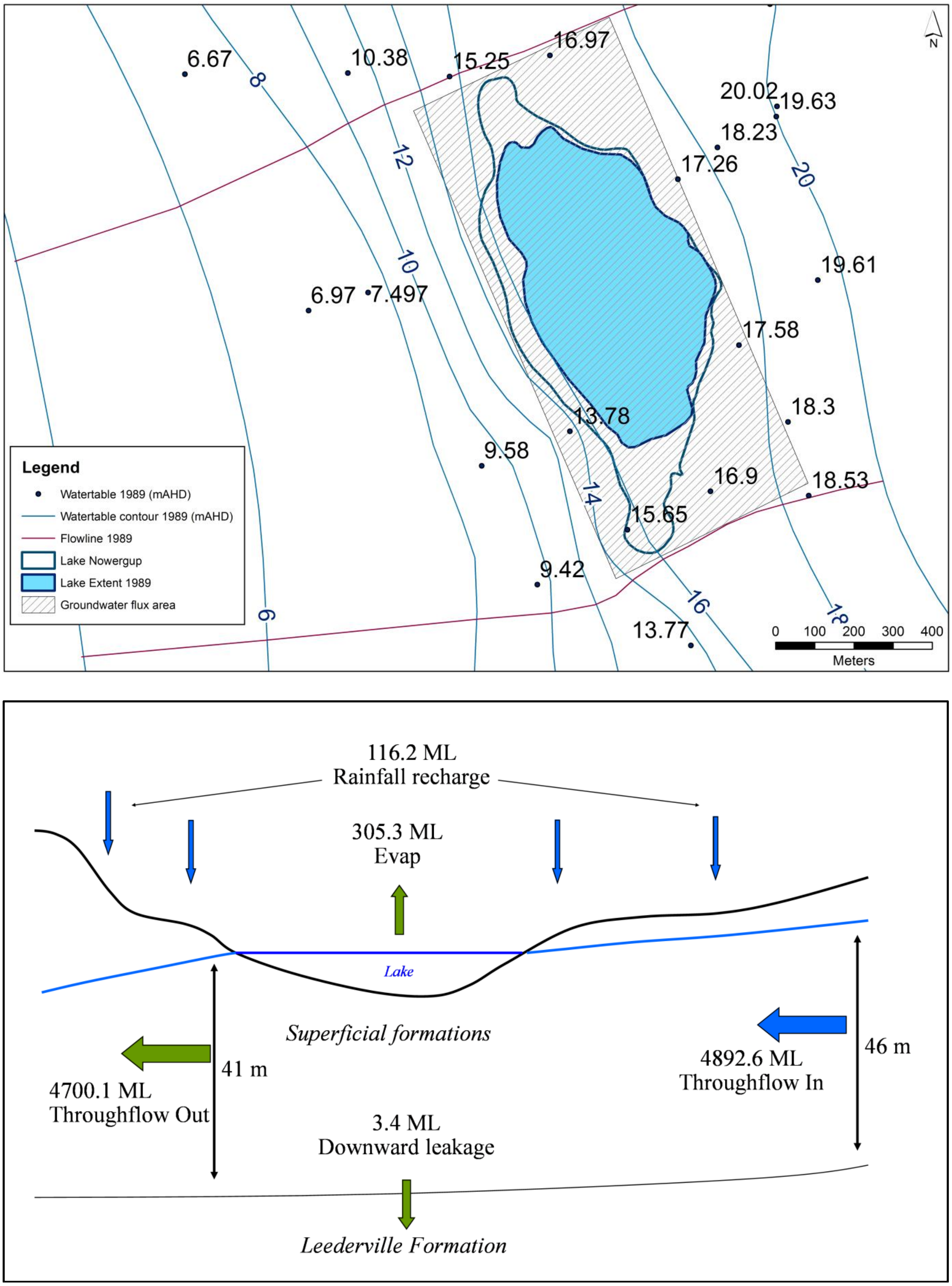


Figure 5-19 Calculated throughflow for Lake Nowergup - 1989 (ML/year)

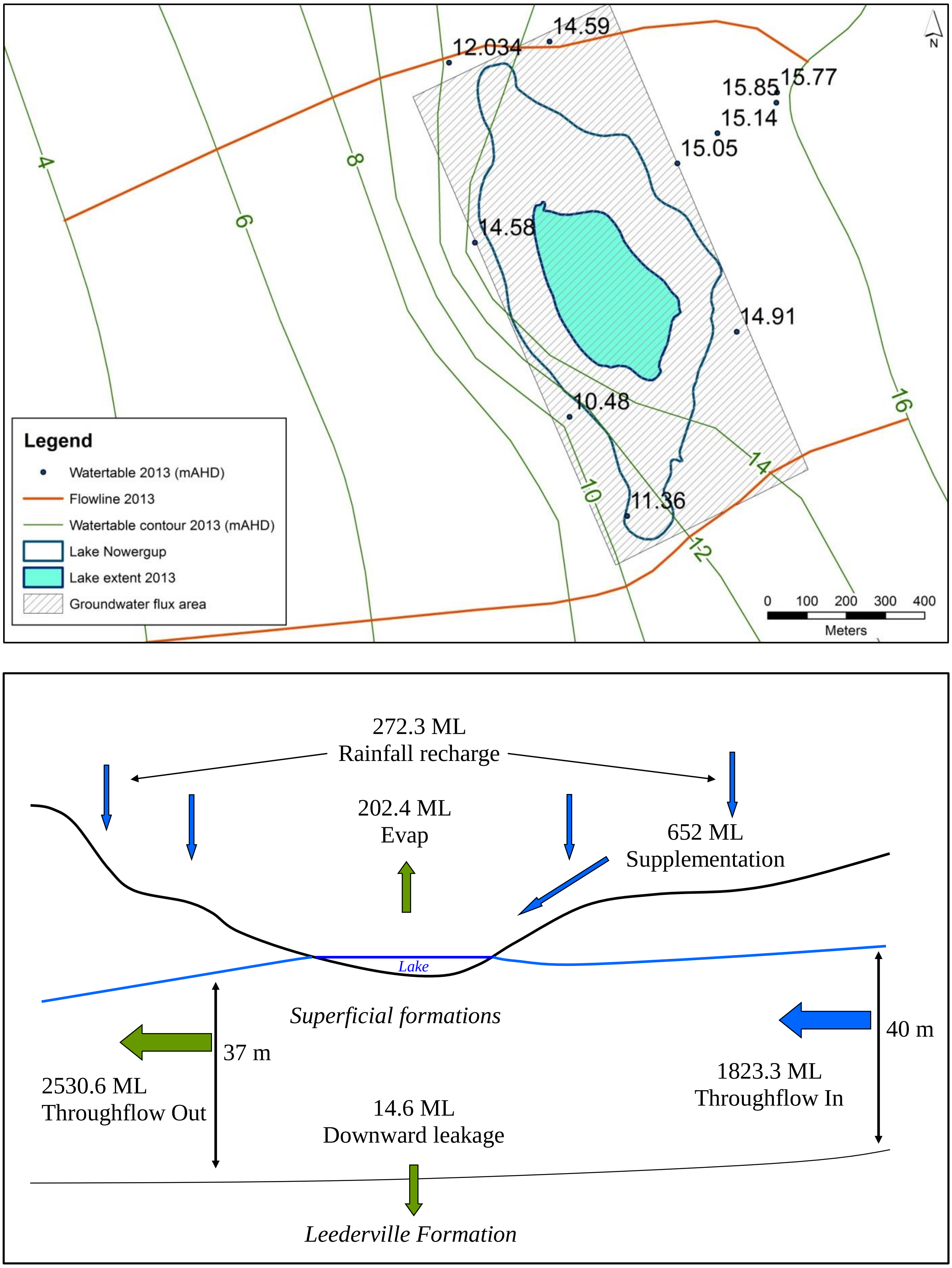


Figure 5-20 Calculated throughflow for Lake Nowergup - 2013 (ML/year)

5.4.4 Effectiveness of lake supplementation

As groundwater levels fall beneath the lake, the downward hydraulic gradient between the lake water body and the watertable increases, causing an increase in the rate of downward leakage from the lake. As the watertable below the lake declines, the rate of supplementation will need to increase to maintain the target lake water level. Failure to increase supplementation as the watertable falls causes a contraction of the lake area and declining lake water levels until the lake water balance components (rainfall + supplementation – evaporation) equate to the losses caused by the downward leakage. Without lake supplementation, lake water levels would have declined to approximately the level of the watertable in the underlying Superficial aquifer, which in 2014 would have been about 13.5 mAHD compared to current lake levels of around 14.5 to 15 mAHD (determined from air-photography and bathymetry).

Figure 5-21 shows the projected lake supplementation required to maintain lake water levels at around 16.2 mAHD. This is based on calculations using Darcy's Law, with a vertical hydraulic conductivity of 0.17 m/day (see Section 4.1.4) between the lake and upper half of the Superficial aquifer (about 20 m) with the 1989 lake extent of 285,060 m^2. The average deficit between rainfall and evaporation (1.269 m) is also incorporated. This demonstrates why earlier years of supplementation largely achieved maintenance of the desired lake levels and why in more recent years, particularly since 2010, desired lake levels have not been achieved even at similar rates of supplementation. At current watertable elevations of 13.5 to 14.5 mAHD, it is estimated that an average annual rate of lake supplementation of 2000 to 2700 ML will be required. This would increase to 4000 ML if the watertable declined to 12 mAHD.

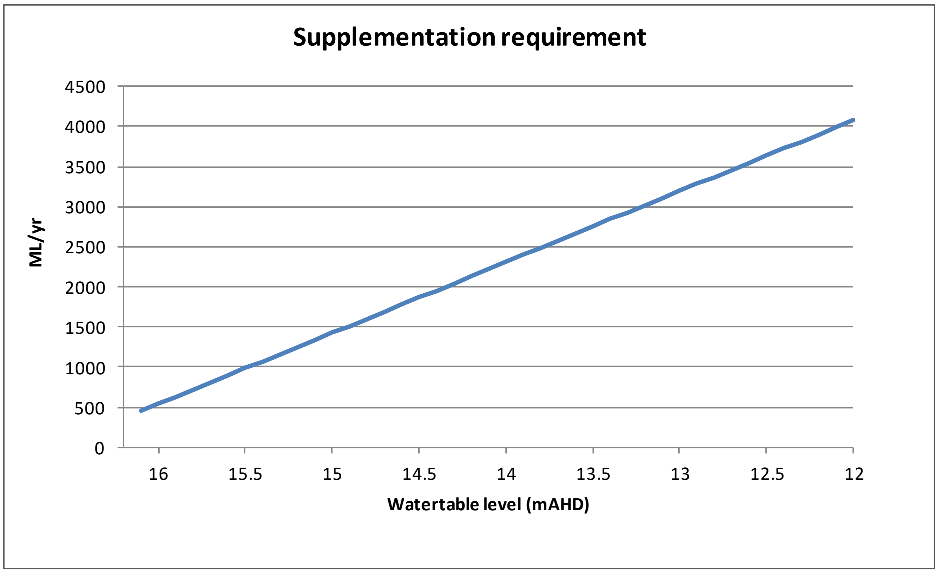


Figure 5-21 Approximate lake supplementation to maintain lake water levels above 16.2 mAHD.

5.4.5 Summary of water budgets and groundwater fluxes

Groundwater throughflow passing from Lake Nowergup:

- Historical calculations of groundwater throughflow have been made previously and by this study for the coastal plain area including Lake Nowergup using flownet analysis and from groundwater sub-area water budgets simulated by PRAMS;
- Various calculations of throughflow west from Lake Nowergup show that there has been a general decrease in throughflow between 1989 and 2013. An outlier calculation is for 1992 by Davidson (1995), who calculated a much lower throughflow as a result of adopting a lower value for hydraulic conductivity and hydraulic gradient for the Superficial aquifer;
- Groundwater throughflow calculations from Lake Nowergup made in this study across a 1300 m section perpendicular to the flow direction were 4700.1 ML in 1989 and 2530.6 ML in 2013.

The main changes in water budget between 1990-91 and 2012-13 based on PRAMS v3.5:

- There is a large decrease in groundwater flow passing down-gradient from the Carabooda and Nowergup Groundwater Sub-areas to the Eglinton and Quinns Groundwater Sub-areas;
- There is also much less groundwater passing to the coast from these coastal sub-areas.

Leakage of groundwater downward from the Superficial aquifer into the Leederville aquifer:

- Is a small component of the groundwater fluxes at Lake Nowergup;
- The decline in watertable levels resulting from the downward leakage can be significant, as the depletion of groundwater stored in the Superficial aquifer occurs over a large area. Depleting 14.6 ML/year of groundwater from the Superficial aquifer in the lake area is equivalent to a decline in the watertable of about 0.1 m/year.

Effectiveness of lake supplementation:

- Without lake supplementation, lake water levels would have declined to approximately the level of the watertable in the surrounding Superficial aquifer, and the lake would therefore have been almost totally dry by 2014;
- The rate of water leakage from the lake increases as groundwater levels fall beneath the lake, so that the rate of supplementation will need to increase to maintain the lake water level;
- To maintain lake water levels above 16.2 mAHD, it is estimated that an average annual rate of lake supplementation of 2000 to 2700 ML will be required at the current watertable elevation of 13.5 to 14.5 mAHD, and that this would increase to 4000 ML if the watertable declined to 12 mAHD.

6 Review of groundwater modelling

A review of numerical groundwater models that have incorporated the area of Lake Nowergup was commissioned for this study and conducted by WorleyParsons (WorleyParsons, 2015). The results of the review are summarised below.

6.1 Groundwater models

The Perth Urban Water Balance Study (PUWBS) (Cargeeg et al., 1987) created a large scale-model of the Perth region that was used to examine groundwater management options for Perth. It was a single layer saturated model of the Superficial formations. Groundwater recharge to the watertable was calculated using a Vertical Flux Model with three layers (zones). Interaction with the underlying Leederville Formation was simulated using leakage coefficients.

CSIRO (Townley et al., 1993) constructed a cross-sectional model of the Superficial Formation under Lake Pinjar and Lake Nowergup to the coast. The model was created to examine possible hydrogeological parameters that would allow a plume of evaporated water originating from Lake Pinjar to be detected at Lake Nowergup. It simulated a homogeneous anisotropic aquifer in steady-state. The results of the model showed that a high hydraulic conductivity anisotropy ratio (horizontal divided by vertical) and dispersivity ratio (longitudinal divided by transverse) were necessary in order to find the distinct signature of evaporated water observed at Lake Nowergup. This model is not considered further in this report due to its cross-sectional construction and as it simulates only the Superficial Formation.

Rust-PPK (1996a, b) developed the Perth Artesian Aquifer model for the confined aquifers under the Swan Coastal Plain. This was linked with the PUWBS model and called the Perth Groundwater Resource Model (Martinick McNulty, 1999).

The Perth Regional Aquifer Modelling System (PRAMS) (Davidson & Yu, 2008; CyMod Systems, 2009a, b; De Silva et al., 2013) was constructed to assist in development of sustainable groundwater management strategies for the Perth region. It includes a revised Vertical Flux Model, and simulates the Swan Coastal Plain aquifers from the Superficial Formation down to the Yarragadee Aquifer. The PRAMS model uses cell sizes of 500 m and consists of 13 layers. The PRAMS model replaced PUWBS and related models.

A local area model was constructed by Sinclair Knight Merz (SKM) (2009a, b) for the Lake Nowergup Area. It is derived from the PRAMS model and consists of 7 layers, with 5 layers for the Superficial Formation, 1 layer for the Kardinya Shale Member and 1 layer for the Leederville Formation. The number of layers for the Superficial Formation in the SKM model has increased to 5 from 3 relative to PRAMS (PRAMS v3.2, CyMod Systems, 2009b), and the number of layers for the Leederville Formation has decreased to 1 from 3. The surfaces for the Superficial Formation, Kardinya Shale and Leederville Formation have been obtained from the PRAMS model. The Kardinya Shale is included to the west of Lake Nowergup as previously interpreted by Davidson (1995), and modelled by the latest version of PRAMS (v3.5). The model consists of cells with dimensions of 50 x 50 m in the vicinity of the lake, and 100 x 100 m elsewhere.

PRAMS and the Lake Nowergup Local Area Model are reviewed in further detail below as they are the only current operational models relevant to the Lake Nowergup study.

6.2 Review of PRAMS

6.2.1 Model construction

The model encompasses the Swan Coastal Plain between Cervantes in the north to Mandurah in the south, from the Darling Fault in the east to the Vlaming sub-basin boundary/Badaminna Fault system off-shore in the west.

6.2.2 Parameterisation, boundary conditions and calibration

For this study, the parameter distributions from PRAMS v3.5 were extracted for layers 1 to 3 (Superficial Formation), 5 (Kardinya Shale) and 6 to 7 (Leederville Formation). Layer 4 represents the Mirrabooka and Rockingham aquifers which are absent in the Lake Nowergup area, and therefore not relevant to the study. These parameters were the horizontal and vertical hydraulic conductivity, specific storage, specific yield, aquifer top and aquifer thickness. These are coarse representations appropriate for a regional model. The parameters are varied across the area within each layer by using zonations.

The boundary conditions for the PRAMS model are no-flow on the northern, eastern and southern sides of the model. In the west the head is specified as 0.5 mAHD at and beyond the coast in Layer 1, and in Layer 5 at the offshore fault. Vertical hydraulic conductivity is increased in the aquitard layers (5, 9, 10 and 11) at this fault.

The calibration of the PRAMS model is an ongoing process as more information on hydrogeology becomes available. The initial model (PRAMS 3.0, CyMod Systems, 2009a) presented the calibration results as a predicted versus observed head plot, a table with average and maximum error bounds and a figure with the distribution of residuals at October 1992. The initial revision (PRAMS 3.2, CyMod Systems, 2009b) improved the calibration for the Superficial and Leederville Formations, presenting the new results with the distribution of remainders using an average for the year 1999. PRAMS v3.5 (De Silva et al., 2013) was updated further with a focus on the confined aquifer systems. It presented comparisons of simulated and observed hydrographs for a number of bores including Bore AM20A in the Leederville Formation near Lake Nowergup. It shows that the modelled heads are consistently around 1 to 3 m below the observed levels, but the model adequately simulates the seasonal fluctuations and trends.

6.2.3 Limitations

PRAMS is a very large model designed to simulate the regional groundwater system. Consequently, it has a coarse discretisation and takes a considerable time to run. As such, smaller-scale hydrogeological features are not included within the model. As the properties between cells in the simulation procedure are averaged, at least 3 adjacent cells (layers) are required to represent low hydraulic conductivity features. Thus the minimum size to include a horizontal, low hydraulic conductivity area in the PRAMS model is 1.5 km.

6.2.4 Summary

The PRAMS model is suitable for examining broad aspects of pumping impacts in the Lake Nowergup area, but the results will be approximate. Local areas of low permeability within the Superficial aquifer, such as the clayey sand facies of the Tamala Limestone, and clay layers in the lower Ascot Formation, are not incorporated due to cell size. This will compromise the accuracy of simulated water levels about Lake Nowergup.

6.3 Review of Lake Nowergup Local Area Model

6.3.1 Model construction

The Lake Nowergup Local Area Model (or SKM model) extends from the coast in the west to east of Lake Pinjar, and between flow lines approximately 5 km north and south of Lake Nowergup. Extent of the model is shown by Figure 6-1. The Superficial formations are divided into 5 layers within the model. These were the two lower layers from the PRAMS model representing the Superficial aquifer, with the upper layer of the PRAMS model subdivided to include an upper surficial layer (1 m thick) for the lake boundary condition, and two aquifer layers. No reason is given for the use of two layers but it is suspected it is used for greater precision in simulating groundwater flow in the vicinity of Lake Nowergup.

Figure 6-1 Area of SKM Lake Nowergup Local Area Model (Figure 9 from SKM, 2009a).

6.3.2 Parameterisation, boundary conditions and calibration

The parameterisation of the model consists of 9 zones in the Superficial Formation (3 for Tamala Limestone and 6 for Bassendean Sand), 2 zones for Kardinya Shale, with a third zone in the Kardinya Shale layer where the Kardinya Shale is absent, and a single zone for the Leederville Formation. All layers in the Superficial formations have the same parameter zonations. No basis is given for the parameter zone distribution in the Superficial formations or Kardinya Shale. Table 6-1 presents the parameter values used in the calibrated model, and Figure 6-2 shows the distribution of hydraulic conductivity parameters for the Superficial aquifer layers.

Boundary conditions used in the model included a general head on the eastern boundary with a specified head of 51 mAHD and a conductance of 1000 m/day. The western boundary used a specified head of 0 mAHD to represent the coast in the Superficial formations. The southern and northern boundaries were assumed to be parallel to groundwater flow lines and thus were no-flow boundaries. No outlet was specified in the west for the Leederville Formation or Kardinya Shale layers.

Pumping from public water-supply bores is metered, while licensed private bores have only recently been metered and pumping from unlicensed bores is not metered. The assumption in the SKM model is that 40% of the licensed allocation is removed from the aquifer. No pumping was assigned for unlicensed bores, but as urbanisation has only recently occurred within the model domain, this was a reasonable assumption for the calibration period. It is noted that unlicensed pumping in urban areas may be part of the recharge and evapotranspiration multipliers discussed below.

A potential concern with the model was that pumping may be located too close to northern and southern no-flow boundaries, and thus overestimate the drawdown. However, examination of the piezometric heads within the calibration period showed contours almost perpendicular to these boundaries, and therefore the northern and southern no-flow boundaries did not significantly impact the drawdown simulations.

The Vertical Flux Model used in PRAMS was replaced by recharge and evapotranspiration rates associated with different land uses. Ten different land uses were identified, although transition between different land uses at different times increased the number of recharge and evaporation zones to 24. The extinction depth for evapotranspiration for all zones was set to 2 m below the ground surface.

The calibration was undertaken by manual variation of the hydraulic conductivity, recharge and evapotranspiration multipliers. The storage parameters (specific storage and specific yield) may also have been varied but are not mentioned in the text of the SKM model report. For the Superficial aquifer, comparisons between the observed and simulated water levels were good for both absolute levels of water levels and their variation over time. However the horizontal and vertical hydraulic conductivity (0.015 m/day for both) for the zone immediately west of Lake Nowergup (Zone 14) is extremely low. This may be an artefact introduced into the model to simulate the steep fall in the watertable west of Lake Nowergup. The use of a 2 m extinction depth for the evapotranspiration for the whole domain is incompatible with deep-rooted vegetation in parts of the domain. As the land use is zoned for both recharge and evapotranspiration, it would be relatively simple to include a deeper extinction depth for mature pine plantations and banksia forest or other parts of the domain where greater extinction depths may be warranted.

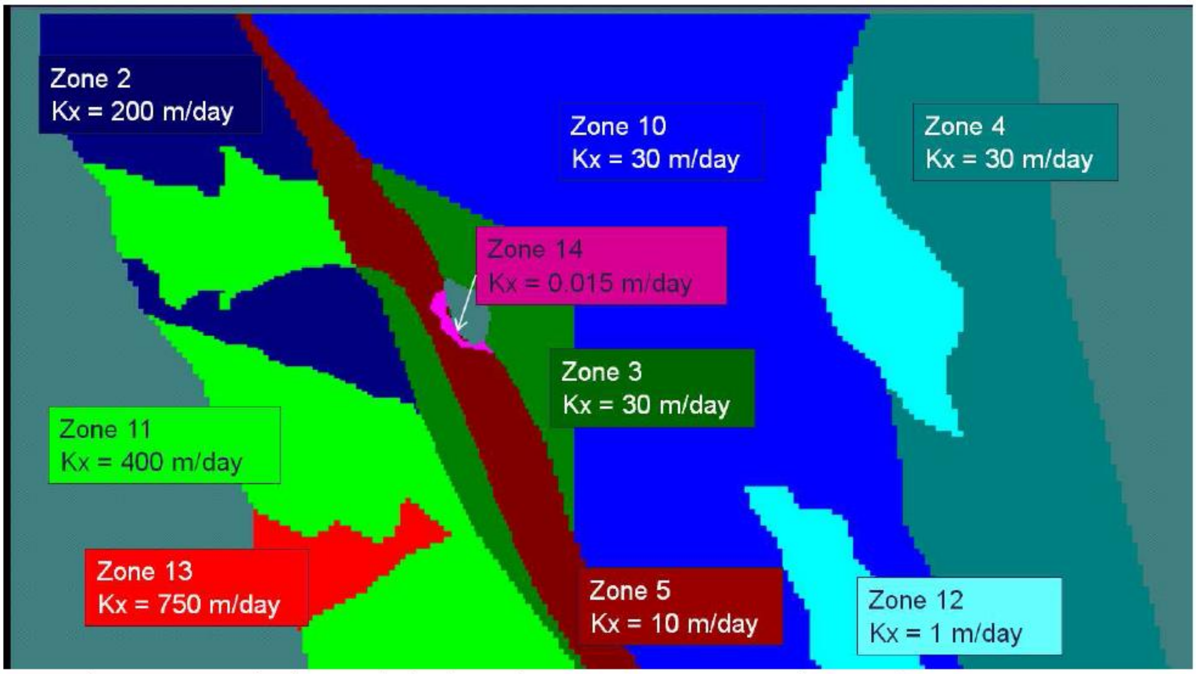
There was a poor match between observed and simulated potentiometric heads in the Leederville aquifer. A concerning aspect is that the model predicts potentiometric heads in the southwestern part of the Leederville aquifer adjacent to the coast declining to below 0 mAHD after 1998. There are no observation bores within the Leederville Formation in this vicinity to check this result.

A sensitivity analysis undertaken by SKM multiplied hydrogeological parameters (hydraulic conductivity, specific yield and recharge) until the simulated heads for the calibration period resulted in the simulation exceeding a calibration measure. This resulted in an upper and lower bound (multiplier) for the parameter. No description is available of whether individual zonal parameters were modified or whether the multiplier was applied across all zones. It is suspected that the latter occurred. Similarly, it is not known whether vertical hydraulic conductivity was varied along with the horizontal hydraulic conductivity. The sensitivity analysis found that the model became unstable for increased hydraulic conductivity and it was hypothesised that this occurred due to the large change in the hydraulic conductivity at the contact between the Bassendean Sand and Tamala Limestone.

Table 6-1 Calibrated hydraulic parameter values for zones in the SKM Lake Nowergup Local Area Model (Table 6-3 from SKM, 2009a).

Property Zone	Aquifer Represented	Kx	Ky	Kz	Specific Storage Ss (m^{-1})	Specific Yield Sy	Effective Porosity	Total Porosity
Superficial Aquifers – Layers 1 through 5								
Zone 2	Tamala Limestone	200	200	20	0.0005	0.25	0.2	0.35
Zone 3	Bassendean Sand/Gnangara Sand	30	30	3	0.0005	0.25	0.2	0.35
Zone 4	Bassendean Sand/Gnangara Sand	30	30	3	$5x10^{-5}$	0.2	0.15	0.3
Zone 5	Bassendean Sand/Gnangara Sand	10	10	1	$5x10^{-5}$	0.2	0.15	0.3
Zone 10	Bassendean Sand/Gnangara Sand	30	30	3	$5x10^{-5}$	0.2	0.15	0.3
Zone 11	Tamala Limestone	400	400	40	$5x10^{-5}$	0.25	0.2	0.35
Zone 12	Bassendean Sand/Gnangara Sand	1	1	0.1	$5x10^{-5}$	0.2	0.15	0.3
Zone 13	Tamala Limestone	750	750	75	$5x10^{-5}$	0.25	0.2	0.35
Zone 14	Bassendean Sand/Gnangara Sand	0.015	0.015	0.015	$5x10^{-5}$	0.2	0.15	0.3
Osborne Formation – Layer 6								
Zone 6	Kardinya Shale	0.005	0.005	0.0015	$1x10^{-6}$	0.2	0.15	0.3
Zone 7	Kardinya Shale	2	2	0.0015	$1x10^{-6}$	0.2	0.15	0.3
Zone 8	Nominal thickness where Kardinya Shale is absent	8	8	0.8	$1x10^{-6}$	0.2	0.1	0.25
Leederville Aquifer – Layer 7								
Zone 9	Leederville Aquifer	1.5	1.5	1.5	$1x10^{-6}$	0.2	0.1	0.25

Note there is no zone 1 in the model (purely a chance artefact of the calibration process



Note: In all zones Ky = Kx and Kz is one tenth of Kx (except for Zone 14 where Kx = 0.0015 and Kz = 0.015)

Figure 6-2 Hydraulic conductivity distribution for the Superficial aquifer – Layers 1 to 5 (Figure 29 from SKM, 2009a).

6.3.3 Limitations

There are a number differences between how boundary conditions are represented in the SKM model and PRAMS, and inconsistencies with latest Australian Groundwater Modelling Guidelines (AGMG) (Barnett et al., 2012), which were published after the model was constructed.

The western boundary of the model is inconsistent with the PRAMS model. The SKM model extends only as far as the coast and specifies the head at the coast of 0.0 mAHD for the whole Superficial aquifer. It is recommended that the model be extended seaward to the Badaminna Fault, and that the approach taken by PRAMS is adopted where an equivalent head of 0.5 mAHD is used in the top-most aquifer layer over the coastal cells.

The use of a constant head of 51 mAHD as part of the general head boundary on the eastern boundary may need to be reconsidered. As the boundary is distant to the areas of interest in the model, a seasonal variation in the head is probably not needed but, long-term trends (declining watertable and piezometric heads within the Leederville Formation) should be included.

The vertical representation of the Kardinya Shale should be refined, or adapted for the Pinjar Member. Current practice, as recommended by the AGMG (Barnett et al., 2012), is to use three layers in a groundwater model to represent an aquitard to avoid averaging out low vertical hydraulic conductivities within models. It could also include a high vertical hydraulic conductivity zone at the western boundary to simulate the Badaminna Fault similar to PRAMS. It is noted that the PRAMS model uses high anisotropy in the Leederville Formation with a high horizontal conductivity of up to 8 m/day, and a vertical hydraulic conductivity of $1x10^{-4}$ m/day, while the SKM model uses the same value of 1.5 m/day for both horizontal and vertical hydraulic conductivity. The use of a low vertical hydraulic conductivity for the Leederville Formation where it is overlain by Kardinya Shale would preclude the need to increase the number of layers of the Kardinya Shale.

The model uses different zones to represent various hydrogeological properties in the Superficial formations, but the zonations used for vertical hydraulic conductivity are the same as used for the horizontal parameters. A reassessment of the hydrogeology in the vicinity of Lake Nowergup in this study has found that the Superficial formations contain vertical zones that could be represented by the model layers for better parameterisation of the aquifer. At the base of the Superficial formations, the Ascot Formation may have a high horizontal hydraulic conductivity, but clay layers toward the base probably create an interval of lower vertical hydraulic conductivity. Also, the clayey sand facies of the Tamala Limestone identified west of, and underlying the lake, which corresponds to the steep groundwater gradient in the Superficial formations is important and could be better represented.

Observations at two selected bores located at a distance from Lake Nowergup and not included in the presented calibration results are compared with the simulated results to verify model performance away from the effect of lake supplementation. Figure 6-3 compares the observed and simulated responses at bore PM33, located within the Superficial formations approximately 1.3 km southeast of Lake Nowergup. Apart from an initial 1 m head difference, it shows a close match between the simulated and observed hydrographs, giving confidence in the model for this area for the Superficial aquifer. Figure 6-4 compares the response at bore AM20A in the Leederville Formation approximately 2 km northwest of the lake. This shows a major difference between the observed and simulated responses. The initial heads used in the simulation are approximately 9 m below observed levels, and the response to the commissioning of the Quinns borefield Leederville production bores from 1999 (Figure 35, SKM, 2009a) is very muted compared to the observed heads and those simulated using PRAMS (Figure 45, De Silva et al., 2013). Possible deficiencies in the SKM model related to this include the vertical representation of the Kardinya Shale mentioned above and the low value of the horizontal hydraulic conductivity of 1.5 m/day in the SKM model compared to the 8 m/day in the PRAMS model.

The specific storage used in the SKM model for the Leederville Formation ($1x10^{-6}m^{-1}$) is smaller than the value used for the PRAMS model ($4x10^{-6}m^{-1}$ for layer 6 and $3x10^{-6}m^{-1}$ for layer 7). This may have contributed to the low piezometric heads simulated in the southwest adjacent to the coast in the Leederville Formation.

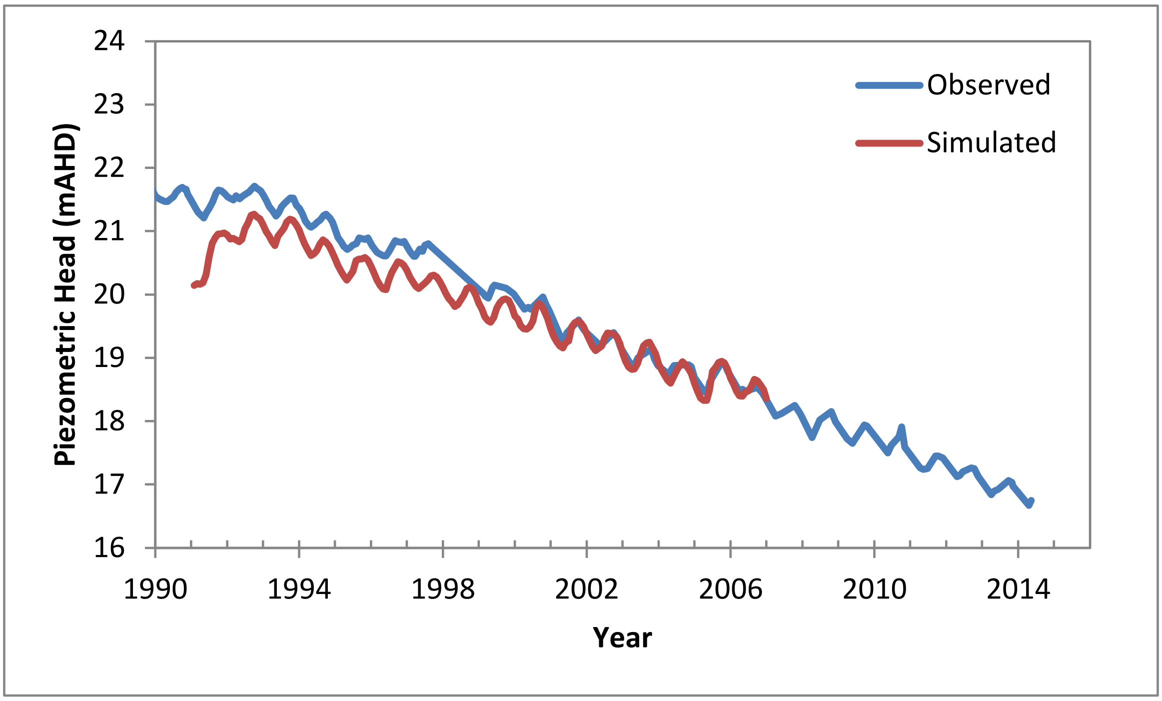


Figure 6-3 Observed and simulated head - Bore PM33, Superficial formations.

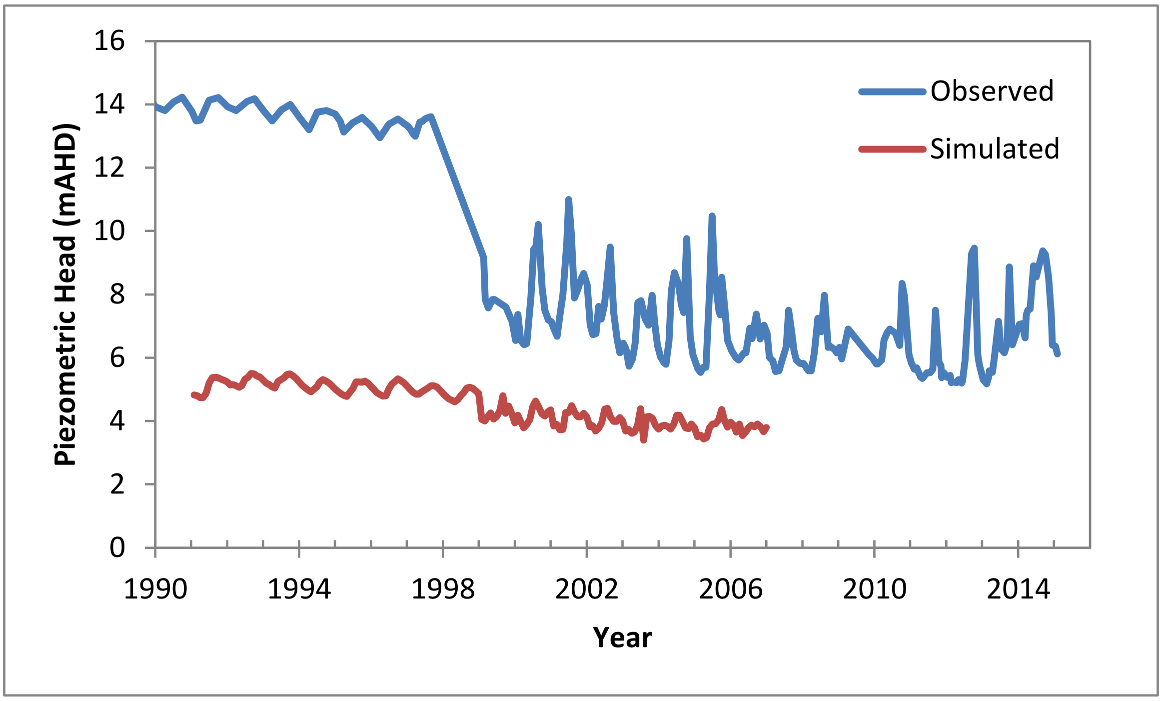


Figure 6-4 Observed and simulated head - Bore AM20A, Leederville Formation.

6.3.4 Summary

Due to deficiencies mostly in modelling of the Leederville aquifer, the SKM Lake Nowergup Local Area Model is considered inadequate for simulations involving pumping from the Leederville aquifer without further work. The model may also require some modifications within the Superficial formations to reflect the revised hydrogeology in the vicinity of Lake

Nowergup. Following these modifications, the model should then be suitable for creating model scenarios to apportion drawdown to various pumping sources within the Superficial aquifer.

7 Evaluation of factors impacting the watertable at Lake Nowergup

Hydrographs from observation data show the changes in groundwater levels beneath the coastal plain about Lake Nowergup, but it is not clear to what extent an activity or environmental factor is responsible for the changes. Associations from analysis of hydrographs can only be made on a comparison of timing (e.g. commencement of pumping, start of a drying period etc.) and the proximity of Lake Nowergup to activities that could impact water levels. To aid in assessing the relative importance of each factor contributing to the watertable decline observed at the lake, several different methods have been employed:

- Distance drawdown calculations,
- HARTT analysis,
- PRAMS verification scenarios,
- Schematic Modflow simulations.

7.1 Cooper – Jacob distance-drawdown; Leederville aquifer

Calculations of the drawdown propagating outward from the production bores within the Leederville aquifer can be made using the distance – drawdown method developed by Cooper and Jacob (1946). This method is applicable to horizontally isotropic confined aquifers. The Cooper – Jacob distance-drawdown solution is given by Equation 7-1. Assumptions include that:

- The aquifer is homogeneous, isotropic, and of uniform thickness,
- The aquifer is infinite in extent,
- The aquifer is confined,
- All storage is derived from aquifer storativity, and is isolated from leakage and other recharge sources.

$$s = \frac{2.3\,Q}{4\pi KD} \log \frac{2.25KDt}{r^2S}$$

Where:
S = drawdown (m)
Q = volume pumped (m^3/day)
KD = transmissivity of aquifer (m^2/day)
r = radius (m)
S = storativity of aquifer

Equation 7-1 Cooper - Jacob distance-drawdown solution.

Clearly, conditions in the Leederville aquifer do not meet the required assumptions. The most significant for these calculations is that the Leederville aquifer is a leaky system, with interchange of groundwater with the overlying Superficial aquifer being significant where the

Kardinya Shale or Pinjar Member is absent. Groundwater leakage will have the effect of attenuating the drawdown cone within the Leederville aquifer emanating from the pumping bores, so that the distance drawdown calculations will significantly over state the degree of potentiometric head decline, and this will become more significant with greater distances from the pumping bore. Calculations are, however, useful in identifying which production bores have the greatest potential to result in reduced potentiometric heads in the aquifer below Lake Nowergup.

Table 7-1 presents parameters for each production bore in the Leederville aquifer used in the Cooper – Jacob Solution, and are based on the PRAMS parameters for layer 7 representing the Leederville Formation Wanneroo Member. A transmissivity value is used which is the average of that at the lake (800 m^2/day) and that at the production bore. The same approach is used for storativity, where the value at the lake is 3 x 10^{-4}. Calculations are made for the period of 1989 to 2013 (5479 days).

From the Cooper – Jacob Solution, the total calculated drawdown at Lake Nowergup resulting from the superimposition of all the Leederville production bores in the Pinjar and Quinns borefields is 18.9 m. This drawdown is almost double that believed to have occurred within the Leederville aquifer (10 m) beneath the lake since 1989. The calculation is however useful in that it establishes an upper limit for the drawdown of potentiometric heads that could occur within the Leederville aquifer in response to the groundwater pumping from this aquifer.

From the calculations, it is evident that production bores Q145 and Q205 in the Quinns borefield have the greatest potential to cause drawdown within the Leederville aquifer beneath the lake. This is principally due to their closer proximity to the lake and higher pumping rates from these bores. The potential for drawdown impacts at the lake from bore Q205 may be greatest as most of the area between the bore and lake has the Pinjar Member of the Leederville Formation present between the Wanneroo Member and Superficial aquifer. The Pinjar Member is a finer-grained and lower permeability unit that would create more confined conditions, thus allowing greater propagation of drawdown toward the lake.

Table 7-1 Calculated drawdown in the Leederville aquifer beneath Lake Nowergup for pumping of Pinjar and Quinns borefield Leederville aquifer bores over 1989 - 2013 (5479 days) using Cooper - Jacob distance-drawdown.

Bore	r (m)	Q (m^3/d)	KD (m^2/day)	S	Drawdown (m) beneath lake
P25	9700	4154	760	0.00033	2.48
P65	8375	3133	776	0.00029	1.97
P105	9785	4115	624	0.00023	3.06
Q145	4420	6458	880	0.00033	4.33
Q155	5815	2220	880	0.00033	1.38
Q165	5405	2216	880	0.00033	1.34
Q205	3740	6848	972	0.00036	4.35

Note: r = radius, Q = pumping rate, KD = transmissivity, S = aquifer storativity

7.2 Estimation of drawdown using schematic Modflow simulations

7.2.1 Model construction

A schematic groundwater model utilising Modflow has been developed to evaluate the relative impact on groundwater levels at Lake Nowergup resulting from various groundwater pumping activities. Interactions between Lake Nowergup and groundwater are not simulated. This modelling approach is intended as an alternative method for establishing the likely magnitude of water level declines in the area of the lake rather than as an accurate representation of actual water levels. The Superficial and Leederville aquifers are each represented by a model layer (layers 1 and 2), utilising hydraulic parameters from the current version of PRAMS (v3.5). At Lake Nowergup, values for horizontal hydraulic conductivity of 40 m/day and 8 m/day were used for Layers 1 and 2 respectively. Vertical hydraulic conductivity was set at 2 m/day for Layer 1 and 0.0005 m/day for Layer 2, as used in PRAMS for the corresponding aquifers. No additional calibration has been undertaken.

The model grid, shown by Figure 7-1, extends well outside of the main study area to minimise boundary effects for pumping simulations, with the mesh cell size refined down to 250 x 250 m at Lake Nowergup, allowing resolution of hydrogeological units down to 750 m width. Boundary conditions for Layer 1 representing the Superficial aquifer comprise constant heads at the eastern margin of the model and at the coast. Layer 2 for the Leederville aquifer has constant heads off-shore at the western margin of the model grid, but a no-flow boundary at its eastern limit. These boundary conditions are consistent with that used in PRAMS.

Layer 2 represents the Wanneroo Member of the Leederville Formation, which comprises the most transmissive part of the Leederville aquifer. The Pinjar Member in the upper Leederville Formation is absent at the lake, while the deeper Mariginiup Member has a significantly lower permeability and is omitted. Kardinya Shale forms an aquitard present between the Superficial and Leederville aquifers in the western and southern portions of the model, but is not represented directly by a model layer. Instead, the influence of the aquitard is represented in the model by applying the vertical hydraulic conductivity (5×10^{-5} m/day) used in PRAMS to Layer 2 for the areas of Kardinya Shale. Although the Kardinya Shale is now considered absent west of the lake, these parameters can effectively represent the Pinjar Member of the Leederville Formation.

Groundwater recharge is applied to the model to allow for some attenuation of drawdown over larger distances, as would be expected in reality. A recharge rate equivalent to 21% of rainfall is applied over the model area to the Superficial aquifer (Layer 1), which is consistent with the average model recharge used in PRAMS. The average rainfall from 1989 to 2013 was 724 mm, and therefore the average annual recharge used is 152 mm, or about 0.416 mm per day. This recharge has been kept constant for all time-steps in transient simulations, and therefore does not simulate the effect of rainfall variability between years.

To test the effect that a zone of low hydraulic conductivity within the Superficial aquifer immediately west of Lake Nowergup will have on simulated pumping impacts, a model version has also been used incorporating this feature. A lower hydraulic conductivity zone in the Superficial aquifer of 10.9 m/day derived from throughflow calculations (see Section 4.1.4) is tested for an area 1 km wide extending north – south along the coastal plain.

7.2.2 Model scenarios

Scenarios simulated by the model are:

- Public pumping from the Pinjar and Quinns borefields, including both Superficial and Leederville aquifers – each of the borefields has been simulated separately. Simulations of the Quinns Leederville borefield include Whitfords Leederville production bores WT15 and WT45 adjacent to the southern boundary. Recent reduction in pumping from the Pinjar and Quinns borefields has been incorporated in the transient simulations;
- Private pumping in the Carabooda and Nowergup Groundwater Sub-areas for allocations of 100 ML and greater, which represent about 80% of total allocations in the Carabooda Groundwater Sub-area, and 62% in the Nowergup Groundwater Sub-area (this was a simplification to avoid the large number of small allocations through these areas);
- Pumping from the supplementation bore 2/00 within the Leederville aquifer adjacent to Lake Nowergup.

Both steady-state and transient simulations were run to represent the predicted final drawdown and the progressive drawdown to date. For the steady-state simulations a daily average pumping rate since commissioning of the bores has been used. The transient simulations use annual production rates averaged as daily rates for individual bores, and are run from 1989 to 2013 inclusive (25 years) with stress periods of 1 year duration with 4 time steps.

As pumping data are not available for private production, the licensed water allocations have been used as an approximation. Recent analysis of metered bores by DoW (2013 BEAD data provided by DoW) in these sub-areas suggest that groundwater pumping exceeds the allocated volumes by around 10% to 20%. However, this may be countered by approximately 20% of the water irrigated percolating back to the watertable, as estimated by previous studies (Davidson, 1995; Cymod, 2009a). Private pumping would have been less than the allocated licenses for much of the simulated period as the entitlements were progressively utilised for new or expanded irrigated developments, possibly approaching around the full entitlement within about the last 10 years. Consequently, the transient simulations would exaggerate drawdown in the earlier stages.

Results from the simulations are summarised in Table 7-2, which presents the watertable decline for a model cell in Layer 1 located on the lake. The table includes a drawdown for each scenario from the steady-state simulation and the final transient stress period time step. A plot of transient drawdown at the lake for Layer 1 is shown by Figure 7-2. Transient drawdown in the Leederville aquifer (Layer 2) in response to groundwater pumping from the aquifer (Pinjar Leederville, Quinns Leederville and supplementation bore 2/00) is presented in Figure 7-3. Simulated drawdown in Layer 1 at the lake is also presented in Table 7-3 for the model version using the zone of low hydraulic conductivity in the Superficial aquifer just to the west.

Table 7-2 Simulated watertable decline (m) for Layer 1, Lake Nowergup.

Scenario	Steady-state	Transient
Superficial aquifer pumping		
Public – Pinjar	0.43	0.26
Public – Quinns	0.20	0.20
Private – Carabooda	0.97	0.89
Private – Nowergup	0.89	0.91
Leederville aquifer pumping		
Public – Pinjar	0.43	0.27
Public – Quinns	0.52	0.28
Supplementation bore 2/00	0.07	0.05
Total	*3.51*	*2.86*

Notes: Steady-state – is the simulated drawdown that would result long-term once conditions reach an equilibrium, and therefore represents the final levels;
Transient – is the drawdown resulting over the simulation period, and therefore represent levels at a specific point in time.

Table 7-3 Simulated watertable decline (m) for Layer 1, Lake Nowergup – using low hydraulic conductivity zone.

Scenario	Steady-state	Transient
Superficial aquifer pumping		
Public – Pinjar	0.60	0.37
Public – Quinns	0.16	0.15
Private – Carabooda	1.3	1.11
Private – Nowergup	1.2	1.21
Leederville aquifer pumping		
Public – Pinjar	0.63	0.36
Public – Quinns	0.73	0.37
Supplementation bore 2/00	0.10	0.07
Total	*4.72*	*3.64*

Model simulation results using a zone of low hydraulic conductivity in the Superficial aquifer immediately west of Lake Nowergup produce water levels and drawdown that are much closer to those observed in the Lake Nowergup area. It demonstrates that this low hydraulic conductivity zone is important in the simulation of water levels in the Superficial aquifer about the lake and has a significant influence on the drawdown impact from pumping. There is a marked increase in drawdown simulated resulting from pumping in the Nowergup, Carabooda and Pinjar areas from those indicated using PRAMS hydraulic parameters without the low hydraulic conductivity zone. Due to the apparent better representation of the Superficial aquifer by this model version, the impacts simulated are considered to probably be more indicative of what will occur. It is concluded that simulation results from the PRAMS groundwater model probably under-predict drawdown in the Superficial aquifer about the coastal chain of lakes resulting from pumping groundwater from the Superficial and Leederville aquifers east of this area.

7.2.3 Simulated drawdown in the Superficial aquifer

The total simulated steady-state drawdown at Lake Nowergup is 3.51 m, while the final drawdown for transient conditions, approximately representing current conditions, is 2.86 m.

This implies that the present drawdown in watertable levels (transient drawdown) represent over 81% of the long-term total (steady-state) that would be expected from the historical pumping regime. The model version using the low hydraulic conductivity zone gives larger drawdown values, with 4.72 m and 3.64 m for the steady-state and transient simulations respectively. In addition to these simulations, a steady-state simulation was run for Leederville production bores in the Wanneroo borefield, which yielded a drawdown at the lake of about 0.1 m, while the final transient drawdown was just under 0.1 m (0.06 m and 0.09 m for each model version).

Model results suggest that the largest contributor to drawdown in the Superficial aquifer at the lake has been from pumping of private groundwater allocations from the Superficial aquifer in the Nowergup and Carabooda Groundwater Sub-areas, followed by drawdown from the Leederville production bores of the Pinjar and Quinns borefields, and Superficial production bores of the Pinjar borefield. Final transient water levels resulting from private pumping are approaching the simulated steady-state levels, indicating that the watertable decline resulting from this pumping is probably close to equilibrium and that there may be only limited additional drawdown resulting from this pumping if the discharge rates remain relatively constant, although the alternative model using a low hydraulic conductivity zone west of the lake suggests another 0.2 m decline may eventuate. As the model has only included private allocations of 100 ML/year and greater, the simulated drawdown will be conservative. Proportioning the simulated drawdown for the full allocations in the sub-areas suggests steady-state drawdown levels of about 1.2 m and 1.4 m respectively for Carabooda and Nowergup Groundwater Sub-areas. For the low hydraulic conductivity zone model version, this is 1.6 m and almost 1.9 m for Carabooda and Nowergup Groundwater Sub-areas respectively. For the transient simulations, the drawdown at 2013 proportioned for full allocations is 1.4 m and 1.9 m for the Carabooda and Nowergup Groundwater Sub-areas, for a total of 3.3 m.

The transient simulations predict similar levels of drawdown resulting from pumping by each of the Water Corporation borefields (treating the Superficial and Leederville aquifer components separately), producing between 0.2 and 0.28 m decline at the lake in the Superficial aquifer, or 0.15 to 0.37 m drawdown for the low hydraulic conductivity zone model version. Drawdown impacts from the Quinns Superficial borefield have stabilised, as demonstrated by the similar predicted drawdown in both the steady-state and transient simulations, and transient drawdown trend shown in Figure 7-2 and Figure 7-4. Meanwhile, the significant difference between the simulated transient drawdown and predicted steady-state drawdown from pumping by the Pinjar Superficial, Pinjar Leederville and Quinns Leederville borefields suggests the watertable would decline further with continued pumping from these borefields at historical rates. This is also seen in the transient drawdown trends for these borefields (Figure 7-2). The projected additional drawdown from these borefields is about 0.6 m, or almost 0.9 m for the low hydraulic conductivity zone version model. Recent reductions in pumping from the Water Corporation borefields will however reduce future impacts. The modelling suggests that drawdown in the Superficial aquifer in response to pumping from the Leederville aquifer supplementation bore 2/00 is minimal (about 0.05 to 0.07m) and has almost stabilised at current pumping rates.

Monitoring bore PM33 within the Superficial aquifer is located about 1.3 km southeast of the lake and is sufficiently distant to avoid the influence of lake supplementation on water levels (supplementation of water into the lake is not included in the simulations). Therefore the bore should be suitable for comparison of the simulated drawdown with that observed. The watertable in bore PM33 declined by almost 4.9 m from 1989 to the end of 2013. The simulated steady-state drawdown at the bore is 3.7 m, while the predicted transient drawdown is almost 2.8 m for all of the pumping combined. When it is considered that the watertable has fallen by around 1 m due to changes in rainfall (see HARTT analysis), it is apparent that the transient simulations are under-stating the actual drawdown by about 1 m and should have simulated a decline of about 3.9 m. However, the model version using a low hydraulic conductivity zone west of the lake simulated a transient drawdown of 3.4 m at PM33, which is closer to the observed decline.

To test the effect that a greater vertical hydraulic conductivity for the Leederville aquifer would have on the drawdown levels at the watertable about the lake, a steady-state simulation was run where it was doubled to 0.001 m/day. This showed that there was an additional 0.28 m long-term decline in watertable levels resulting from a combination of all the Leederville aquifer pumping.

7.2.4 Simulated drawdown in the Leederville aquifer

The closest Leederville aquifer observation bore to the lake is bore AM20A, located about 2 km northwest of the lake. Potentiometric head levels in the bore have declined by about 8.6 m from 1989, including a rapid drop of about 7 m coinciding with commissioning of the Quinns Leederville borefield. This compares with a simulated steady-state drawdown for Layer 2 of 6.9 m (7.6 m for low hydraulic conductivity zone version), and transient drawdown of 5.7 m at this site (same for both model versions). It is therefore apparent that the transient simulations are under-predicting drawdown of the potentiometric head in the Leederville aquifer at bore AM20A resulting from pumping in the Quinns Leederville borefield. This is probably a result of the drawdown approaching steady-state conditions more rapidly than simulated.

The steady-state model simulation predicts a reduction in potentiometric head within the Leederville aquifer beneath Lake Nowergup of almost 10 m in response to pumping from the Leederville aquifer (Pinjar Leederville borefield 1.8 m, Quinns Leederville borefield 5.4 m, Wanneroo borefield 0.6 m, and supplementation bore 2/00 1.55 m). Drawdown trends in the Leederville aquifer predicted by the transient simulation are shown by Figure 7-3 for each bore/borefield, which together produce a total of about 6.6 m drawdown. Potentiometric head decreases rapidly in response to commencement of pumping from the Quinns Leederville borefield and supplementation bore 2/00, and subsequently fluctuates with variations in pumping rates. Drawdown from pumping in the more distant Pinjar Leederville borefield has been more gradual, due to the incremental increase in production from the borefield, but rapidly reaches stable levels in response to pumping. The low hydraulic conductivity zone version of the model produced very similar results for Layer 2.

It is likely that the actual drawdown in the Wanneroo Member portion of the Leederville aquifer below the lake is greater than that indicated by the transient simulation. At bore AM20A the transient simulated drawdown is about 64% of the actual drawdown, and applying this proportion to modelled water levels in the area beneath Lake Nowergup suggests actual drawdown beneath the lake should be about 10 m (potentiometric head of about 7 mAHD). This drawdown is closer to that simulated in steady-state, and similar to the drawdown interpreted between monitoring bores in the Leederville aquifer (AM20A, AM21A and AM23A).

It is also close to that obtained from a recent (2015) water level measurement taken in supplementation bore 2/00 when the pump was not operating.

7.2.5 Conclusions on future drawdown

An approximation of potential future changes in groundwater levels at Lake Nowergup if historical pumping rates were to continue is given by the difference between the modelled transient levels (representing current groundwater levels) and modelled steady-state levels (which is the predicted long-term level caused by pumping). From Table 7-2 and Table 7-3, the watertable would have declined by over an additional 0.6 m at Lake Nowergup before equilibrium conditions were reached under the historical pumping regime, while the model version using a zone of low hydraulic conductivity west of the lake indicates an additional decline of about 1.1 m. However, recent reduced pumping rates from the Pinjar and Quinns borefields (Pinjar Superficial reduced to 650 ML/year and Leederville 1.75 GL in 2014, and Quinns Leederville at 5.7 GL in 2014) result in higher steady-state water levels.

Table 7-4 presents the steady-state simulated drawdown at the lake relative to non-pumping levels for the Water Corporation borefields reduced pumping rates compared with the final simulated transient drawdown levels from historical pumping. This indicates that there should be some recovery in current water levels resulting from reduced pumping from the Pinjar borefield of about 0.25 m, but still an additional drawdown from the Quinns borefield possibly just over 0.1 m, mostly from pumping of Leederville production bores. The reduction in pumping rates has decreased the ultimate drawdown by between about 0.8 m and 1.2 m at the lake when compared with the simulated steady-state levels based on historical pumping rates that would have been the predicted long-term drawdown.

Table 7-4 Simulated future steady-state drawdown (m) from reduced Water Corporation pumping rates relative to non-pumping levels compared with final historical pumping transient drawdown (i.e. predicted future compared to current simulated drawdown).

Borefield	Final transient drawdown – historical pumping	Future steady-state drawdown – PRAMS parameters	Future steady-state drawdown – low hydraulic conductivity zone	Difference (+ = rise, - = fall)
Pinjar				
Superficial	0.26	0.09	0.1	+0.17 to +0.16
Leederville	0.27	0.19	0.2	+0.08 to +0.07
Quinns				
Superficial	0.2	0.21	0.15	-0.01 to +0.05
Leederville	0.28	0.32	0.46	-0.04 to -0.18

Groundwater pumping impacts on future water levels about Lake Nowergup should be relatively stable as a result of reduced pumping from the Water Corporation borefields. It would appear that drawdown from the Quinns Superficial borefield has reached equilibrium at the lake, and the drawdown caused by private pumping in the Nowergup and Carabooda Groundwater Sub-areas has, or is very close to stabilising. There should be no further decline of the watertable due to pumping from supplementation bore 2/00 at current pumping rates.

A small recovery in response to reduced Water Corporation pumping should largely counter-act a potential decline caused by private pumping of groundwater indicated by the low hydraulic conductivity zone schematic model version. It is concluded that the potentiometric head drawdown in the Leederville aquifer is closer to the steady-state drawdown than that given for transient conditions, and therefore it is possible that some of the future watertable decline predicted in response to pumping from the aquifer may have already occurred and that the recovery from reduced Water Corporation pumping may be even greater than indicated.

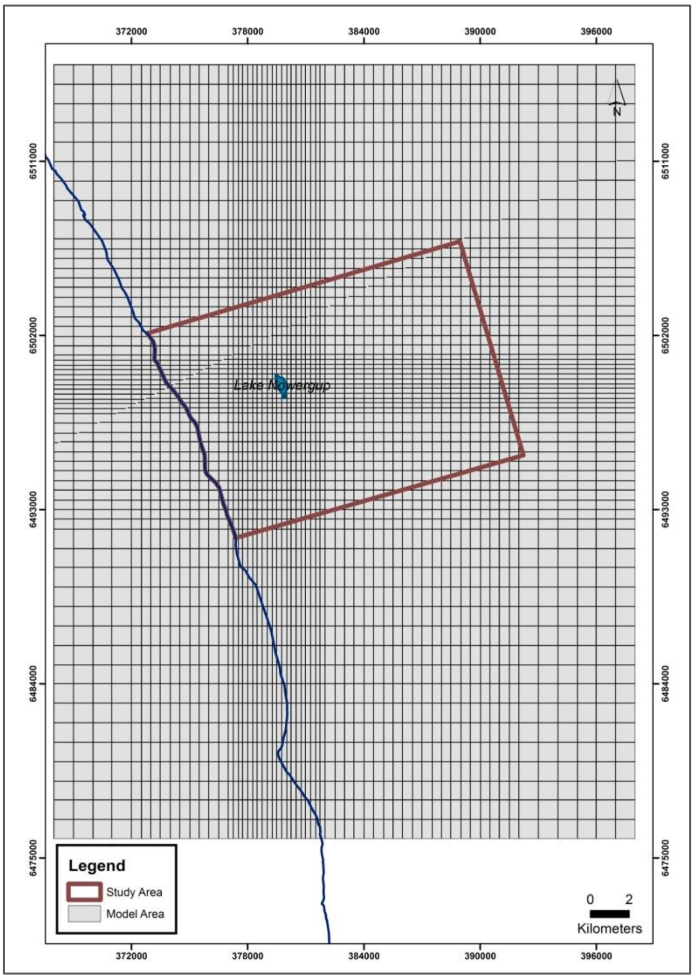


Figure 7-1 Model grid area.

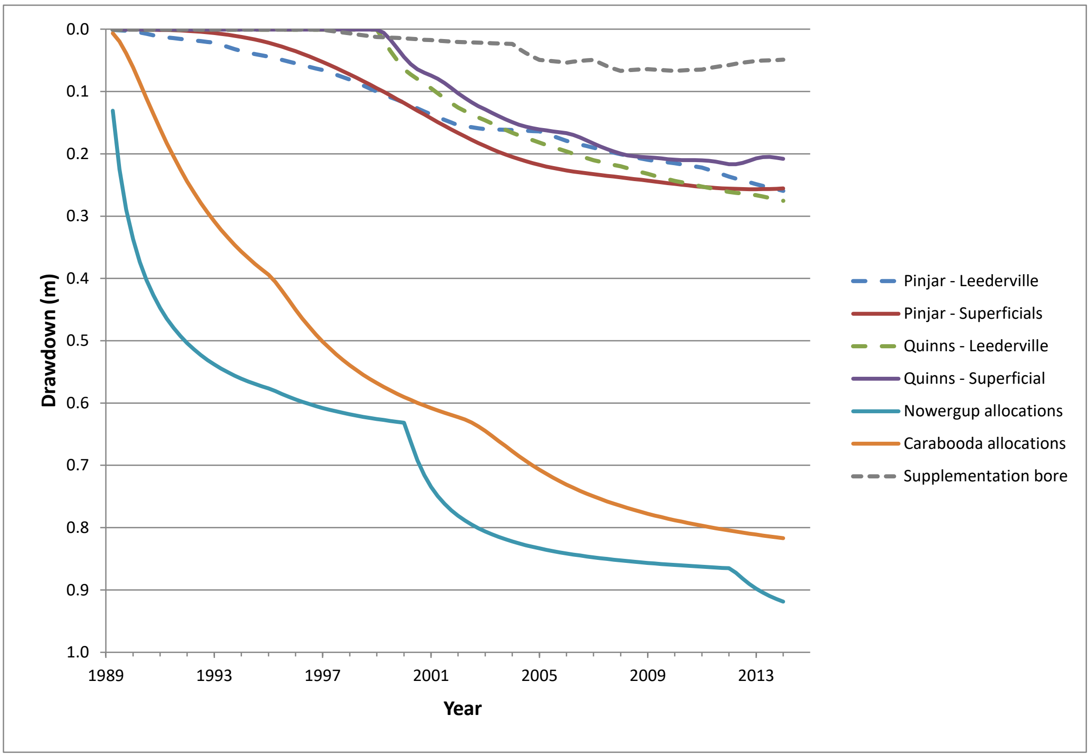


Figure 7-2 Transient simulation - watertable drawdown, Layer 1 (Superficial aquifer) beneath Lake Nowergup.

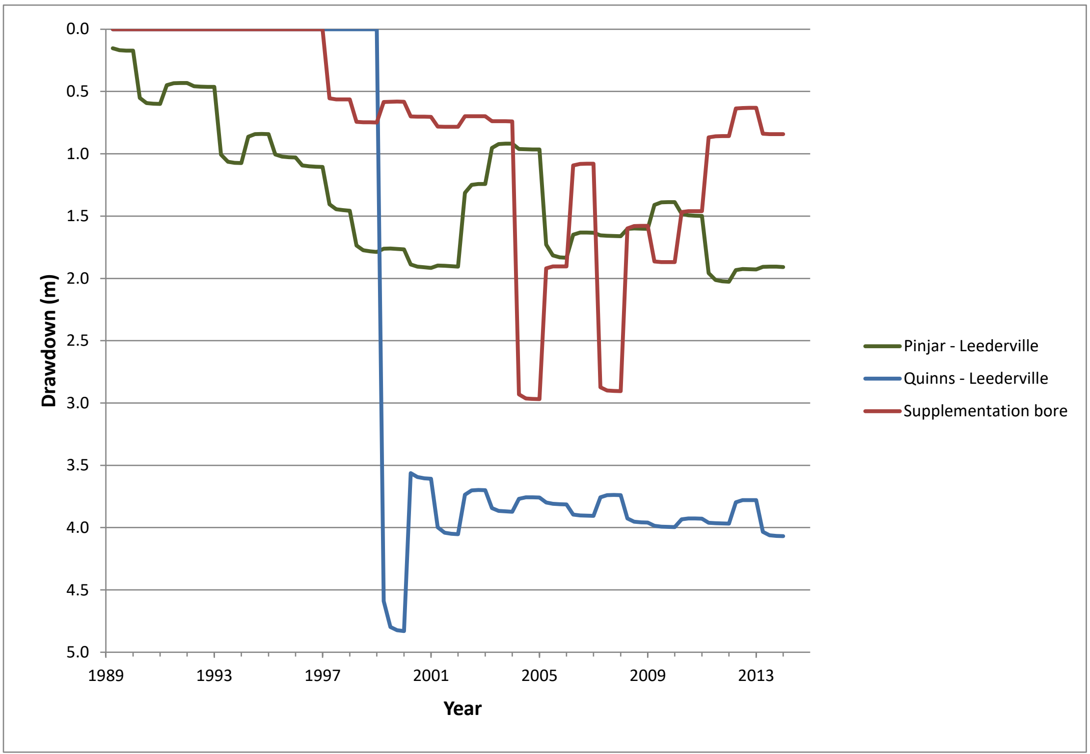


Figure 7-3 Transient simulation - potentiometric head drawdown, Layer 2 (Leederville aquifer) beneath Lake Nowergup.

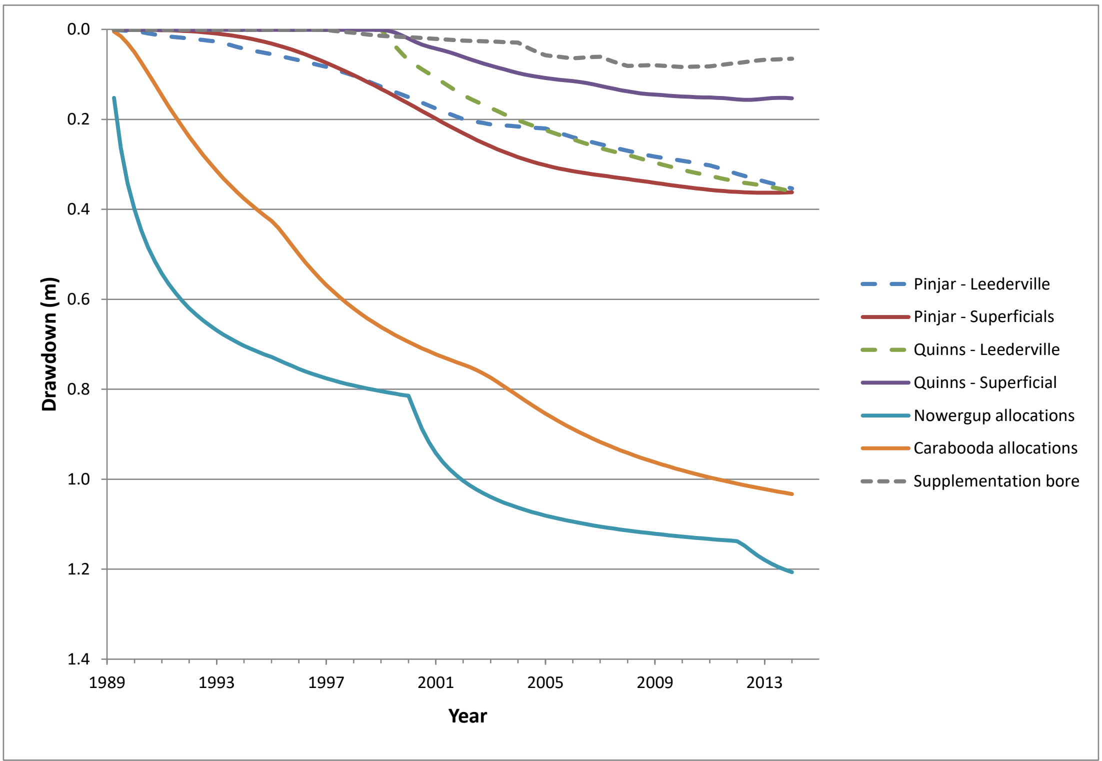


Figure 7-4 Transient simulation using zone of low hydraulic conductivity in Superficial aquifer west of Lake Nowergup - watertable drawdown, Layer 1 (Superficial aquifer) beneath Lake Nowergup.

7.3 HARTT analysis

Hydrographs from monitoring bores with a sufficient data record have been evaluated using HARTT (Hydrograph Analysis – Rainfall and Time Trend) software that was developed by Department of Agriculture (Ruhi Ferdowsian), and employs data analysis functions in Microsoft Excel worksheets. The process incorporates a multiple linear regression analysis to separate the effects of rainfall from other factors that may have an influence on groundwater levels over time. Detailed explanations for the use of HARTT are given by Department of Agriculture (Ferdowsian, et al., 2001). Examples of its application upon the Swan Coastal Plain are presented by Kretschmer and Kelsey (2012), and Kelsey (2014).

The HARTT analysis is undertaken in two steps. In the initial step HARTT uses an accumulated deviation function to separate the rainfall trend from underlying groundwater level trends, and determine the time lag between rainfall and its impact on groundwater. This is followed by multiple regression analysis incorporating one or more factors (treatments) that may also impact groundwater levels, enabling estimation of the influence of each factor.

HARTT utilises the cumulative deviation from mean rainfall (CDFM) to evaluate the effect of rainfall patterns on groundwater levels. The analysis herein utilises SILO rainfall data for near the lake. Previous work has used 1907 as an origin date for rainfall upon the Swan Coastal Plain in the northern Perth region (Yesertener, 2008) and this is used here in the calculation of the long-term mean in establishing the CDFM. Other more recent work has identified 1960 (Kelsey, 2014) and 1945 (Degens et al., in prep) as suitable origin dates over other parts of the coastal plain for the CDFM analysis. Accumulative annual residual rainfall (AARR) has been used in the analysis, which results in calculated water levels that display seasonal effects.

The origin date used for rainfall in the CDFM analysis influences the change in water level attributed to rainfall patterns derived by the analysis, resulting in some over- or under-estimation in the regression. Water level changes attributed to rainfall using a 1907 origin date are larger than those derived from 1960 and 1942. The latter origin dates were also tested for bores used in the HARTT analyses, and these were found to possibly over-state the drawdown at some locations. The smallest influence on waterlevels is found when using the 1942 origin, which may under-state drawdown at some locations. Testing of a 1960 origin date resulted in a water level decrease due to rainfall patterns over 1989 to 2014 that are an average of 65% compared to those using a 1907 origin for the analyses undertaken in this assessment. Normally a suitable origin date would be identified by undertaking a regression analysis using a range of dates for calibration monitoring bores where water levels have not been affected by any factors apart from rainfall, with the origin where rainfall explains most of the variation in water levels accepted. However, it was not possible to identify any appropriate bores in the study area which had not been influenced by other factors (chiefly pine plantations and groundwater pumping) during the monitoring period that had a larger impact on water levels than rainfall.

A limitation of the HARTT analysis is that the regression can fail to appropriately differentiate the degree of water level change resulting from treatments when two or more have similar timing, such as groundwater pumping commencing in different areas around the same time. This has influenced the analysis at several locations, especially about the east side of Lake Nowergup.

Factors which may impact groundwater levels vary between locations. The study area can be divided into three smaller areas, each with its own set of factors potentially impacting groundwater levels. These areas are:

- Western coastal plain (west of Lake Nowergup), which effectively comprises the area of Tamala Limestone where groundwater levels are influenced by the Quinns Superficial borefield and urbanisation that has expanded across the area during approximately the last 20 years.
- Eastern coastal plain (east of Lake Nowergup), where groundwater levels are influenced by pine plantations, Pinjar Leederville borefield, and private abstraction in the Carabooda and Nowergup Groundwater sub-areas.
- Adjacent to Lake Nowergup, where groundwater levels are influenced by the same factors as those in the eastern coastal plain, but with the added factors of lake supplementation and pumping from the Quinns borefield (both Superficial and Leederville).

The location of monitoring bores used for the HARTT analysis and summary of results are presented in Figure 7-5, for which the results are discussed below. Charts showing the HARTT analysis for each of the monitoring bores analysed are presented in Appendix A.

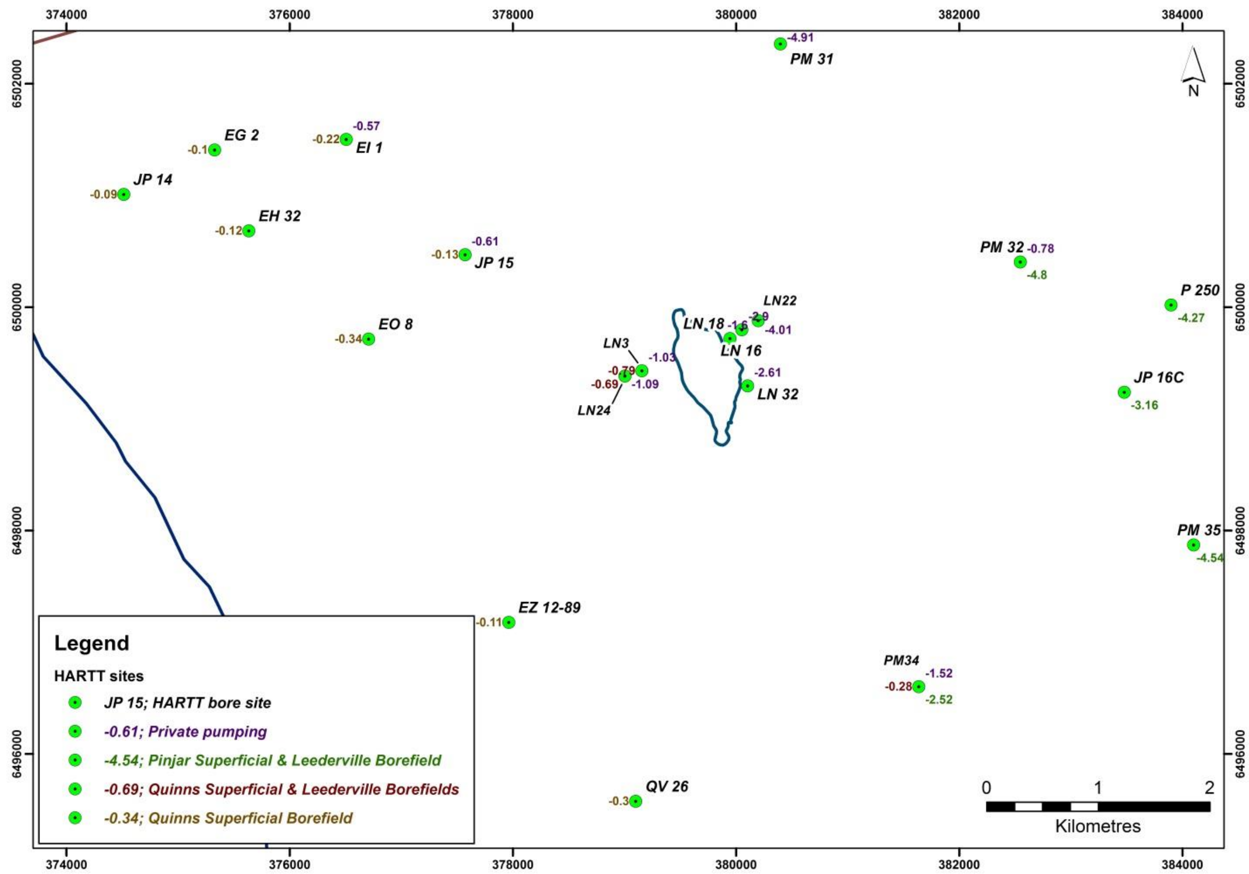


Figure 7-5 HARTT analysis monitoring bores summary of results, January 1989 to July 2014.

7.3.1 Coastal plain west of Lake Nowergup (sites within Tamala Limestone)

Monitoring bores used for the HARTT analysis of potential impacts at sites within the Tamala Limestone are given in Table 7-5. The treatments applied were rainfall, Quinns Superficial borefield pumping and urbanisation, with private pumping applied at some sites. Pumping from the Quinns Leederville borefield had no discernible impact in the hydrographs of monitoring bores analysed and was not applied as a treatment in the HARTT analysis of monitoring bores within this area. The lack of an impact from the Leederville aquifer pumping is probably due to the intervening Pinjar Member of the Leederville Formation, which is a low permeability member forming an aquitard between the Leederville aquifer and Superficial aquifer. A degree of fit for the calculated curve compared to the water level data at each bore site as given by R^2 of >0.7 show that the regression models reasonably capture the variation in water levels, but that there is some discrepancy. Much of the discrepancy may be a result of local factors such as land clearing and groundwater pumping. A HARTT analysis chart for bore EH 32-89 is presented by Figure 7-6 as a representative analysis for this area.

Pumping commenced from the Quinns borefield in 1999, and cumulative production from the borefield is applied as a regression treatment from that date. Equilibrium in groundwater levels from bore EH 32-89 is established fairly quickly after the initial falls following commencement of pumping from the Quinns borefield. This is most likely a consequence of the very high aquifer transmissivity. Equilibrium conditions in other plots for the area are reached variously between May 2002 and May 2005. Once equilibrium levels are reached, the treatment values for the Quinns borefield are no longer cumulatively increased in the regression analysis. To account for changes in annual pumping from the Quinns Superficial borefield after equilibrium conditions are reached, the treatment value for pumping is adjusted proportionally on the ratio of annual abstraction at the time equilibrium was reached and annual abstraction in subsequent years. This accounts for reduced pumping from the Quinns Superficial borefield from 2012, which has been about 75% of the previous annual pumping rate. The result of reduced pumping is demonstrated in bore EH 32-89 (Figure 7-6) which shows a rise in groundwater levels attributed to the combination of increased rainfall, clearing for urbanisation and reduced pumping from the Quinns superficial borefield from 2011.

A rise in groundwater levels following clearing of native vegetation and subsequent urbanisation is evident at the monitoring bore sites west of Lake Nowergup. This is the result of increased groundwater recharge rates. The start of this effect is seen variously on the hydrographs from around 2000 to 2010, approximately coincident with the northward urban expansion. This effect is included as a regression treatment from these dates for the various bores.

Effects from private groundwater pumping in the Carabooda Groundwater Sub-area are evident in the plots of two of the monitoring bore sites used in the HARTT analysis for the area west of Lake Nowergup. These are bores EI 1-89 and JP 15, which are located about the eastern portion of Tamala Limestone close to the Carabooda area. These effects are not apparent on plots for other monitoring bores in the area.

A summary of changes in watertable levels over the western coastal plain for each factor as determined from the HARTT analysis between January 1989 and July 2014 is included in Table 7-5. In response to changes in annual rainfall since 1989 groundwater levels have declined mostly by between 0.29 m and 0.44 m, although a range of 0.17 m to 0.34 m was obtained using a 1960 rainfall origin. The larger fall determined at bores EZ 12-89 and QV 26-89 are considered to be the result of the regression analysis unable to properly separate the influence of rainfall from other factors, particularly the effect of clearing associated with urbanisation which appears to be over-stated for these locations. The effect of local pumping and possible subsequent recovery may have also influenced these two sites. Following clearing and urbanisation, groundwater levels are assessed to have risen by 0.36 m to 0.41 m, with the effects at bores EZ 12-89 and QV 26-89 again being over-stated. Monitoring at several bores ceased prior to any effect from urbanisation becoming evident.

The effect of groundwater pumping from the Quinns Superficial borefield is evident at all HARTT sites upon the western coastal plain. Depending on the location of the monitoring bores, the groundwater level is assessed by HARTT as having declined by between 0.09 m and 0.34 m in response to the Quinns Superficial borefield. At bore EI 1-89, the regression analysis was unable to separate the influence of the Quinns borefield and private pumping in the Carabooda Groundwater Sub-area, where a combined drawdown impact of 0.79 m has been found since 1989. Examination of the hydrograph at this site shows an additional decline in groundwater levels of about 0.22 m from October 2000 to May 2003 compared to the pre-existing rate of decline, which would appear to be associated with pumping from the Quinns Superficial borefield. This implies that the portion of drawdown resulting from Carabooda pumping is about 0.57 m. Private pumping from the Carabooda area is therefore assessed as having resulted in a decline of watertable levels of 0.57 m and 0.61 m at EI 1-89 and JP 15 respectively.

Table 7-5 HARTT analysis - Assessed effects on groundwater level change (m) west of Lake Nowergup, January 1989 - July 2014.

Bore	R^2	Rain	Quinns Superficial	Private[a]	Urbanisation
EG 2-89	0.708	-0.44	-0.10		+0.38
EH 32-89	0.735	-0.32	-0.12		+0.41
EI 1-89	0.832	-0.40	-0.79[b]		-
EO 8-89	0.856	-0.29	-0.34		-
EZ 12-89	0.844	-0.77	-0.11		+0.79
JP14	0.770	-0.43	-0.09		-
JP15	0.938	-0.31	-0.13	-0.61	+0.36
QV 26-89	0.508	-1.11[c]	-0.30		+1.45[c]

Notes: a – Carabooda Sub-area private licensed allocations
b – Regression analysis unable to separate Quinns and private abstraction
c – Results appear to be influenced by local pumping and recovery

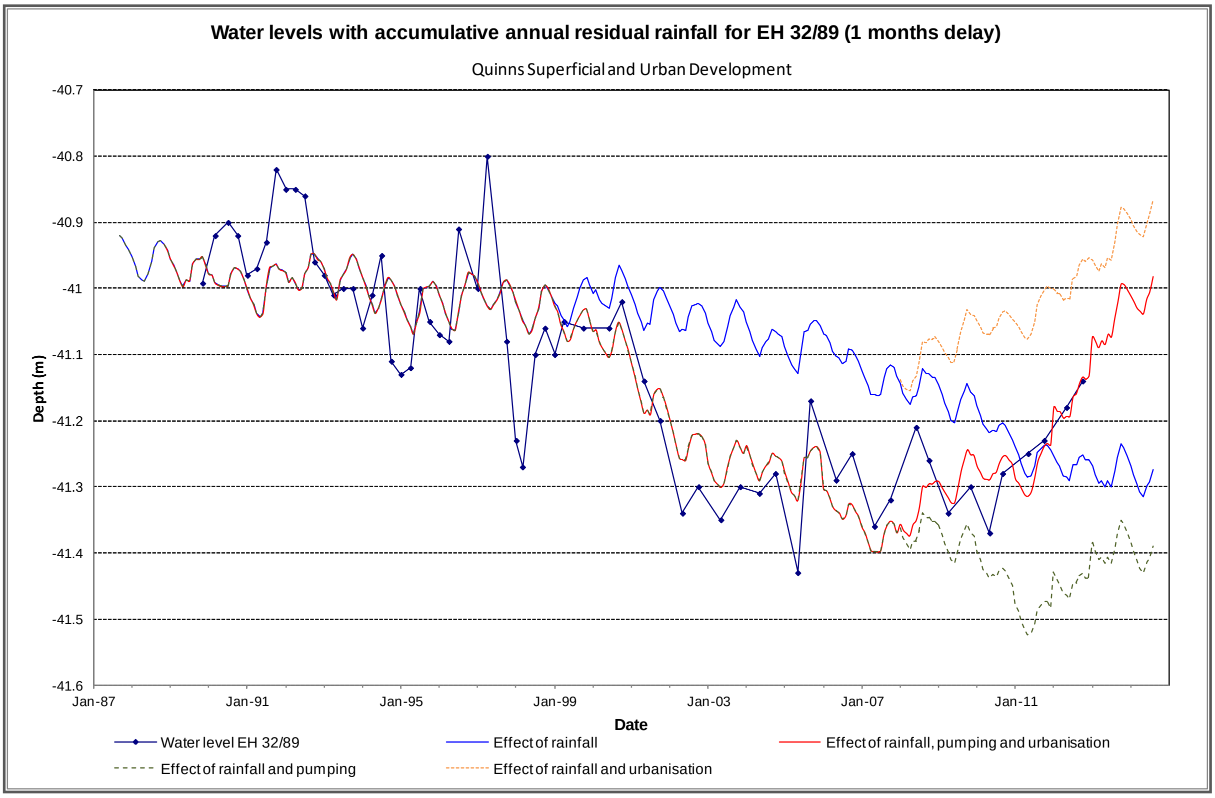


Figure 7-6 HARTT analysis bore EH 32-89.

7.3.2 Coastal Plain east of Lake Nowergup (sites within Bassendean Sand)

Monitoring bores used in the HARTT analysis over the eastern portion of the coastal plain are given in Table 7-6. These sites are mostly within the Bassendean Sand, but possibly extend into the Ascot Formation at some sites (PM35, JP16C and P250). The treatments applied were rainfall, pine plantations, Pinjar Leederville borefield pumping, and private pumping in the Carabooda and Nowergup Groundwater Sub-areas. The area has not been urbanised, and there is no discernible influence from pumping in the Pinjar and Quinns Superficial borefields. Only one site (PM34) has an apparent effect from the Quinns Leederville borefield pumping. A HARTT analysis chart for bore PM32 is shown by Figure 7-7 as a representative analysis for this area.

The HARTT analysis of water levels in this area established correlations between hydrograph trends and the effect from reduced recharge associated with pine plantations. However, an equilibrium state was reached by 1989 so no impact on water levels is attributed to the pine plantations since then.

A watertable decline in response to changing annual rainfall of between 0.21 m (bore PM32) and 1.45 m (bore JP16C) since 1989 is determined by the analysis, while using a 1960 origin date for the rainfall CDFM yielded values of between 0.12 m and 0.96 m respectively. However, for bore JP16C it appears that the analysis has overstated the effect from changing rainfall and understated the influence from groundwater pumping. If rainfall is responsible for 0.4 m of the decline at the bore (similar to that found by HARTT for nearby sites), then this would imply drawdown from pumping should be around 4.2 m.

The Pinjar borefield started operations in 1989 and pumping from the borefield is discernible in the HARTT analysis plots for monitoring bores in the eastern part of the coastal plain almost immediately. However, the effects from pumping of the Superficial and Leederville components cannot be separated at the monitoring bore sites due to similar timing for pumping from each aquifer. Since 1989, the decline in groundwater levels attributed to the Pinjar borefield by HARTT analysis ranges between 2.52 m and 4.80 m, with drawdown decreasing westward away from the borefield. The size of this drawdown is probably larger than actually caused by the borefield, and most of the decline may have been caused by local pumping from the Superficial aquifer. This can happen in a HARTT analysis when treatments have a similar timing, in this case pumping from the Pinjar borefield and possibly private pumping in the Carabooda, Nowergup and Neerabup Groundwater Sub-areas. The lack of private pumping data also contributes to the difficulty in separating the effect of this pumping by the regression analysis. Influence from the Quinns Leederville borefield is identified as contributing to the groundwater level decline at monitoring bore PM34, which is a westerly site in this area.

Impacts on groundwater levels from private pumping in the Carabooda and Nowergup Groundwater Sub-areas are resolved at monitoring bore sites over the westerly portion of the area. In the Nowergup Groundwater Sub-area, the drawdown attributed to private pumping was 0.78 m and 1.52 m for monitoring bores PM32 and PM34, respectively. Again, the analysis is considered to have attributed too little of the drawdown to the closer private pumping and too much to the Pinjar Leederville borefield, and has probably resulted due to the similar timing for increased pumping from both areas and the poor input data for private pumping for which there is no metering. Monitoring bore PM31 in the Carabooda Groundwater Sub-area that is situated in close proximity to large private groundwater allocation points, showed a groundwater level decline of 4.91 m associated with the private pumping. However, as the analysis was unable to resolve the influence from the Pinjar Leederville borefield, some of the decline may be due to that pumping.

Table 7-6 HARTT analysis - Assessed effects on groundwater levels (m) east of Lake Nowergup, January 1989 - July 2014.

Bore	R^2	Rain	Quinns (Leederville)	Pinjar (Leederville-Superficial)	Private
PM31	0.990	-1.11		-4.91[a]	
PM32	0.996	-0.21		-4.80	-0.78[b]
PM34	0.992	-0.64	-0.28	-2.52	-1.52[b]
PM35	0.994	-0.37		-4.54	
JP16C	0.986	-1.45		-3.16[c]	
P250	0.984	-0.68		-4.27[c]	

Notes: a – Mainly Carabooda allocations, but drawdown probably includes some effect from Pinjar Leederville borefield
b – Nowergup private allocations
c – Will include drawdown from private pumping in the Nowergup Groundwater Sub-area

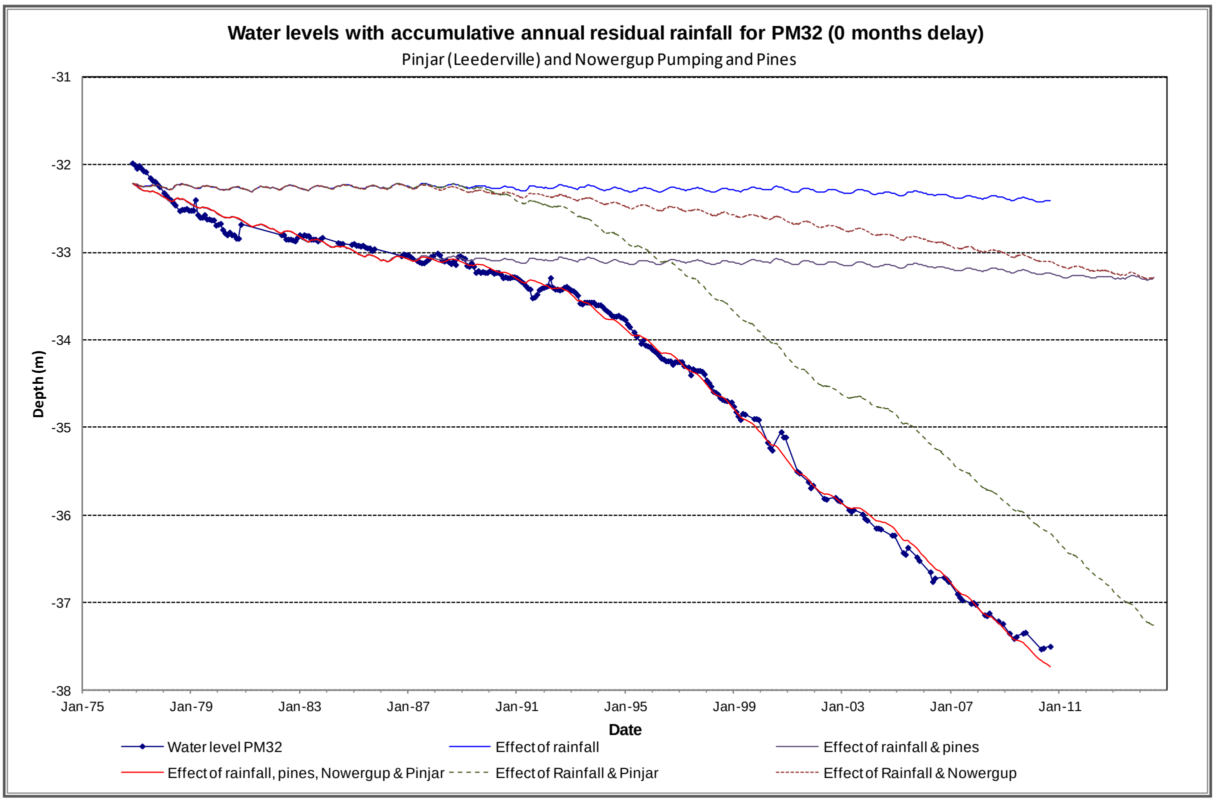


Figure 7-7 HARTT analysis bore PM32.

7.3.3 Vicinity of Lake Nowergup

Monitoring bores used for the HARTT analysis in the vicinity of Lake Nowergup for the period from January 1989 to July 2014 are given in Table 7-7. These include Superficial aquifer bores LN3 and LN24 on the west side of the lake, and LN16, LN22, and LN32 on the eastern side. It was not possible to get meaningful coefficients from LN6 with regression analysis. Bore LN18 in the upper-most Leederville aquifer east of the lake is also included. Treatments applied were rainfall, the Quinns borefield (combined Superficial and Leederville aquifers), Pinjar borefield (Leederville aquifer), private production for the Nowergup Groundwater Sub-area and lake supplementation. A summary of the best results for each bore are included in Table 7-7, showing the effect on watertable levels of each treatment at July 2014 relative to January 1989. HARTT analysis charts for bores LN3 and LN16 are respectively presented by Figure 7-8 and Figure 7-9 as representative analyses for this area about the west and east sides of the lake.

HARTT analysis for sites on the western side of the lake showed the watertable has declined by 0.92 to 0.97 m in response to rainfall changes during this period, while a 1960 origin for the CDFM gave a response of 0.64 m for LN3 (LN24 regression failed). The analysis also suggests that pumping from the Quinns borefield is responsible for 0.69 to 0.79 m decline. It is evident that some drawdown effect from private pumping east of the lake propagates westward beneath the lake, with private pumping causing 1.03 to 1.09 m decline. It also finds the effect of lake supplementation has been to raise levels by about 0.45 m at a distance up to 400 m west of the lake. The analysis was not able to distinguish trends associated with groundwater pumping from the Pinjar borefield, possibly due to the larger impact from private pumping masking the effect.

HARTT analysis for sites about the eastern side of Lake Nowergup yield a watertable decline of 2.05 to 2.69 m in response to a decrease in rainfall, while for the 1960 origin it was 1.22 m to 1.59 m. This is significantly greater than west of the lake and is inconsistent with the analysis for other more distant sites within Bassendean Sand where the average decline in watertable attributed to climate since 1989 is 0.75 m (although this effect may be greater at the lake). It is therefore considered that the analysis for sites about the eastern margin of the lake has not been able to successfully differentiate the effects of rainfall from lake supplementation, excessively increasing the influence of each. Effects of pumping from the Pinjar borefield and private abstraction in the Carabooda and Nowergup Groundwater Sub-areas could not be differentiated from each other by the analysis at bores within the Superficial aquifer east of the lake, which yield a combined drawdown of between 2.61 and 4.01 m. This is larger than the observed drawdown from pumping effects west of the lake.

Lake supplementation would appear to have had a greater effect east of the lake than in the west, with the HARTT analysis indicating that the watertable is 1.73 to 2.05 m higher to the east as a result. However, it is likely that this effect has been over-stated in the analysis, with much of the difference made-up by the over-estimated decline from rainfall (i.e. the rise from supplementation should be reduced by about the same amount that the decline resulting from rainfall is over-estimated, possibly about 1 to 1.5 m). It was not possible to discern impacts from pumping from the Quinns borefield east of the lake, although it is possible that the pumping is responsible for a small decline that cannot be distinguished from other influences.

Table 7-7 HARTT analysis – Assessed effects on groundwater levels (m) at Lake Nowergup, 1989 - 2014.

<table>
<tr><th>Bore</th><th>R^2</th><th>Rain</th><th>Quinns</th><th>Pinjar</th><th>Private</th><th>Supplementation</th></tr>
<tr><td colspan="3">Western side of lake</td><td></td><td></td><td></td><td></td></tr>
<tr><td>LN3</td><td>0.981</td><td>-0.97</td><td>-0.79</td><td></td><td>-1.03</td><td>+0.45</td></tr>
<tr><td>LN24</td><td>0.979</td><td>-0.92</td><td>-0.69</td><td></td><td>-1.09</td><td>+0.46</td></tr>
<tr><td colspan="3">Eastern side of lake</td><td></td><td></td><td></td><td></td></tr>
<tr><td>LN16</td><td>0.964</td><td>-2.42</td><td></td><td colspan="2">-2.9</td><td>+1.78</td></tr>
<tr><td>LN22</td><td>0.978</td><td>-2.05</td><td></td><td colspan="2">-4.01</td><td>+1.73</td></tr>
<tr><td>LN32</td><td>0.928</td><td>-2.69</td><td></td><td colspan="2">-2.61</td><td>+2.05</td></tr>
<tr><td colspan="3">Leederville aquifer</td><td></td><td colspan="2"></td><td></td></tr>
<tr><td>LN18</td><td>0.911</td><td>-2.36</td><td></td><td>-0.34</td><td>-1.6</td><td>+1.72</td></tr>
</table>

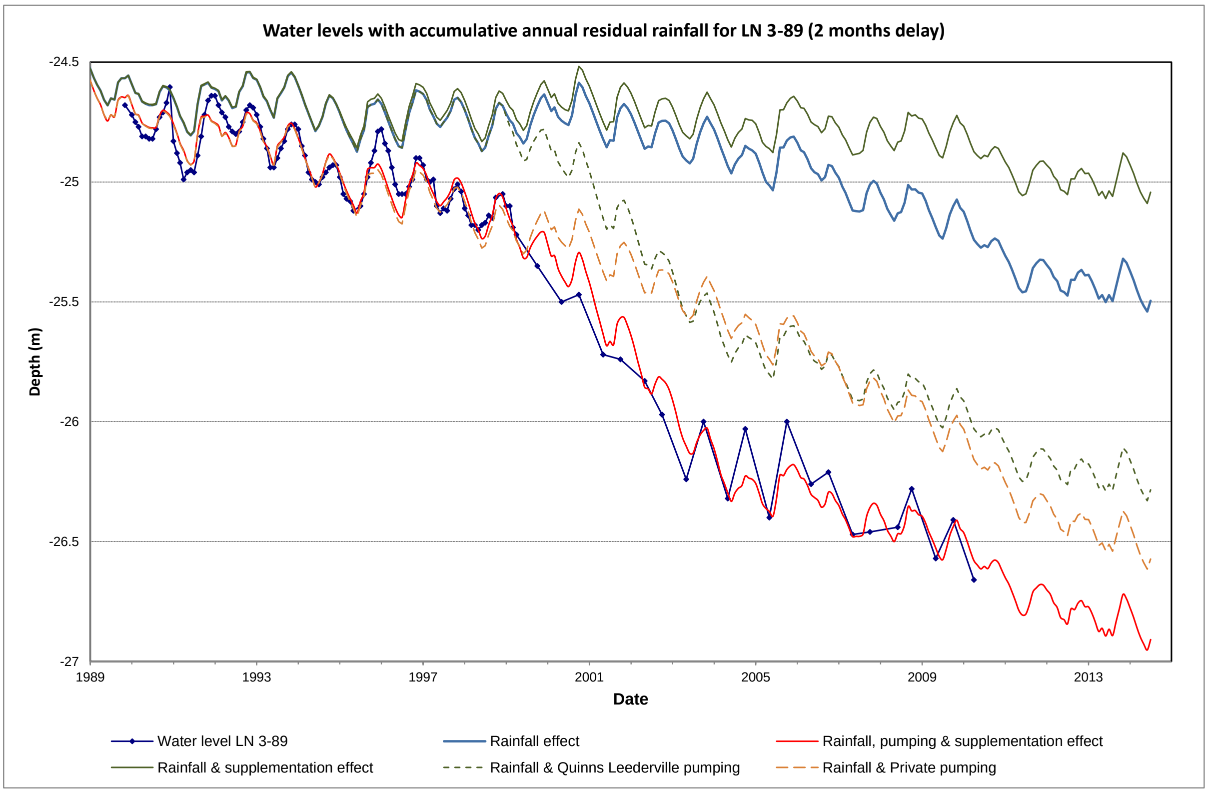


Figure 7-8 HARTT analysis bore LN3.

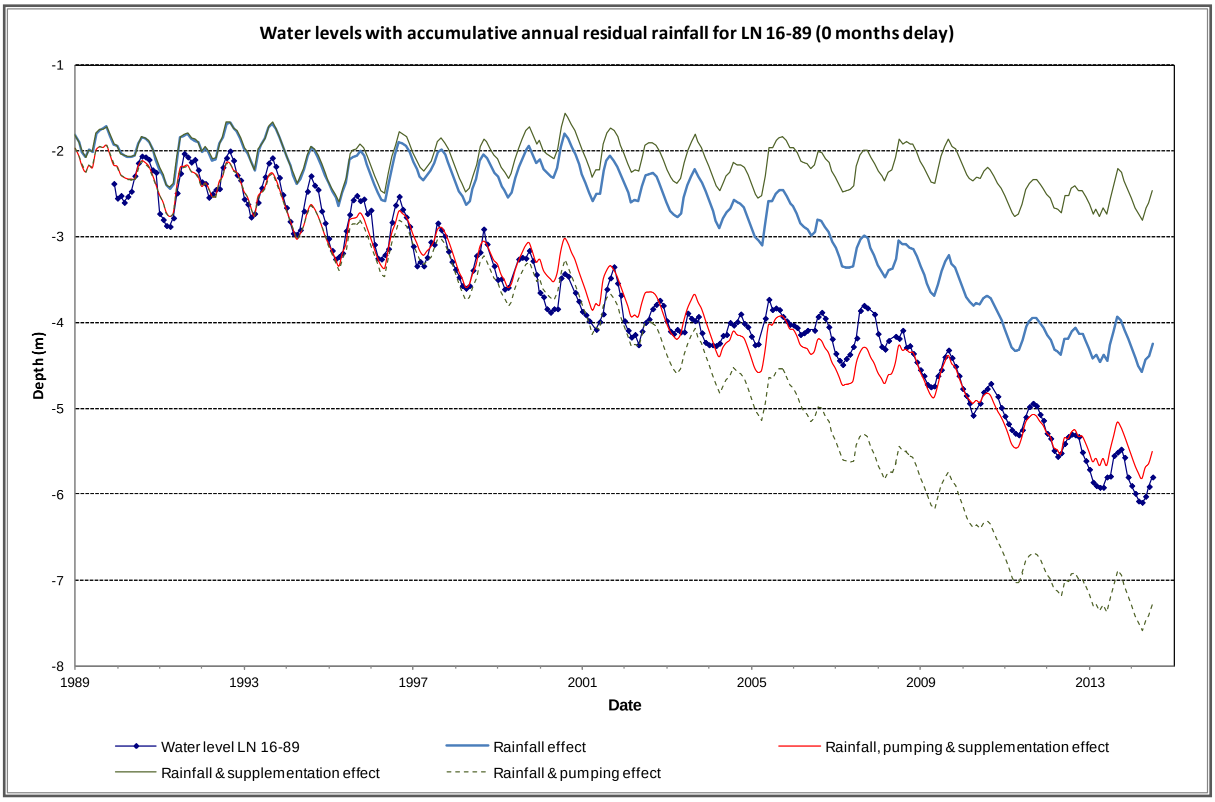


Figure 7-9 HARTT analysis bore LN16.

7.4 PRAMS verification scenarios

Verification modelling using PRAMS by the DoW simulates the recovery in water levels to June 2013 under a series of scenarios involving ceasing of different groups of groundwater pumping from 1995. Resulting levels are compared to a base scenario where all pumping continues and increases in-line with actual pumping since 1995. These scenarios provide a useful evaluation of the potential drawdown resulting from each pumping activity, within the limitations and accuracy of the PRAMS model. The simulated difference in watertable levels between the base scenario and the relevant scenario represents most of the drawdown caused by the relevant pumping up until 2013. These scenarios comprise:

- Verification scenario 1 – no Water Corporation pumping from the Superficial aquifer,
- Verification scenario 2 – no Water Corporation pumping from the Leederville aquifer,
- Verification scenario 3 – no Water Corporation pumping from the Yarragadee aquifer,
- Verification scenario 4 – no private pumping,
- Verification scenario 5 – no pumping.

Results generated from these scenarios are presented in Appendix B, which also includes hydrograph time-series plots for monitoring bore PM33 located about 1.3 km southeast of Lake Nowergup within the Superficial aquifer.

Hydrographs for monitoring bore PM33 show the following responses to each scenario:

- Water levels rise about 0.5 m when all Water Corporation Superficial production bores stop pumping (VS 1),
- Water levels rise about 1 m when all Water Corporation Leederville bores stop pumping (VS 2),
- There is minimal response in water levels when there is no pumping from the Water Corporation Yarragadee bores (VS 3),
- Water levels rise 2.8 m when there is no private pumping (VS 4),
- Water levels rise 4.1 m when there is no pumping (VS 5).

Simulated recovery in the watertable determined at Lake Nowergup from the scenarios (plans in Appendix B) are presented in Table 7-8. An additional scenario also considered changes from 1995 to 2013 caused by climatic changes in rainfall and land-use (mostly urbanisation and pine plantation harvesting), which showed a decline of the watertable at Lake Nowergup of 0.4 – 0.5 m over this period.

Table 7-8 PRAMS verification scenarios - Impact at Lake Nowergup.

Verification scenario	Water level rise (m)
1. No public Superficial aquifer pumping	0.4 – 0.5
2. No public Leederville aquifer pumping	0.7 – 0.75
3. No public Yarragadee aquifer pumping	0.1
4. No private pumping	2.5
5. No pumping of groundwater	3.7

8 Relative importance of factors responsible for changes in the watertable at Lake Nowergup

Various factors resulting in changes to the water balance have influenced groundwater levels at Lake Nowergup over time. These include recharge rates through rainfall or land-use changes, and groundwater discharge, particularly the pumping of groundwater. Changes to the water balance produce an increase or decrease in groundwater storage within the unconfined aquifer and pressure changes in confined aquifers, with associated changes in the elevation of the watertable.

Approaches used in this study to establish potential impacts of the factors likely to have contributed to water level changes at Lake Nowergup included:

- Assessment of hydrograph changes in relation to pumping and changing rainfall and land-use,
- Distance drawdown calculations using analytical (Cooper – Jacob) and numerical (modelling) approaches,
- HARTT water level monitoring data regression analysis,
- Use of schematic Modflow simulations,
- Verification scenarios from PRAMS.

Hydrographs from observation bores show the actual changes in water levels over time, but it is frequently unclear as to how important an activity or environmental change is in setting the trend, with more than one factor typically relevant over a period. Often associations can be made only on a comparison of timing (e.g. commencement of pumping) and the proximity to the lake of an activity that could impact water levels, and it can be difficult to quantify cause and effect simply from the hydrographs.

The HARTT regression analysis can be useful in differentiating the various factors responsible for water level fluctuations. However, incorrect correlations can be made when various treatments have a similar timing and where the input data for a treatment is not well quantified, which is the case for private groundwater pumping.

Analytical calculations using equations such as Cooper – Jacob for the confined Leederville aquifer over-predict drawdown levels within the Leederville aquifer, mainly due to the Leederville aquifer being leaky. But these do provide a check on the scale of likely drawdown predicted by other methods and an indication of the relative contribution to drawdown from individual production bores. This approach is most relevant where the Wanneroo Member of the Leederville aquifer is more effectively confined by overlying Pinjar Member of the Leederville Formation.

Simulations using groundwater models can make detailed predictions on the impacts, but are limited by how well the model conceptualises the actual hydrogeology, which may not be fully understood, and how well it is calibrated. Other limitations include grid size and layering that may not be able to adequately represent actual hydrogeological conditions.

Each approach has limitations, but does provide insights into the hydrogeological dynamics, and when considered together, enables an assessment of the relative importance of each factor in contributing to watertable variations.

8.1 Early drawdown during 1973 to 1978 (Phase 1)

During the period from about 1973 to 1978 watertable levels fell relatively evenly over the area, but maybe somewhat greater in the pine plantations, southern Nowergup area and about eastern Carabooda. About the eastern side of Lake Nowergup the watertable declined by about 0.74 m at bore JP17 over 3 years, falling by a rate of 0.25 m/year, which was about the average rate observed within the Bassendean Sand. Lake water levels also declined over this period, where the minimum level declined by up to 0.48 m, although by the end water levels had mostly recovered to be only about 0.16 m lower in 1979. At bore JP15, located about 2 km northwest of the lake, the watertable fell by 0.39 m.

As this period precedes any significant groundwater pumping in the Nowergup and Carabooda areas, or commissioning of the Pinjar and Quinns borefields, the decline in levels is attributed as mainly a response to reduced groundwater recharge rates resulting from lower rainfall and the effect of maturing pine plantations east of the lake. The widespread and relatively uniform nature of the watertable decline supports an aerially extensive recharge phenomena rather than local activities such as pumping as the cause for this decline. A drought experienced over the period of 1975 to 1977, when well below average rainfall averaging under 610 mm occurred, would have had a significant impact on watertable levels.

Conclusions of the main trends and causes for water level decline during 1973 to 1978:

- Decreased rainfall and maturing pine plantations east of Lake Nowergup were responsible for most of the groundwater level decline probably between 0.39 m and 0.74 m, and lake levels of 0.16 m.

8.2 Relatively stable watertable levels from 1979 to 1992 (Phase 2)

Watertable levels were generally stable or declined at a generally lower rate of less than 0.1 m/year beneath most of the area after 1978 until 1992. The rate of decline was greater in the Carabooda area, suggesting an additional impact from local pumping. East of Lake Nowergup the watertable was stable (bore JP17). The watertable gradually declined by 0.9 m southeast of the lake over this period at bore PM33 (1.3 km from the lake). West of the lake, the watertable was stable at JP15 (2 km northwest of the lake), with rises and falls during this period attributed to years of above or below average rainfall. Monitoring of the LN series of monitoring bores about Lake Nowergup commenced too late to detect the gradual decline in watertable levels.

Monitoring of lake water levels show a gradual decline in the seasonal low levels, falling by around 0.35 m from 1977 to 1991 (average of about 0.025 m/year). It is likely that the watertable at the lake fell by a similar amount.

Overall the period from 1979 to 1992 received relatively stable rainfall, and therefore climatic changes in rainfall probably did not contribute to any appreciable watertable decline. A continued gradual drawdown in watertable levels seen beneath the pine plantations to the east may have had a small impact on levels about the lake, but the majority of the decline about the lake would more likely have been the result of groundwater pumping. An apparent drawdown cone is discernible increasing from 0.35 m at the lake to 0.9 m southeast at bore PM33, which points to possible impact from local pumping where market gardens along Wesco Road were probably the main source.

Pumping from the Wanneroo Leederville aquifer borefield located about 14 km southeast of the lake commenced in 1977. However, there was no reduction of the potentiometric head evident in the Leederville aquifer at monitoring bore AM20A (2 km northwest of the lake) until 1986 when a gradual decline commenced. It is therefore concluded that any impact upon the watertable at the lake would have been small in response to groundwater pumping from the Wanneroo Leederville aquifer. The Pinjar Leederville borefield commenced pumping in 1989, but no additional influence is seen over 1989 to 1993 in bore AM20A, and therefore does not appear to have impacted the lake area during this time. Transient simulations suggest that pumping from the Wanneroo Leederville borefield would have resulted in a watertable drawdown of up to 0.04 m at the lake at the end of this period.

Both the HARTT analysis and simulated watertable drawdown using the schematic model show that private groundwater pumping was the dominant cause for falling watertable levels about the lake for the period of 1989 to end of 1993. HARTT analysis results presented in Table 8-1 attribute 0.2 to 0.3 m of the watertable decline adjacent to the east lake side (LN18 and LN32) to private pumping, with the size of the decline increasing east away from the lake (LN16 and LN22). Just west of the lake the watertable decline caused by private pumping was a little over 0.1 m (LN3 and LN24). Other factors had minimal influence on watertable levels.

Table 8-2 presents the predicted watertable drawdown using the schematic model for each of the pumping areas over the period. The drawdown simulated by the model version using PRAMS parameters was a little less than for the model incorporating a low hydraulic conductivity zone in the Superficial aquifer just west of the lake, with the largest difference for private pumping in the Nowergup Groundwater Sub-area. The simulations appear to over-predict the private pumping drawdown, which apply the full private licensed allocations probably earlier than occurred, when in reality production has incrementally increased over time to the current levels. Therefore, the pumping rate is too high in the model and consequently the simulated drawdown is too great for this period (total simulated drawdown of about 0.8 m, instead of observed drawdown of around 0.3 m).

Conclusions of the main trends and causes for water level decline during 1979 to 1992:

- Groundwater levels were stable or declined marginally, falling by about 0.3 m at the lake,
- Private groundwater pumping in the Nowergup and Carabooda Groundwater Sub-areas was the main cause for the observed decline,
- Any impact upon the watertable caused by pumping from Leederville bores in the Wanneroo borefield would have been small.

Table 8-1 HARTT analysis watertable declines (m), Lake Nowergup 1989 – 1992.

	Rainfall	Lake Supp.	Private	Pinjar	Quinns
East side of lake					
LN32	-0.04	+0.01	-0.33	-	-
LN18	-0.03	+0.01	-0.20	-0.02	-
LN16	-0.03	+0.01	-0.36	-	-
LN22	-0.03	+0.01	-0.52	-	-
West side of lake					
LN3	-0.04	0	-0.13	-	-
LN24	-0.03	0	-0.14	-	-
Conclusion	-0.03	+0.01	-0.30	-	-

Table 8-2 Simulated drawdown (m), schematic Modflow model 1989 - 1992.

	Pinjar – Leederville	Pinjar – Superficial	Quinns – Leederville	Quinns – Superficial	Supp. bore	Private – Nowergup	Private – Carabooda
Using PRAMS parameters							
Drawdown (m)	0.020	0.006	-	-	-	0.408	0.302
Incorporating low K zone in Superficial aquifer west of lake							
Drawdown (m)	0.025	0.008	-	-	-	0.517	0.310

8.3 Rapid drawdown in watertable levels from 1993 to 2014 (Phase 3)

The watertable about Lake Nowergup began declining at an accelerated rate from the year 1993, falling fairly uniformly until 1998 (a gap in monitoring at many sites makes it difficult to assess the period 1999-2002). This contrasts with the very low rates of watertable decline within the Tamala Limestone beneath the western coastal plain until 2001, after which there was a rapid decline of about 0.4 m to 0.5 m over 2 to 3 years coincident with pumping from Superficial aquifer bores of the Quinns borefield. About the western margin of the lake, the watertable fell by 2.9 to 3.7 m between 1993 and 2014. The decline is similar adjacent to the eastern lake margin where the watertable fell by about 3 m. The decline increased with distance east from the lake, where within about 500 m the watertable probably fell by over 4 m.

Lake surface water levels were generally stable from 1993 to 1996, but seasonal minimum levels dropped by up to 0.45 m over the period 1996 to 2002. Lake supplementation achieved a recovery in water levels after 2002 which lasted to 2007, but from 2007 lake surface water levels have fallen rapidly, dropping over 2 m by 2014 from the peak level. Based on 2014 air-photography the lake surface water level is probably now about 14.5 to 15 mAHD.

Phase 3 of declining watertable levels about Lake Nowergup from 1993 to 2014 can be sub-divided into the following periods 1993 – 1998, 1999 – 2002 and 2003 – 2014. These periods mostly reflect the influence of lake supplementation on the watertable about the lake.

8.3.1 1993 – 1998

From 1993 to 1998, the watertable fell by around 0.7 m about the eastern margin of Lake Nowergup, 0.95 m at the northwestern margin, and about 0.6 m around the southern part of the lake. It is thought that the groundwater level beneath the lake probably fell by between 0.5 and 0.7 m over this time, when the minimum lake levels declined by 0.49 m.

The groundwater level decline increases east away from the lake to over 1.4 m at bore JP17 (380 m northeast of lake), and decreases west away from the lake to 0.25 m at bore LN24 (about 500 m from lake). Although there were several years with below average rainfall (1993, 1994, and 1997), the Accumulative Residual Annual Rainfall is generally stable, suggesting that the rainfall influence on watertable levels is probably only minor. HARTT analysis indicates the decline attributed to rainfall changes was about 0.1 m west of the lake over this time (bores LN24 and LN3). A less certain analysis east of the lake gave values of about 0.3 m. When using a 1960 origin date for the analysis, a small decline in watertable levels is indicated, where rainfall is attributed with causing 0.03 m to 0.06 m decline.

Lake supplementation would also have had minimal influence on the watertable about the lake over the period prior to regular supplementation from 1998. HARTT analysis attributes a rise in the watertable in response to lake supplementation of 0.05 m west of the lake and about 0.2 m east of the lake, although the eastern values are probably over-stated.

During the period there was a large increase in pumping in the Carabooda area associated with expansion of market gardening along Carabooda Road, establishment of a turf farm (Carabooda Turf Farm) and avocado farm, and significant development further north in the Safari Place area (including Benara Nurseries). There was also some development and expansion of market gardens in the Nowergup area along Dayrell Road and north of Wesco Road. The Pinjar borefield also commenced operating in the period.

HARTT analysis (Table 8-3) west of the lake shows an effect from private pumping of about 0.25 m within 350 m of the lake margin by the end of 1998, although this would have been greater closer to the lake as pumping activities were east of the lake. The analysis was not definitive for the eastern side of the lake where pumping from private bores and the Pinjar borefield could be differentiated only in bore LN18. For LN18 the analysis attributed a 0.39 m decline as of end-1998 to private pumping and 0.1 m to the Pinjar Leederville aquifer borefield. The total drawdown from pumping increases east away from the lake.

Results from the schematic model (Table 8-4) suggest the largest contributor to falling watertable levels at the lake from 1993 to end-1998 was private pumping in the Carabooda Groundwater Sub-area, followed by private pumping in the Nowergup Groundwater Sub-area responsible for about 0.1 m decline. The model also suggests that production bores of the Pinjar borefield had an effect on watertable levels, with a decline of probably around 0.1 m for each of the Leederville and Superficial components.

Conclusions of the main trends and causes for water level decline during 1993 to 1998:

- The watertable at Lake Nowergup fell by at least 0.5 m, with the decline increasing east of the lake and decreasing to the west,
- A large increase in private pumping in the Carabooda Groundwater Sub-area was the main cause for watertable decline, accounting for about 0.3 m of the decline, while private pumping in the Nowergup Groundwater Sub-area contributed another 0.1 m,
- Pinjar borefield resulted in a decline of around 0.1 m for each of the Superficial and Leederville pumping,
- Rainfall patterns resulted in a decline in watertable levels of up to 0.3 m, but probably closer to 0.1 m,
- Lake supplementation raised watertable levels at the lake by up to 0.2 m.

Table 8-3 HARTT analysis watertable declines (m), Lake Nowergup 1993 – 1998.

	Rainfall	Lake Supp.	Private	Pinjar	Quinns
East side of lake					
LN32	-0.32	+0.22	-0.64	-	-
LN18	-0.28	+0.19	-0.39	-0.08	-
LN16	-0.28	+0.19	-0.71	-	-
LN22	-0.24	+0.19	-1.00	-	-
West side of lake					
LN3	-0.11	+0.05	-0.25	-	-
LN24	-0.09	+0.05	-0.27	-	-
Conclusion	-0.3	+0.2	-0.6	-0.1	-

Table 8-4 Simulated drawdown (m), schematic Modflow model 1993 – 1998.

	Pinjar - Leederville	Pinjar - Superficial	Quinns - Leederville	Quinns - Superficial	Supp. bore	Private – Nowergup	Private – Carabooda
Using PRAMS parameters							
Drawdown (m)	0.078	0.089			0.012	0.087	0.259
Incorporating low K zone in Superficial aquifer west of lake							
Drawdown (m)	0.100	0.123			0.013	0.135	0.347

8.3.2 1999 – 2002

A rapid fall in the watertable of just over 1 m is seen from 1999 to end-2002 at LN3 and LN24 in the Tamala Limestone clayey sand facies around 300-500 m west of the lake, and fell by about 0.8 m at the western margin of the lake. The watertable fell about 0.7 m beneath the eastern side of the lake over the same period, but there was a smaller decline of 0.4 m at JP17 northeast of the lake. There was a larger decline of 1.07 m southeast of the lake at PM33.

Accumulative Annual Residual Rainfall shows a small downward trend in rainfall following 1999 (1960 origin produced a small rise). The HARTT analysis (Table 8-5) indicates only a minor influence of this decline in rainfall on the watertable over the period; about 0.05 m west of the lake (bores LN3 and LN24), and less than 0.2 m east of the lake (bores LN16, 18, 22 and 32). Using a 1960 origin gave a decline from rainfall of -0.03 m to -0.04 m about the eastern side of the lake and a rise of 0.01 m to the west. Lake supplementation is attributed to have raised watertable levels by almost 0.2 m at the lake.

Commencement of pumping from the Quinns borefield (Superficial and Leederville aquifers) in 1999 had an obvious impact on watertable levels within the Tamala Limestone west of the lake between 1999 and end-2002. Hydrograph and HARTT analysis of monitoring bores in the western portion of the coastal plain attributes about 0.4 to 0.5 m fall in the watertable to pumping from Superficial production bores of the Quinns borefield, and the decline is seen mostly onward from 2001. Further inland about the west side of Lake Nowergup the watertable fell by more than that observed to the west and commenced falling earlier. This suggests that another pumping activity is responsible for falling watertable levels before 2001, and that no more than 0.4 m of the drawdown by end-2002 is a result of pumping from Superficial bores of the Quinns borefield. Based on timing, it is considered that pumping from the Quinns borefield Leederville aquifer production bores has probably contributed most of the additional watertable drawdown observed about the west side of the lake. Pumping from the Leederville aquifer production bores commenced about a year earlier than from the Superficial aquifer production bores, which would account for the earlier drawdown seen by the lake.

The HARTT analysis (Table 8-5) and schematic model (Table 8-6) show that the main cause for the declining watertable during this period is pumping from the Quinns borefield. Suggested contributions from the Superficial and Leederville aquifer bores in the borefield are similar, with a combined decline indicated of a little over 0.25 m by modelling. The simulated watertable decline from the Quinns borefield appears to be less than indicated by the hydrographs, possibly due to the model simulating propagation of the impact from the Leederville aquifer pumping more slowly than actually occurred. This would imply that the vertical permeability is greater than that used for the modelling. HARTT analysis suggests that about 0.5 m of the drawdown up to 500 m west of the lake (bores LN3 and LN24) is a result of Quinns borefield pumping.

A significant impact from the Pinjar borefield is also suggested by the schematic model of around 0.2 m. HARTT analysis of data from bore LN18 indicates that the Pinjar borefield caused 0.06 m decline in the watertable at this site, which is similar to the simulated Leederville component of the Pinjar borefield (0.06–0.08 m). It is possible that any drawdown impact caused by Superficial bores of the Pinjar borefield could not be differentiated from private pumping by the HARTT analysis, and that about 0.1 m drawdown is due to pumping of Pinjar Superficial production bores.

Continued private pumping east of the lake would have been responsible for some of the decline observed over 1999 to end-2002. The schematic model indicates around 0.3 m of watertable decline at the lake from private pumping, with about 0.2 m resulting from pumping in the Nowergup Groundwater Sub-area. HARTT analysis attributes 0.2 m of the watertable decline west of the lake to private pumping (bores LN3 and LN24), and about 0.3 m at the eastern margin of the lake (bore LN18), with the decline increasing east from the lake to almost 0.8 m (bore LN22). The relatively large decline of over 1 m observed over this time in monitoring bore PM33 southeast of the lake suggests increased private pumping in this area.

Conclusions of the main trends and causes for water level decline during 1999 to 2002:

- Watertable levels fell by 0.7 m to 0.8 m at the lake,
- Pumping from the Quinns borefield (combined Superficial and Leederville production bores) was responsible for most of the decline, causing the watertable to fall by over 0.25 m at the lake, and possibly up to 0.4 m,
- Private pumping in the Nowergup and Carabooda Groundwater Sub-areas has caused about 0.3 m of decline, with most of this from Nowergup pumping,
- Pinjar borefield pumping may have caused around 0.2 m of the decline,
- Rainfall patterns resulted in about 0.1 m decline in the watertable,
- Pumping of the supplementation bore has had minimal impact on the watertable of about 0.01 m decline,
- Lake supplementation has raised the watertable about the lake by about 0.2 m.

Table 8-5 HARTT analysis watertable declines (m), Lake Nowergup 1999 – 2002.

	Rainfall	Lake Supp.	Private	Pinjar	Quinns
East side of lake					
LN32	-0.21	+0.19	-0.49	-	-
LN18	-0.18	+0.16	-0.30	-0.06	-
LN16	-0.19	+0.16	-0.54	-	-
LN22	-0.16	+0.16	-0.77	-	-
West side of lake					
LN3	-0.04	+0.04	-0.19	-	-0.56
LN24	-0.06	+0.04	-0.2	-	-0.48
Conclusion	-0.1	+0.2	-0.4	-0.1	-0.50

Table 8-6 Simulated drawdown, schematic Modflow model 1999 – 2002.

	Pinjar - Leederville	Pinjar - Superficial	Quinns - Leederville	Quinns - Superficial	Supp. bore	Private – Nowergup	Private – Carabooda
Using PRAMS parameters							
Drawdown (m)	0.061	0.093	0.146	0.128	0.010	0.181	0.077
Incorporating low K zone in Superficial aquifer west of lake							
Drawdown (m)	0.084	0.128	0.174	0.08	0.013	0.235	0.113

8.3.3 2003 – 2014

Since 2003, the watertable has fallen slightly over 2 m about the southeast area of Lake Nowergup, decreasing to just over 1 m about the northwest side, and probably by around 1.6 m beneath the lake. The decline decreases rapidly further west, at about 0.7 m about 500 m west of the lake. The watertable was initially relatively stable near the lake as a result of lake supplementation, but fell away after 2008.

Below average rainfall between 2003 and 2010 produced a pronounced downward trend in the Accumulative Annual Residual Rainfall that would be expected to contribute toward a declining watertable, but since 2010 annual rainfall has been close to average. HARTT analysis attributes between 0.21 m and 1.45 m decline in the watertable to rainfall at sites over the larger area in the Bassendean Sand (Tables 8–3,8–4 and 8–7), although it was mostly between about 0.3 m and 0.7 m over 2003 to 2014. Just west of the lake, the analysis indicated about 0.7 m (bores LN3 and LN24) of the decline resulted from rainfall changes (Table 8-7) and that at sites in the Tamala Limestone toward the coast it contributed mostly 0.2 m to 0.3 m to the decline. The analysis could not appropriately separate effects of rainfall and lake supplementation about the eastern lake side, where the HARTT analysis attributed about 1.6 m of the decline to rainfall changes, although this was about 1.2 m with a 1960 rainfall origin. It is, however, considered that rainfall patterns did not contribute much more than 0.7 m to the decline east of the lake (i.e. HARTT has over-stated the decline by about 0.9 m).

The HARTT analysis found that over 2003 to 2014 lake supplementation maintained watertable levels 0.35 m higher just west of the lake at monitoring bores LN3 and LN24. About the east side of the lake, HARTT analysis attributes about 1.4 m rise in the watertable to supplementation, but it is considered to have actually been responsible for maintaining watertable levels about 0.5 m higher (estimated by reattributing effects of rainfall and supplementation in Table 8-7 by 0.9 m, which is approximately the amount that the rainfall effect has been over-stated by HARTT).

About the west side of Lake Nowergup, HARTT analysis (Table 8-7) found that onward from 2003 private pumping was responsible for most of the fall seen in the watertable related to groundwater pumping impacts, attributing about 0.4 m (LN3 and LN24) of the decline to private pumping occurring in the Nowergup and Carabooda Groundwater Sub-areas. On the east lake side HARTT analysis was generally unable to differentiate effects caused by private pumping from other areas of groundwater pumping, but does attribute an average of almost 1.4 m decline in the watertable to the combined effect of pumping. If the drawdown resulting from the Pinjar borefield were about 0.2 m as suggested by modelling, then the private impact would be up to about 1.2 m.

The HARTT analysis did separate the effect of private and Pinjar borefield pumping for bore LN18, which provided a result indicating 0.63 m decline to private pumping and 0.17 m to the Pinjar borefield. However, as bore LN18 is within the upper-most part of the Leederville aquifer it may have experienced a greater impact from the Pinjar borefield Leederville aquifer production bores and less from private pumping from the Superficial aquifer, and therefore may not be representative for watertable responses east of the lake. Schematic model simulations indicate that private pumping would have resulted in a drawdown of around 0.3 m to 0.4 m from the two sub-areas, with over 0.2 m of the drawdown probably coming from the Carabooda Groundwater Sub-area. However, based on the HARTT analysis it would appear that the modelling has under-stated impacts from private pumping, possibly due to the full allocations (those less than 100 ML/year) not being included in the simulation.

Drawdown impacts resulting from the Quinns Superficial (Tamala Limestone) production bores have probably reached a near equilibrium condition by this time and are unlikely to have contributed much to the watertable decline. HARTT analysis associates a minor decline in the watertable with pumping effects from the Quinns borefield, which is probably in response to pumping from the Leederville productions bores. There was no effect from the Quinns borefield identified east of the lake, and no impact of the Pinjar borefield seen to the west from the HARTT analysis. Schematic modelling (Table 8-8) found up to about 0.25 m drawdown at the lake due to pumping from the Quinns Borefield (combined Superficial and Leederville production bores), and possibly a little over 0.2 m decline caused by the Pinjar borefield (combined). The model would appear to have over predicted the drawdown resulting from the Quinns borefield during this period, possibly due to more of the drawdown impact occurring before 2003.

Conclusions of the main trends and causes for water level decline during 2003 to 2014:

- The watertable has declined by about 1.6 m at the lake,
- Rainfall patterns are responsible for around 0.7 m decline in the watertable,
- Although it is difficult to quantify, most of the observed drawdown is probably a result of increased private pumping in the Nowergup and Carabooda Groundwater Sub-areas, which is likely to have been over 0.4 m and possibly up to 1.2 m, with the most likely effect being responsible for about 0.8 m,
- Water Corporation pumping from the Pinjar borefield (combined Superficial and Leederville) has caused possibly a little over 0.2 m of drawdown, while the Quinns borefield may have resulted in less than 0.1 m drawdown at the lake,

- Lake supplementation has raised watertable levels by about 0.4 m to 0.5 m at the lake.

Table 8-7 HARTT analysis watertable declines (m), Lake Nowergup 2003 – 2014.

	Rainfall	Lake Supp.	Private	Pinjar	Quinns
East side of lake					
LN32	-1.84	+1.59	-1.03	-	-
LN18	-1.61	+1.33	-0.63	-0.17	-
LN16	-1.65	+1.40	-1.26	-	-
LN22	-1.40	+1.36	-1.78	-	-
West side of lake					
LN3	-0.72	+0.35	-0.40	-	-0.03
LN24	-0.70	+0.35	-0.43	-	-0.04
Conclusion	-1.6	+1.40	-0.8	-0.2	<0.05

Table 8-8 Simulated drawdown (m), schematic Modflow model 2003 – 2014.

	Pinjar - Leederville	Pinjar - Superficial	Quinns - Leederville	Quinns - Superficial	Supp. bore	Private – Nowergup	Private – Carabooda
Using PRAMS parameters							
Drawdown (m)	0.099	0.068	0.129	0.079	0.027	0.112	0.172
Incorporating low K zone in Superficial aquifer west of lake							
Drawdown (m)	0.143	0.102	0.186	0.073	0.038	0.168	0.259

8.4 Relative ranking of factors contributing to the historical watertable decline from 1989 to 2014

Each of the main factors contributing to the watertable decline at Lake Nowergup are presented in Table 8–9, together with a summary of the decline caused by each factor determined by the evaluation techniques used in this study. The effect of pine plantations had reached an equilibrium by 1989 and had no subsequent influence on groundwater levels, while their effect before this time is effectively included with rainfall.

Table 8-9 Watertable decline (m) at Lake Nowergup from 1989 – assessment comparison.

Method	Climatic	Private pumping	Water Corporation Superficial aquifer		Water Corporation Leederville aquifer		Supp. bore
			Pinjar	*Quinns*	*Pinjar*	*Quinns*	
Hydrograph analysis	>0.7			<0.4			
HARTT	1.2-2.7	2.6-2.9[a]	-	-		<0.79[b]	-
PRAMS verification	0.4-0.5[c]	2.5	0.4 – 0.5		0.7		-
Modflow simulation[d]	-	1.8-2.3	0.26-0.37	0.15-0.2	0.27-0.36	0.28-0.37	0.05-0.07

Notes:
a – combined private and Water Corporation pumping
b – combined impact from Superficial and Leederville production bore pumping
c – applies from 1995
d – transient simulation 1989 – 2013

Conclusions from this study on the contribution each factor has had on the declining watertable levels experienced at Lake Nowergup are presented by Table 8-10. This table presents the drawdown at the lake assessed for each of the main pumping areas and changing rainfall over several time periods corresponding with the different phases of watertable decline. The results are ranked from '1' for the greatest impact to '6' for the least. As this study is concerned with the impact from groundwater pumping, the influence from climate and lake water supplementation are excluded from the ranking.

Total watertable decline at the lake from 1973 to 2014 is found to be between 3.5 m and 5.2 m from the combination of all factors, which is partially off-set by lake supplementation that has raised levels by 0.6 m to 0.8 m. Changes in rainfall patterns are assessed as causing a 1.05 to 1.45 m decline in the watertable, and groundwater pumping has resulted in a total decline of between 2.5 and 3.8 m. Private pumping of groundwater in the Nowergup and Carabooda Groundwater Sub-areas is concluded to have the largest impact on the watertable at Lake Nowergup from pumping (1.4 to 2.4 m). The actual decline in watertable levels at the lake was about 3.5 m between 1989 and 2014, while based on lake water levels it is estimated to have fallen around 0.6 m from 1973 to 1989 (there was no monitoring adjacent to the lake prior to 1989). This suggests that groundwater levels at Lake Nowergup have fallen by about 4.1 m since 1973, which is within the range presented in Table 8-10.

Table 8-10 Watertable change (m) factors and ranking of contribution from groundwater pumping.

Period	Phase 1	Phase 2	Phase 3			Total	Ranking
	1973 – 1978	**1979 – 1992**	**1993 – 1998**	**1999 – 2002**	**2003 – 2014**		
Rainfall	0.5	0.05	0.1	0.1	0.3 – 0.7	1.05 – 1.45	
Nowergup & Carabooda	0	0.3	0.3 – 0.5	0.2 – 0.4	0.6 – 1.2	1.4 – 2.4	1
Pinjar – Superficial	-	0	0 – 0.1	0.1	0.1	0.2 – 0.3	5
Pinjar – Leederville	-	0	0.1	0.1	0.1 – 0.15	0.3 – 0.35	3
Quinns – Superficial	-	-	-	0.2	0.05 – 0.1	0.25 – 0.3	4
Quinns – Leederville	-	-	-	0.2 – 0.3	0.1	0.3 – 0.4	2
Supp. Bore	-	-	-	0.01	0.03 – 0.04	0.04 – 0.05	6
Lake supp.	-	-	-	+0.2	+0.4 - +0.6	+0.6 – +0.8	
Total	*0.5*	*0.35*	*0.5 – 0.8*	*0.71 – 1.01*	*0.68 – 1.99*	*2.74 – 4.65*	

8.4.1 Climate and land-use

A drying climate and pine plantations have been responsible for a portion of the decline in watertable levels beneath the coastal plain. This effect is assessed to have totalled between 1.15 and 1.65 m at Lake Nowergup since 1973. A period with well below average rainfall reducing groundwater recharge rates from 1975 to 1978 was mainly responsible for the early fall in watertable by about 0.5 to 0.7 m, although the effect of maturing pine plantations to the east may have also contributed to this decline. A period of relatively stable annual rainfall between 1979 and 1992 supported a mostly steady watertable, with the small decline of only about 0.05 m attributed to rainfall and possibly pine plantations.

Several years with below average rainfall from 1993 to 1998 (1993, 1994, and 1997) caused a minor fall in the Accumulative Residual Annual Rainfall, and an associated small decline in watertable over this period. HARTT analysis attributes declines in the watertable from rainfall effects of between about 0.1 m (west) and 0.3 m (east) over the period, although the evaluation east of the lake is uncertain. It is therefore considered that decreased rainfall resulted in around 0.1 m watertable decline at the lake between 1993 and 1998.

There was a gradual downward trend in the Accumulative Annual Residual Rainfall from 1999 to 2002. The HARTT analysis attributes declines in the watertable from rainfall effects of between 0.04 m (west) to about 0.2 m (east) about the lake over this period. It is therefore concluded that decreased rainfall resulted in a 0.1 watertable decline at the lake between 1999 and 2002.

Below average rainfall between 2003 and 2010 produced a downward trend in the Accumulative Annual Residual Rainfall (AARR), but with close to average annual rainfall since 2010 the rate of decline in the AARR was subsequently less. This pattern was reflected in the falling watertable. HARTT analysis attributes declines in the watertable from rainfall effects of between 0.7 m (west) and 1.8 m (east) from 2003 to 2014. HARTT analysis of data from sites on the eastern side of the lake appears to have over-estimated the decline from rainfall. Nonetheless, it is considered that rainfall has caused between 0.3 and 0.7 m decline in the watertable at the lake between 2003 and 2014.

PRAMS verification scenarios show a climatic effect on watertable levels of 0.5 m from 1995 to 2013, which is slightly less than the decline for the equivalent period derived from HARTT analysis.

8.4.2 Private pumping in the Nowergup and Carabooda Groundwater Sub-areas

Private pumping of groundwater in the Nowergup and Carabooda Groundwater Sub-areas is identified as the dominant cause for the watertable decline observed at Lake Nowergup until 2014. The methods used in this study to assess the impact of this pumping give comparative results. Schematic transient modelling give a decline in the watertable of 2.6 m when proportioned for the full allocations in the two groundwater sub-areas, although this was almost 3.6 m when simulations include a zone of low hydraulic conductivity in the Superficial aquifer just west of the lake. There are differences in timing between simulated impacts and observed drawdown that has resulted from the timing for increasing pumping rates used in the model. The PRAMS verification scenario gave a private pumping effect of 2.5 m. HARTT analysis for 1989 to 2014 attributes about 1 m of the decline on the western side of the lake as a response to private pumping, but between 2.61 and 4.01 m on the eastern side, although this includes a component caused by pumping from the Pinjar borefield (both Superficial and Leederville production bores).

There was minimal impact from private pumping prior to 1978, but a gradual decline in the watertable at the lake from 1979 to 1992 attributable to private pumping is evident from 1979, which totalled 0.3 m. From 1993 to 1998, there was a large increase in pumping in the Carabooda area and further development and expansion of market gardens in the Nowergup area. HARTT analysis attributes declines in the watertable from the private pumping of between 0.25 m (west) and 0.39 to 1 m (east) about the lake over the period, but for most sites east of the lake the analysis could not separate the effects of private pumping from pumping of the Pinjar borefield (both Superficial and Leederville production bores). However, the schematic modelling suggests that the influence from the Pinjar borefield is less than 0.2 m at this time. It is concluded that the watertable fell by up to 0.5 m at the lake in response to the private pumping from 1993 to 1998.

Continued increases in private pumping east of the lake over 1999 to 2002 would have been responsible for some of the watertable decline observed over this period. HARTT analysis attributes declines in the watertable from private pumping of about 0.2 m (west) to 0.3 m (east) about the lake over the period, with declines increasing eastward from the lake. It is concluded that private pumping was responsible for about 0.3 m of drawdown at the lake over this period.

Further increased private pumping in the Nowergup and Carabooda Groundwater Sub-areas since 2003 is probably responsible for most of the observed drawdown from this time. HARTT analysis indicates that 0.4 m of the decline west of the lake over the period is due to private pumping, while to the east it indicated combined private and Pinjar borefield pumping was responsible for between 0.8 and 1.0 m of the decline. It is considered around 0.6 to 1.2 m is attributable to private pumping and about 0.2 m to the Pinjar borefield (Superficial and Leederville production bores) based on HARTT analysis and schematic modelling.

Schematic modelling results indicate that private pumping in the Carabooda Groundwater Sub-area was the largest contributor to the falling watertable between 2003 and 2014, closely followed by private pumping in the Nowergup Groundwater Sub-area. The simulations also suggest that the watertable stabilized relatively quickly, and that most of the decline from private pumping has occurred at the lake already.

8.4.3 Water Corporation Pinjar borefield

The Pinjar borefield, comprising both production bores in the Superficial aquifer and Leederville aquifer, is over 8 km from the lake. Even though the borefield is relatively distant from the lake, the analysis here suggests that an influence does extend as far as the lake. There is greater potential for some watertable decline at Lake Nowergup from pumping the Leederville aquifer production bores due to the more extensive transmission of drawdown in the potentiometric heads within the Leederville aquifer. The total decline in the watertable at Lake Nowergup from pumping both the Superficial and Leederville bores in the Pinjar borefield is determined to be up to 0.65 m, with 0.3 to 0.35 m of that total attributed to Leederville production bores.

Schematic modelling at the end of the transient simulation (2013) for pumping from the Pinjar Superficial borefield gives watertable decline of 0.26 m at Lake Nowergup, compared with a steady-state decline of 0.43 m, which is 0.37 m and 0.6 m respectively for the model version incorporating a zone of low hydraulic conductivity west of the lake. It is anticipated that the model over-predicts the drawdown at the lake resulting from Pinjar Superficial production bores, largely due to attenuating processes not incorporated in the model such as evapotranspiration, which would decrease with a falling watertable and so reduce the rate of falling watertable. The model predicts the watertable decline at the lake from pumping the Leederville aquifer bores to be 0.27 m at the end of the transient simulation and 0.43 m at steady-state, but is 0.36 m and 0.63 m respectively for the model version incorporating the low hydraulic conductivity zone. Actual decline in water levels at the lake from this pumping is consistent with that indicated with the transient schematic model using the low hydraulic conductivity zone.

PRAMS Verification scenario modelling attributed a watertable decline at the lake of 0.7 to 0.75 m in response to pumping from the Leederville aquifer bores of the Pinjar, Wanneroo, Quinns and Whitfords borefields. The schematic model prepared for the current study showed that the Pinjar Leederville borefield causes about 43% of the decline from the combined Water Corporation Leederville production bores, and if this is apportioned to the PRAMS Verification modelling, it would indicate that Pinjar borefield pumping from the Leederville aquifer is responsible for a drawdown of almost 0.3 m at Lake Nowergup up to 2013.

There is no effect on the watertable evident at Lake Nowergup from the Pinjar borefield until 1992. Based on HARTT analysis and schematic modelling it is concluded that from 1993 to 2002 pumping from Leederville aquifer production bores within the Pinjar borefield probably caused no more than a 0.2 m decline, while pumping from the Superficial aquifer production bores may have contributed up to 0.2 m decline. HARTT analysis has not been effective in separating the impact of the Pinjar borefield upon the watertable.

Schematic modelling shows an ongoing gradual declining trend in the watertable in response to pumping from the Pinjar Leederville borefield onward from 2003. A small decline of 0.1 m may be attributed to the Superficial aquifer production bores of the Pinjar borefield during this period.

8.4.4 Water Corporation Quinns borefield

Groundwater pumping from both the Superficial and Leederville aquifers by the Quinns borefield has contributed to the watertable decline at Lake Nowergup. The assessment has found that the pumping from the Quinns borefield caused a total decline of 0.55 m to 0.7 m, which comprises 0.25 m to 0.3 m from the Superficial aquifer pumping and 0.3 m to 0.4 m from the Leederville aquifer pumping.

Schematic modelling suggests that the watertable decline at Lake Nowergup caused by pumping from the Quinns Superficial production bores has reached a stable level of up to 0.2 m. Pumping from the Leederville aquifer production bores is shown to cause a decline of almost 0.4 m by end-2013 in the transient simulation, and up to 0.7 m for steady-state.

PRAMS verification scenarios indicate that Water Corporation pumping from the Superficial aquifer is responsible for a watertable decline of 0.4 to 0.5 m at the lake, which will comprise effects from both the Quinns and Pinjar borefields. PRAMS also predicts that the Quinns Leederville aquifer production bores have caused about 0.3 m of watertable decline (assuming 44% of the response to the Water Corporation Leederville aquifer pumping is from the Quinns borefield as suggested by the schematic model prepared for this study). HARTT analysis of bore data from west of the lake attributes a total decline to the Quinns borefield (both Superficial and Leederville aquifer production bores) of about 0.5 m to 0.6 m.

There was a marked decline in the watertable within the Tamala Limestone once pumping commenced from the Quinns borefield in 1999. Up to 0.3 m of the decline is attributed to the Quinns Superficial production bores, although this was not generally seen until 2001 due to pumping from these bores starting about a year later than the Leederville production bores. Therefore, the fall in the watertable between 1999 and 2001 about the western side of the lake (around 0.3 m) is considered to be from another activity or activities. Based on timing, the Leederville aquifer production bores of the Quinns borefield have probably contributed most of the additional decline observed about the western side of the lake.

Schematic modelling also gives the main cause for the falling watertable between 1999 and 2002 as pumping from the Quinns borefield, with similar contributions from each of the Superficial and Leederville aquifer bores (total up to 0.3 m). The simulated response appears to be less than indicated by hydrographs.

HARTT analysis suggests that most of the watertable decline west of the lake is a result of Quinns borefield pumping (combined Superficial and Leederville aquifer bores). The analysis attributes about 0.5 m of the decline between 1999 and the end of 2002 to the borefield, and that of this up to 0.3 m is attributed to pumping from the Leederville aquifer.

From 2003, the impact resulting from Quinns borefield Superficial aquifer pumping has probably reached near equilibrium conditions and is unlikely to contribute further to subsequent declines in the watertable at Lake Nowergup. This conclusion is supported by the results of the schematic model. Further decline in the watertable at the lake has likely occurred due to continuing drawdown in the Leederville aquifer beneath the lake in response to pumping from the Quinns Leederville aquifer borefield. Schematic modelling suggests almost 0.2 m of additional decline has occurred since 2003 as a result of pumping these Leederville aquifer bores, while HARTT analysis attributes much less than 0.1 m to that pumping. It is concluded that around 0.1 m of watertable decline has resulted from pumping the Quinns Leederville borefield since 2003.

8.4.5 Supplementation bore 2/00

Groundwater pumping from the supplementation bore 2/00 in the Leederville aquifer at Lake Nowergup is predicted to cause only a minor decline in the watertable. Monitoring bore hydrographs do not show any identifiable response in the watertable resulting from pumping of this bore. Model simulations show final transient drawdown of up to 0.07 m by 2013 compared to the steady-state drawdown of up to 0.1 m. Therefore, drawdown in the watertable from this pumping is near steady-state levels and unlikely to significantly increase under the current pumping regime.

There appears to have been only very minor watertable decline from the supplementation bore between 1999 and 2002, with almost all of the decline occurring onward from 2003. The decline may have been marginally greater if vertical permeability of the Leederville aquifer is higher than that used in the groundwater modelling.

8.4.6 Lake supplementation

Supplementation of lake water commenced at Lake Nowergup in a significant way from 1998, and has resulted in raising the watertable about the lake above where it would have been without the supplementation due to leakage of water from the lake. Based on monitoring bore hydrographs and HARTT analysis, it is concluded that the watertable has risen by around 0.6 to 0.8 m as a result of the supplementation.

Prior to 1998, supplementation would have had a minimal influence on the watertable. Between 1998 and the end of 2002, the supplementation probably resulted in a 0.2 m rise in the watertable, with HARTT analysis giving values of 0.05 m west of the lake and about 0.2 m east of the lake. Since 2003, hydrographs suggest that the supplementation has been responsible for maintaining the watertable at about 0.35 to 0.55 m higher than it otherwise would have been. HARTT analysis of bores west of the lake indicate that from 2003 a rise of watertable levels by 0.35 m is due to supplementation, but adjacent to the lake the rise would have been greater. About the east side of the lake the HARTT analysis was not able to separate effects of rainfall and lake supplementation, but comparison with rainfall effects elsewhere suggests that lake supplementation would have caused a rise in the watertable of about 0.9 m.

8.5 On-going trends and possible remedial actions

The long-term watertable at Lake Nowergup is projected to remain relatively stable in response to on-going groundwater pumping. Recent reductions in pumping rates of the Water Corporation borefields has decreased the ultimate drawdown by between about 0.8 m and 1.2 m at the lake. There should be a recovery in levels of about 0.25 m from pumping from the Pinjar borefield, while additional drawdown from the Quinns borefield Leederville production bores of just over 0.1 m is anticipated. Water levels about the lake could take around 10 years to fully respond to the reduced pumping. Drawdown from the Quinns Superficial borefield has reached equilibrium at the lake, while that caused by private pumping in the Nowergup and Carabooda Groundwater Sub-areas has, or is very close to stabilising, where any additional drawdown from current private pumping should not exceed about 0.3 m. The influence of future rainfall and land-use changes on watertable levels will be superimposed upon the pumping effects.

There are several options that could help raise the lake water levels of Lake Nowergup. Large reductions in groundwater pumping would allow recovery in groundwater levels and lake water levels, with private pumping in the Nowergup and Carabooda Groundwater Sub-areas offering the greatest short term benefit. Apart from reducing groundwater pumping, other strategies that have potential to raise watertable and lake levels are:

- Increased lake supplementation,
- Shifting private production from the Superficial aquifer to the Leederville or Yarragadee aquifer,
- Artificial aquifer recharge,
- Increasing groundwater recharge rates up-gradient of the lake.

It is estimated from Darcy's Law that as of 2014 at least 2000 ML/year of water is required for lake supplementation to maintain lake water levels at around 16.2 mAHD. In the longer-term this may increase to 4000 ML/year if the watertable declines to about 12 mAHD (see Section 5.4.4 'Effectiveness of lake supplementation').

Shifting of private pumping from the Superficial aquifer to the Leederville or Yarragadee aquifer in the Nowergup and Carabooda Groundwater Sub-areas would result in a recovery of the watertable at the lake. As the largest cause for declining watertable levels at Lake Nowergup has been private pumping from the Superficial aquifer in these sub-areas, this may also offer the most significant and quickest recovery in watertable levels if production can be shifted from the aquifer. The schematic model predicts that by shifting all private pumping from the Superficial to Leederville aquifers the long-term watertable decline decreases from 1.86 m to 0.5 m, representing a recovery in the watertable of 1.36 m. These results include the additional drawdown caused by the greater leakage into the Leederville aquifer. The simulations indicate that potentiometric heads in the Leederville aquifer would decline by an additional 4.6 m. If pumping is shifted into the deeper Yarragadee aquifer, then there should be a full recovery in groundwater levels from the drawdown caused by private pumping in these groundwater sub-areas, which could be around 2 m.

Although it may not be practical to shift all of the private pumping to the deeper confined aquifers, much of the benefit could still be gained by moving the largest producing bores that are closest to the lake. Before such a strategy was adopted, further evaluations should be undertaken, including the ability of the Leederville aquifer to sustain increased pumping, which would include investigation drilling and testing of the Leederville Formation, establishment of monitoring bores, and refinement of the Local Area Model to allow appropriate testing of proposed changes. A disadvantage in shifting pumping to the Leederville aquifer is that the area over which a drawdown in the watertable is experienced will be significantly increased and may impact other environmentally significant locations, including Loch McNess to the north.

Moving production to the Yarragadee aquifer would avoid local impacts, but may have some implications at more distant sites where the aquifer is hydraulically connected with the surface environment, such as Yeal Nature Reserve upon the north-eastern Gnangara Mound. The injection or infiltration of groundwater pumped from the Yarragadee aquifer into the Superficial aquifer east of the lake could be considered as a strategy. This would help support the watertable and partially off-set private groundwater pumping from the Superficial aquifer in the Nowergup and Carabooda Groundwater Sub-areas. It is projected that the recharge of 2 GL per year into the Superficial aquifer about 500 m northeast of the lake would result in watertable levels rising by about 1.4 m at the lake, with about 70% of this rise occurring within 5 years from the start of artificial recharge.

Groundwater recharge rates can be increased up-gradient of the lake to raise watertable levels by changing land-use types. Water efficient and environmentally sensitive urbanisation would be the most effective means of achieving significantly higher groundwater recharge rates and an associated rise in watertable levels. One potential area for urbanisation are pine plantations about 3 km to 6 km east of the lake, and extending 2 km north-south, where pine tree removal has already been largely completed. The distance of this area from the lake will, however, reduce the potential benefit on watertable levels resulting from urbanisation. An alternative area for urbanisation is immediately east of the lake, covering much of the Nowergup horticultural area from about 500 m to 1.8 km east of the lake and extending 2 km north and south.

Simulations using the schematic model with a recharge rate increased to about 50% rainfall (equivalent to 0.001 m/day or 365 mm/yr) for these urbanised areas from a pre-existing 20% rainfall recharge rate (0.000416 m/day or 151 mm/yr) showed a rise in the watertable at Lake Nowergup of 0.39 m in response to urbanisation of the pine plantation area and 0.27 m rise from urbanisation immediately east of the lake, totalling 0.66 m for both areas combined. The Lake Nowergup Local Area Model (SKM, 2009a) found clearing of pine plantations and replacement by grasslands with an associated increase in recharge rates from 0 to 30% of rainfall resulted in a watertable rise of 4 m beneath the plantation and 2 m rise at Lake Nowergup. The greater rise in the watertable predicted by the Local Area Model is largely due to the much larger areas of clearing simulated, where all pine plantations have been removed. It is suspected, however, that the predicted rise is excessive due to the area of increased recharge apparently covering areas much larger than the pine plantations. Much of the pine clearing has already occurred east of Lake Nowergup, but to date there has been minimal influence on watertable levels.

There would be little advantage in shifting the supplementation bore 2/00 to a site more distant from the lake to reduce its effect on the watertable as the apparent drawdown in the Superficial aquifer caused by pumping this bore is low. Shifting the bore to a site more distant from the lake would reduce the drawdown effect only marginally. A greater benefit would be gained by establishing the bore deeper into the Leederville aquifer, although the existing bore (2/00) may already be screened in the lower-most portion of the Wanneroo Member (main part of aquifer).

A deeper bore would therefore have to be constructed in the underlying Mariginiup Member of the Leederville Formation. The lower permeability (both horizontal and vertical) of the Mariginiup Member would further hydraulically isolate the bore from the Superficial aquifer, and therefore pumping of the bore would have less impact on the watertable. However, it would make for a lower capacity bore, and several bores may therefore be required to meet the supply. An alternative water source is the deeper Yarragadee aquifer present beneath the site, for which there would be practically no impact at the watertable if used as a supplementation water source.

9 Conclusions

Lake water levels within Lake Nowergup are effectively controlled by water levels within the adjoining and underlying Superficial aquifer, where the declining watertable has been directly responsible for declining lake levels. Lake Nowergup has transitioned from a throughflow lake before 2002 to a lake now dependent on artificial maintenance by the pumping of supplementation water into the lake. As of 2014, the lake water level is estimated to be up to 0.8 m higher than that which probably would have occurred without supplementation.

Hydrogeology

The Superficial aquifer comprises the Bassendean Sand and Ascot Formation east of the lake, and the Tamala Limestone with Ascot Formation west of the lake, which form a transmissive unconfined aquifer that is hydraulically connected with Lake Nowergup. The Tamala Limestone at the site comprises a calcareous clayey sand facies that is overlain by a limestone facies of calcareous arenite west of the lake.

Previous work did not fully recognise the significance of the clayey sand facies in the lower Tamala Limestone in creating a zone of low permeability within the Superficial aquifer. The clayey sand facies present beneath the lake and possibly extending up to 1 km west of the lake transitions into a calcareous sand toward the coast. The clayey sand facies thins westward from the lake and forms a tapering wedge between the limestone facies and calcareous sand. Hydraulic parameters are not available for the clayey sand facies, but its hydraulic conductivity derived from lithology and through-flow analysis is probably in the order of a few metres per day. The zone of steep watertable gradient between the Bassendean Sand and limestone facies portion of the Tamala Limestone occurs through the clayey sand facies.

A clay layer up to 10 m thick in the upper part of the clayey sand facies is present about the western margin of the lake and probably extends beneath the western portion of the lake where it may sub-crop lake bed deposits. The clayey sand facies and upper clay layer create a low permeability zone that supports a downward hydraulic gradient between the lake and the underlying Superficial aquifer about the west side of the lake. The highly transmissive limestone facies does not extend as far east as Lake Nowergup, and does not extend below the watertable until around 1 km west of the lake.

Lake bed deposits of sand, silt and organic clay form a low permeability floor to the lake that provides an interval resistive to groundwater flow. Higher levels of the lake floor about the lake margins are probably more permeable with greater hydraulic connection between the lake and aquifer, particularly up-gradient about the eastern lake side. This zone of higher permeability allows for more rapid lateral movement of groundwater into the lake when the watertable elevation is sufficiently high, probably greater than approximately 6.2 mAHD. The average vertical hydraulic conductivity beneath Lake Nowergup, including the lake bed deposits and clayey sand facies of the Tamala Limestone, is calculated from water flux rates and Darcy’s Law to be an average of approximately 0.17 m/day over the upper 20 m of the Superficial aquifer.

The Ascot Formation is a permeable unit within the lower portion of the Superficial aquifer. It is up to 21 m thick at the lake, with a hydraulic conductivity probably greater than 47 m/day. However a dark grey sandy clay bed present in the lower part of the unit has low permeability and is interpreted to form an extensive but probably discontinuous aquitard about the eastern area of Lake Nowergup. Hydrograph responses to groundwater pumping from the Leederville aquifer show that this sandy clay layer impedes the hydraulic connection between the Superficial aquifer and underlying Leederville aquifer, at least locally east of the lake.

The Leederville aquifer underlies the Superficial aquifer at Lake Nowergup, which comprises the Wanneroo member as its uppermost unit in this area. The Wanneroo member contains the thickest and coarsest sand beds of the formation, and forms the most permeable part of the aquifer, with a hydraulic conductivity of 43.5 m/day determined from test pumping over the main sand interval at the lake. Over the full aquifer, incorporating silt and shale layers, the average hydraulic conductivity is probably around 10 m/day. There is a good degree of vertical hydraulic continuity within the Wanneroo member, while clay layers present in the lower Ascot Formation reduces the hydraulic connection between the Leederville aquifer and the overlying Superficial aquifer.

The drawdown impact at the watertable resulting from reduced potentiometric heads in the Leederville aquifer is sensitive to the vertical hydraulic conductivity through the Leederville aquifer. Based on schematic modelling and hydrograph analysis, it is suspected that the vertical hydraulic conductivity of the Leederville aquifer is somewhat greater about Lake Nowergup than the 5×10^{-4} m/day value used in the regional PRAMS groundwater modelling, but possibly less than double (1×10^{-3} m/day) this value.

Existing groundwater models

A review of existing groundwater models relevant for the Lake Nowergup area has found that the PRAMS model is suitable for evaluating regional drawdown attributable to different pumping operations, although local impacts may vary somewhat due to variations in aquifer hydraulic parameters not captured in the regional model. The relatively large 500 m grid-size means that small features such as the zone of low hydraulic conductivity in the vicinity of Lake Nowergup cannot be effectively incorporated and that results about these features will be approximate.

The SKM Local Area Model may require some modifications within the Superficial aquifer to reflect the revised hydrogeology in the vicinity of Lake Nowergup. It would then be suitable for modelling scenarios within the Superficial aquifer. However there are some deficiencies in the modelling of the Leederville aquifer and the model would need to be revised to be suitable for modelling potential impacts of pumping from the Leederville aquifer.

Watertable declining trends

Hydrographs from monitoring bores show that the watertable has been declining for most of the period since 1973 within the Bassendean Sand component of the Superficial aquifer east from the coastal chain of lakes. Three main phases of declining watertable are evident:

- Phase 1 1973 to 1979 – rapid watertable decline,
- Phase 2 1980 to 1992 – gradual declining or stable watertable,
- Phase 3 1993 to 2014 – significant increase in the rate of watertable decline, which increases further from the year 2000.

Phase 1 precedes any significant groundwater pumping in the area, and the falling watertable at this time is in response to reduced groundwater recharge rates due to lower average annual rainfall and the effect of maturing pine plantations. A period of relatively stable rainfall during

Phase 2 helped maintain watertable levels until about end-1992, except in the Carabooda Groundwater Sub-area where some drawdown in the watertable is seen that may be due to local pumping. From 1993 the watertable enters a period of more rapid decline in Phase 3, which increases even further from 2000. Phase 3 corresponds with a significant increase in groundwater pumping from the Pinjar Borefield, which commenced incrementally from 1993 to 1997, and the Quinns Borefield from 1999, and significant increase in groundwater pumping for horticultural activities in the Carabooda Groundwater Sub-area northeast of the lake, with additional pumping in the Nowergup Groundwater Sub-area to the southeast. A prolonged period of lower rainfall from 2000 to 2010 would have contributed to the increased rate of decline from 2000.

To the west within the Tamala Limestone, the watertable declined at very low rates until about the year 2001. Monitoring bores located toward the eastern limit of the Tamala Limestone near the Carabooda area did show a progressive decline in the watertable commencing in 1994 that is considered associated with pumping in the Carabooda Groundwater Sub-area. A rapid decline in the watertable of around 0.2 to 0.3 m is seen within the Tamala Limestone from 2001 in response to the commencement of pumping from the Quinns Superficial aquifer borefield. A recovery trend in the watertable starting from 2005 in the south of the study area but starting progressively later further north may be related to the effect of increased groundwater recharge from land clearing and urbanisation, and reduced pumping from the Quinns Superficial borefield on-ward from 2012.

About Lake Nowergup watertable hydrographs show similar trends as observed at the sites further from the lake, with the exception that lake supplementation maintained or at least partially held up watertable levels for a period between 2002 and 2008.

Lake water levels and supplementation

Without on-going lake supplementation, the lake would now have become dry during summer – autumn, with only a small area of open water developing during winter. The rate of supplementation needs to increase to maintain the criteria lake water levels as the watertable level at the lake declines. Failure to increase supplementation as the watertable declines will result in a contraction of the lake area and declining lake water level until the lake water balance matches downward leakage from the lake, with some variation caused by rainfall and evaporation. This process is responsible for the lake contraction over the last several years. At the current watertable of 13.5 to 14.5 mAHD, it is estimated that lake supplementation of 2000 to 2700 ML per year will be required to maintain lake levels at around 16.2 mAHD. This would require constant supplementation averaging around 7000 kL/day. In the long-term as the watertable further declines in response to on-going groundwater pumping the rates of lake supplementation may have to increase toward 4 GL per year.

Factors contributing to the watertable decline at Lake Nowergup

The watertable declined by slightly more than 0.5 m at Lake Nowergup between 1973 and 1989 and by more than 3 m since 1989, and may have fallen by up to 4.1 m. Factors contributing to the decline are:

- Changing rainfall and land-use,
- Private groundwater pumping in the Nowergup and Carabooda Groundwater Sub-areas,

- Pumping for public supplies from the Pinjar and Quinns borefields, including both Superficial aquifer and Leederville aquifer production bores,
- Pumping of the lake supplementation bore.

Based on the analysis undertaken, it is concluded that drawdown resulting from all of the factors considered in this assessment totals between 3.5 m and 5.2 m. This is partially off-set by lake supplementation that has raised the watertable by 0.6 m to 0.8 m. Private pumping of groundwater in the Nowergup and Carabooda Groundwater Sub-areas is assessed as having had the largest impact on the watertable at Lake Nowergup, resulting in a decline of 1.4 m to 2.4 m since 1979. Pumping from the Pinjar and Quinns borefields for public water supply is determined to have contributed 1.0 m to 1.3 m of the decline, while the supplementation bore at Lake Nowergup has had minimal effect on the watertable, probably causing less than 0.1 m of the decline. Changes in rainfall are assessed as causing 1.05 m to 1.45 m of the watertable decline since 1973.

The most immediate impacts on the watertable at Lake Nowergup result from private pumping from the Superficial aquifer in the Nowergup and Carabooda Groundwater Sub-areas, and pumping in the Quinns Superficial borefield for public water supply. The drawdown resulting from pumping in these areas have or have almost reached stable levels. Impacts from the Quinns Superficial borefield appeared to occur within just a few years of the commencement of pumping.

Drawdown of potentiometric head in the Leederville aquifer associated with pumping from the aquifer results in a more gradual watertable decline. The vertical hydraulic conductivity through the Leederville aquifer is the most significant parameter controlling the degree of potentiometric head loss from this aquifer propagating upward to the watertable. Leakage of groundwater downward from the Superficial aquifer into the Leederville aquifer has been found to be a small component of the groundwater fluxes at Lake Nowergup, but it represents a significant contributor to declines in the watertable because it occurs over an extensive area.

Future watertable trends

It is anticipated that long-term watertable levels about Lake Nowergup will remain relatively stable in response to on-going groundwater pumping. Recent reductions in pumping rates of the Water Corporation borefields has limited future drawdown impacts, with some recovery projected from reduced pumping in the Pinjar borefield, although benefits of this reduced pumping could take about 10 years be fully realised at the lake. Most of the impact at the lake from private pumping in the Nowergup and Carabooda Groundwater Sub-areas has already occurred, with about another 0.3 m of decline possible before reaching an equilibrium. At current pumping rates, impacts from the Quinns Superficial borefield and the supplementation bore have probably stabilised. Increased groundwater recharge resulting from urbanisation west of the lake may mitigate some of the declines attributed to Quinns Superficial borefield pumping (maybe 0.1 to 0.2 m). The influence of future rainfall and land-use changes on watertable levels will be superimposed upon the pumping effects.

Recovery Options

Options that could help raise lake levels of Lake Nowergup, apart from a reduction of groundwater pumping, include increased lake supplementation, a shift in private production from the Superficial aquifer to the Leederville or Yarragadee aquifer, artificial aquifer recharge and increased groundwater recharge rates up-gradient of the lake such as that associated with urbanisation.

10 Recommendations

Recommendations presented here are intended to provide options for consideration in addressing the falling water levels of Lake Nowergup. Regulatory and economic constraints that will influence management decisions are not considered herein.

Revise lake supplementation strategy

Revise the lake supplementation strategy to account for increasing rates of supplementation required to maintain lake water levels as the watertable declines further.

Improved monitoring of lake water levels and watertable levels beneath the lake will be required to allow for effective lake supplementation planning. Detailed monitoring of supplementation rates (daily) and lake water levels (currently not monitored below 16 mAHD) are needed, as well as watertable levels, particularly in the closest monitoring bores about the eastern, northern and southern margins of the lake. Greater detailing of the lake floor topography would allow better mapping of lake extents and volumes associated with various lake water levels. This would facilitate improved calculation of the lake water balance (including rainfall and evaporation), downward leakage from the lake, and its relationship to the watertable.

A supplementation trial discharging water to the lake at a sufficiently high rate to maintain lake levels at 16.2 mAHD for an extended period is recommended, preferably conducted for a minimum of one year. A pumping rate of around 7000 kL/day would be required. If pumping is restricted to times of off-peak power, then the bore will need to be pumped at a proportionally greater rate to achieve the daily volume required. The original test pumping analysis of supplementation bore 2/00 indicated that it should be capable of pumping in excess of 10,000 kL/day on a sustainable basis (Varma, 2000) if appropriately equipped. A review of the construction and test pumping of the existing bore is required to assess if it is capable of meeting the required supply rate when pumping is limited to off-peak periods. Monitoring data collected during the trial would be used to prepare a more accurate water balance model for the lake that can be used for future planning.

A revised lake supplementation strategy developed using the water balance model prepared from the supplementation trial data should be implemented. To maintain criteria lake water levels it is anticipated that supplementation will be required on a daily basis possibly throughout the year, as any prolonged period without supplementation will result in a rapid fall in lake water levels. As watertable levels continue to decline, the rate of lake supplementation would have to be increased.

Hydrogeological characterisation

Further hydrogeological characterisation of the Tamala Limestone clayey sand facies and Ascot Formation clay layer, for incorporation in subsequent revisions to the conceptual hydrogeological model and Local Area Model (and would benefit future PRAMS revisions).

The lithology, extent and hydraulic properties of the clayey sand facies in the Tamala Limestone are not well defined. An investigation into the clayey sand facies could involve obtaining core through the zone at several sites. The core would be geologically logged, noting the lithology and sedimentary structures, and retained for laboratory analysis of permeability. Bores should be established within the unit for test pumping or slug tests to assess hydraulic conductivity values. The investigation could consider including a geological study of the Tamala Limestone in the transition area to determine the changing depositional environments related to each of the facies types, which may allow for more confident spatial extrapolation of each facies over the area.

Continuity of the clay layer within the lower Ascot Formation is not well defined. Mapping the thickness and extent of this unit could be aided by running down-hole gamma-ray surveys within the deeper monitoring bores, and any subsequent bores that may be drilled in the area. These would allow more accurate definition of clay intervals within the bores.

Monitoring

Establish monitoring bores in the Leederville aquifer, and re-establish watertable monitoring at selected bores about the lake.

Monitoring bores should be constructed into the Leederville Formation near the lake and at sites between the lake and the Pinjar and Quinns borefields to monitor drawdown of potentiometric levels in response to Leederville aquifer pumping. These monitoring bores should be screened approximately within the middle portion of the Wanneroo Member.

Monitoring of many LN-series bores ceased in 1999. At selected sites (such as LN11 and LN26) monitoring should resume so that changing groundwater levels about the lake can be assessed. It may be advantageous to establish additional nested monitoring bores into various levels of the Superficial aquifer at sites as close to the lake water body as possible about the eastern (midway along lake), northern and southern sides. This will allow for better profiling of the vertical hydraulic gradient near the lake and the influence of infiltrating water from the lake.

Local Area Model

The Local Area Model requires adjustments to the parameter distribution and further calibration so that it can be used to test watertable recovery options.

Revision to the parameter distribution for layers representing the Superficial aquifer in the Local Area Model is required along with further calibration to incorporate the improved understanding of hydrogeological concepts about the lake, such as the low permeability zone west of the lake, and vertical variability through the Superficial aquifer. This should allow for more accurate modelling of the Superficial aquifer about the lake and the influence that it has on the lake. Further calibration is also required to improve modelling of the Leederville aquifer as the model is not currently suitable to examine the influence of groundwater pumping from this aquifer. A high anisotropy should be used for the Leederville aquifer, similar to PRAMS. There should also be a high vertical hydraulic conductivity zone at the western boundary off-shore to simulate the Badaminna Fault, similar to the approach used in PRAMS.

The use of a 2 m extinction depth for evapotranspiration over the whole domain is incompatible with deep-rooted vegetation in parts of the domain. Therefore, a deeper extinction depth for mature pine plantations and banksia forest should be used.

Some alteration of the model extent and boundary conditions are required to more appropriately model the aquifers. The model should be extended offshore to the Badaminna Fault, and the approach taken by PRAMS should be used where an equivalent head of

0.5 mAHD is used in the topmost aquifer layer over the coastal cells. The general head boundary at the eastern boundary of the model should not be fixed at a constant head of 51 mAHD, but allowed to vary in line with long term water level trends in the Superficial and Leederville aquifers.

Following the required modifications and calibration, the model should then be used to verify drawdown projections resulting from the areas of groundwater pumping, and to test the viability of watertable recovery strategies.

<u>Strategies for recovery in watertable levels</u>

Strategies for the recovery in watertable levels could involve the shifting of production from the Superficial aquifer to the Leederville aquifer, artificial recharge and urbanisation to increase groundwater recharge rates.

Schematic modelling suggests that shifting of private pumping from the Superficial aquifer to the Leederville aquifer in the Nowergup and Carabooda Groundwater Sub-areas would result in the most rapid watertable recovery of up to 1.36 m at the lake. Much of this benefit could be gained by moving only the largest producing bores that are closest to the lake into the deeper Leederville aquifer. Further hydrogeological evaluations would be required to establish the ability of the Leederville aquifer to sustain the increased pumping and the impact that increased pumping from the Leederville aquifer would have on the watertable over the larger area. This evaluation may include investigation drilling and testing of the Leederville aquifer, and the establishment of monitoring bores. Following analysis of the investigation data and revisions to the Local Area Model, model simulations should be undertaken to test the proposed strategy. As the benefit in shifting production from the Superficial to Leederville aquifer diminishes with increasing distance from the lake, the model should be used to determine the distance from the lake beyond which there is no advantage in shifting production. A possible constraint to shifting groundwater pumping to the Leederville aquifer would be increased watertable drawdown at Loch McNess to the north.

An alternative to pumping water from the Leederville aquifer would be to shift pumping to the deeper Yarragadee aquifer. This would have the advantage in that there should be practically no impact on the watertable about Lake Nowergup (or Loch McNess), although some impact could result in the north-eastern Gnangara Mound area where the Yarragadee aquifer is hydraulically connected with the Superficial aquifer.

Watertable levels about Lake Nowergup can be raised by artificial recharge of the Superficial aquifer in the vicinity of the eastern margin of the lake. Groundwater could be pumped from the Yarragadee aquifer and either infiltrated or injected into the Superficial aquifer. This may be an efficient strategy in off-setting the drawdown impacts from private pumping in the Carabooda Groundwater Sub-area, where the recharge of about 2 GL/year negates the drawdown caused by pumping of around 8 GL/year in that sub-area.

Water efficient and environmentally sensitive urbanisation would be an effective means of achieving significantly higher groundwater recharge rates and an associated rise in the watertable. Potential areas for urbanisation include pine plantations (recently harvested) about 3 to 6 km east of the lake, and extending 2 km north-south, and an area immediately east of the lake, covering much of the Nowergup horticultural area from about 0.5 to 1.8 km east of the lake and extending 2 km north and south. Schematic modelling suggests that increasing the recharge rate to about 50% of rainfall for both areas combined could lead to a rise in the watertable at Lake Nowergup of 0.66 m.

Although pumping groundwater from the supplementation bore has caused a maximum decline at the watertable of only about 0.07 m, if pumping is increased to around 4 GL/year then the drawdown could increase to in excess of 0.2 m. The most effective means to reduce the impact from the supplementation bore on the watertable would be to replace the bore with another, constructed deeper in the Leederville Formation or into the Yarragadee aquifer. The deeper Leederville aquifer may not be sufficiently conductive to provide sufficient yield from a single bore, which potentially could be very low yielding if constructed into the Mariginiup Member of the Leederville Formation. The deeper Yarragadee aquifer is present at the lake from a depth of about 300 m beneath the South Perth Shale, and should be sufficiently conductive for adequate bore yields.

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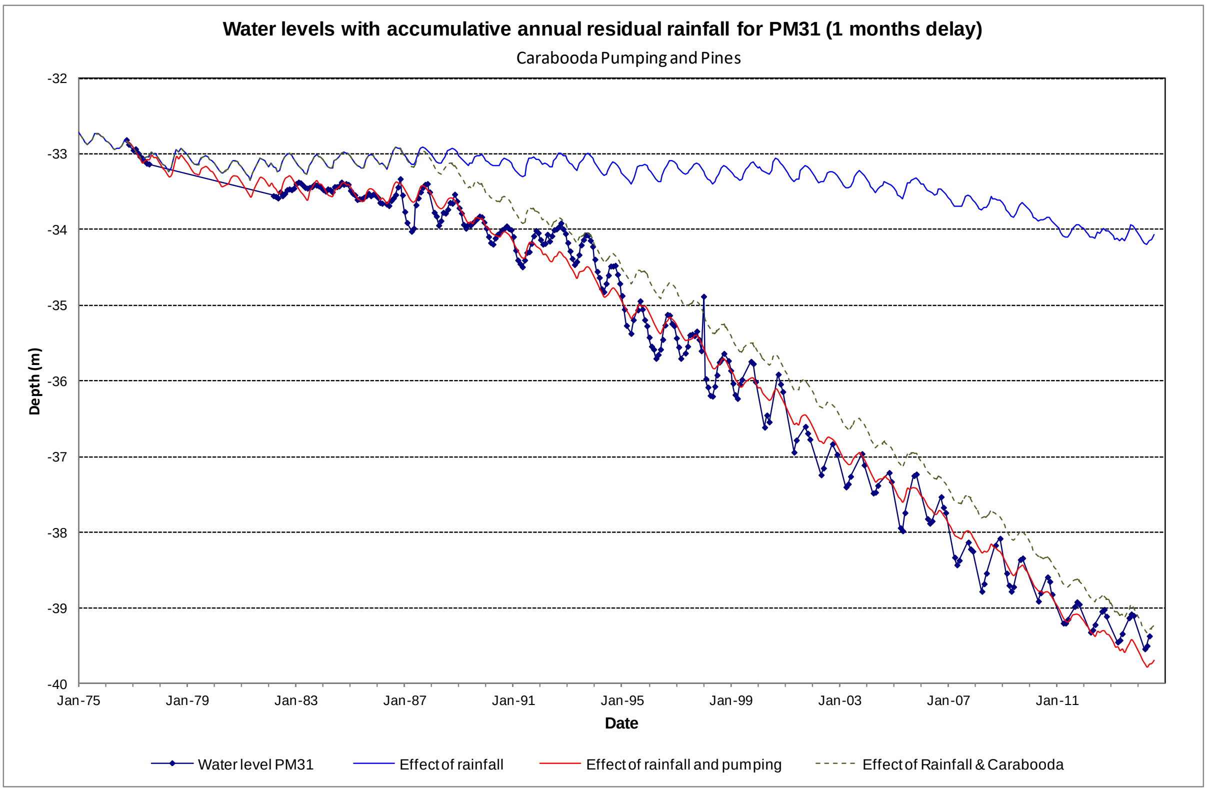
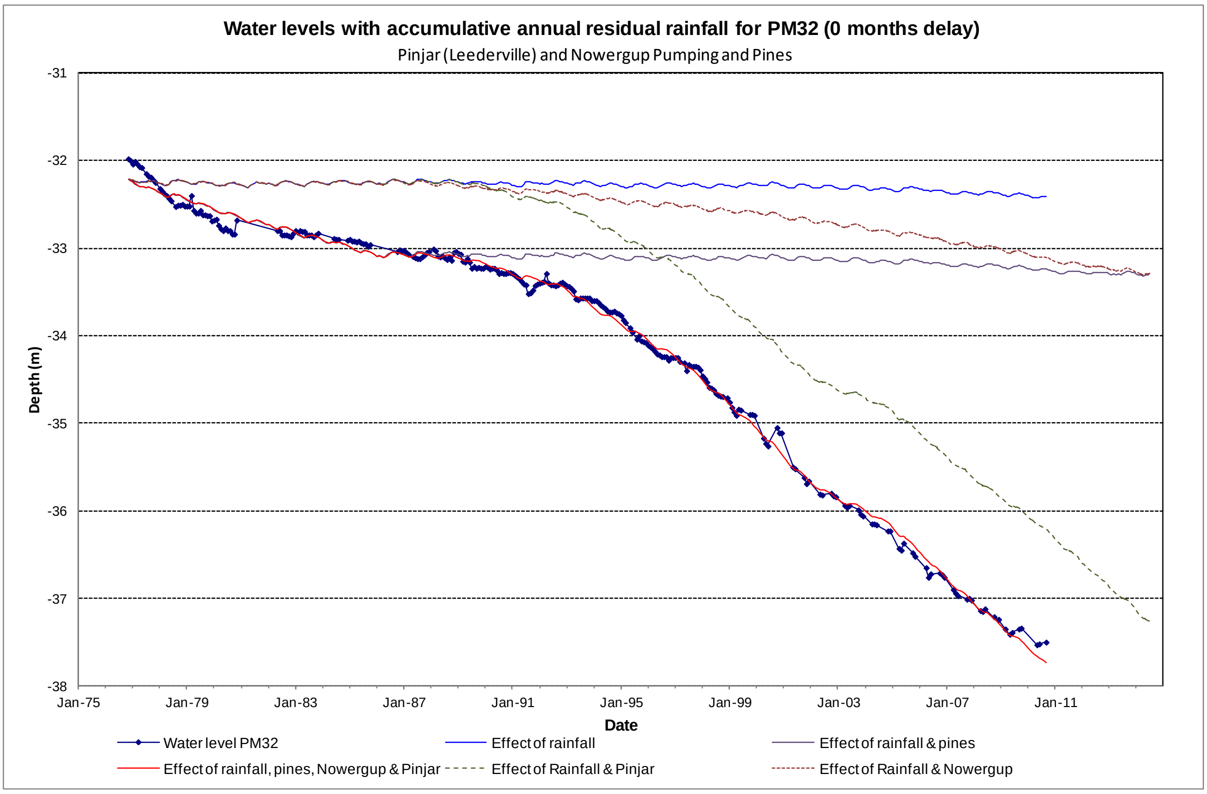
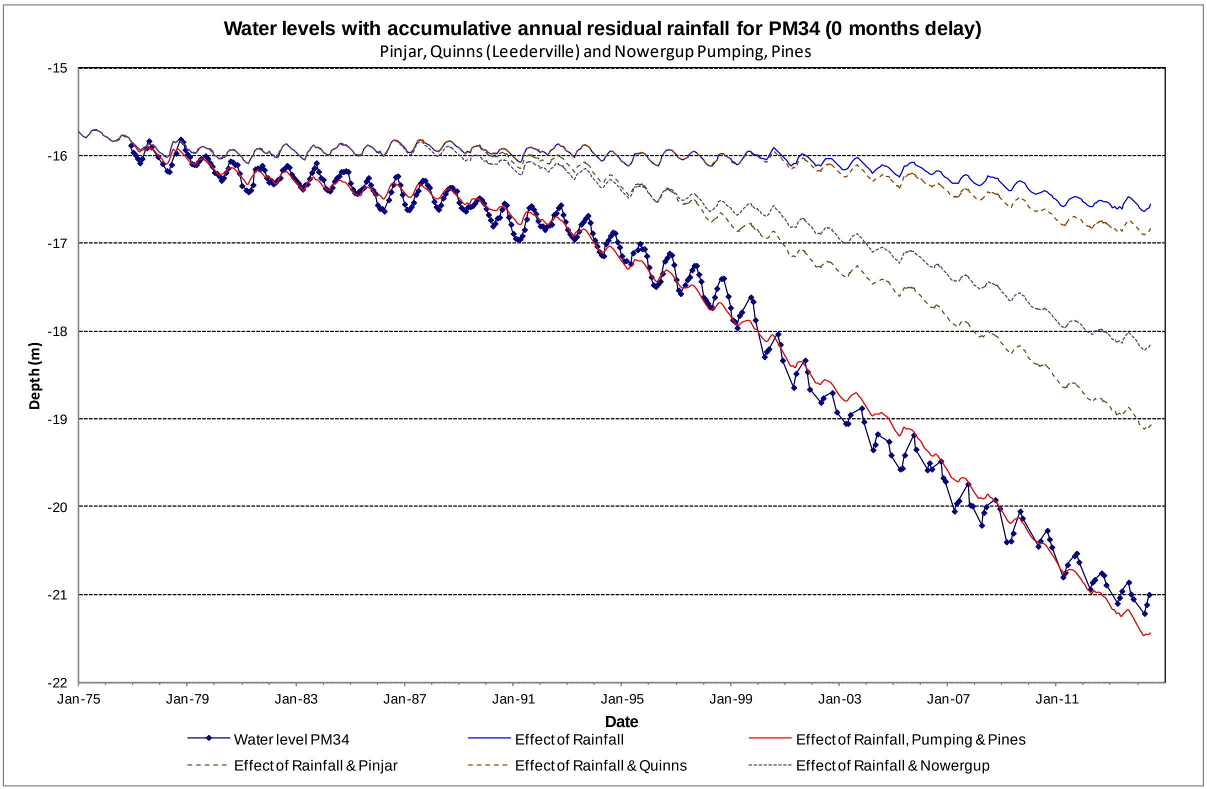
Appendices

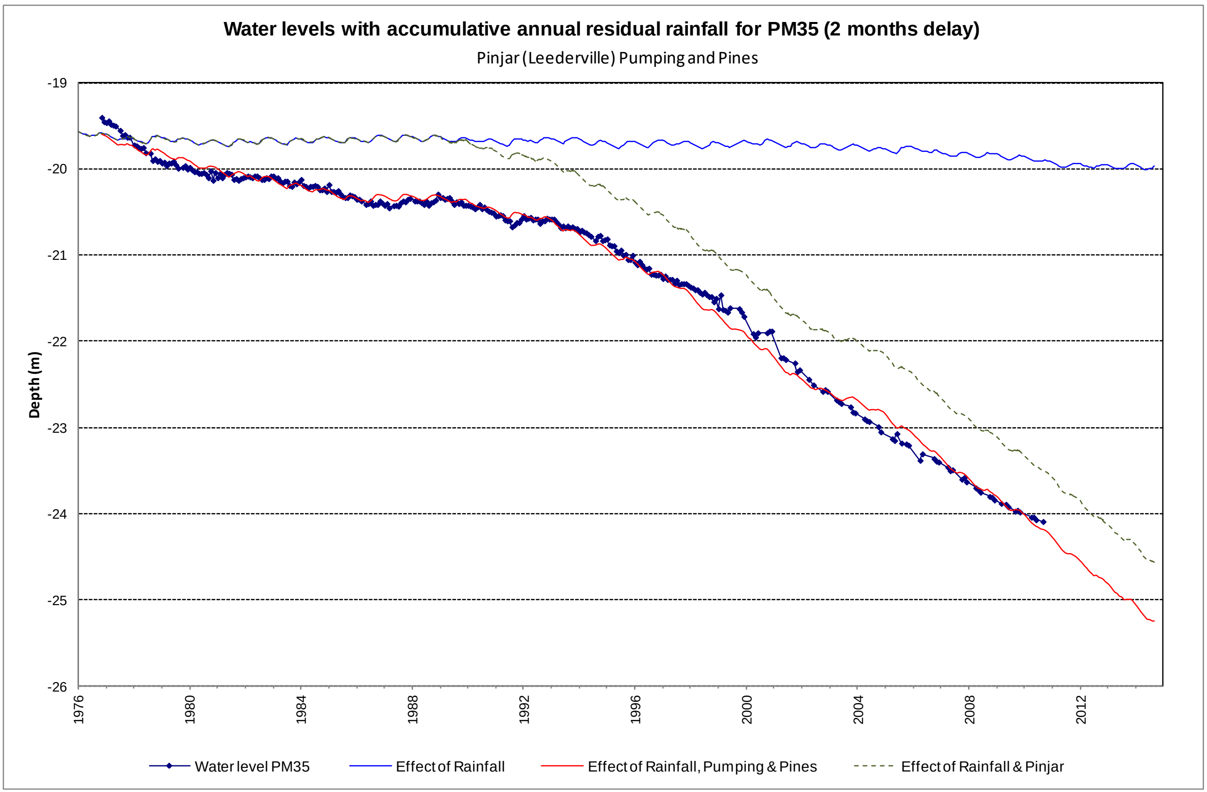
Appendix A: HARTT analysis charts

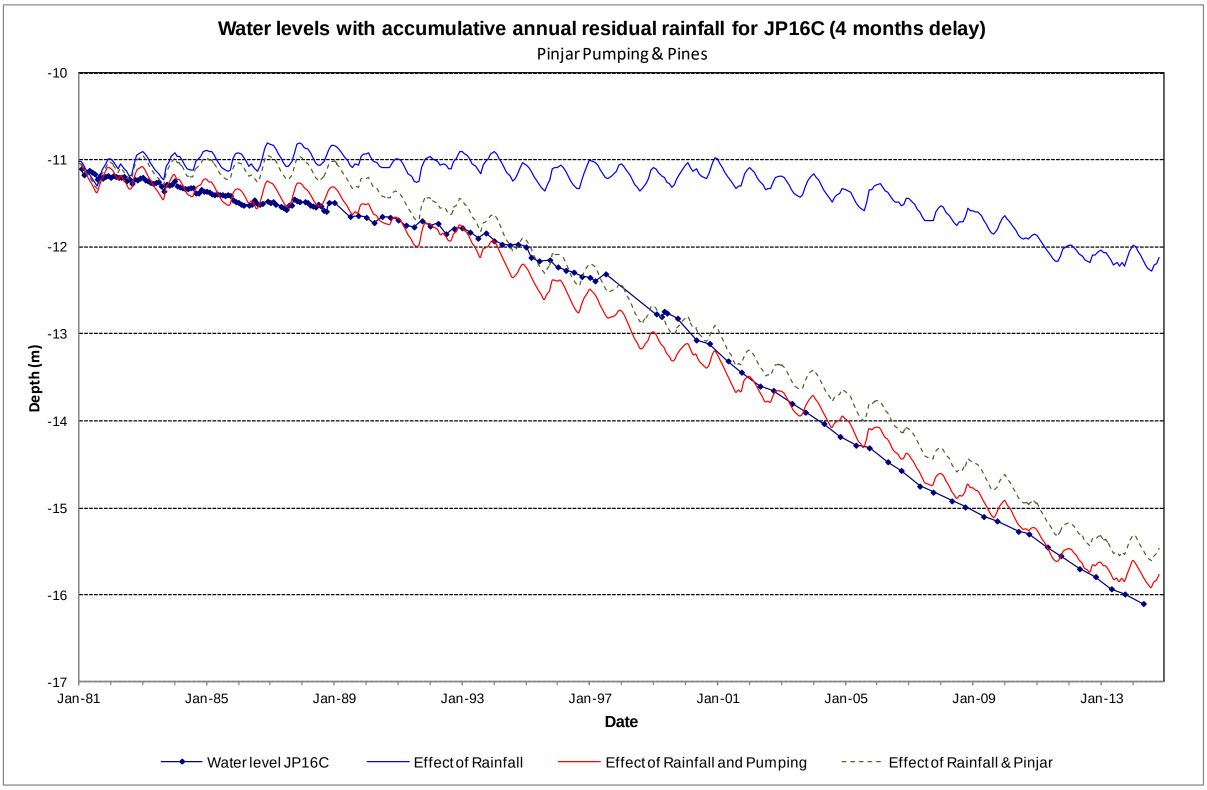
HARTT sites east of Lake Nowergup



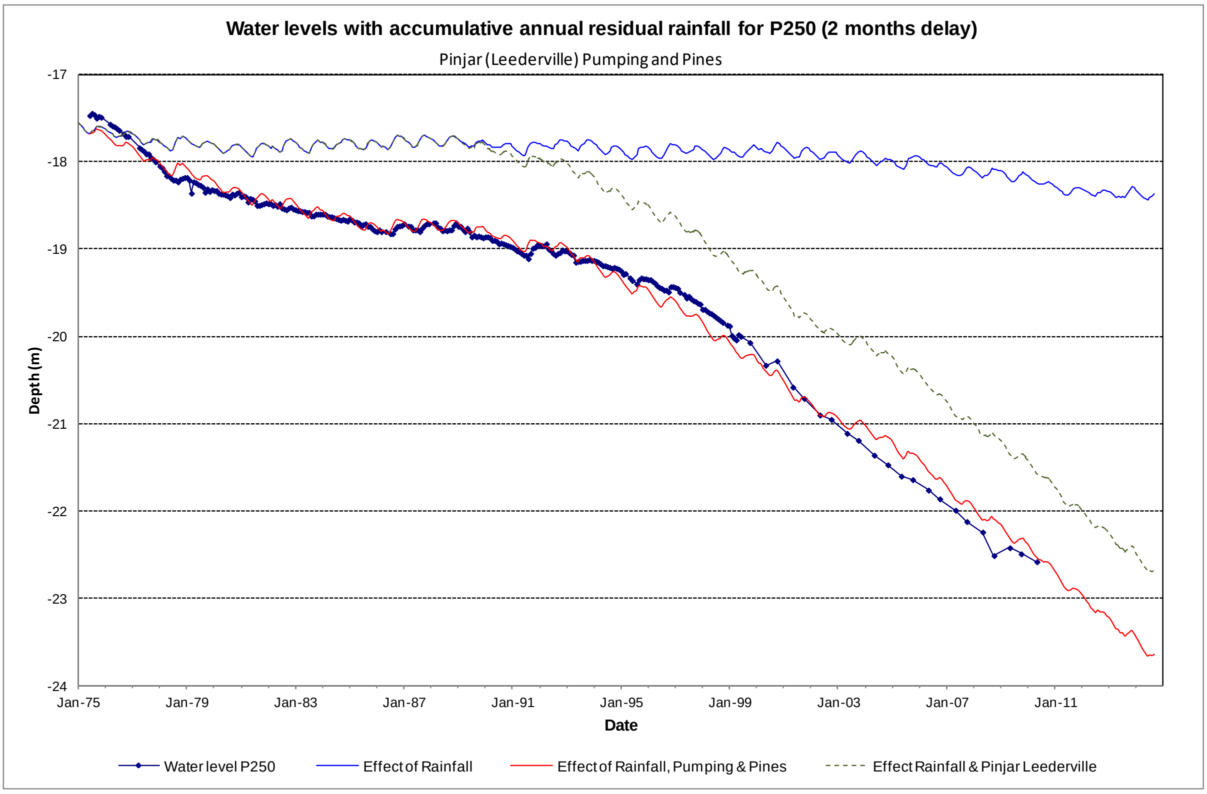



Water levels with accumulative annual residual rainfall for PM34 (0 months delay)
Pinjar, Quinns (Leederville) and Nowergup Pumping, Pines
Depth (m)
-15
-16
-17
-18
-19
-20
-21
-22
Jan-75
Jan-79
Jan-83
Jan-87
Jan-91
Jan-95
Jan-99
Jan-03
Jan-07
Jan-11
Date
Water level PM34
Effect of Rainfall
Effect of Rainfall, Pumping & Pines
Effect of Rainfall & Pinjar
Effect of Rainfall & Quinns
Effect of Rainfall & Nowergup


Water levels with accumulative annual residual rainfall for PM35 (2 months delay)
Pinjar (Leederville) Pumping and Pines
Depth (m)
-19
-20
-21
-22
-23
-24
-25
-26
1976
1980
1984
1988
1992
1996
2000
2004
2008
2012
Water level PM35
Effect of Rainfall
Effect of Rainfall, Pumping & Pines
Effect of Rainfall & Pinjar

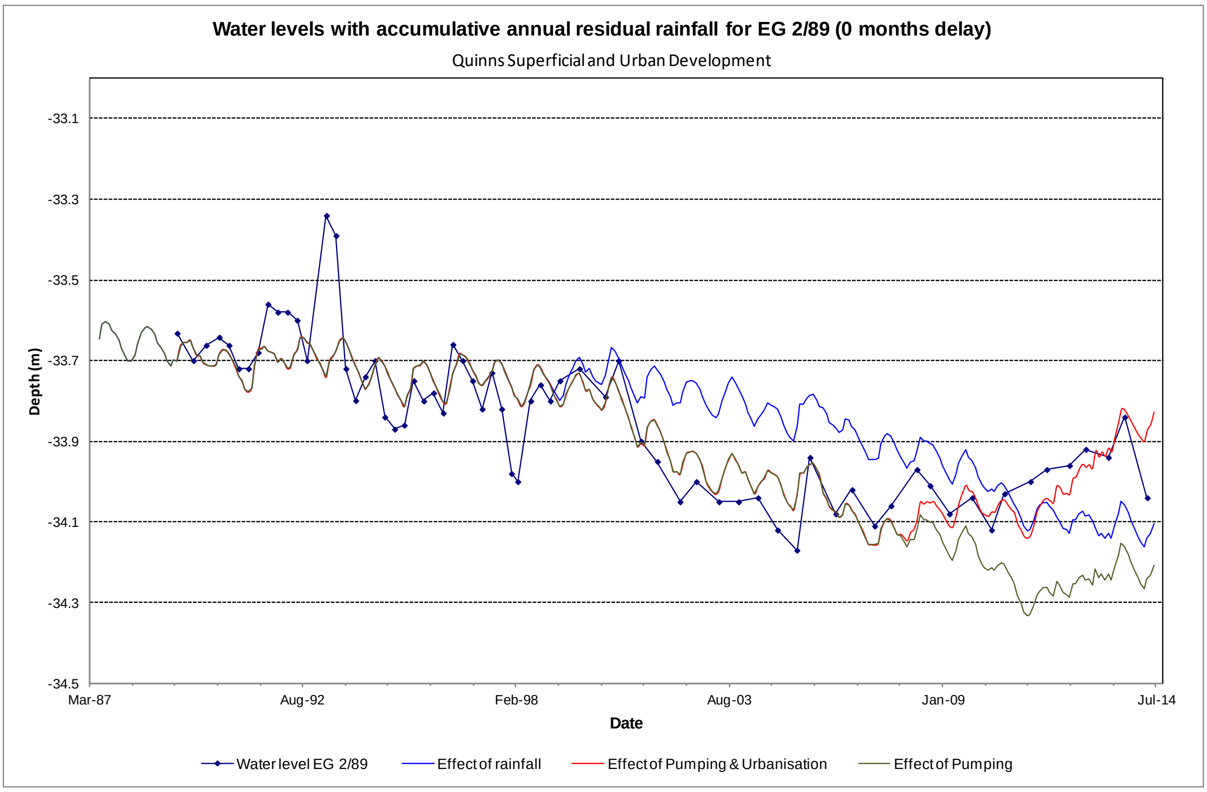


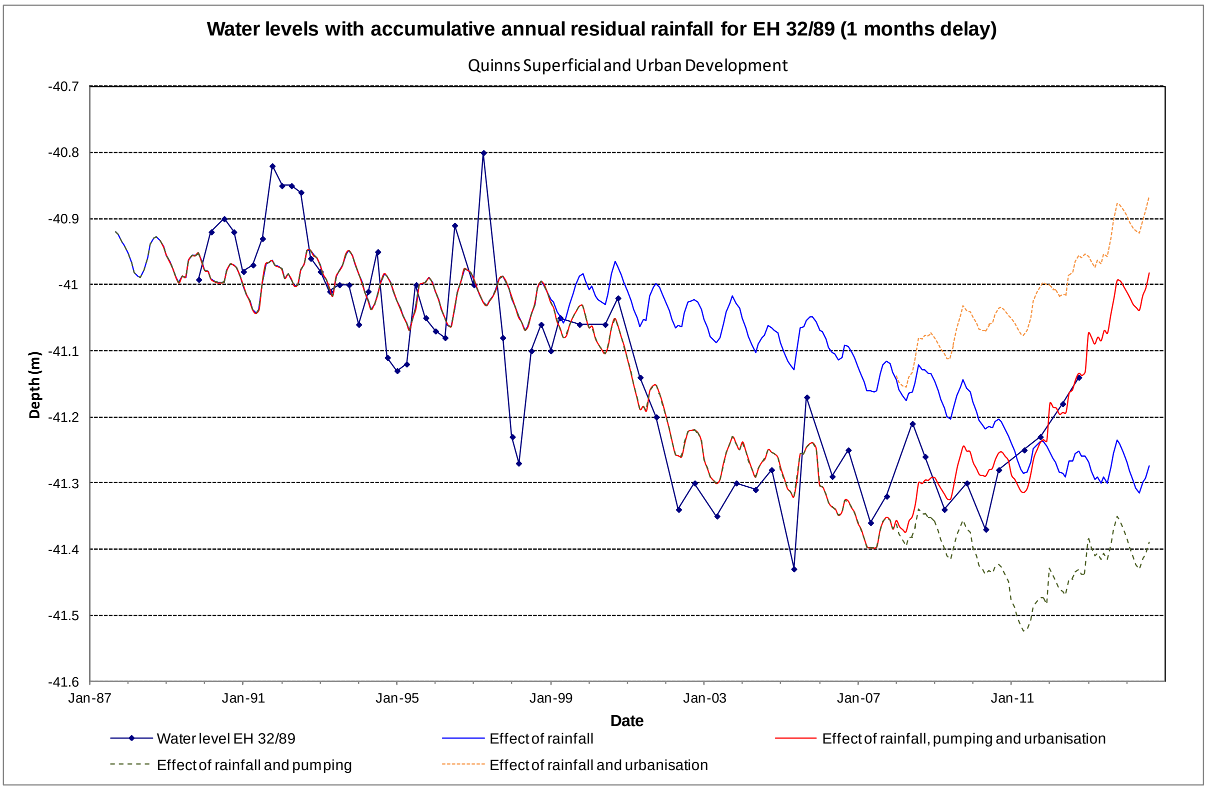
Water levels with accumulative annual residual rainfall for JP16C (4 months delay)
Pinjar Pumping & Pines
Depth (m)
-10
-11
-12
-13
-14
-15
-16
-17
Jan-81
Jan-85
Jan-89
Jan-93
Jan-97
Jan-01
Jan-05
Jan-09
Jan-13
Date
Water level JP16C
Effect of Rainfall
Effect of Rainfall and Pumping
Effect of Rainfall & Pinjar

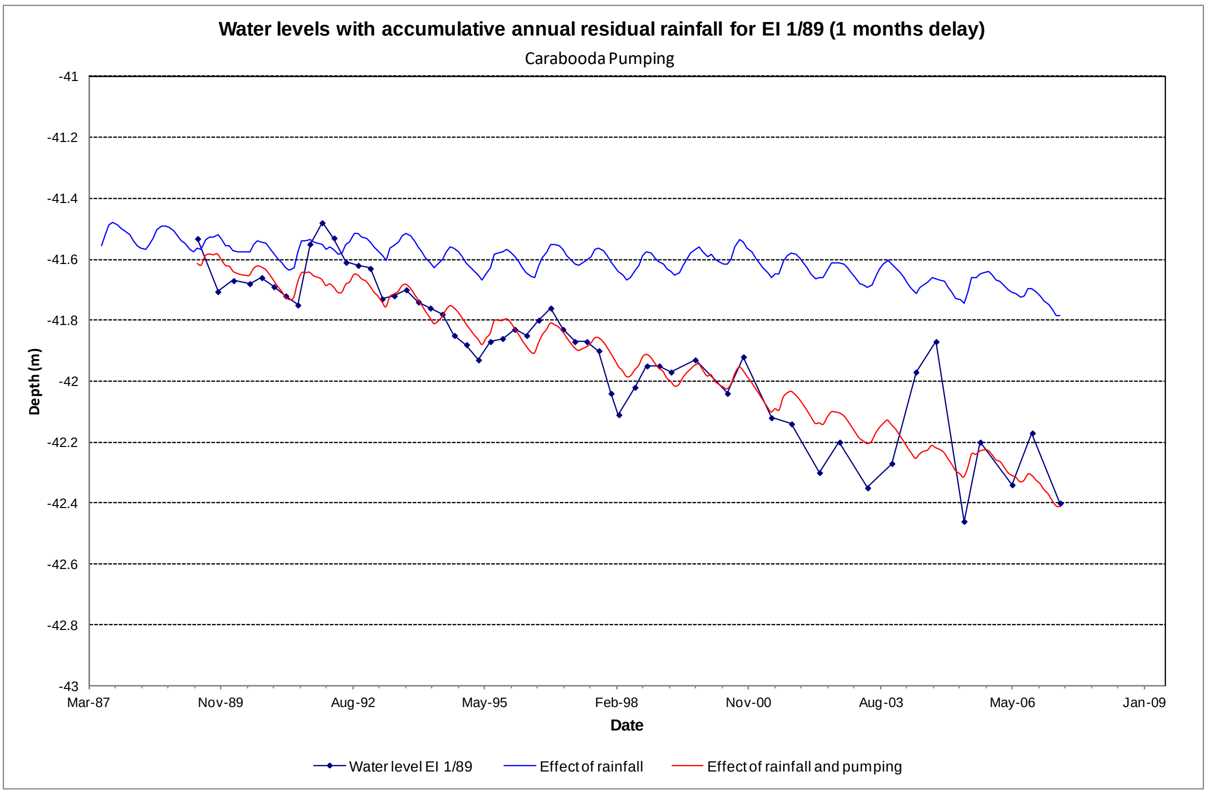


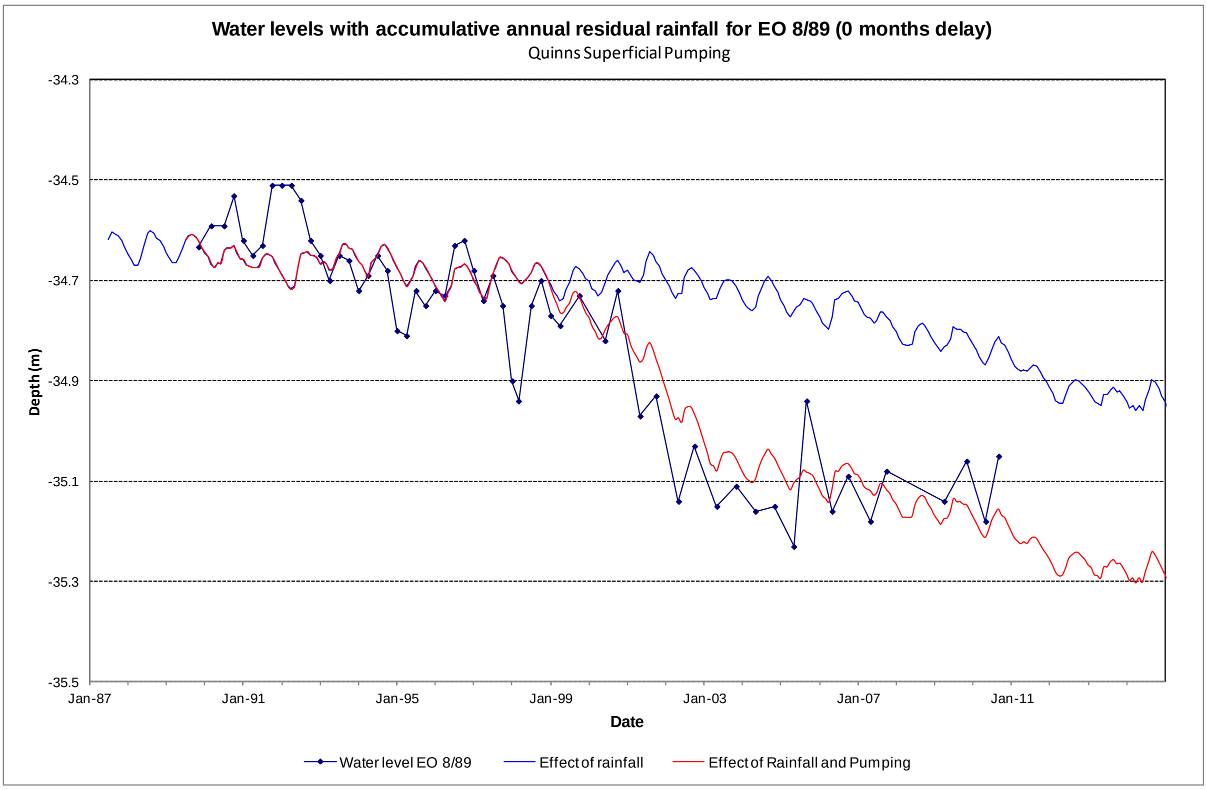
Water levels with accumulative annual residual rainfall for P250 (2 months delay)
Pinjar (Leederville) Pumping and Pines
Depth (m)
-17
-18
-19
-20
-21
-22
-23
-24
Jan-75
Jan-79
Jan-83
Jan-87
Jan-91
Jan-95
Jan-99
Jan-03
Jan-07
Jan-11
Date
Water level P250
Effect of Rainfall
Effect of Rainfall, Pumping & Pines
Effect Rainfall & Pinjar Leederville

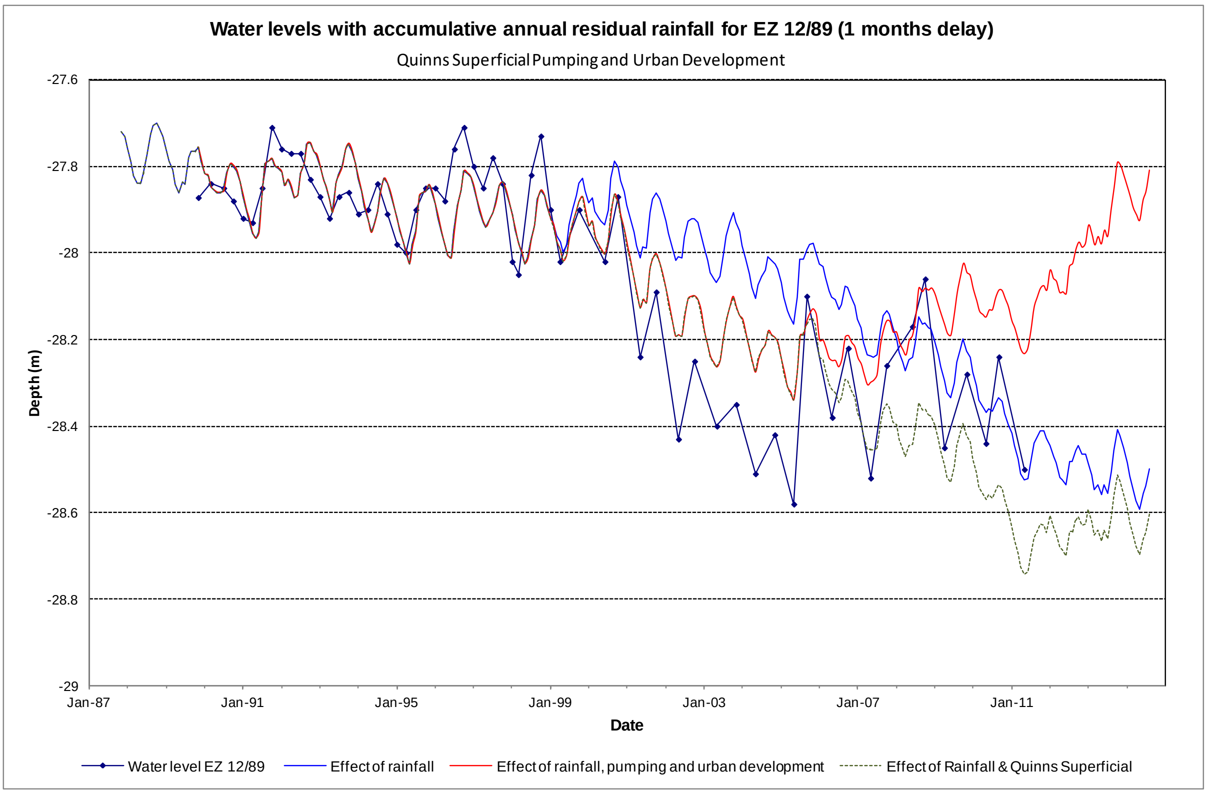
HARTT sites west of Lake Nowergup

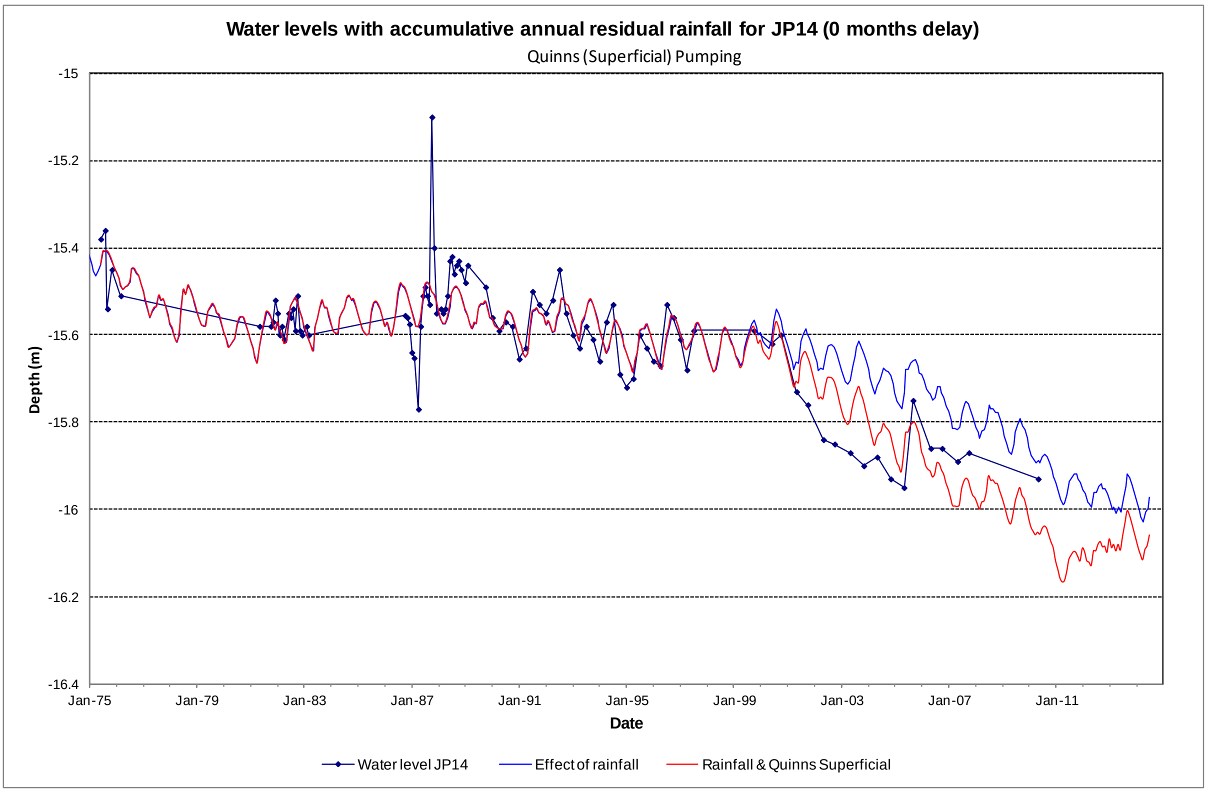


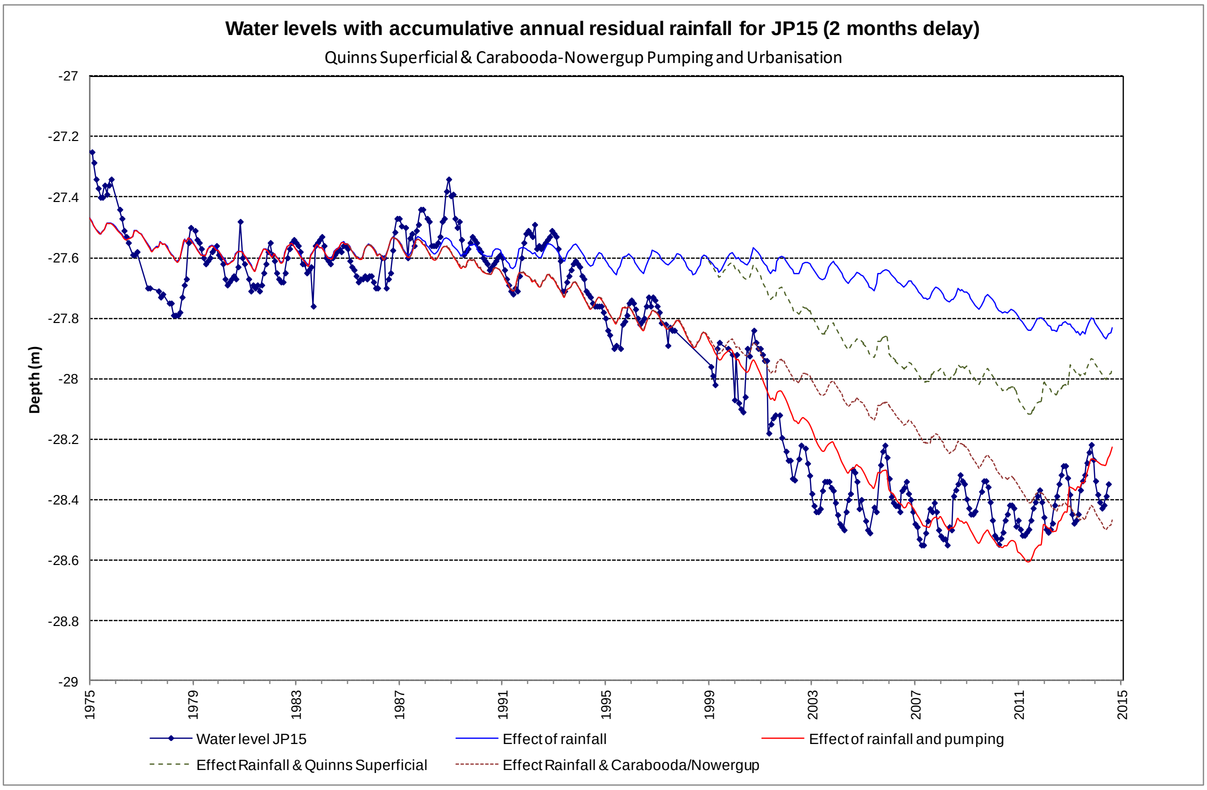


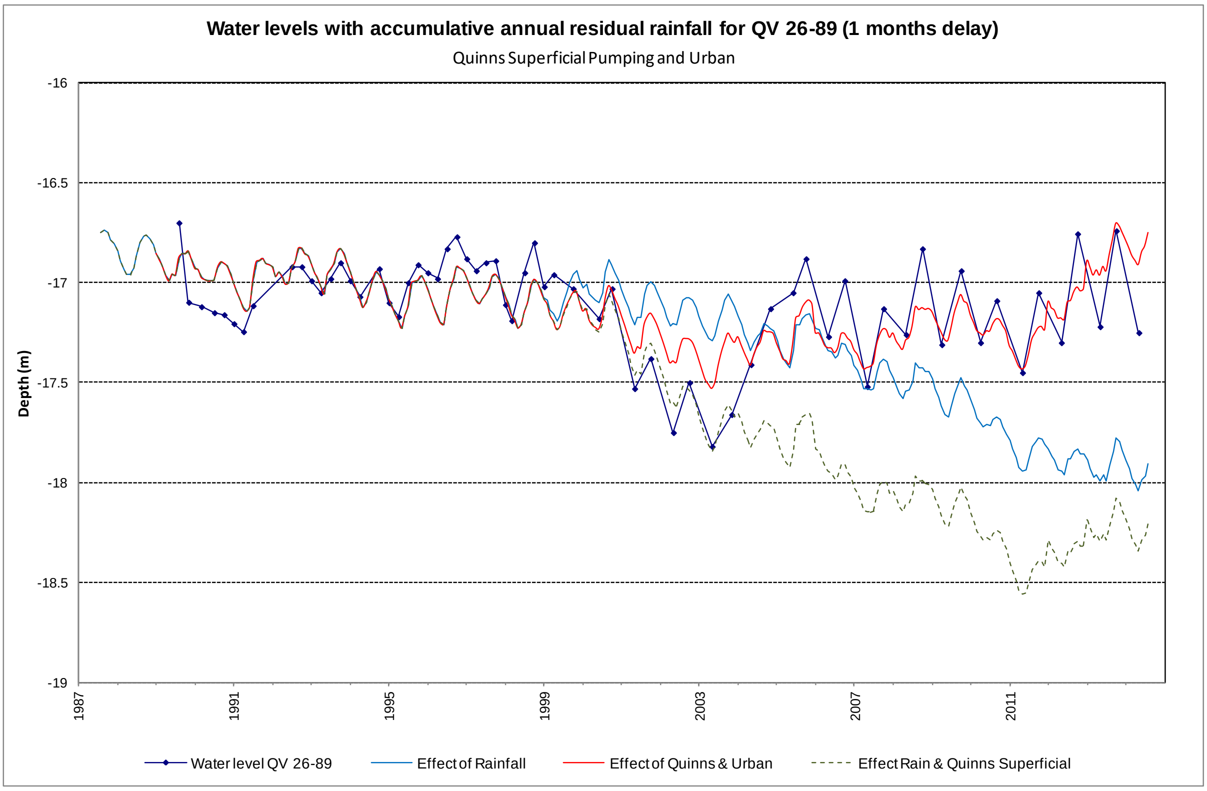

Water levels with accumulative annual residual rainfall for EI 1/89 (1 months delay)
Carabooda Pumping
Depth (m)
-41
-41.2
-41.4
-41.6
-41.8
-42
-42.2
-42.4
-42.6
-42.8
-43
Mar-87
Nov-89
Aug-92
May-95
Feb-98
Nov-00
Aug-03
May-06
Jan-09
Date
Water level EI 1/89
Effect of rainfall
Effect of rainfall and pumping


Water levels with accumulative annual residual rainfall for EO 8/89 (0 months delay)
Quinns Superficial Pumping
Depth (m)
-34.3
-34.5
-34.7
-34.9
-35.1
-35.3
-35.5
Jan-87
Jan-91
Jan-95
Jan-99
Jan-03
Jan-07
Jan-11
Date
Water level EO 8/89
Effect of rainfall
Effect of Rainfall and Pumping

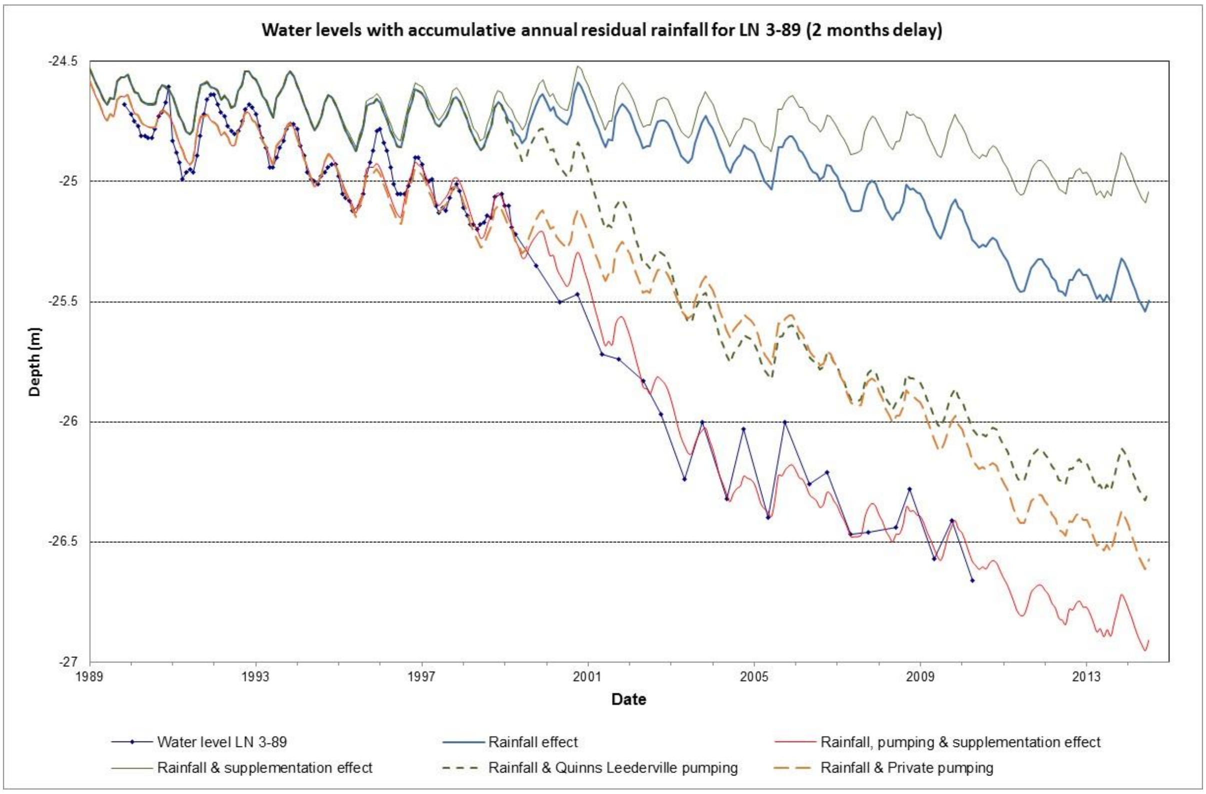

Water levels with accumulative annual residual rainfall for EZ 12/89 (1 months delay)
Quinns Superficial Pumping and Urban Development
-27.6
-27.8
-28
-28.2
-28.4
-28.6
-28.8
-29
Depth (m)
Jan-87
Jan-91
Jan-95
Jan-99
Jan-03
Jan-07
Jan-11
Date
Water level EZ 12/89
Effect of rainfall
Effect of rainfall, pumping and urban development
Effect of Rainfall & Quinns Superficial

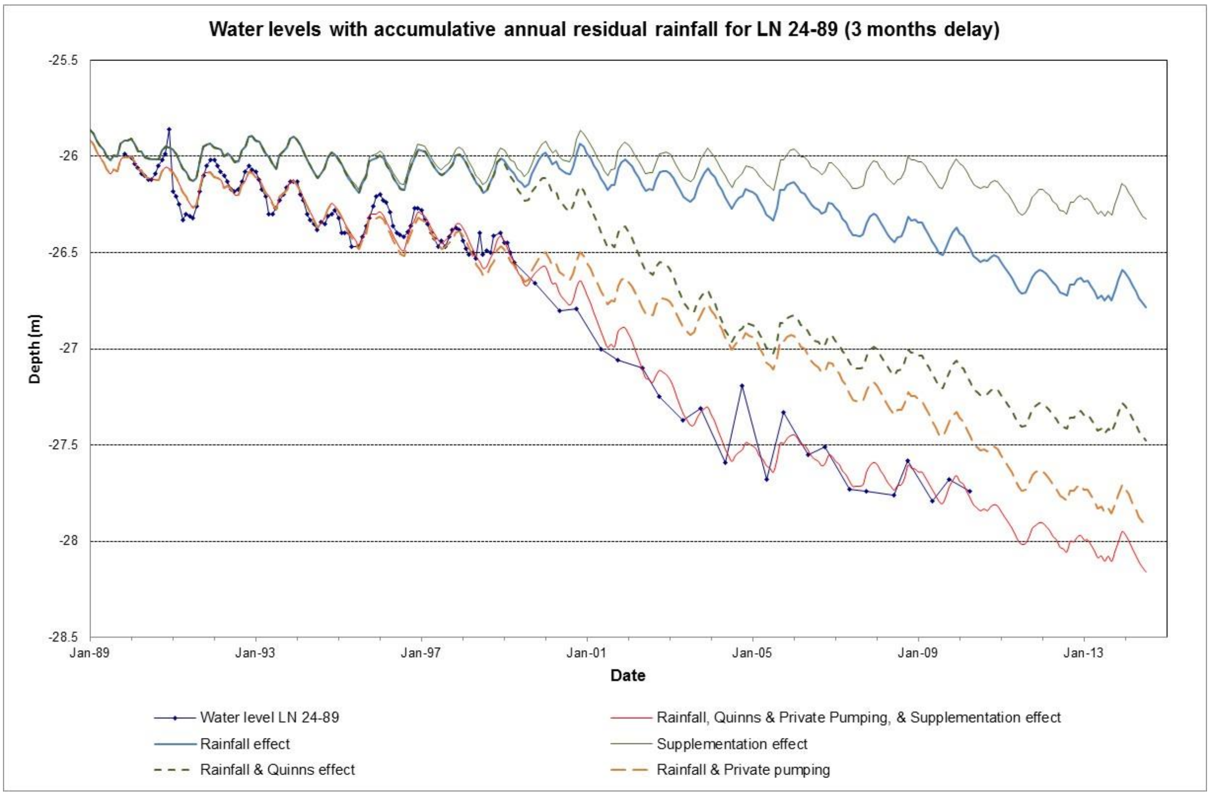

Water levels with accumulative annual residual rainfall for JP14 (0 months delay)
Quinns (Superficial) Pumping
-15
-15.2
-15.4
-15.6
-15.8
-16
-16.2
-16.4
Depth (m)
Jan-75
Jan-79
Jan-83
Jan-87
Jan-91
Jan-95
Jan-99
Jan-03
Jan-07
Jan-11
Date
Water level JP14
Effect of rainfall
Rainfall & Quinns Superficial

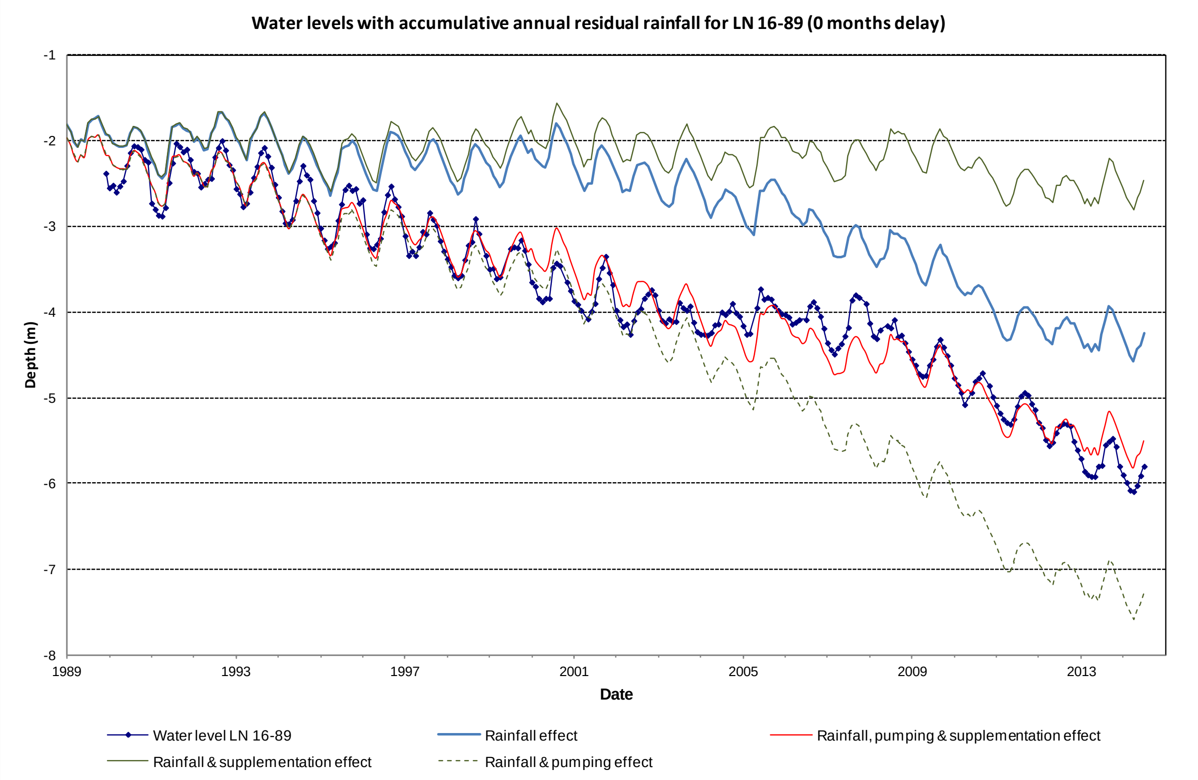

Water levels with accumulative annual residual rainfall for JP15 (2 months delay)
Quinns Superficial & Carabooda-Nowergup Pumping and Urbanisation
Depth (m)
-27
-27.2
-27.4
-27.6
-27.8
-28
-28.2
-28.4
-28.6
-28.8
-29
1975
1979
1983
1987
1991
1995
1999
2003
2007
2011
2015
Water level JP15
Effect of rainfall
Effect of rainfall and pumping
Effect Rainfall & Quinns Superficial
Effect Rainfall & Carabooda/Nowergup

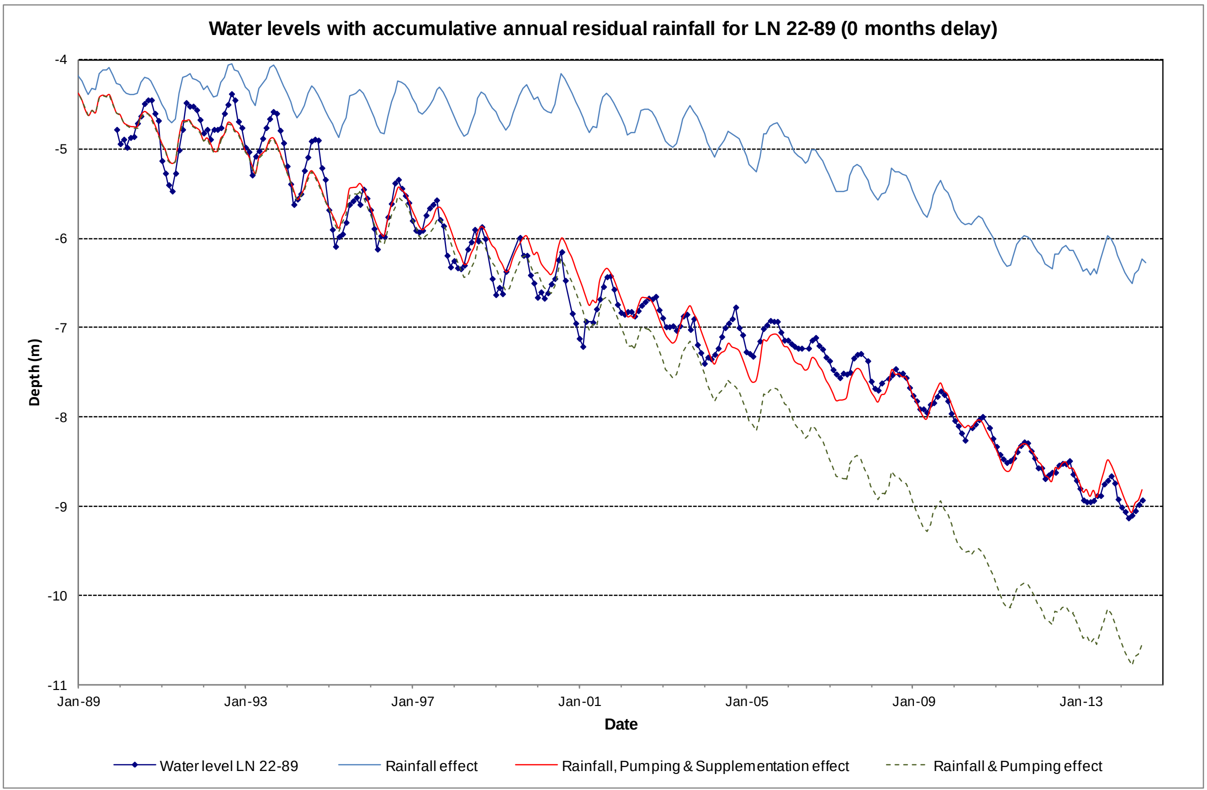

Water levels with accumulative annual residual rainfall for QV 26-89 (1 months delay)
Quinns Superficial Pumping and Urban
Depth (m)
-16
-16.5
-17
-17.5
-18
-18.5
-19
1987
1991
1995
1999
2003
2007
2011
Water level QV 26-89
Effect of Rainfall
Effect of Quinns & Urban
Effect Rain & Quinns Superficial

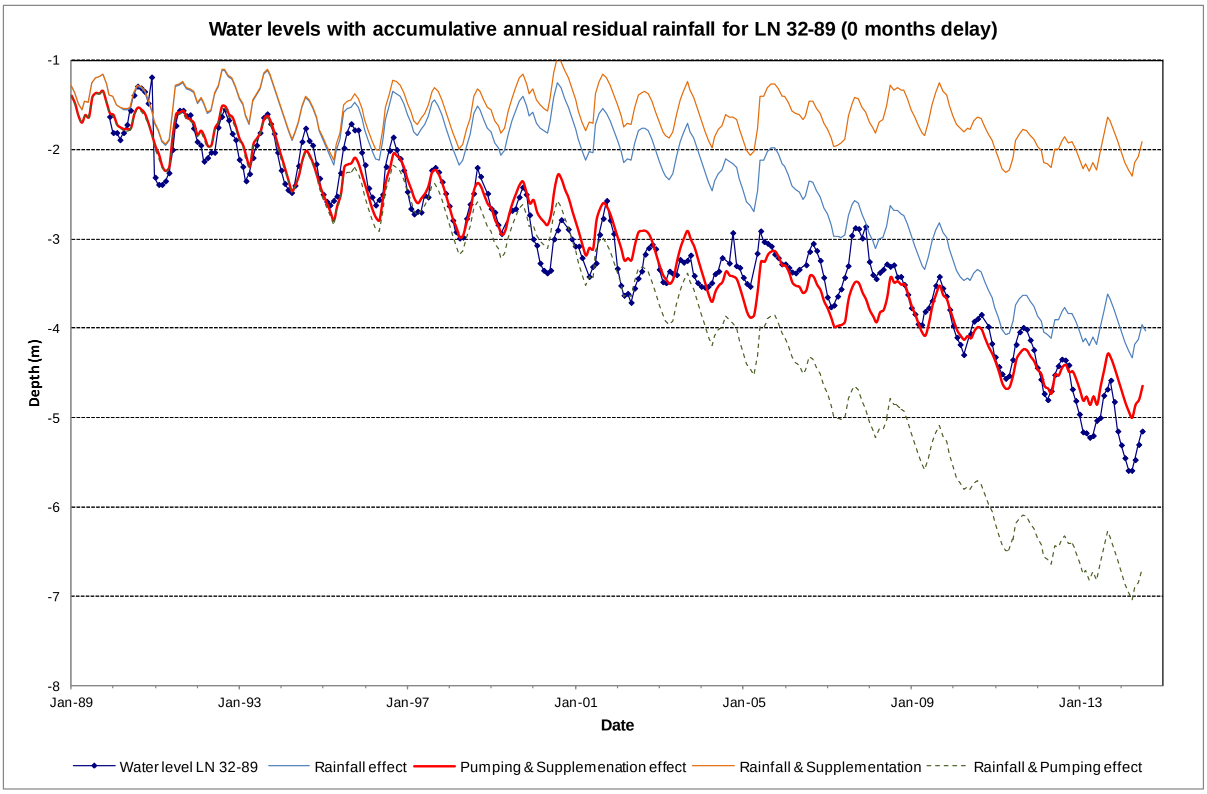
HARTT sites about Lake Nowergup

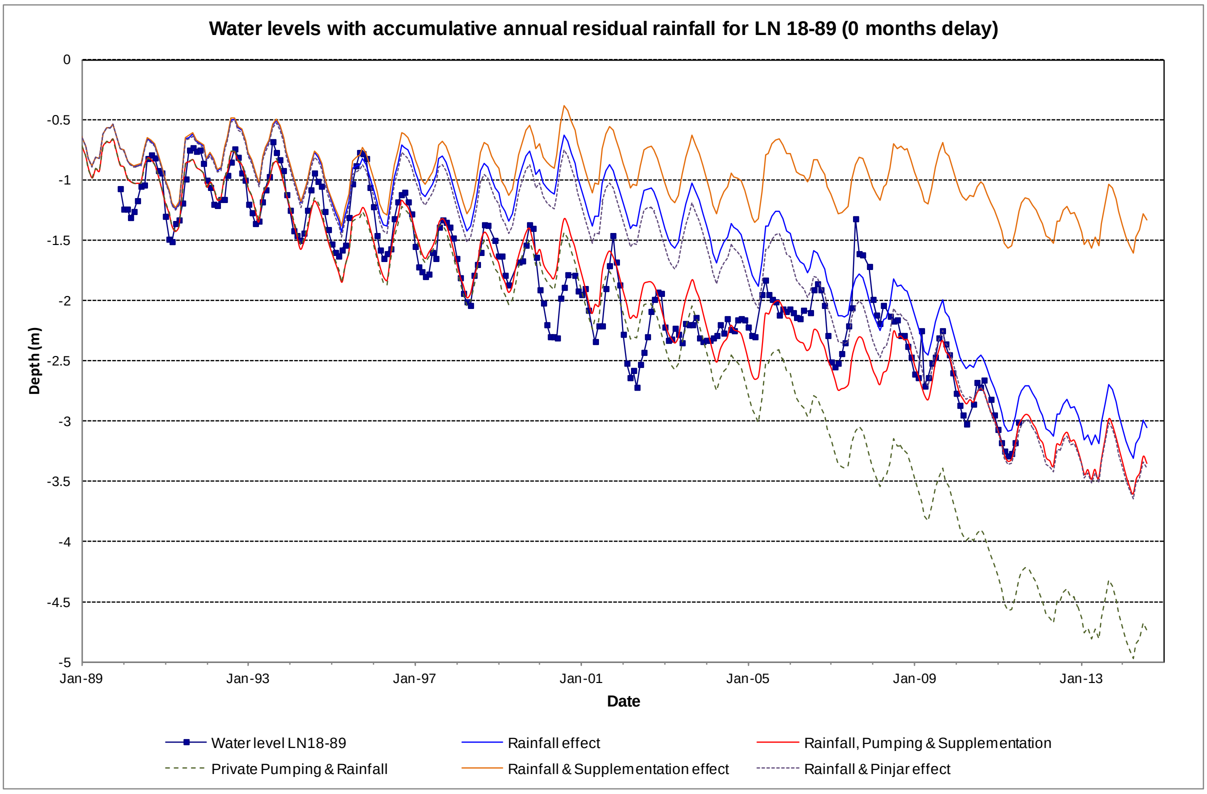





Water levels with accumulative annual residual rainfall for LN 16-89 (0 months delay)
Depth (m)
Date
Water level LN 16-89
Rainfall effect
Rainfall, pumping & supplementation effect
Rainfall & supplementation effect
Rainfall & pumping effect


Water levels with accumulative annual residual rainfall for LN 22-89 (0 months delay)
Depth (m)
Date
Water level LN 22-89
Rainfall effect
Rainfall, Pumping & Supplementation effect
Rainfall & Pumping effect


Water levels with accumulative annual residual rainfall for LN 32-89 (0 months delay)
Depth (m)
-1
-2
-3
-4
-5
-6
-7
-8
Jan-89
Jan-93
Jan-97
Jan-01
Jan-05
Jan-09
Jan-13
Date
Water level LN 32-89
Rainfall effect
Pumping & Supplemenation effect
Rainfall & Supplementation
Rainfall & Pumping effect

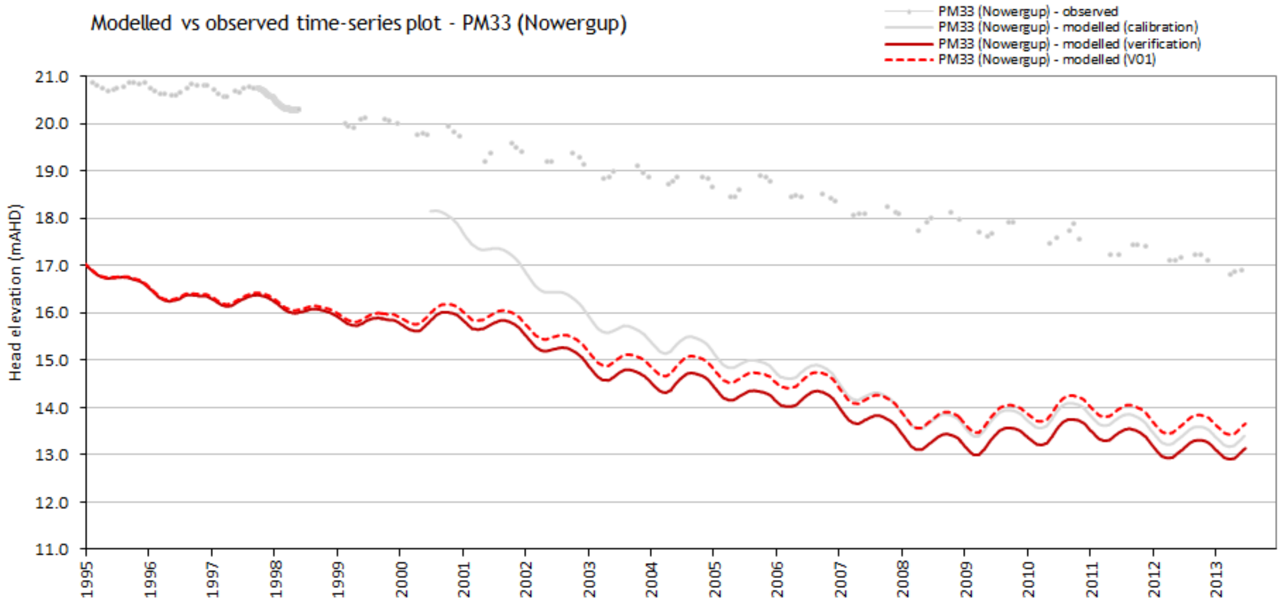

Water levels with accumulative annual residual rainfall for LN 18-89 (0 months delay)
Depth (m)
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
Jan-89
Jan-93
Jan-97
Jan-01
Jan-05
Jan-09
Jan-13
Date
Water level LN18-89
Rainfall effect
Rainfall, Pumping & Supplementation
Private Pumping & Rainfall
Rainfall & Supplementation effect
Rainfall & Pinjar effect

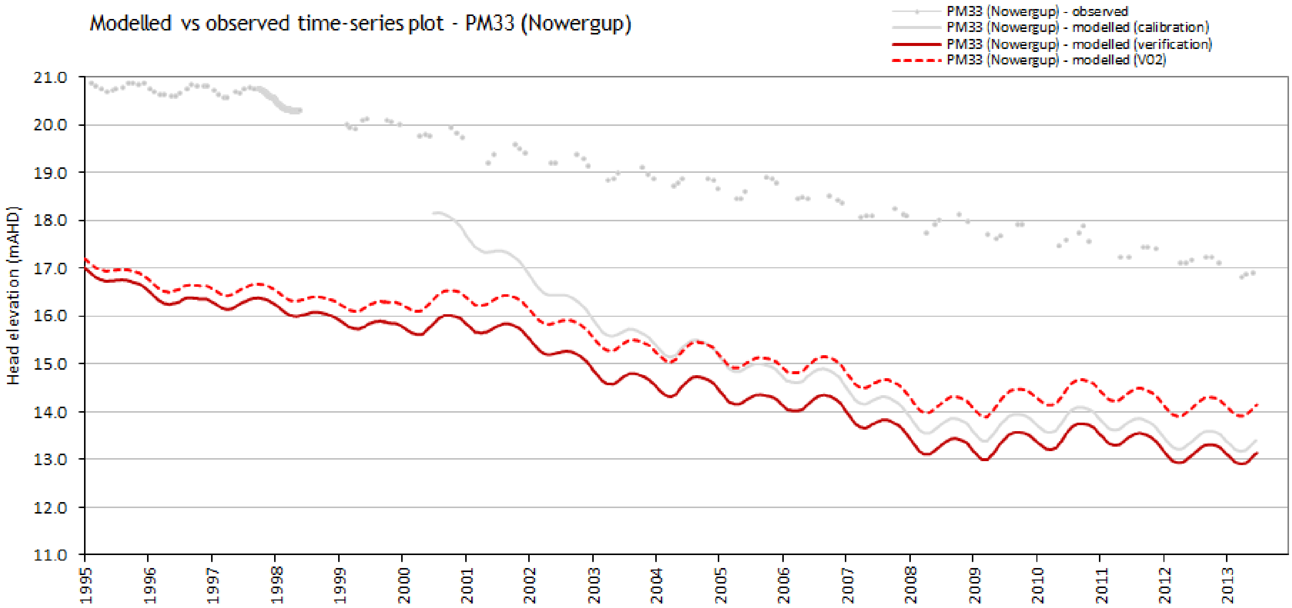
Appendix B: PRAMS verification scenarios

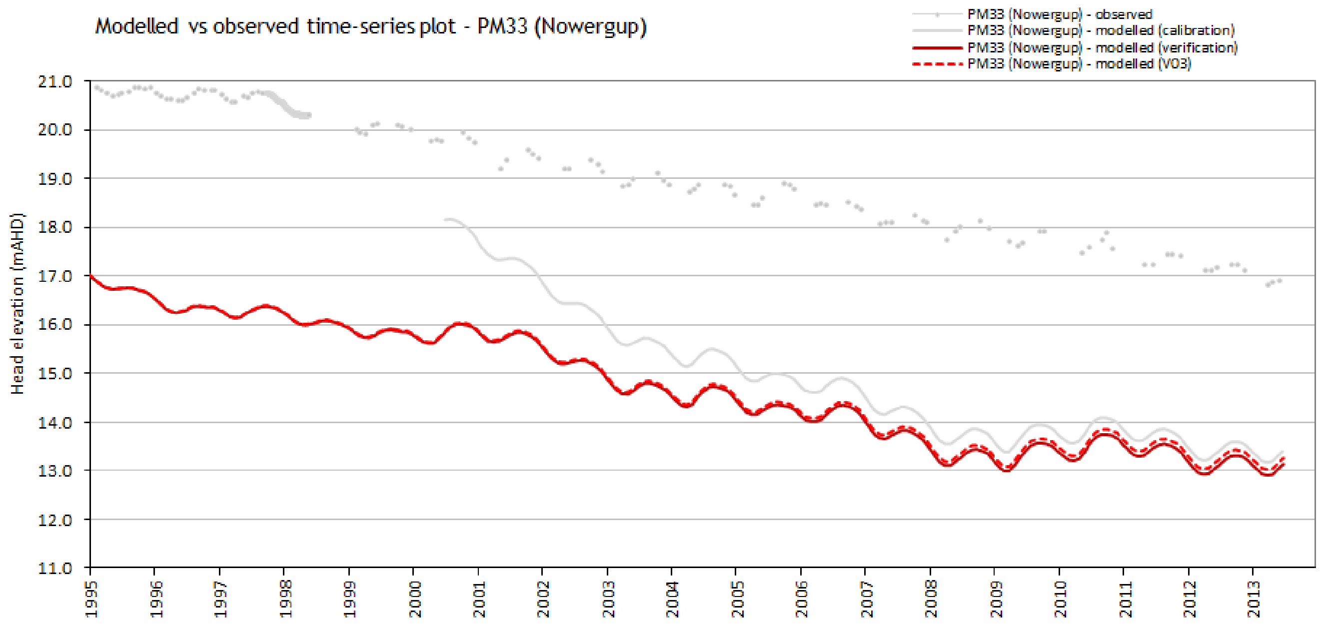
PRAMS Verification Scenarios – time-series plots for monitoring bore PM33

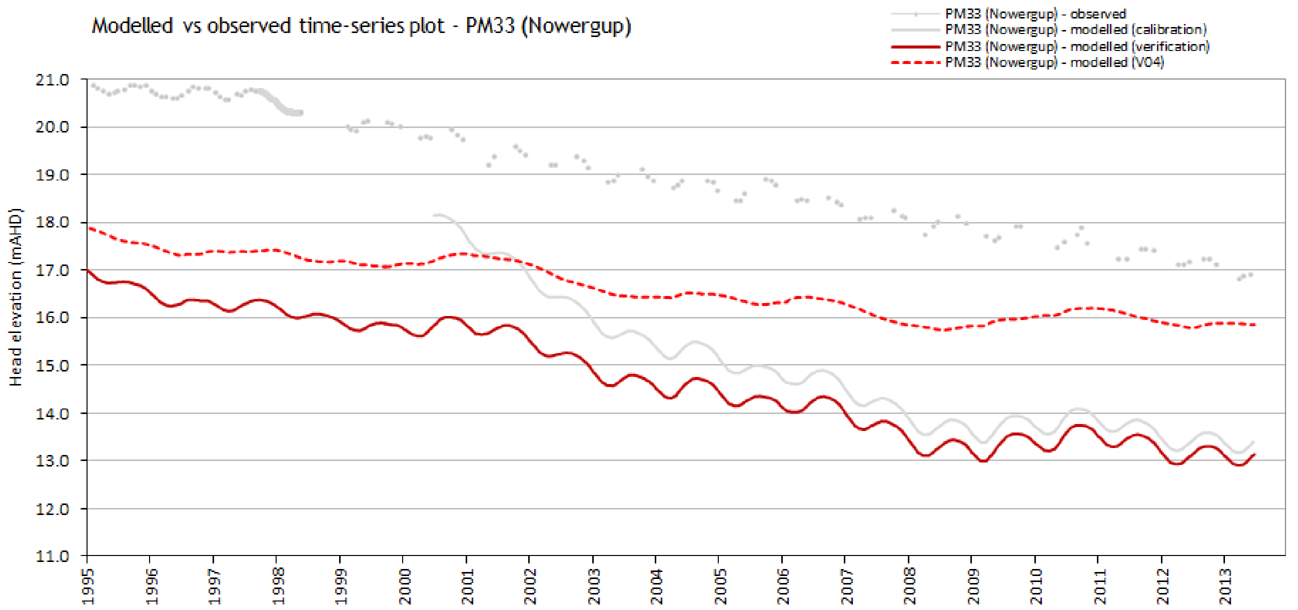
Verification scenario to display

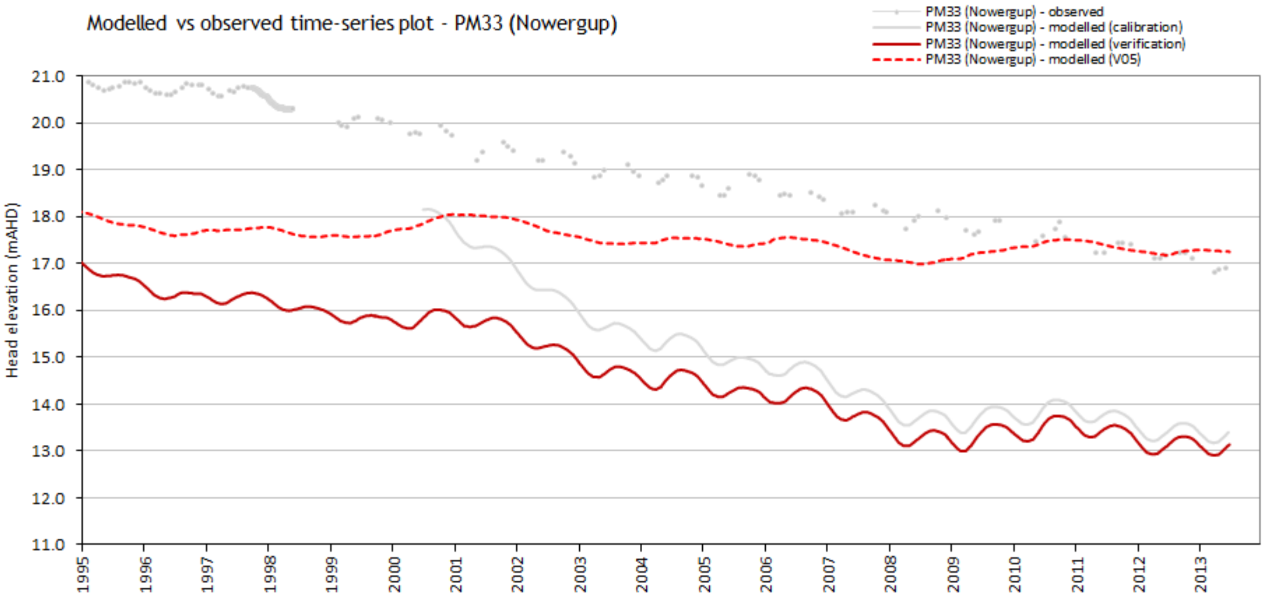
- ○ V01 - No Water Corporaiton Superficial pumping
- ○ V02 - No Water Corporation Leederville pumping
- ○ V03 - No Water Corporation Yarragadee pumping
- ○ V04 - No private abstraction
- ◉ V05 - No abstraction

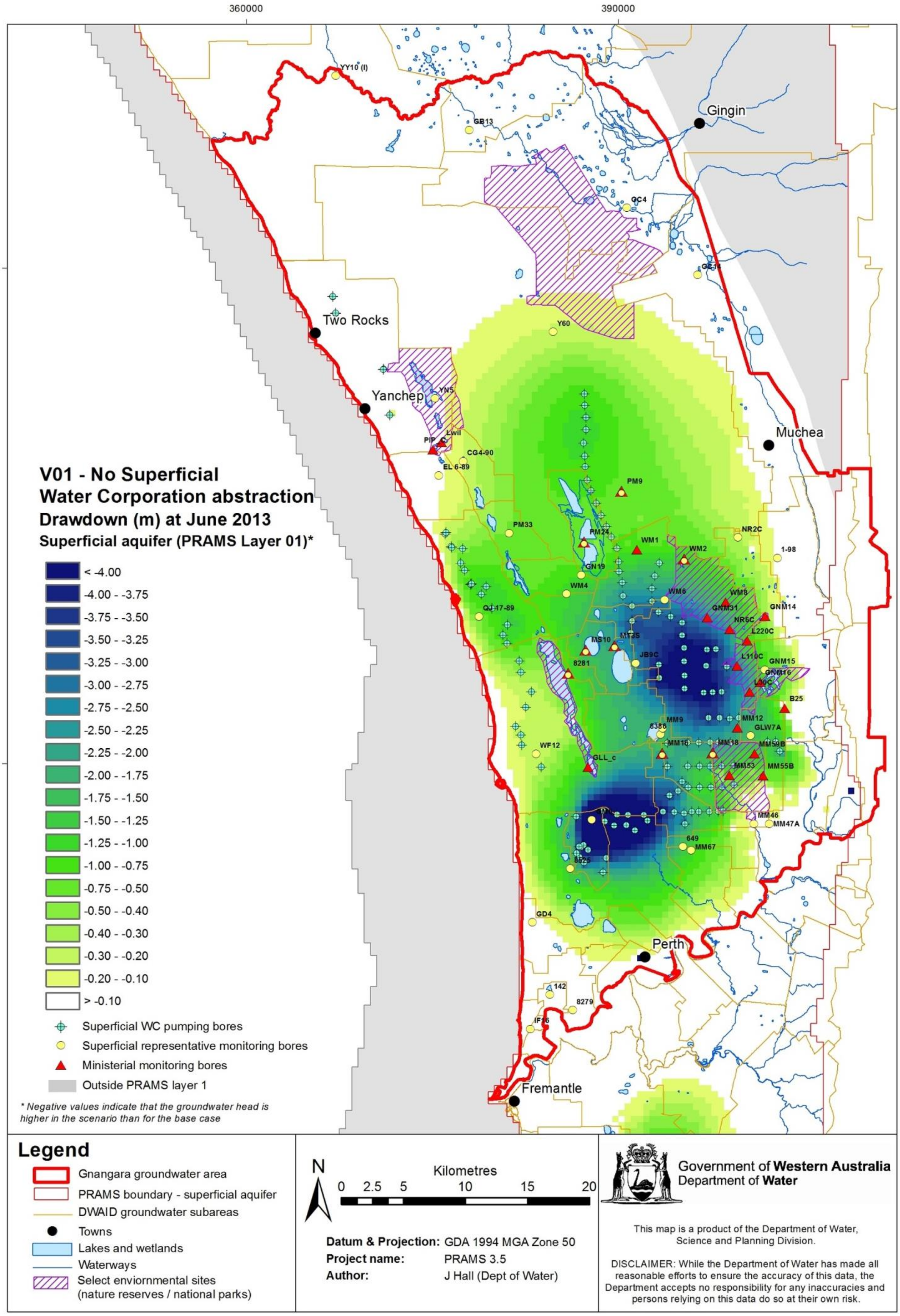


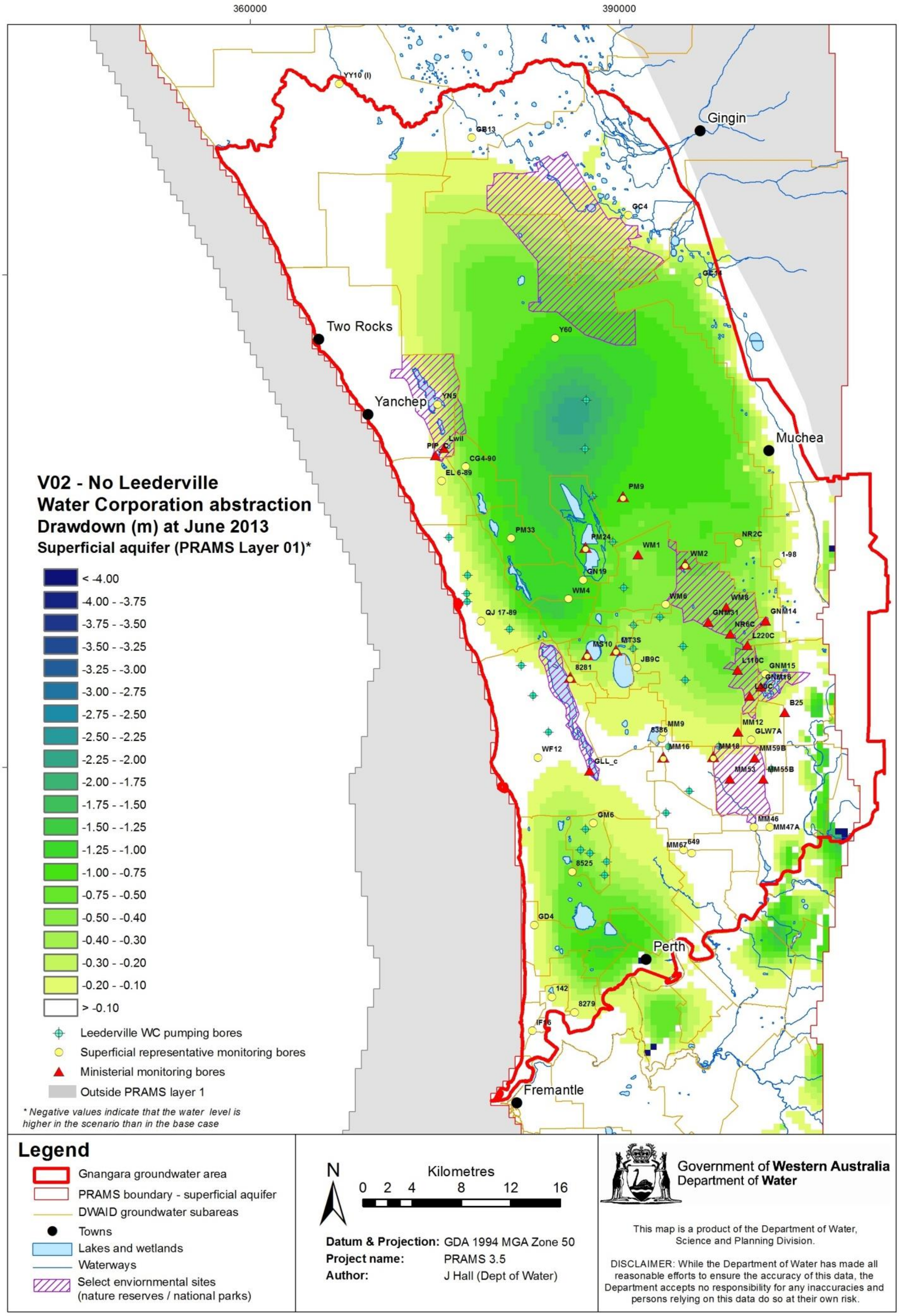



Modelled vs observed time-series plot - PM33 (Nowergup)
PM33 (Nowergup) - observed
PM33 (Nowergup) - modelled (calibration)
PM33 (Nowergup) - modelled (verification)
PM33 (Nowergup) - modelled (V03)
Head elevation (mAHD)
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013


Modelled vs observed time-series plot - PM33 (Nowergup)
PM33 (Nowergup) - observed
PM33 (Nowergup) - modelled (calibration)
PM33 (Nowergup) - modelled (verification)
PM33 (Nowergup) - modelled (V04)
Head elevation (mAHD)
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013


Modelled vs observed time-series plot - PM33 (Nowergup)
PM33 (Nowergup) - observed
PM33 (Nowergup) - modelled (calibration)
PM33 (Nowergup) - modelled (verification)
PM33 (Nowergup) - modelled (V05)
Head elevation (mAHD)
21.0
20.0
19.0
18.0
17.0
16.0
15.0
14.0
13.0
12.0
11.0
1995
1996
1997
1998
1999
2000
2001
2002
2003
2004
2005
2006
2007
2008
2009
2010
2011
2012
2013


360000
390000
6520000
6480000
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
YY10 (I)
GB13
GC4
Y60
YN5
PM9
PM33
PM24
WM1
WM2
NR2C
1-98
GN19
WM4
WM6
WM8
GNM31
GNM14
NR6C
L220C
MS10
MT3S
JB9C
8281
L110C
GNM15
GNM16
B25
MM9
8386
MM12
GLW7A
WF12
GLL_c
MM18
MM53
MM55B
MM46
MM47A
649
MM67
GD4
142
8279
V01 - No Superficial
Water Corporation abstraction
Drawdown (m) at June 2013
Superficial aquifer (PRAMS Layer 01)*
< -4.00
-4.00 - -3.75
-3.75 - -3.50
-3.50 - -3.25
-3.25 - -3.00
-3.00 - -2.75
-2.75 - -2.50
-2.50 - -2.25
-2.25 - -2.00
-2.00 - -1.75
-1.75 - -1.50
-1.50 - -1.25
-1.25 - -1.00
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.40
-0.40 - -0.30
-0.30 - -0.20
-0.20 - -0.10
> -0.10
Superficial WC pumping bores
Superficial representative monitoring bores
Ministerial monitoring bores
Outside PRAMS layer 1
* Negative values indicate that the groundwater head is higher in the scenario than for the base case
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
Waterways
Select enviornmental sites (nature reserves / national parks)
N
Kilometres
0 2.5 5 10 15 20
Datum & Projection: GDA 1994 MGA Zone 50
Project name: PRAMS 3.5
Author: J Hall (Dept of Water)
Government of Western Australia
Department of Water
This map is a product of the Department of Water, Science and Planning Division.
DISCLAIMER: While the Department of Water has made all reasonable efforts to ensure the accuracy of this data, the Department accepts no responsibility for any inaccuracies and persons relying on this data do so at their own risk.


360000
390000
6520000
6480000
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
V02 - No Leederville
Water Corporation abstraction
Drawdown (m) at June 2013
Superficial aquifer (PRAMS Layer 01)*
< -4.00
-4.00 - -3.75
-3.75 - -3.50
-3.50 - -3.25
-3.25 - -3.00
-3.00 - -2.75
-2.75 - -2.50
-2.50 - -2.25
-2.25 - -2.00
-2.00 - -1.75
-1.75 - -1.50
-1.50 - -1.25
-1.25 - -1.00
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.40
-0.40 - -0.30
-0.30 - -0.20
-0.20 - -0.10
> -0.10
Leederville WC pumping bores
Superficial representative monitoring bores
Ministerial monitoring bores
Outside PRAMS layer 1
* Negative values indicate that the water level is higher in the scenario than in the base case
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
Waterways
Select enviornmental sites (nature reserves / national parks)
N
Kilometres
0 2 4 8 12 16
Datum & Projection: GDA 1994 MGA Zone 50
Project name: PRAMS 3.5
Author: J Hall (Dept of Water)
Government of Western Australia
Department of Water
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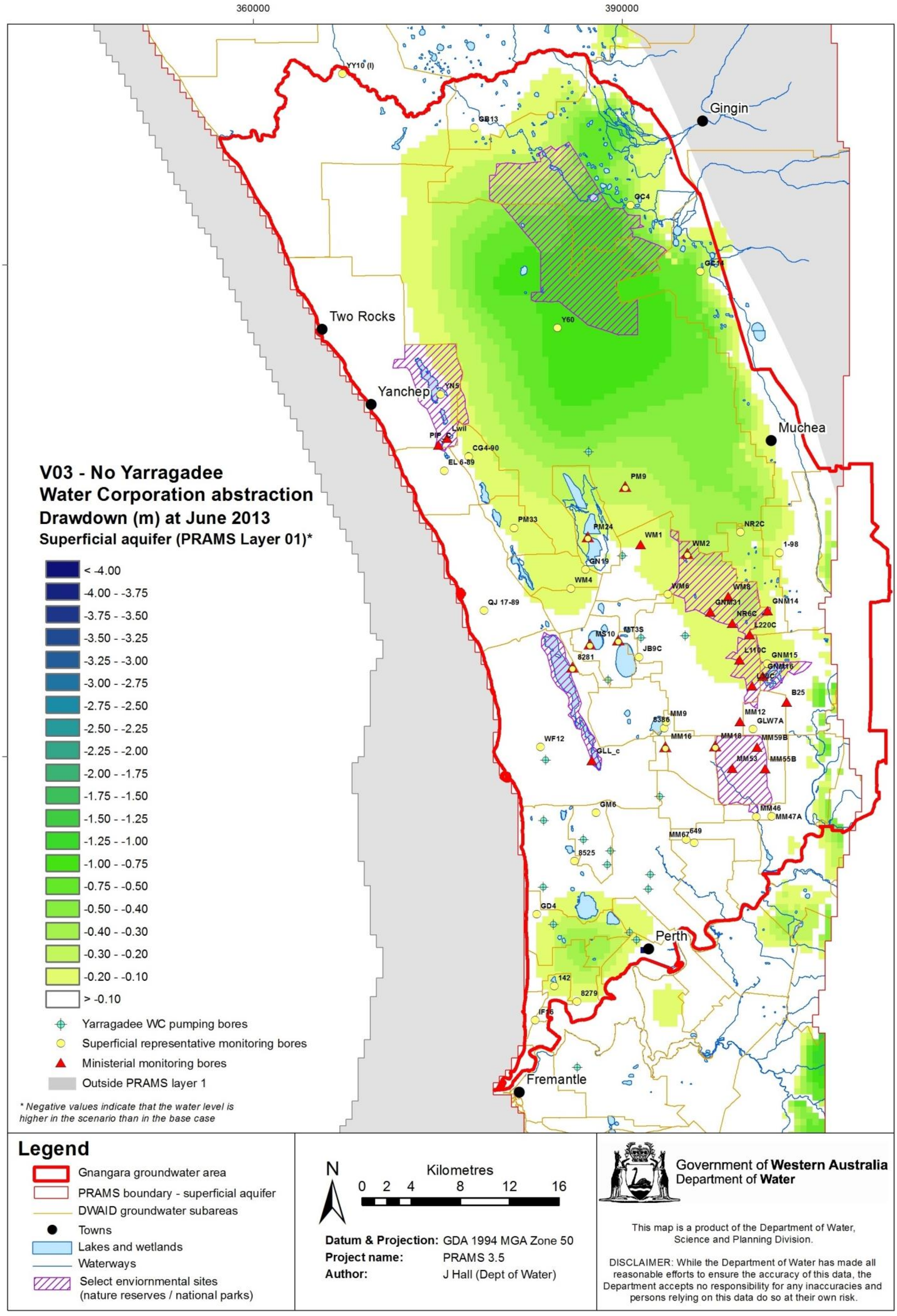
360000
390000
6520000
6480000
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
V03 - No Yarragadee
Water Corporation abstraction
Drawdown (m) at June 2013
Superficial aquifer (PRAMS Layer 01)*
< -4.00
-4.00 - -3.75
-3.75 - -3.50
-3.50 - -3.25
-3.25 - -3.00
-3.00 - -2.75
-2.75 - -2.50
-2.50 - -2.25
-2.25 - -2.00
-2.00 - -1.75
-1.75 - -1.50
-1.50 - -1.25
-1.25 - -1.00
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.40
-0.40 - -0.30
-0.30 - -0.20
-0.20 - -0.10
> -0.10
Yarragadee WC pumping bores
Superficial representative monitoring bores
Ministerial monitoring bores
Outside PRAMS layer 1
* Negative values indicate that the water level is higher in the scenario than in the base case
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
Waterways
Select enviornmental sites (nature reserves / national parks)
N
Kilometres
0 2 4 8 12 16
Datum & Projection: GDA 1994 MGA Zone 50
Project name: PRAMS 3.5
Author: J Hall (Dept of Water)
Government of Western Australia
Department of Water
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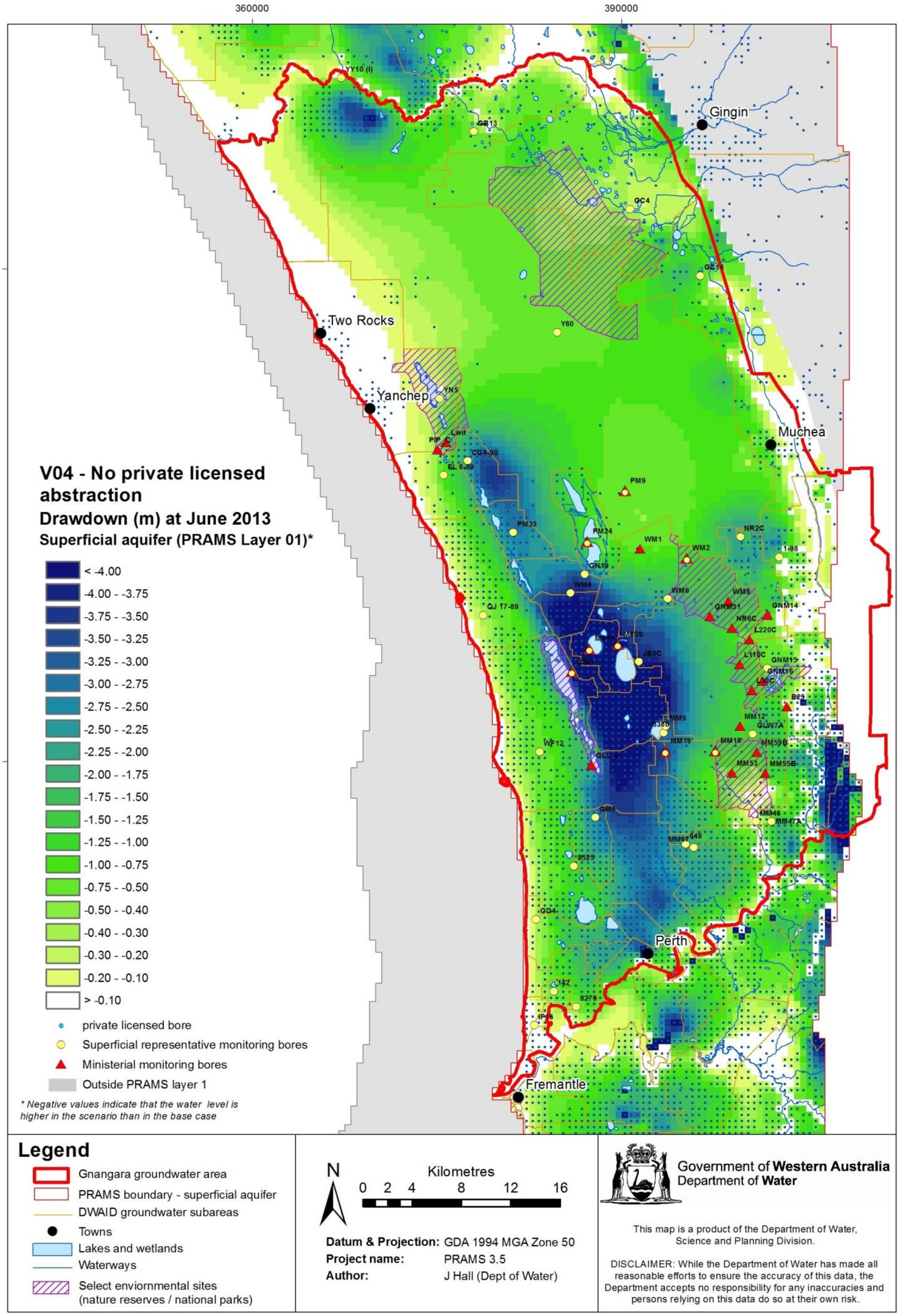

V04 - No private licensed abstraction
Drawdown (m) at June 2013
Superficial aquifer (PRAMS Layer 01)*
< -4.00
-4.00 - -3.75
-3.75 - -3.50
-3.50 - -3.25
-3.25 - -3.00
-3.00 - -2.75
-2.75 - -2.50
-2.50 - -2.25
-2.25 - -2.00
-2.00 - -1.75
-1.75 - -1.50
-1.50 - -1.25
-1.25 - -1.00
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.40
-0.40 - -0.30
-0.30 - -0.20
-0.20 - -0.10
> -0.10
private licensed bore
Superficial representative monitoring bores
Ministerial monitoring bores
Outside PRAMS layer 1
* Negative values indicate that the water level is higher in the scenario than in the base case
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
360000
390000
6520000
6480000
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
Waterways
Select enviornmental sites (nature reserves / national parks)
N
Kilometres
0 2 4 8 12 16
Datum & Projection: GDA 1994 MGA Zone 50
Project name: PRAMS 3.5
Author: J Hall (Dept of Water)
Government of Western Australia
Department of Water
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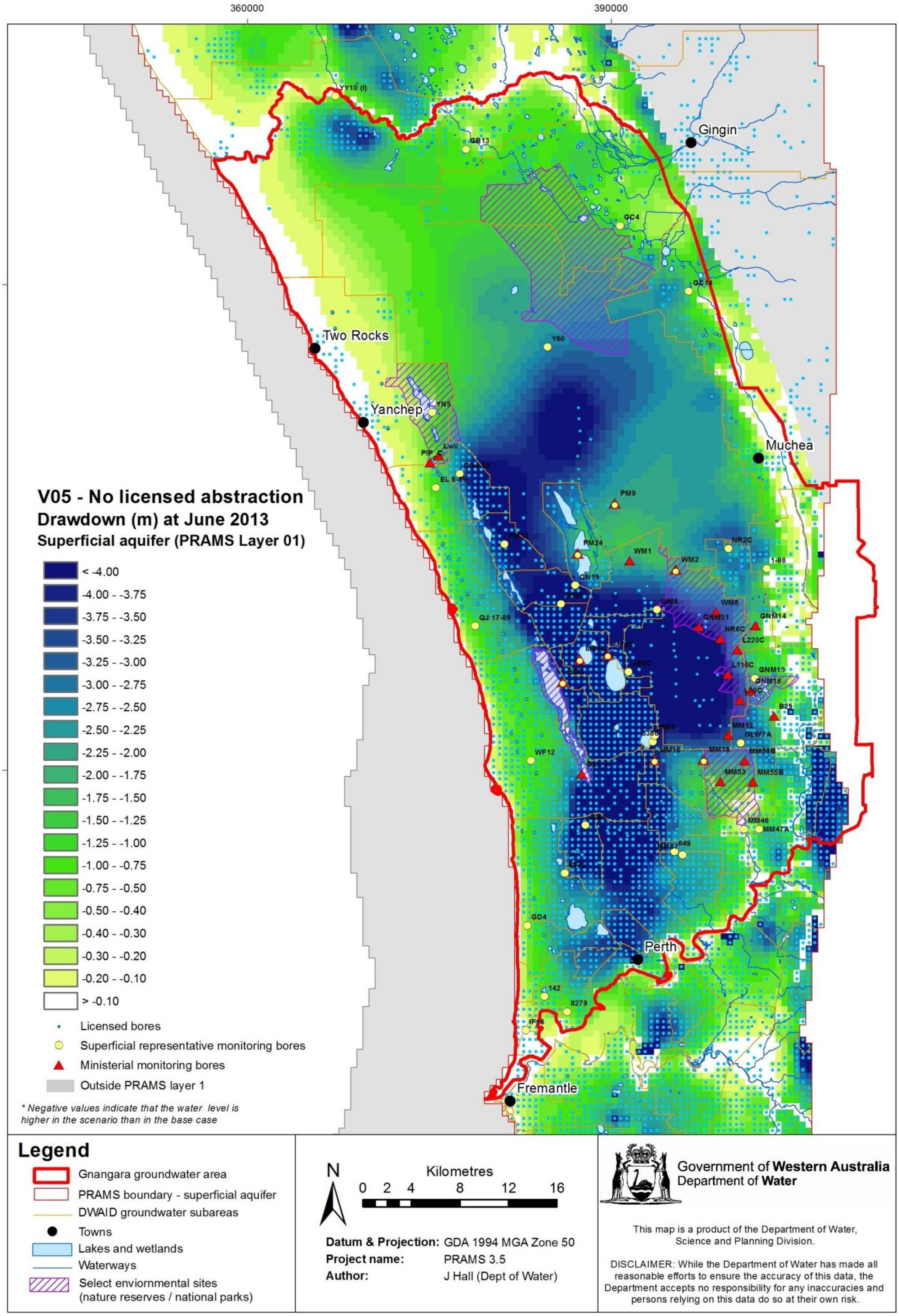
V05 - No licensed abstraction
Drawdown (m) at June 2013
Superficial aquifer (PRAMS Layer 01)
< -4.00
-4.00 - -3.75
-3.75 - -3.50
-3.50 - -3.25
-3.25 - -3.00
-3.00 - -2.75
-2.75 - -2.50
-2.50 - -2.25
-2.25 - -2.00
-2.00 - -1.75
-1.75 - -1.50
-1.50 - -1.25
-1.25 - -1.00
-1.00 - -0.75
-0.75 - -0.50
-0.50 - -0.40
-0.40 - -0.30
-0.30 - -0.20
-0.20 - -0.10
> -0.10
Licensed bores
Superficial representative monitoring bores
Ministerial monitoring bores
Outside PRAMS layer 1
* Negative values indicate that the water level is higher in the scenario than in the base case
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
360000
390000
6520000
6480000
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
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Select enviornmental sites (nature reserves / national parks)
N
Kilometres
0 2 4 8 12 16
Datum & Projection: GDA 1994 MGA Zone 50
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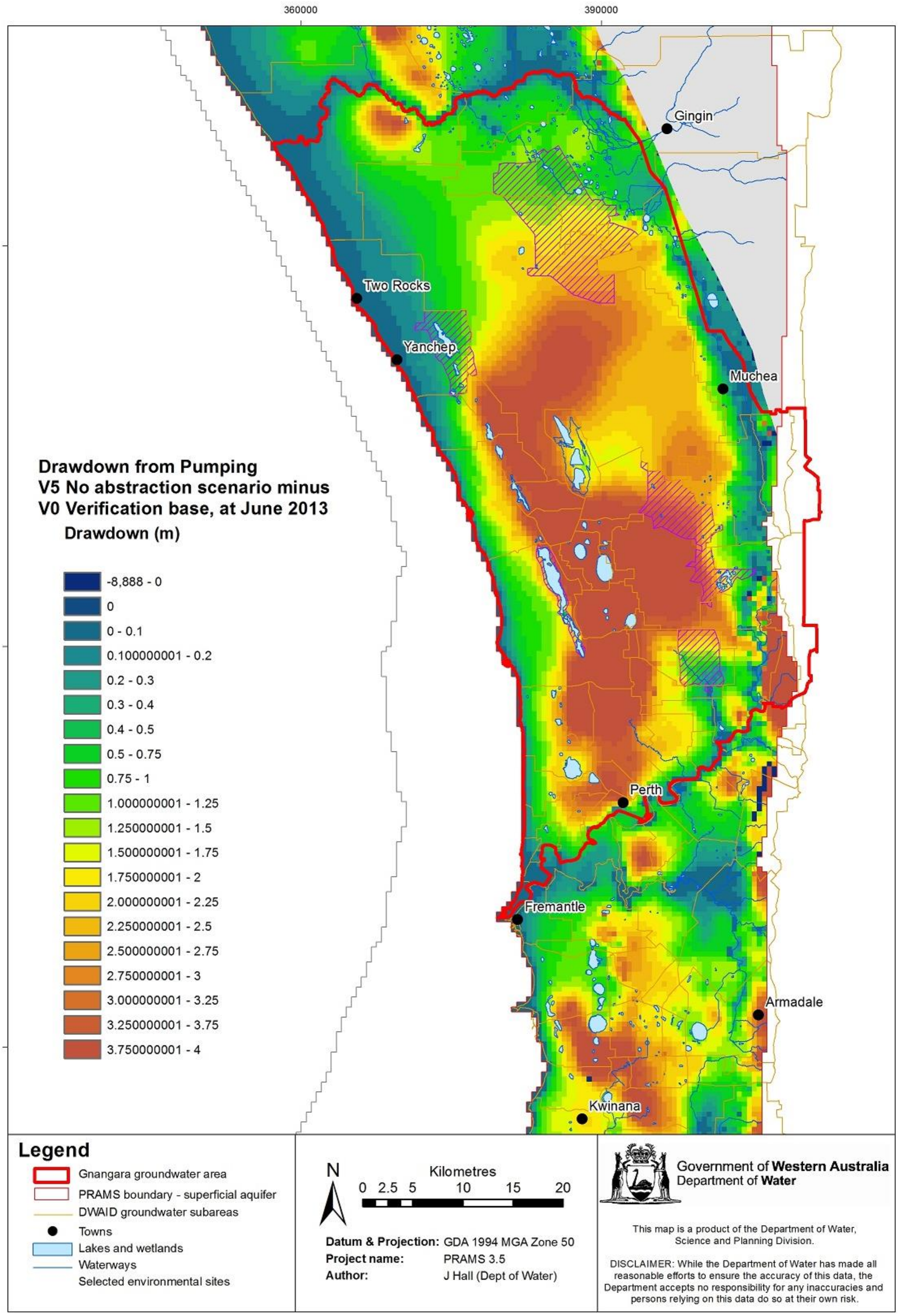
360000
390000
6520000
6480000
6440000
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
Armadale
Kwinana
Drawdown from Pumping
V5 No abstraction scenario minus
V0 Verification base, at June 2013
Drawdown (m)
-8,888 - 0
0
0 - 0.1
0.100000001 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.75
0.75 - 1
1.000000001 - 1.25
1.250000001 - 1.5
1.500000001 - 1.75
1.750000001 - 2
2.000000001 - 2.25
2.250000001 - 2.5
2.500000001 - 2.75
2.750000001 - 3
3.000000001 - 3.25
3.250000001 - 3.75
3.750000001 - 4
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
Lakes and wetlands
Waterways
Selected environmental sites
N
Kilometres
0 2.5 5 10 15 20
Datum & Projection: GDA 1994 MGA Zone 50
Project name: PRAMS 3.5
Author: J Hall (Dept of Water)
Government of Western Australia
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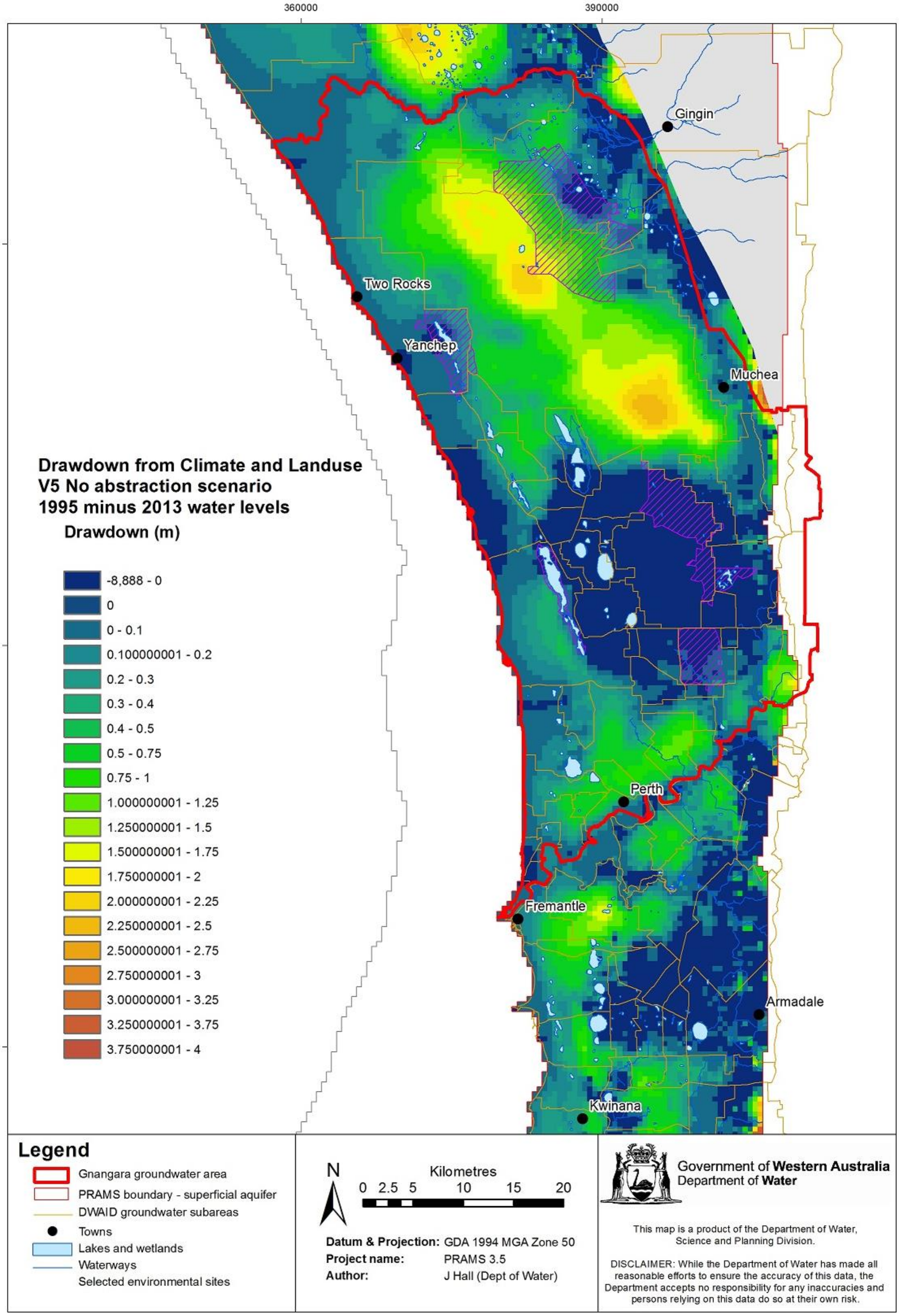
360000
390000
6520000
6480000
6440000
Gingin
Two Rocks
Yanchep
Muchea
Perth
Fremantle
Armadale
Kwinana
Drawdown from Climate and Landuse
V5 No abstraction scenario
1995 minus 2013 water levels
Drawdown (m)
-8,888 - 0
0
0 - 0.1
0.100000001 - 0.2
0.2 - 0.3
0.3 - 0.4
0.4 - 0.5
0.5 - 0.75
0.75 - 1
1.000000001 - 1.25
1.250000001 - 1.5
1.500000001 - 1.75
1.750000001 - 2
2.000000001 - 2.25
2.250000001 - 2.5
2.500000001 - 2.75
2.750000001 - 3
3.000000001 - 3.25
3.250000001 - 3.75
3.750000001 - 4
Legend
Gnangara groundwater area
PRAMS boundary - superficial aquifer
DWAID groundwater subareas
Towns
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N
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