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

Securing Western Australia's water future

Loch McNess hydrogeology and causes of water-level decline (1975–2011)

Hydrogeological record series

Report no. HG60
May 2016

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

Loch McNess hydrogeology and causes of water-level decline (1975–2011)

Department of Water

Hydrogeological record series

Report no. 60

May 2016

Department of Water
168 St Georges Terrace
Perth Western Australia 6000
Telephone +61 8 6364 7600
Facsimile +61 8 6364 7601
National Relay Service 13 36 77
www.water.wa.gov.au

May 2016

ISSN 1836-2869 (print)
ISSN 1836-2877 (online)

ISBN 978-1-921992-89-6 (print)
ISBN 978-1-921992-90-2 (online)

Acknowledgements

The Department of Water would like to thank the following for their contribution to this publication: Andrew Paton, Mike Hammond, Brad Degens, Sandie McHugh, Joel Hall, Ben Marillier, Cahit Yesertener and Mischa Cousins from the Department of Water; Rob Foulds, Yanchep National Park volunteer and member of the West Australian Speleological Group; and Alison Pritchard, Yanchep National Park Manager.

Recommended reference

Kretschmer, P & Kelsey, P 2016, *Loch McNess hydrogeology and causes of water level decline (1975–2011)*, Hydrogeological record series, HG60, Department of Water, Western Australia.

For more information about this report, contact Peta Kelsey, Water Science Branch.

Disclaimer

Contents

Figures

Tables

Appendices

Summary

This report was substantially written in 2012. When the authors refer to ‘current’, they are referring to the conditions and groundwater abstraction volumes that prevailed in 2011.

The findings and recommendations from this work have been used to guide decisions related to water allocation and licensing. Since 2013 the Department of Water has partially redistributed abstraction from the Leederville aquifer at the Pinjar borefield closest to Loch McNess to other parts of the integrated water supply scheme to minimise impacts on wetlands. Other water entitlements to the west of Loch McNess have been reviewed as part of allocation planning for the north-west urban growth corridor.

Loch McNess, located within the Yanchep National Park, is a significant wetland with high conservation status and statutory protection. It is a valuable community asset that received an average of 233 100 visitors each year between 2002 and 2007 (Perriam et al. 2008).

Loch McNess, on the western margin of the Gnangara Mound, is part of a wetland chain that is more resilient to a drying climate than other wetlands on the Mound because it is closer to the coast where water levels are buffered by sea level.

Nevertheless, the lake hydrology has changed and lake levels have fallen, harming its ecological and social values. Loch McNess was a permanently-full flow-through lake before 2006. At the end of the 2011/12 summer, shallow water covered less than one-third of the lake area, and the water was turbid and of poor quality.

This assessment has updated our understanding of the lake’s hydrogeology. Inflow is through springs and the lake bed from the Superficial aquifer to the east. These flows are influenced by interaction between the Superficial and Leederville aquifers, as there is no confining layer between the aquifers in this area. Outflow is through the western lake bed and, when lake levels are high, through spillover into the caves and the karstic aquifer to the west. Until 2006, lake levels were reasonably constant and maximum water levels were controlled by spillover into the caves. The spillover masked the effects of decreasing inflow to the lake. Since 2006, outflows have been greater than inflows and lake levels have progressively fallen. The falling watertable around Loch McNess also resulted in the drying of the Yanchep Caves and in 2005 the Department of Environment and Conservation started pumping water into the caves to protect their endemic stygofauna.

Analyses of water-level data revealed that watertable decline has mainly been due to pumping from the Superficial aquifer at Yanchep National Park and at Yanchep Beach, and from the Leederville aquifer, and reduced recharge due to declining rainfall. The watertable decline near Loch McNess caused by Superficial aquifer abstraction at the Pinjar borefield on the Gnangara Mound and in the Carabooda horticultural area was estimated to be minor. Clearing of pine plantations from 2002 onwards has not induced a watertable response close to Loch McNess.

Pumping from the Superficial aquifer to the west of the lake to supplement the Yanchep Caves and pumping near the eastern shore have inadvertently contributed to watertable decline at the lake. The decline to the west of Loch McNess is as much as 3 m for 1991–2010, mainly due to these local abstractions, but also to reduced rainfall and the abstractions in the Yanchep Beach area.

The head gradient from the Leederville to the Superficial aquifer near Loch McNess has weakened with time. At a set of nested bores on the western shore of the lake, the hydraulic head gradient changed from upward to downward in 1999.

Pumping that caused head-level decline in the Leederville aquifer has also contributed to water-level decline in the Superficial aquifer at the lake. The watertable decline to the east of Loch McNess for the period 1991–2010 was approximately 1.5 m. Analysis showed that approximately 1.0 m can be attributed to Leederville aquifer abstraction. The remaining decline (~0.5 m) can be attributed to decreasing rainfall.

To increase the lake water levels, in the medium term, groundwater levels can be raised by reducing pumping from the Superficial aquifer at, and to, the west of the lake, and also reducing Leederville aquifer pumping, primarily at the Pinjar borefield to the east.

During this study, abstraction from the Superficial aquifer for the ring-main in the national park was reduced and cave supplementation stopped after the then Department of Environment and Conservation was made aware of the their effects on Loch McNess.

Pumping in the Yanchep groundwater area to the west should be spread across subareas A–G to avoid concentration of pumping directly down hydraulic gradient of Loch McNess. Future allocation from the Superficial aquifer to the west of Loch McNess should be less than 50 per cent of discharge to the ocean, to avoid groundwater decline on the western side of Loch McNess and protect against seawater intrusion. This allocation approach is consistent with previous approaches applied in the 1980s by Rockwater and the Geological Survey of Western Australia, which stated that total allocation should be less than 50 per cent of the total flow-through. The previously-established allocation limit of 365 ML/year for subarea G needs to be reviewed to take into consideration the decreased rainfall and changed land uses.

It is also recommended that pumping from the Leederville aquifer at the Pinjar borefield is progressively reduced to pre-1998 abstraction rates (preferably less than 3 GL/year). The pumping at this borefield before 1998 appeared not to be having significant impact on water levels near Loch McNess. Abstraction at other Leederville aquifer borefields may also be affecting hydraulic head in the Loch McNess area, so an investigation of the relative impacts of pumping from the Quinns and Pinjar, Leederville aquifer borefields on groundwater levels in the Loch McNess area (where the Leederville and Superficial aquifers are in hydraulic connection) should be undertaken.

Pine plantations on the central part of the Gnangara Mound are thought to cause groundwater decline through the interception of recharge. Groundwater levels did not respond to recent pine clearance in the Loch McNess area. This may be due to ongoing below-average rainfall, or to the area cleared being small (< 150 ha). More than 3500 ha of the pine plantations remain to the east of Loch McNess and future removal of these would be expected to result in increased recharge to groundwater. It is recommended that pine plantations are removed and not replanted. Water-level responses may take some time to appear but this land-use change will increase the recharge and so increase the inflows to Loch McNess

.

1 Introduction

A special reserve including Loch McNess and the Yanchep Caves was established in the 1930s with the support of Sir Charles McNess to create and protect ‘one of the finest assets and beauty spots in Western Australia’ (*West Australian* 1935). Surveys have shown Loch McNess and the caves within the Yanchep National Park form a unique aquatic ecosystem that supports rare and highly-threatened ecological communities (English et al. 2003; Cook & Janicke 2005 Knott et al. 2006; 2008). Loch McNess has statutory protection under the Environment Protection (Swan Coastal Plain Lakes) Policy 1992, is listed in the *Directory of important wetlands in Australia* (Environment Australia 2001), and is a Conservation Category Wetland (managed in accordance with Environmental Protection Authority bulletins 685 and 686). Yanchep National Park is also very valuable to the community as a recreational asset. Between 2002 and 2007, an average of 233 100 people visited the national park each year (Perriam et al. 2008).

During the past 15 years falling groundwater levels initially led to the streams within the caves drying. Since 2006, lake water levels have also dropped, resulting in large areas of the lake drying during summer (Figure 1). This has encouraged terrestrial weeds to invade the lake bed and resulted in the loss of many of the recreational and environmental values of the Yanchep National Park (Sommer & Horwitz 2011).

Loch McNess is 5 km east of Yanchep within the Yanchep National Park (Figure 2 and Figure 3). It lies near a boundary between the sandy siliceous aquifer of the Gnangara Mound to its east and the karst coastal limestone aquifer to its west. The Yanchep Caves, which surround the lake, have been the subjects of technical investigations since 1911, some of which are reported in publications of the local caving society. More recent studies have focused on supporting the cave groundwater supplementation trial. This scheme has been ongoing in various forms for nine years with the aim of protecting the critically-threatened stygofauna community living within the caves (Barber 2003; DoW 2006).

Hydrogeological studies have been undertaken for the Superficial aquifer’s karst limestone areas to the west of Loch McNess, and these are particularly useful for describing the pre-development and pre-major-abstraction hydrogeology of the area (e.g. Rockwater 1976c). To the east of Loch McNess the impacts of pine plantations, reducing rainfall and increasing abstraction are recognised (DoW 2008). More recently, the *Perth shallow groundwater systems investigation – Loch McNess* has provided important information on the hydrochemistry of Loch McNess and confirmed the lake to be a groundwater connected flow-through system (DoW 2011).

This current study updates knowledge of the hydrogeology of the lake and caves and reviews the history of groundwater abstraction in the Yanchep Beach area. It also explains the most likely causes of rapid declines in lake water levels since 2006 and gives guidance for better groundwater management to restore some of the hydrogeological processes and water levels of this important environmental asset.

Figure 1 Loch McNess in August 2007 (top), and in September 2015 (bottom)

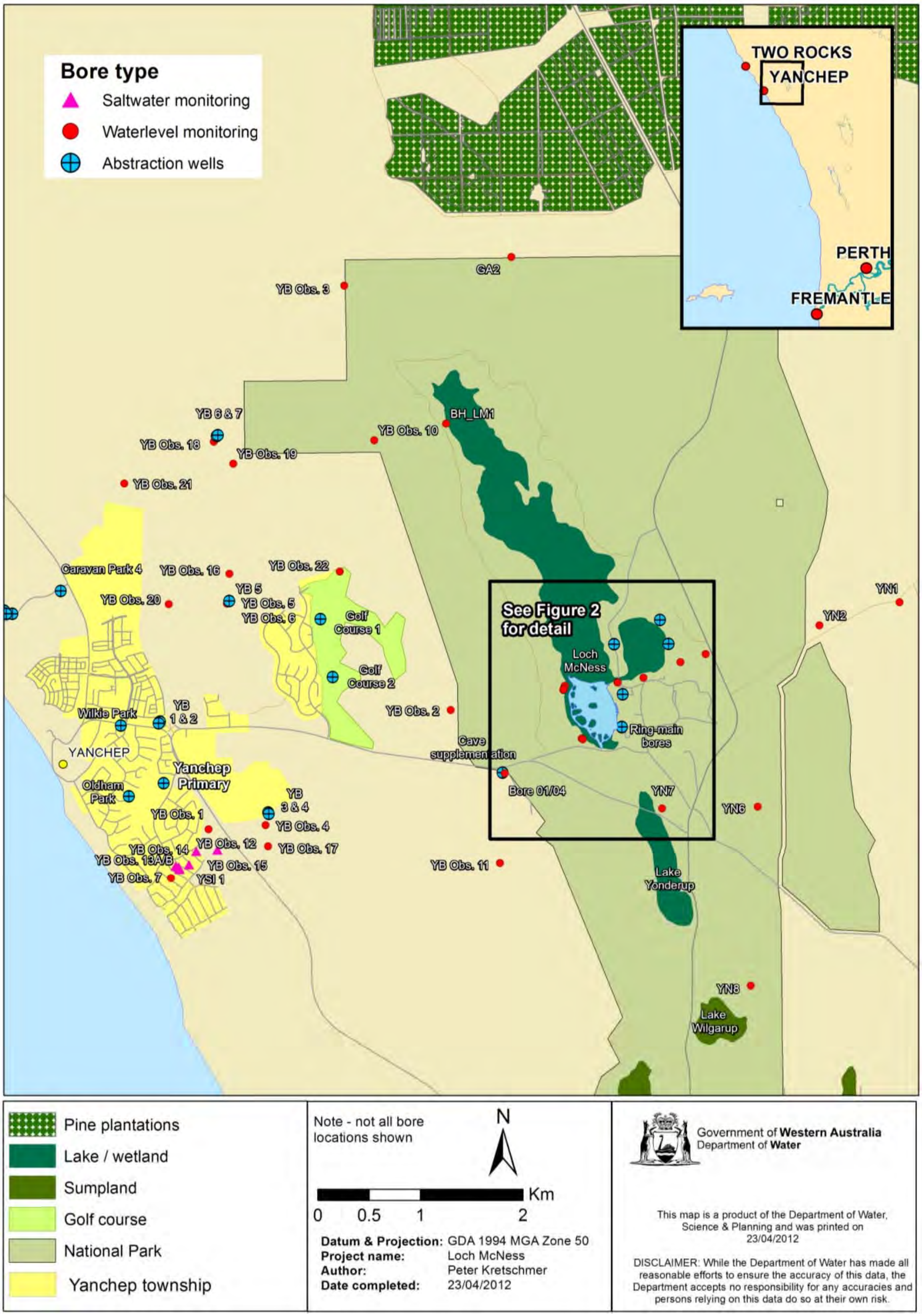


Figure 2 Yanchep Beach study area

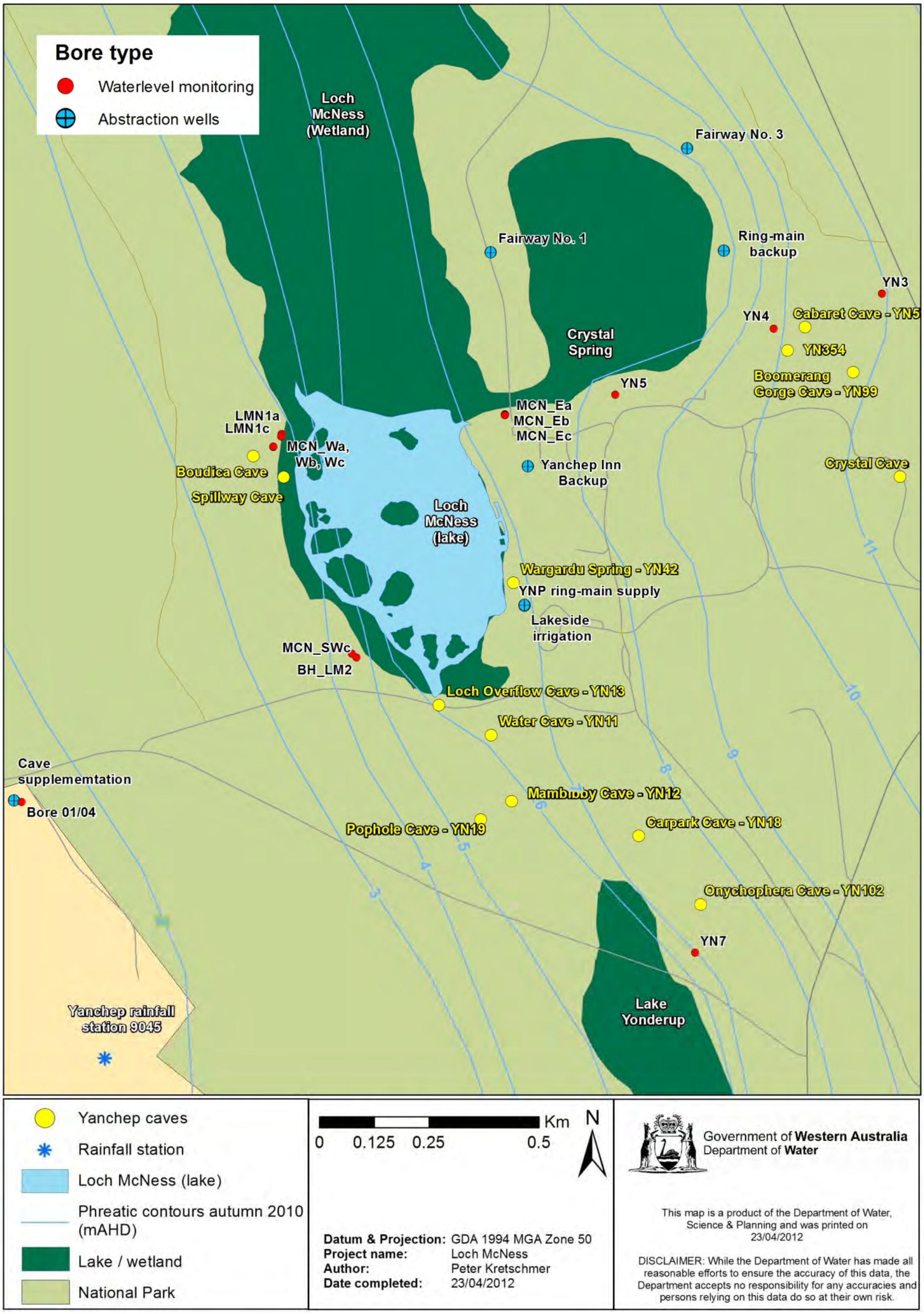


Figure 3 Loch McNess study area

2 Climate

Yanchep National Park, in which Loch McNess is located, has a Mediterranean climate with hot, dry summers and cool, wet winters. Most rainfall falls between May and September (Figure 4). The long-term (1906–2011) average annual rainfall is 757 mm and the average annual potential evaporation is 1950 mm (site 9045).

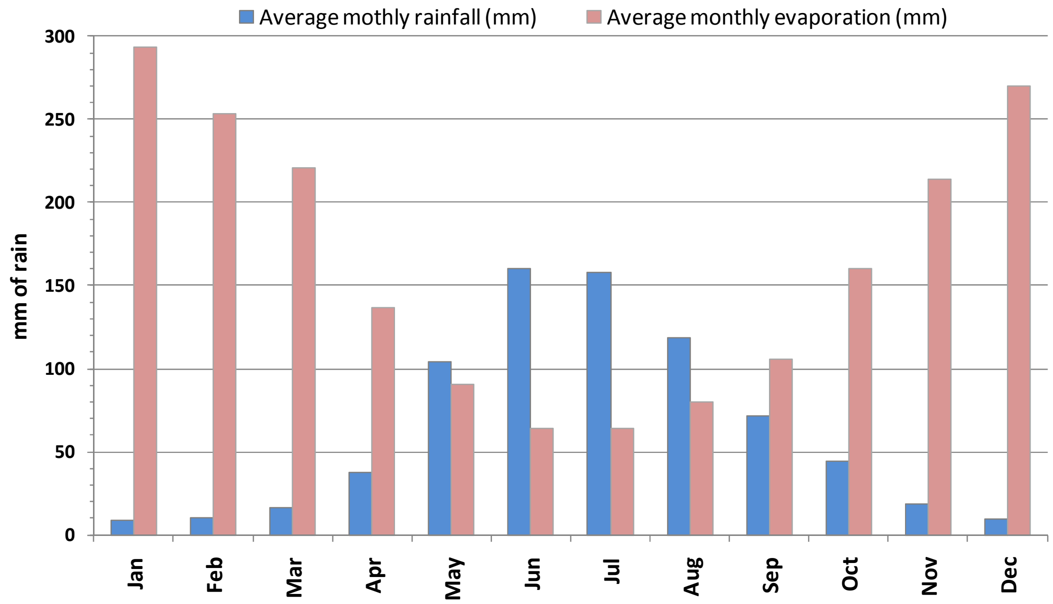


Figure 4 Average monthly rainfall and potential evaporation (1906–2011; site 9045)

Over the past decades rainfall has been decreasing (Figure 5). Average annual rainfall at Yanchep (site 9045) has decreased from 749 mm in 1975–88, to 684 mm in 1989–2005 and then to 599 mm in 2006–12 (Figure 5).

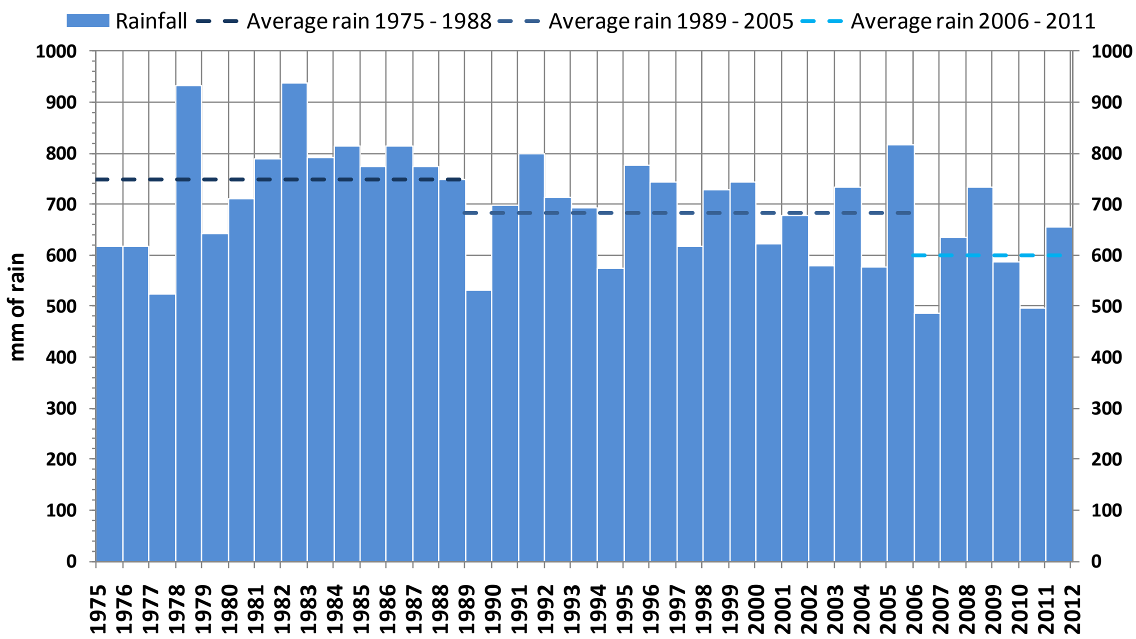


Figure 5 Yanchep rainfall (site 9045), with average annual rainfalls for 1975–88, 1989–2005 and 2006–12

3 Geology and geomorphology

Loch McNess is located on the Swan Coastal Plain within the Perth Basin, a north-trending sediment-filled trough extending approximately 1000 km along the south-western margin of the Australian continent. The Perth Basin developed following rifting of continental plates along the Darling Fault, beginning in the early Permian and culminating in the separation of Greater India from Gondwana by the Early Cretaceous. Sediment deposition and erosion have been episodic through to the current day in progradational and fluvial environments (Davidson 1995; Leyland 2012).

The representation of the local geology (Figure 6) has been interpreted from the lithology logs of monitoring bores around Loch McNess, with additional interpretation of the Leederville Formation from Leyland (2011; 2012). The upper surface of the Leederville Formation, consisting of sand or silty sand, was intersected in monitoring bores LMN1a at 35.4 m BGL (–28.1 m AHD) (McPhar Geophysics 1974), MCN_Ea at 36 m BGL (–27.9 m AHD), and MCN_Wa at 38 m BGL (–28.9 m AHD).The interpretation of the base of the Superficial aquifer in the MCN bores differs slightly to the earlier Loch McNess shallow groundwater investigation (DoW 2011). MCN_Ea is interpreted as intersecting the Wanneroo Member of the Leederville Formation rather than the Lancelin Formation, thus making the geological representation consistent with Leyland (2011). This also corrects the issue of the Lancelin Formation being underlain by younger Tamala Limestone in DoW (2011). MCN_Wa is interpreted to intersect the Wanneroo Member at 38 m BGL, compared with 48 mBGL in DoW (2011). This depth corresponds to the increase in the gamma count presented in DoW (2011), and is more consistent with the lithology interpretation in LMN1a (McPhar Geophysics 1974) approximately 30 m away.

The Wanneroo Member of the Leederville Formation subcrops the superficial formations to the east of the Badaminna Fault, and the Kings Park Formation west of the fault (Leyland 2011; 2012). East of the fault, the Wanneroo Member is a very permeable aquifer and lithological logs from bores suggest little clay occurs at the interface of the Leederville and Superficial aquifers. Mapping by Davidson (1995) also confirms that Kardinya Shale is absent in this area. The upper portion of the Leederville Formation was shown to be quite sandy in the 78 m deep bore 01/04 drilled for the cave supplementation trial (Drilling Consultancy 2004; Rockwater 2005b). This bore intersected 30 m of the Leederville Formation between 48 m BGL (–28 m AHD) and 78 m BGL (–58 m AHD). West of the Badaminna Fault, the Kings Park Formation is mostly clay and therefore acts as an aquiclude below the Superficial aquifer. The shallow Quaternary geology near Loch McNess consists of Bassendean Sand, Tamala Limestone and Safety Bay Sand. These form the superficial formation and the Superficial aquifer in the study area. Lithology logs indicate the sandy unit underlying Loch McNess and the caves is unconsolidated quartz-dominant Tamala sand (unofficial title), the same depositional sequence as the Tamala Limestone (Rockwater 2005a; DoW 2011). The use of a suction dredge to remove silty lake bed sediments (Anderson et al. 2005) provides anecdotal evidence of the lake bed being mainly composed on unconsolidated silts and sands. To the west of Loch McNess the Tamala sand interfingers with the Tamala Limestone and also presumably slopes down towards the base of the Superficial formation.

To the east of Loch McNess, the Tamala Limestone sits on top of the Tamala sand which in turn sits above the Bassendean Sand where it slopes down towards the base of the Superficial formation (Figure 6).

Near the coast, a layer of Safety Bay Sand has been deposited as coastal dunes. Easterly projecting dune blowouts of the Safety Bay Sand are visible in the surface geology mapping (Figure 7). In the mapped area, Safety Bay Sand is thought to have little interaction with the saturated zone of the Superficial aquifer.

Loch McNess is one of a complex of wetlands that extend north-south along the Swan Coastal Plain. The wetlands near Loch McNess are found between 5 and 7 m AHD and are divided by easterly-projecting dunes of the Tamala Limestone (Appendix A).

Many of the Yanchep Caves have formed where groundwater flowing from the Gnangara Mound has intersected and chemically weathered the Tamala Limestone (Bastian 1996) (Figure 8). Cave formation begins as horizontal solution channels also known as ‘watertable slots’. The solution channels subsequently enlarge due to the collapse and dissolution of roof material into the ‘stream’ of groundwater in the developing cave (Bastian 1996). Figure 9 shows this development stage, with parts of Boudica Cave extending up to 20 m laterally yet remaining only 1 m high. The undulating upper surface of the sand formations can lead to primary and secondary ‘cave source zones’ (Bastian 1996). In the context of Loch McNess, the primary cave zone can be viewed as being the Crystal Cave complex to its east, and the secondary cave zone as being Spillway and Boudica caves to its west (Figure 3).

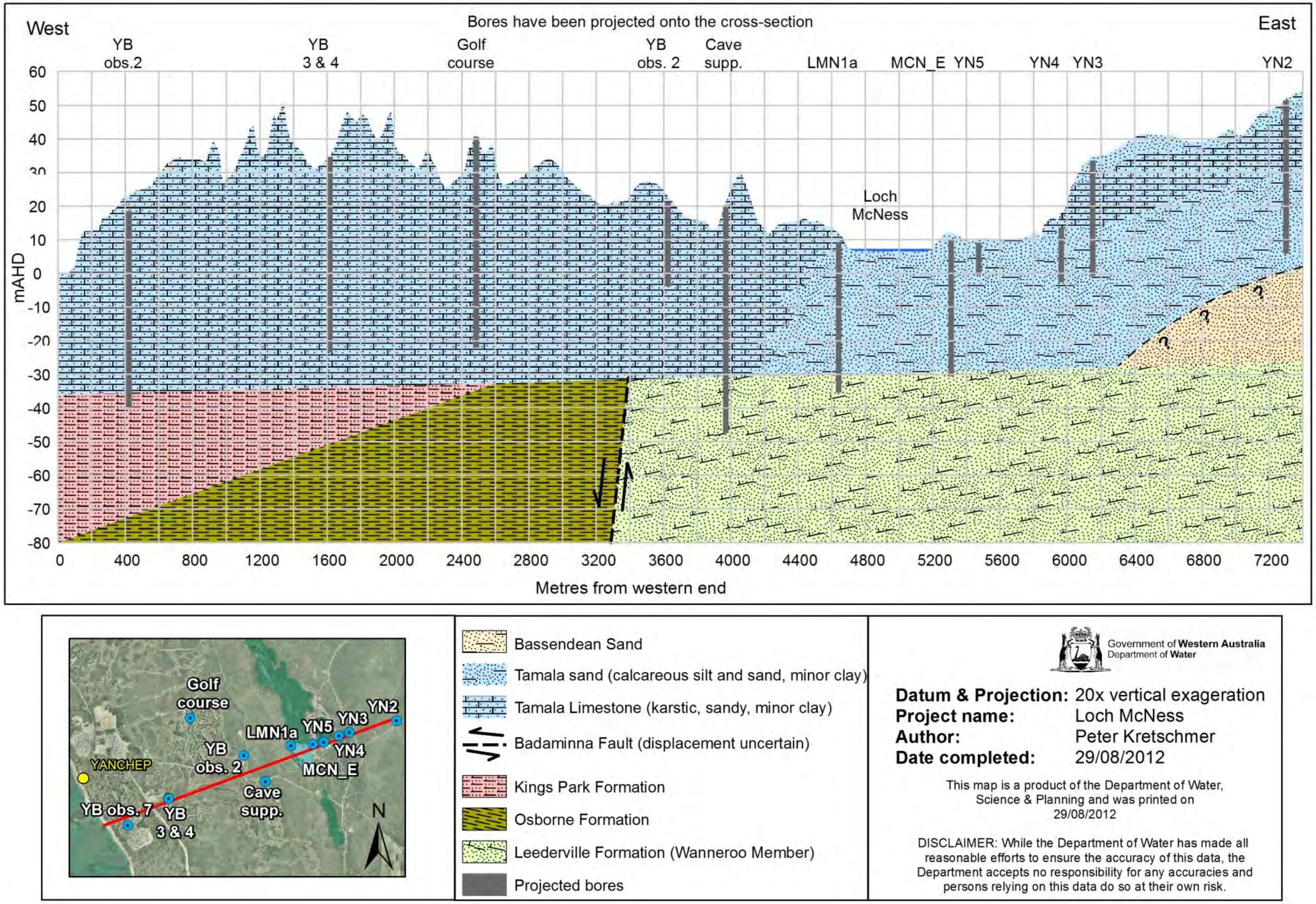


Figure 6 East-west cross-section of the geology underlying Loch McNess and extending westwards to the coastline. Unconformity surfaces not illustrated. Interpretation of Leederville Formation after Leyland (2011).

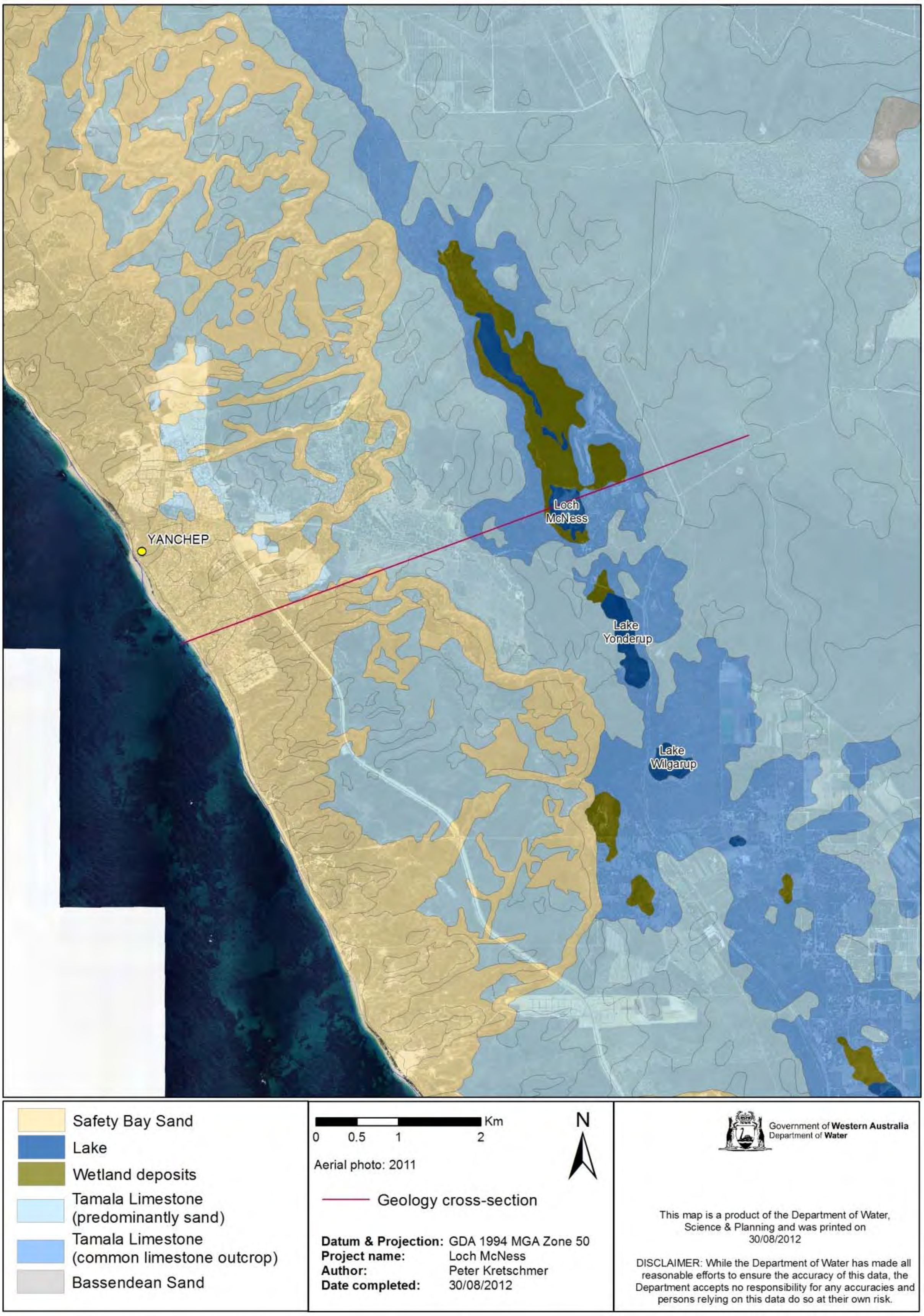


Figure 7 Surface geology (Sourhalle: Department of Agriculture and Food soil mapping)

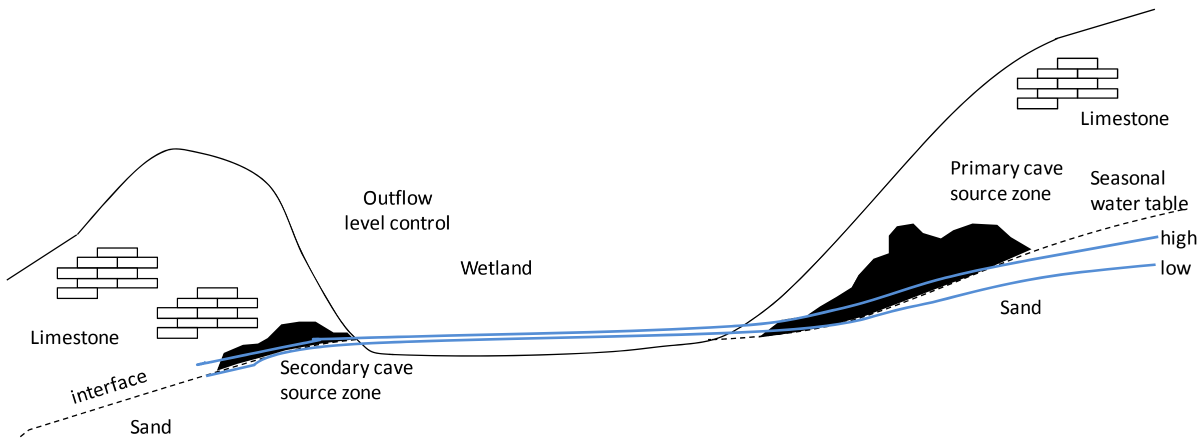


Figure 8 *Conceptual diagram of the cave source zone with the Tamala sand on the bottom and the Tamala Limestone on the top*

Figure 9 *An example of horizontal watertable slots in Loch Overflow Cave (YN13), left, and Boudica Cave (YN566), right. Roof material has collapsed onto the floor of the caves and partly dissolved. Photos and explanation courtesy of Rob Foulds, 2008.*

4 Hydrogeology of Loch McNess

Loch McNess sits on the western edge of the Gnangara Mound, a regional groundwater system located in Quaternary-aged sediments (Figure 2). Groundwater in the Superficial aquifer flows from watertable elevations of more than 50 m above sea level at the centre of the Mound to the coast. The lake, which is 5 km inland, is a surface expression of the watertable (Yesertener 2009). That is, Loch McNess is a flow-through wetland whose water level is dependent on the balance between groundwater inflow and outflow.

Inflow to the lake is primarily from Superficial aquifer discharge from the Gnangara Mound to the east. This is expressed through the lake bed and as springs or seeps on the lake's eastern side. Outflow discharges through the lake bed to the Tamala sand on the lake's western side. At higher lake water levels in the past, there was outflow into caves on the western shoreline.

The lake was deepened with a suction dredge to remove silty-sand wetland sediments in the 1930s and it was dredged again in the 1960s. This was to make it more suitable for boating. The dredge spoil was used to create the islands and flatten the land on the lake's eastern side (Anderson et al. 2005). From a hydrogeological perspective the dredging is thought to have made little difference to groundwater flow in the vicinity of the lake.

In the area around Loch McNess groundwater flows in a west-south-west direction. The thinning of the sand formations from east to west and contact with lower hydraulic conductivity Tamala sand causes groundwater to emerge into the overlying caves and to be expressed at the surface as springs and the lake. The Bassendean Sand generally has a higher hydraulic conductivity (~15 m/day) than Tamala sand (~10 m/day; Salama et al. 2005; DoW 2009a). In the Tamala sand steeper hydraulic gradients result from a combination of its lower conductivity compared with the Bassendean Sand to the east and groundwater draining into the highly conductive karstic Tamala Limestone to the west.

The watertable slots of the Yanchep Caves indicate that zones of high horizontal hydraulic conductivity are likely to be common along the interface of the Tamala sand and Tamala Limestone. Some of the caves may allow shallow hydraulic connection between the lakes. For example, it has been suggested that Loch Overflow Cave (YN13) is a large labyrinthine cave that connects overflows from Loch McNess with Lake Yonderup to its south (Rockwater 2003). A tracer study conducted in September 1968 demonstrated that a Rhodamine B florescent tracer placed in Loch Overflow Cave was recorded in Mambibby (YN12) and Pophole (YN19) caves around 250 m south the following weekend (Bridge 1968).

4.1 Factors controlling groundwater inflow to Loch McNess and the caves

Groundwater in the Superficial aquifer flows in a west-south-west direction from the Gnangara Mound to Loch McNess (Figure 3) and discharges through the lake bed, and to springs and seeps to the lake's east. Recent hydraulic and hydrochemical investigations have confirmed that discharge occurs through the lake bed, as water levels in the Superficial aquifer up-gradient of the lake have a very slight upward gradient in head pressures (DoW 2011). Inflow to the lake would have been greater in the past when groundwater levels to the east were higher. Groundwater levels east of Loch McNess have declined by more than 1.5 m during the past 20 years (Figure 10).

The two notable springs which discharge to Loch McNess are Crystal Spring and Wagardu Spring. Crystal Spring, a large spring/wetland to the north-east of Loch McNess, flows into the lake via a culvert under a road (see Figure 2). Wargardu Spring, a small watertable slot located near the jetty on the eastern shoreline (Figure 11), was once a permanent inflow to Loch McNess but has been mostly dry since the beginning of the 2000s. Additional input to the lake will occur from direct rainfall and carpark runoff, while a minor contribution can be expected from excess irrigation water of grassed areas surrounding Loch McNess and infiltration from the park's nearby water treatment systems.

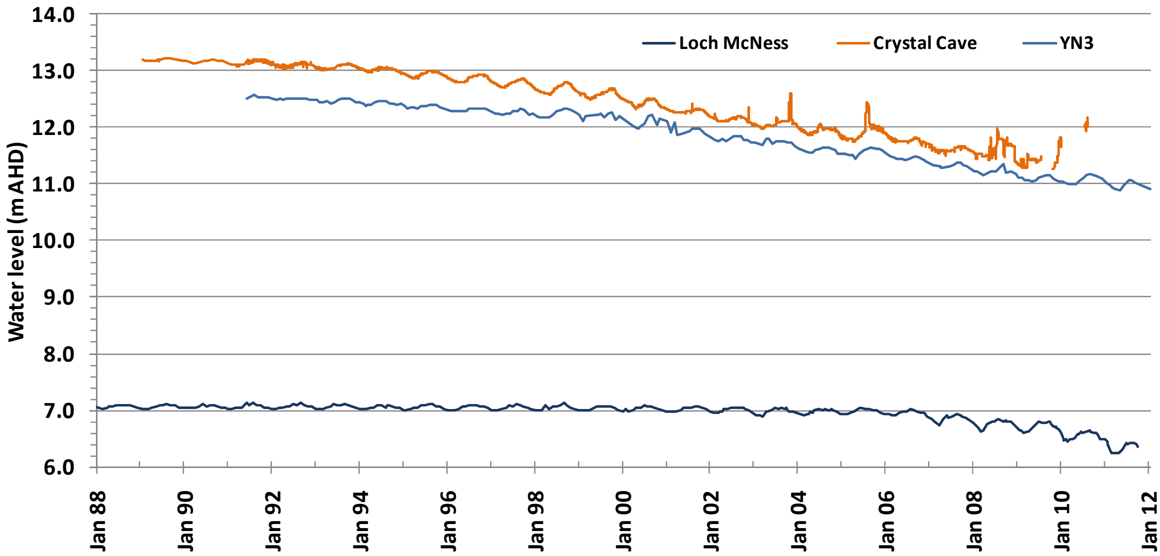


Figure 10 Water levels in Crystal Cave, YN3 and Loch McNess. Effects of the cave supplementation scheme can be seen in Crystal Cave after 2004.

Figure 11 Wargardu Spring, December 2001. Photo courtesy of Rob Foulds.

4.2 Factors controlling outflow from Loch McNess and the caves

Water is lost from the lake via discharge to groundwater through the lake bed, spillover to the caves to the lake's west, and evaporation. The relative volumes of the flows have changed over the past few decades.

The historic maximum water levels of Loch McNess were controlled by the invert level of various outflow caves located in the karst limestone on the western shoreline. This flow dynamic was recognised previously (McPhar Geophysics 1974; WAWA 1995; Rockwater 2003). Although, there has been some disagreement with this observation (Davidson 1995; Bekesi 2007), this report supports the earlier findings. There are at least three caves that were likely to have contributed to controlling the lake's maximum water level at different lake stage heights. Loch Overflow Cave (YN13) at the south-western tip of the lake was originally thought to be the main overflow cave. It was described as receiving outflow in an early 20th century surveyor's report (R Foulds pers. comm. 2012) but there have been no accounts of lake water discharging to the cave in recent decades (Bastian 1999). Water flowing into a more recently discovered cave – Spillway Cave (YN565; Figure 13 and Figure 14) – was observed in February 2005, with higher flow rates observed later in the year (Bastian 2008).

Cave sediments also contain evidence of water flowing from the lake into the caves. Peat sediments occur in some of the caves on the western side of Loch McNess, such as Boudica Cave (YN566; Figure 3; Bastian 2008). These are likely the result of deposition of organic debris from lake overflow (R Foulds, pers. comm. 2012). Similar peaty sediments are absent in caves on the lake's eastern side.

The long monitoring records from bores Bond Development 9 – Loch McNess 1a (LMN1a) and Bond Development 10 – Loch McNess 1c (LMN1c) provide important insights into how climate and abstraction have altered groundwater heads and outflow adjacent to Loch McNess. LMN1a is screened between 37.5 and 42 m BGL at the top of the Leederville aquifer, and LMN1c is screened between 0 and 3 m BGL in the Superficial aquifer (McPhar Geophysics 1974).

The water levels in these bores were adjusted before analysis (in this study) to correct for errors in elevation benchmarks and bore labelling. These errors were detected after differences were noted between water levels recorded in the Department of Water's Water Information System (WIN) and those recorded in reports for the Yanchep Beach – Two Rocks scheme. Notably, the Department of Water's records showed water levels in the Superficial bore (LMN1c) on the western (outflow) side of the lake to be higher than lake levels, which did not make sense. Confusion with bore labelling and subsequent incorrect assignment of resurveyed top-of-casing reference levels have resulted in these long-term hydrographs misleading previous hydrogeological investigations of Loch McNess (Bekesi 2007; DoW 2011).

Until 2006 the caves played an important part in controlling the lake's maximum water levels between 6.9 and 7.1 m AHD. Leakage losses through the lake bed's western side would have been minimal as the observed groundwater hydraulic heads on the western side were close to lake level (Figure 12). Since 2006, the steadily falling Superficial aquifer water levels (seen in LMN1c and other bores such as BH_LMN2 and BH_LMN1 included in Appendix E) have resulted in higher leakage rates through the lake bed of Loch McNess (this is discussed in Section 6). The lowered lake water level has resulted in the cessation of discharge through the spillover caves. As the wetted area of the lake shrank, evaporation from the lake surface would have also proportionally decreased.

Superficial aquifer investigations in 2008 and 2009 identified the current discharge regime. Water from Loch McNess now discharges through the western lake bed to shallow and intermediate depths in the aquifer to the lake's west (DOW 2011).

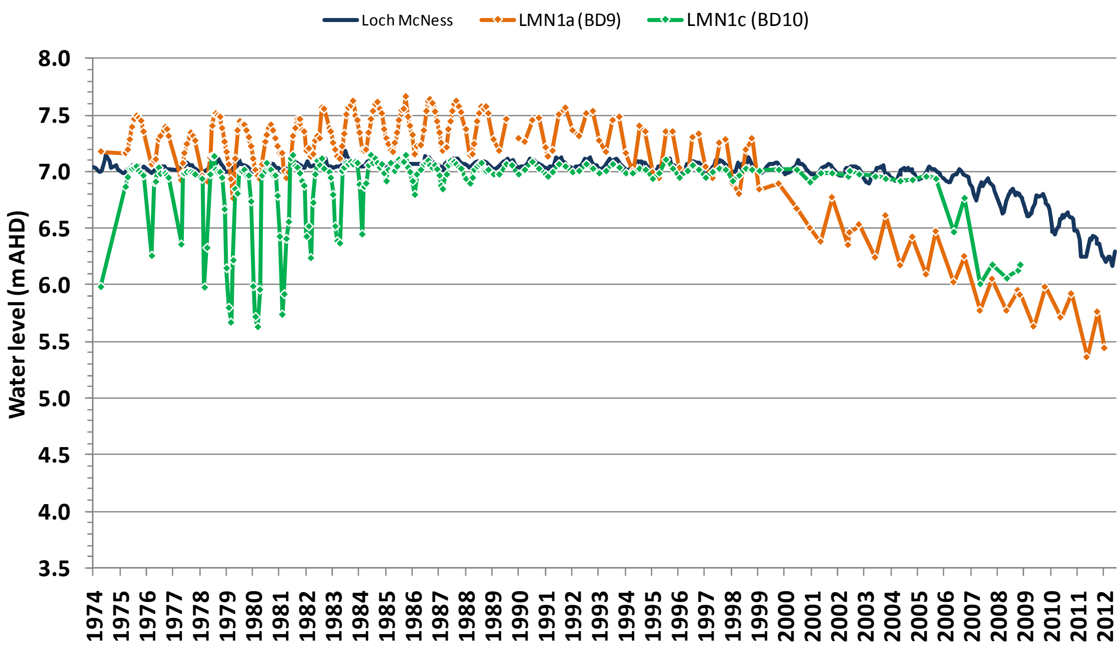


Figure 12 Water levels in Loch McNess, the top of the Leederville aquifer, LMN1a (deep), and the top of the Superficial aquifer, LMN1c (shallow)

Figure 13 *Western edge of Loch McNess bordering Spillway Cave (YN565). View from wetlands walk trail looking north, September 2009. The flow, visible at high levels, is from the right to the left. The blue arrow indicates cave entrance. Photo and explanation courtesy of Rob Foulds.*

Figure 14 *Same location as Figure 13, Spillway Cave (YN565), looking south, 16 April 2010. The blue arrow indicates cave entrance. Photo and explanation courtesy of Rob Foulds.*

4.3 Leederville aquifer interaction

The Leederville and Superficial aquifers are hydraulically connected in the Loch McNess area, where the Wanneroo Member of the Leederville Formation lies below the superficial formations (Figure 15; McPhar Geophysics 1974; Leyland 2012).

Figure 15 shows the flow model for the Leederville aquifer in the region surrounding Loch McNess, as well as the areas where an aquiclude is present and the 1987 hydraulic head differences between the two aquifers (Leyland 2011). The Badaminna Fault in the Leederville aquifer to the west of Loch McNess may impede flows in the Leederville aquifer in a westerly direction (Leyland 2011).

There is evidence that the heads in the Superficial aquifer have decreased in response to reduced heads in the Leederville aquifer in the area where the aquifers are hydraulically connected. Long-term monitoring on the lake's western shore shows that water levels at LMN1a, screened in the upper Leederville aquifer, have declined since 1990 (Figure 12). Since 1999, the hydrographs of LMN1a and LMN1c indicate the hydraulic gradient has been reversed and the Superficial aquifer now discharges to the Leederville aquifer at this location. The relatively short record of hydraulic head in the deep Superficial aquifer bore MCN_Wa also indicates water levels on the western side of Loch McNess are below the water level in the lake. Monitoring of nested bores on the eastern side of Loch McNess during 2008–11 shows only very weak upward gradients continue to occur at the base of the Superficial aquifer (Figure 16). Bore construction information is presented in Appendix D.

The hydraulic connection between the Leederville and Superficial aquifers is also supported by hydrochemical data. Compared with the shallower bores, electrical conductivity in MCN_Ea and MNC_Wa, (screened near the base of the Superficial aquifer) is relatively stable throughout the year, the groundwater is anoxic, and iron concentrations are elevated (DoW 2011). These chemical characteristics, particularly higher iron concentrations are typical of the Leederville aquifer (Davidson 1995). Analysis of iron staining in caves as a result of the cave supplementation trial similarly concluded the supplementation bore (screened in the Superficial aquifer) was probably drawing water up from Leederville aquifer (Crisalis International Pty Ltd 2005).

4.4 Hydrodynamic changes to Loch McNess

Loch McNess remains a groundwater-dependent flow-through wetland. Inflow occurs primarily as Superficial aquifer discharge from the Tamala and Bassendean sands of the Gnangara Mound to the east. This is expressed through the lake bed and as springs or seeps on the lake's eastern side. Outflow occurs as discharge through the lake bed to the Tamala sand on the lake's western side. At higher lake water levels in the past, there was outflow into caves on the western shoreline.

Declining groundwater levels since the mid 1990s have resulted in streams drying within the caves east and west of the lake and decreased groundwater discharge to the lake. Until late 2005, water levels in the lake varied between 6.9 and 7.1 m AHD and reflected control of maximum levels by spillover into caves on the western shoreline. In this earlier regime groundwater inflow from the east was larger than losses through the lake bed and evaporation – with the balance being discharged to the caves. The effect of the overflow into the caves effectively masked the decreasing inflow to the lake due to the decreasing groundwater levels. Since 2006, groundwater inflow has no longer been in excess of evaporation and losses though the lake bed, and lake levels have been falling (by 10–20 cm/year). At the end of the 2011/12 summer shallow water covered less than one-third of the lake area.

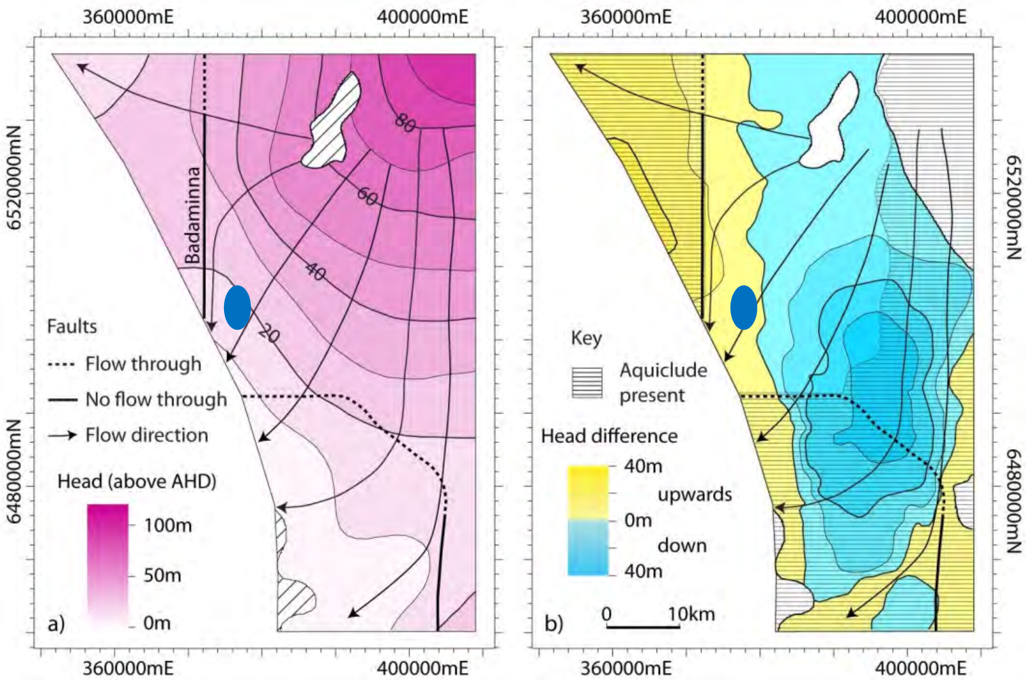


Figure 15 *Flow model for the Leederville aquifer from Leyland (2011). (a) Flow zone with hydraulic head contours (m AHD). (b) Flow zones with head difference between Leederville and Superficial aquifers (10 m isopotentials) and mapping of the Coolyena Group aquiclude (Kardinya Shale). Hydraulic heads are from September 1987. The location of Loch McNess is marked by the blue oval.*

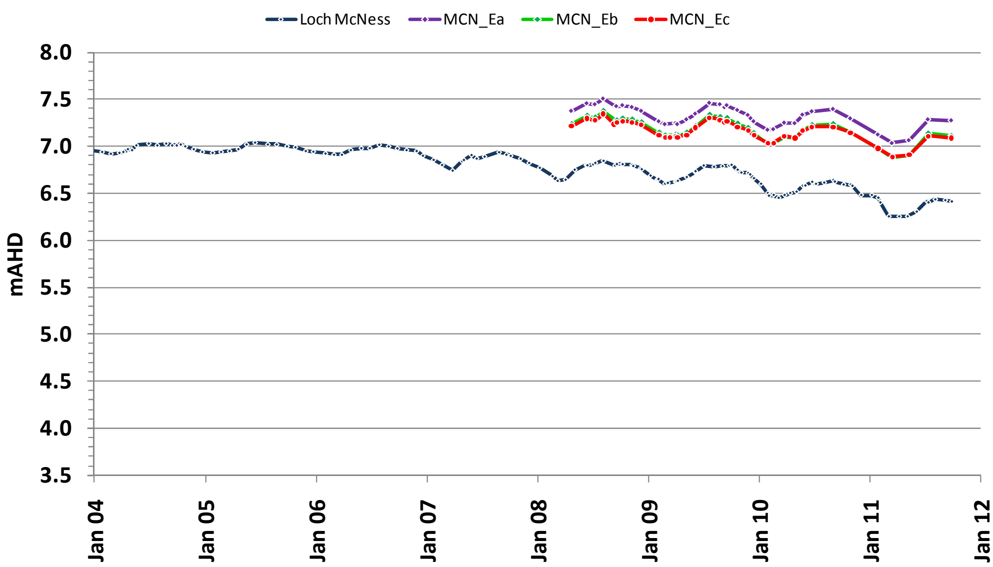


Figure 16 *Water levels in nested bores MCN_Ea (deep), MCN_Eb (intermediate) and MCN_Ec (shallow) relative to Loch McNess levels*

5 Superficial groundwater abstraction in the Yanchep Beach area

One of the main factors that can contribute to declining groundwater levels is groundwater abstraction. The following section summarises the history of over 35 years of groundwater pumping from the Superficial aquifer to the west of Loch McNess.

5.1 Yanchep Beach – Two Rocks water supply scheme

The Yanchep Beach – Two Rocks water supply scheme was initially developed in the 1970s by Bond Corporation Pty Ltd to supply water to the Yanchep Beach and Two Rocks townships, as well as to the Yanchep Sun City development.

In the Yanchep Beach area the water supply scheme involved installing seven public drinking water supply bores, 11 abstraction bores for the golf course and public open space, and 22 water-level and seawater intrusion monitoring bores in the Superficial aquifer. The investigations included pump testing of several abstraction bores, seawater intrusion assessments and the collection of water-level, rainfall and metered abstraction data (summarised in Appendix B including reviews by the Geological Survey of Western Australia).

A groundwater scheme map with seven groundwater allocation subareas (A to G) was produced from the investigations. Maximum annual abstraction limits were specified for each of these subareas (Figure 17; Geological Survey of Western Australia (GSWA) 1972–1983; Rockwater 1983). Subarea G is located directly down hydraulic gradient of Loch McNess. The key hydrogeology findings from the development of the scheme were:

- Transmissivity for the purpose of calculating sustainable supply should be 3300 m^2/day around Yanchep Beach and 15 000 m^2/day near Two Rocks (GSWA 1972–1983).
- The karstic superficial aquifer west of Loch McNess is a strongly anisotropic aquifer, with a horizontal to vertical conductivity of up to 10 000:1 (GSWA 1972–1983). The GSWA reviews also suggest the whole aquifer probably comprises multiple horizontally-flowing aquifers which can be considered separate from each other. Evidence of low vertical conductivity was also supported by the seawater interface being encountered immediately below a clay layer in the aquifer (McPhar Geophysics 1974).
- Water level in Loch McNess was controlled by overflow into cavernous limestone on its western side (McPhar Geophysics 1974). It noted that as the lake's water level rose it discharged rapidly though cavities in the limestone at about the watertable level.

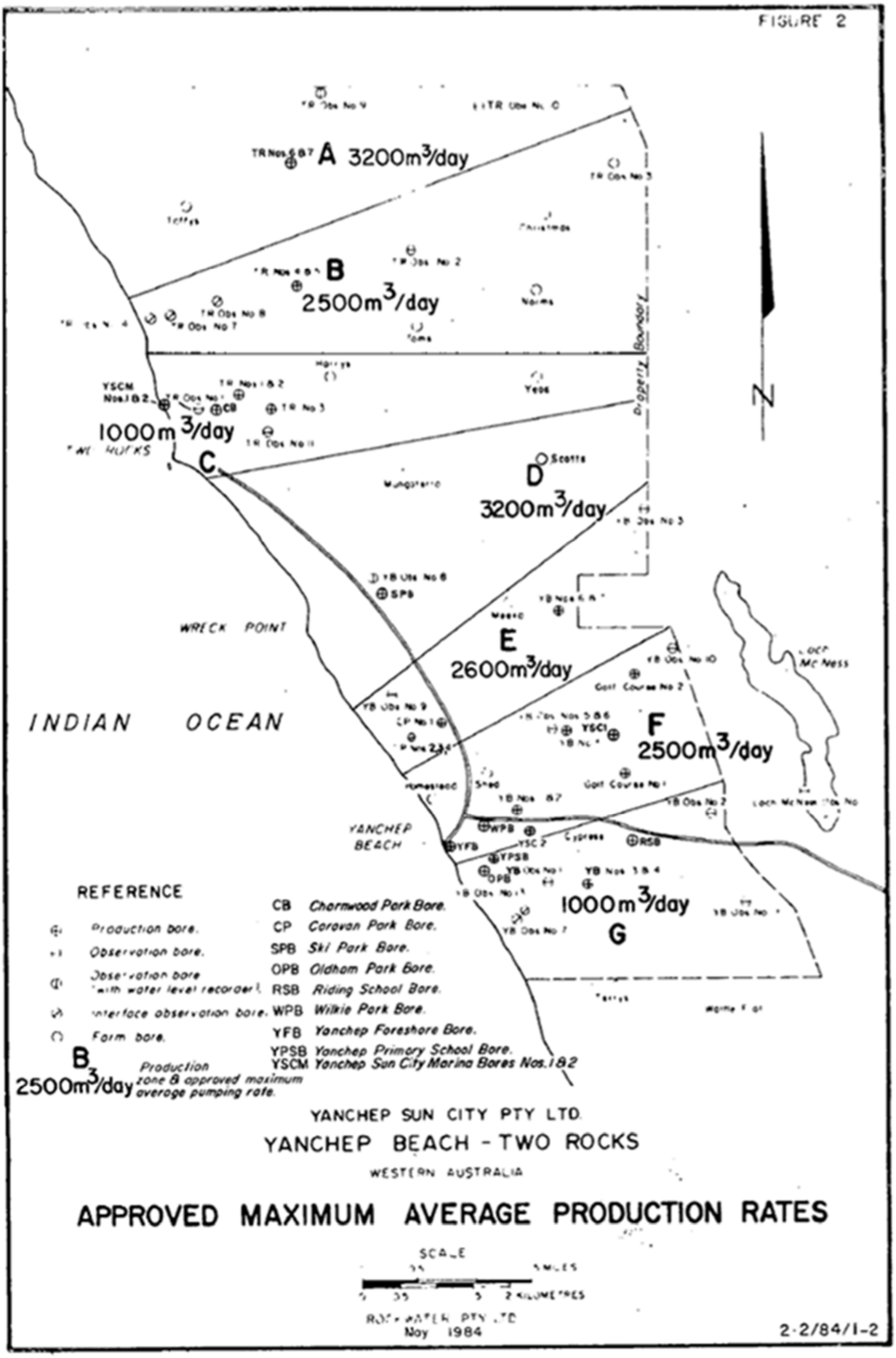


Figure 17 *Yanchep Beach – Two Rocks groundwater scheme final published map of agreed maximum abstraction limits for both private users and schemes (from Rockwater 1983)*

- Loch McNess should not be significantly affected by pumping at Yanchep Beach if there was no pumping to the east and abstraction limits at Yanchep Beach were less than 0.5 ML/day total from subarea G (GSWA 1972–1983). The low limits were also set to protect against the possibility of seawater intrusion at YB 3 and 4 (located in subarea G) given their proximity to the coast (1.5 km).
- Abstraction at Yanchep Beach subarea G to the west of Loch McNess was originally limited to 0.5 ML/day (GSWA 1972–1983), although it was later revised to 1 ML/day (365 ML/year) following advice from Rockwater (October 1974) indicating the initial allocation limit was too conservative. In a letter dated November 1974, GSWA recommended, however, that abstraction be limited to less than 50 per cent of estimated total throughflow to protect against seawater intrusion and impacts on Loch McNess.

Following the initial investigations, the management of the area was as follows:

- Until 1985 water supply was managed by private operators.
- In July 1985, the Yanchep Beach –Two Rocks water supply scheme was taken over by the Water Authority of Western Australia (WAWA 1987).
- In its reports WAWA stated the sustainable allocation limit for the whole Yanchep Beach – Two Rocks scheme area (Figure 17) was 5840 ML/year (16 ML/day), including both public and private abstraction (WAWA 1987), consistent with the final Rockwater scheme review (Rockwater 1983). This was the total abstraction for subareas A to G.
- Although the allocation was not specified separately for the original subareas A to G, WAWA (1990) was consistent with earlier scheme reviews in supporting the practice of spreading the draw evenly among production sites, and stated that the wellfield should be reviewed in two-years time to ensure it was performing satisfactorily.
- WAWA (1990) noted that private abstraction might eventually need to be limited to maintain scheme abstraction within sustainable yields.
- Until 1999 the Water Corporation (formerly WAWA) distributed public drinking water supply pumping between YB 3 and 4 in subarea G and YB 6 and 7 in subarea E. YB 6 and 7 were decommissioned in 1999 and abstraction at YB 3 and 4 increased.

5.2 Historical and recent abstraction in the Yanchep Beach area

The groundwater licences held by the (then) Department of Environment and Conservation (DEC), the Water Corporation and Sun City Golf Club are the most relevant to this discussion as they are the area's large long-term groundwater users. Because DEC's abstractions for the Yanchep National Park and the cave supplementation trial are located directly up-hydraulic-gradient of subarea G and intercept throughflow that would otherwise flow into this subarea (Figure 18), they have been included with those from subarea G when comparing with previously estimated abstraction limits.

The current licences held by these users are:

- Water Corporation – 750 ML/year (375 ML/year from each drawpoint YB 3 and 4); Water Corporation also has a drought contingency of 188 ML/year
- Sun City Golf Club – 160 ML/year (80 ML/year from each drawpoint)
- DEC Yanchep National Park water supply – 137 ML/year
- DEC cave supplementation trial – 54 ML/year.

The Water Corporation groundwater abstraction licence for YB 3 and 4 is more than double the previously-determined abstraction limit for subarea G (365 ML/year; Section 5.1). It should also be noted that groundwater abstracted for cave supplementation was returned to the aquifer, and therefore its net abstraction was small – although it did result in groundwater re-distribution.

Accurate groundwater abstraction data, particularly historical data, are often difficult to obtain. Generally the only reasonably complete records are for the drinking water supply bores. In this case, annual abstraction volumes for Water Corporation bores YB 3 and 4 have been reported for all years and comprehensive data were collected between 1973 and 1985 for the Sun City development. However, metered abstraction data are not available for DEC and the Sun City Golf Club for the full 1973 to 2011 period. Where abstraction data are missing a best estimate of the actual abstraction has been made, based on the data available. For example, abstraction totals for the golf course were not found for the period 1988 to 2000, so the average usage for the period 2001 to 2011 has been applied to those missing years.

For Yanchep National Park there are only meter readings for 2009 to 2011, which show a steeply increasing trend in usage (discussed below). For the years before 2009, an estimate of the park's total usage based on its facilities and standard irrigation rates of grassed areas has been applied.

See Appendix C for tabulated data of measured values and estimated values where data are missing. Figure 19 illustrates the best estimates of abstraction for the above-mentioned large groundwater users, while Figure 20 shows the bore locations.

5.2.1 Abstraction 1975-99

Figure 19 shows that groundwater abstraction was higher in 1976–83 than in 1984–99. This was for several reasons. Firstly, domestic consumption was high (YB 3 and 4) before water meters were introduced and annual water charges were levied on consumers. Rockwater (1981a) notes a reduction in total domestic usage from a peak of 9.0 ML/day in 1976–77 to 3.4 ML/day in 1980–81. Secondly, the golf course increased its Superficial aquifer abstraction from 262 ML in 1979–80 to 344 ML in 1980–81, and to 511 ML in 1981–82 (Golf Course 1 and 2), as a result of operational problems with the golf course's artesian bore (Rockwater 1982a). In 1977–78 bore YB 5 operated at a high rate for a short time. It appears that much of the water pumped from YB 5 was used for the golf course (Rockwater 1977a, 1979a). The golf course's annual abstraction from its superficial bores decreased to 217 ML in 1982–83, then to 192 ML in 1983–84 and then to an average of 188 ML/year for 1985–99.

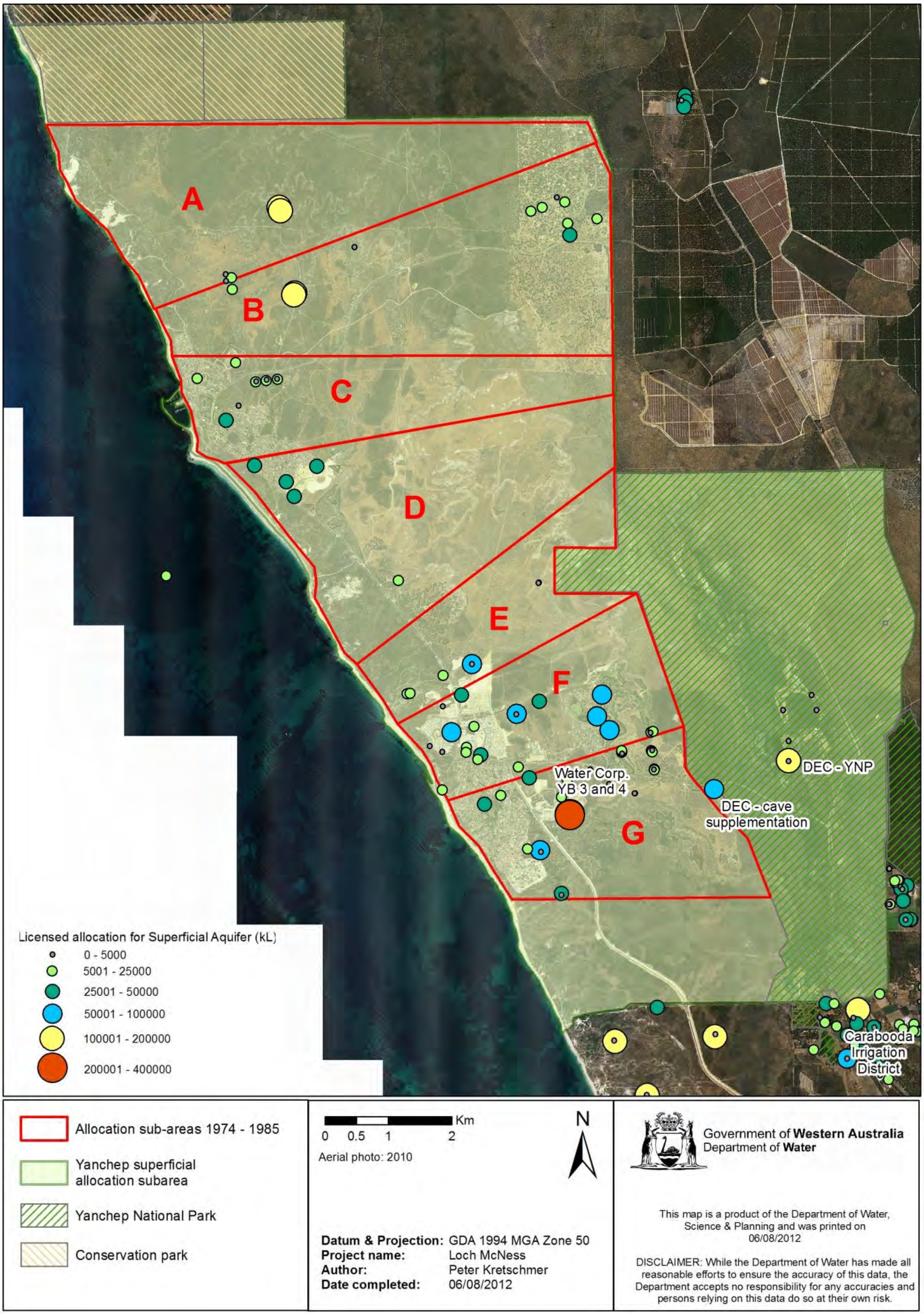


Figure 18 *Map showing current and pending licensed drawpoint abstraction volumes as at November 2011, and the groundwater allocation subareas for the Superficial aquifer used in the 1970s and 1980s. Note the 2010 clear-felling of pine plantations to the north.*

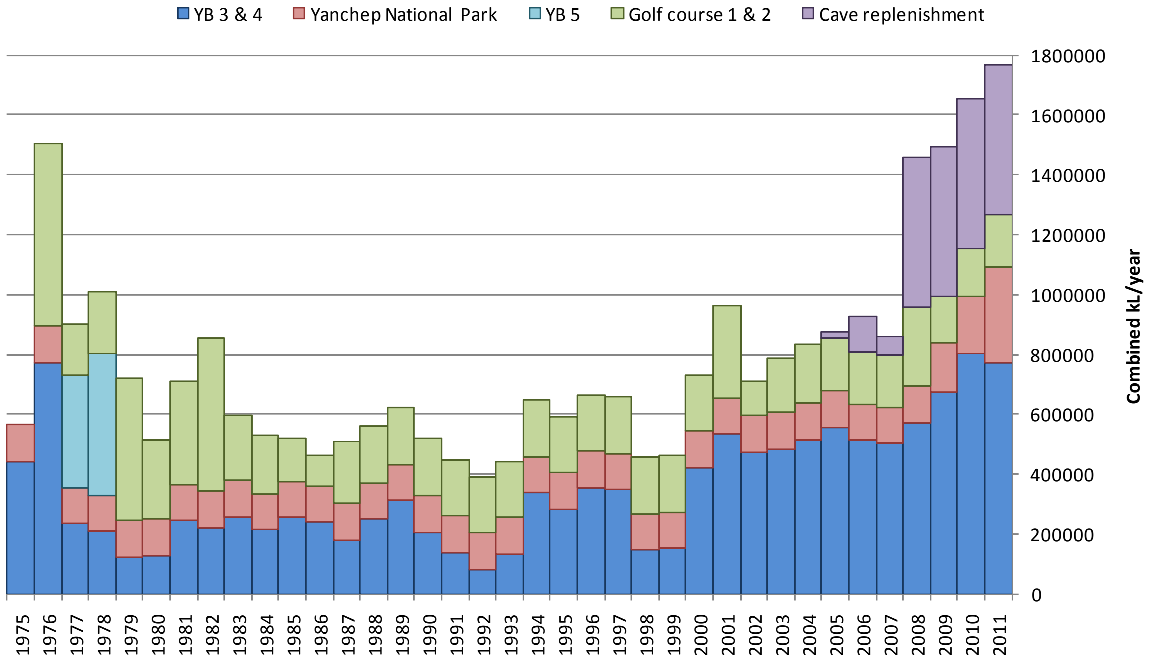


Figure 19 Historical abstraction from the four large groundwater users in the Yanchep Beach area between 1975 and 2011

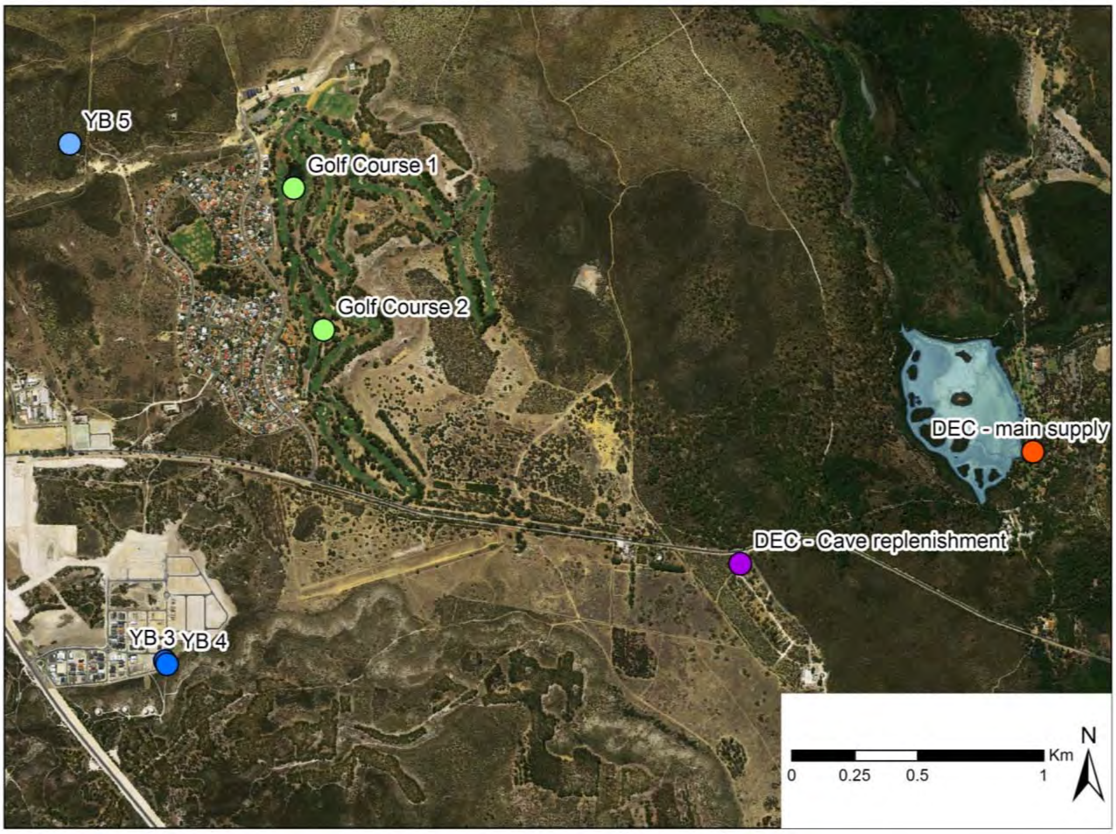


Figure 20 Location of the four major groundwater users in the Yanchep Beach area

Before 2009 (when meters were fitted to abstraction bores in Yanchep National Park) the park's abstraction, based on needs for amenities and irrigation of grassed areas, was estimated to be on average 127 ML/year. During this time, the park irrigated up to three ovals and the grassed areas directly adjacent the lake.

5.2.2 Abstraction 2000–11

Figure 19 shows that since 2000 the Water Corporation has been the largest user in the Yanchep Beach area, averaging 750 ML/year from YB 3 and 4 in 2009–11. There was a step increase in the Water Corporation's abstraction from YB 3 and 4 after 1999 because water supply bores YB 6 and 7 in allocation subarea E were decommissioned. The resulting concentration of draw from YB 3 and 4 is contrary to the recommendations of the earlier scheme investigations, discussed in Section 5.1, which stated that abstraction should be spread north-south across the coastal strip to avoid seawater intrusion and unacceptable impacts on Loch McNess (GSWA 1972–1983; WAWA 1990).

During the 2008–11 the second-biggest user was the DEC cave supplementation scheme. In 2005, DEC established the cave supplementation scheme, which involved transferring water from a bore 800 m west of Loch McNess into several caves east and south of the lake. Establishing actual abstraction rates for the cave supplementation trial has been problematic. For 2005 and 2006, estimates of abstraction have been made from meeting notes and personal communications with staff who worked on the project. During 2005–06 the trial had major technical issues with iron staining in caves. It ran for brief periods at high rates of up to 4 ML/day. In 2007, usage was likely to have been small, as a water treatment system that was being installed was not completed until late 2007. The best estimate of cumulative abstraction during the three years 2005–07 is 200 ML. An audit of the bore in January 2012 found (via the cumulative flow meter) that 2200 ML had been abstracted since the bore was installed in 2005, inferring that an average of approximately 500 ML/year had been pumped for the years 2008–11. This was more than nine times the allocation licence of 54 ML/year. The bore has since been switched off.

Abstraction from the cave supplementation bore could be considered as gross abstraction rather than net abstraction, as the groundwater was returned to the aquifer via the caves with minimal losses. The limited data collected indicated that most water was pumped into Crystal Cave and Carpark Cave, which are located east and south of Loch McNess respectively (Figure 2). While the water pumped into Crystal Cave may flow in the direction of Loch McNess, the supplementation water pumped to Carpark Cave would follow the regional groundwater gradient and flow to the lake's south (Figure 3).

The third-biggest user during the three years, 2009–11, was DEC's Yanchep National Park water supply. As mentioned above, its estimated abstraction was 127 ML/year before 2009. The metered abstraction for the three years – 169 ML (2009), 191 ML (2010) and 320 ML (2011) – illustrates a large increase in usage. Investigations found that most of this water (e.g. 285 ML in 2011) was used to supply the domestic ring-main for irrigation, ablution blocks, Yanchep Inn and other facilities. Further investigation discovered that water from the ring-main was being used to further supplement water flow into Crystal Cave (which DEC stopped immediately). Again, this secondary cave supplementation could be considered as gross abstraction rather than net abstraction, as the water was returned to the aquifer. As the ring-main supply bore is located just 50 m from the lake, it is very likely to affect lake water levels.

The fourth-largest user was the Sun City Golf Club, using an average of 163 ML/year over the three years, 2009–11. The club has two Superficial aquifer bores: the northern bore, Golf Club no. 1 (GC1) and the southern bore, Golf Club no. 2 (GC2). GC2 was once located north of the golf course but it is understood that in 1996 this bore was capped and a replacement constructed adjacent to the southern lake of the golf course. The golf course gets most of its water supply from bore YSC1, screened in the Leederville aquifer. Abstraction from the Superficial aquifer for the three years, 2009–11, averaged very close to the club's licensed allocation of 160 ML/year. This is lower than its average for the period 2001–08 of 198 ML/year. Changes to the course resulted in the two lakes with leaky linings being replaced with one lined lake at the northern end. In addition, a new, more accurate irrigation system was installed (B Anderson, Course Superintendent, pers. comm. December 2011). The golf course's current licence has drawpoint allocations for the course's two Superficial aquifer bores of 80 ML/year each, though approximately three-quarters of the 160 ML/year total is withdrawn from the GC2 near the boundary of allocation subarea G.

5.2.3 Superficial aquifer abstraction in 2011

As previously mentioned, the existing Yanchep groundwater area contains subareas for which allocation limits were set at the initiation of public water supply in the area. These subareas (A–G) are smaller (72 km^2) than the current 115 km^2 Yanchep groundwater area (Figure 18). The allocation limit in the Yanchep groundwater area is now 10 870 ML (DoW 2009b), which is equivalent to 94.5 ML/km^2, compared with 81.1 ML/km^2 in the old subareas A–G.

As of November 2011, 3455 ML had been allocated out of the total 10 870 ML available in the Yanchep groundwater area, which included the allocations for Yanchep National Park (137 ML/year) and the cave supplementation trial (54 ML/year), but excluded abstractions from garden bores, which are exempt from licensing, and the 188 ML/year drought contingency allocation for the Water Corporation. Much of the remaining available groundwater has been reserved for public water supply. In the former A–G groundwater subareas, 3055 of the 5840 ML maximum allocation has been allocated (2785 ML still available for allocation) (Table 1). Note, however, that in 2011, licensed annual abstraction in and immediately upgradient of the former subarea G was 1257 ML, an over-use of 892 ML compared with the recommended allocation of 365 ML (Table 1). This comprises 1101 ML allocated to four large users and 156 ML allocated to many smaller users and excludes the Water Corporation's drought contingency allocation and garden bore abstractions.

Merging the seven subareas (A–G) into the current large, single Yanchep groundwater area has failed to prevent concentration of abstraction at Yanchep Beach, west of Loch McNess.

The assessed sustainable allocations, listed in Table 1, are based on the Rockwater (1983) analysis. These allocation limits are being re-assessed, taking into account the earlier investigations as well as decreasing annual average rainfall and increased urban land use.

Table 1 Current annual drawpoint allocation for the Yanchep Beach – Two Rocks area. Note: abstraction for the Yanchep National Park and cave supplementation scheme has been included in subarea G; but the Water Corporation's drought contingency allocation and garden bore abstractions (exempt from licensing) have not been included.

Subarea area	Currently allocated[1] (ML)	Assessed sustainable allocation[2] (ML)	Current remaining allocation[1] (ML)
A	417	1168	751
B	434	913	478
C	95	365	270
D	138	1168	1030
E	128	949	821
F	586	913	326
G	1257	365	–892
TOTAL	3055	5840	2785

1 – at November 2011; 2 – Rockwater (1983)

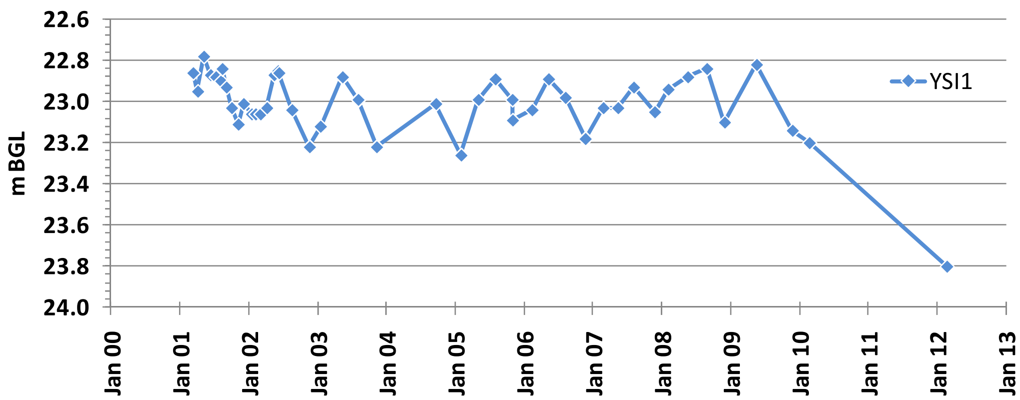
Summary and recommendations:

- Rockwater (1983) published the Yanchep Beach – Two Rocks agreed maximum abstraction limits for private and public users for seven groundwater subareas A–G.
- To protect Loch McNess, allocation should be spread across subareas A–G. Concentration of pumping in subarea G directly to the west (down gradient) of Loch McNess should be avoided.
- The allocation limit for subarea G (365 ML/year) down-gradient of Loch McNess was set to protect Loch McNess from pumping impacts and to minimise the likelihood of seawater intrusion.
- The current allocation (1257 ML/year) affecting subarea G of is 892 ML/year higher than the assessed sustainable allocation of 365 ML/year. Current allocations: Water Corporation 750 ML/year, Sun City Golf Club 160 ML/year, DEC Yanchep National Park water supply 137 ML/year, DEC cave supplementation trial 54 ML/year, small users 156 ML/year.
- In 1999 the Water Corporation decommissioned bores YB 6 and 7 in subarea E and concentrated draw from YB 3 and 4 in subarea G (750 ML/year).
- DEC no longer uses the cave supplementation bore. To protect Loch McNess water levels, pumping at the cave supplementation bore should not resume, and pumping should be relocated away from the lake and caves in Yanchep National Park.

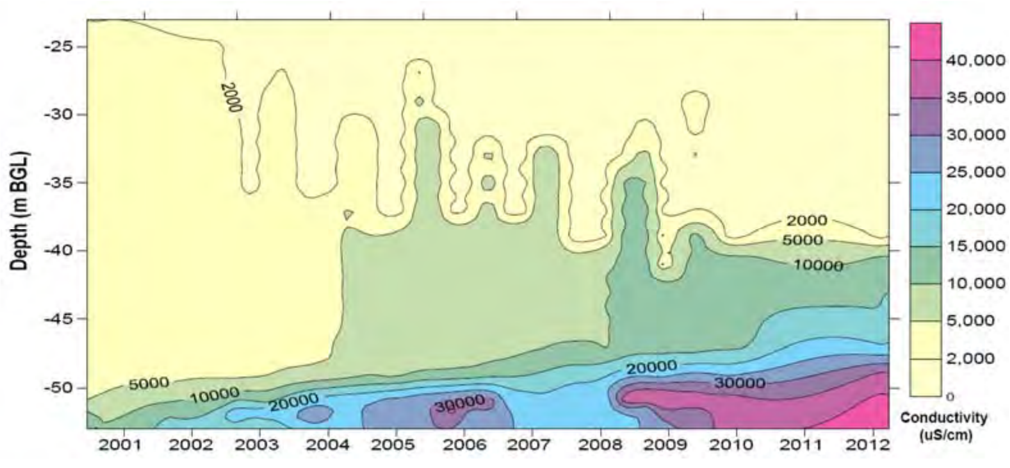
5.3 Seawater intrusion at Yanchep Beach

One of the considerations for water management at Yanchep Beach is the need to avoid seawater intrusion affecting the water supply bores and other users. Pumping groundwater from coastal aquifers can lead to movement of the seawater landward into the aquifers. Typically, seawater moves as a wedge of saline water along the base of the aquifer.

The seawater interface monitoring bore YSI1 is 550 m from the coast and 140 m south of the now-obsolete seawater interface monitoring bores used by the Yanchep Sun City scheme (Figure 2). YSI1 is down hydraulic gradient from YB 3 and 4. The YS1 casing height has not been surveyed so the water levels are presented as metres below ground level (m BGL) (Figure 21).



a



b

Figure 21 Water level (a) and conductivity (b) at Yanchep Beach monitoring bore YSI1 between 2000 and 2012

Until 2010, the water levels in YSI1 appeared to largely represent the seasonal oscillation of ocean heights, with no significant trend. The observation in January 2012, however, indicates that water levels at this bore have fallen (Figure 21a). Electrical conductivity in YSI1 has risen from 5000 µS/cm (2000–3000 mg/L salinity) at the base of the screened interval of YSI1 in June 2000 to more than 40 000 µS/cm (24 000–26 000 mg/L salinity) in 2012 (Figure 21b). This indicates that the saltwater wedge has moved progressively inland since monitoring began (Figure 21b).

Abstraction from YB 3 and 4 during 2000–08 was 484–557 ML/year. In the three years since 2008–09, annual abstraction has been 672 ML, 803 ML and 774 ML respectively. Groundwater levels in the Yanchep Beach abstraction bores YB 3 and 4 have been consistently below 0 m AHD, and as low as –4.5 m AHD during the 2007/08 water year (WorleyParsons 2009). Given that YSI1 is down hydraulic gradient from YB 3 and 4, abstraction from these bores is most likely the major cause of the increase in electrical conductivity in YSI1.

Before major abstraction started in the 1970s, the seawater interface was 600 m inland, 900 m west of YB 3 and 4 (Rockwater 1976a; best illustrated in Rockwater 1980a). The location of the interface has not stabilised and it will probably continue to migrate inland and may affect the Water Corporation bores and those of other users, such as the Oldham Park bore which is 600 m inland (900 m north of YSI1).

Note also that, in the WorleyParsons (2009) report, YSI1 is mislabelled as YBI1, and then incorrectly attributed with water levels from YB 11 located 3000 m inland of YSI1. This may have led to the true risk of seawater intrusion at Yanchep Beach being misunderstood.

Summary and recommendations:

- There is seawater intrusion at Yanchep Beach and it will most likely continue moving inland without management intervention.
- Investigating where the seawater interface will stabilise at current pumping rates is warranted so management and/or monitoring criteria can be established.

6 Causes of water-level decline in Loch McNess

To investigate the likely causes of water-level decline in Loch McNess, hydrographs from Superficial aquifer groundwater monitoring bores near Loch McNess and the surrounding region have been analysed.

The LMN1c hydrograph (see Figure 12) shows that groundwater levels in the Superficial aquifer west of the lake have been lower than the lake water level for the entire record period (1974–2011). This is as expected for a flow-through wetland. The timing of the water-level declines in LMN1c and Loch McNess in 2006–07 shows that the drawdown influencing this bore has most likely also affected the lake water level.

The LMN1a and LMN1c hydrographs also show that hydraulic head gradients in the aquifer have changed from being upward from the Leederville to the Superficial aquifer before 1999, to downward from the Superficial to the Leederville aquifer since 1999 (Figure 12). That is, until 1999 the Leederville aquifer was discharging into the Superficial aquifer at LMN1a/LMN1c, as depicted in Figure 15, and since 1999 the Superficial aquifer has been leaking into the Leederville aquifer. Other bores, east and west of the lake (Appendix E) also show weakening of the hydraulic head gradient.

Four major factors may affect groundwater and lake water levels:

1. increased outflow through the lake bed on the western side due to abstraction from the karstic superficial aquifer to the west
2. decreased groundwater inflows from the Superficial aquifer from the east due to:
    a. pumping from the Superficial aquifer
    b. increasing pine plantation area
3. changes in hydraulic gradient between the Leederville and Superficial aquifers causing the Superficial aquifer water levels to decline
4. reduced rainfall recharge causing Superficial aquifer water levels to decline.

These possible influences on groundwater-level decline around Loch McNess are discussed below. Where significant groundwater decline is attributed to a particular cause, recommendations on possible actions to reduce the decline are given.

6.1 Superficial aquifer abstraction impacts to the west of Loch McNess

Figure 22 shows the Superficial abstraction history for the four major groundwater users around Yanchep (from Figure 19), as well as Loch McNess water levels and the hydrographs for groundwater monitoring bores LMN1c and MCN_Wc. As the shallow bore LMN1c was damaged in a bushfire in 2009, its record has been supplemented with shallow bore MCN_Wc installed in 2008 (screened 5.45–11.45 m BGL), located approximately 25 m south-west. Additional hydrographs for monitoring bores MCN_Wa, MCN_Wb, BH_LM1 and BH_LM2 which are located to the west of Loch McNess are shown in Appendix E.

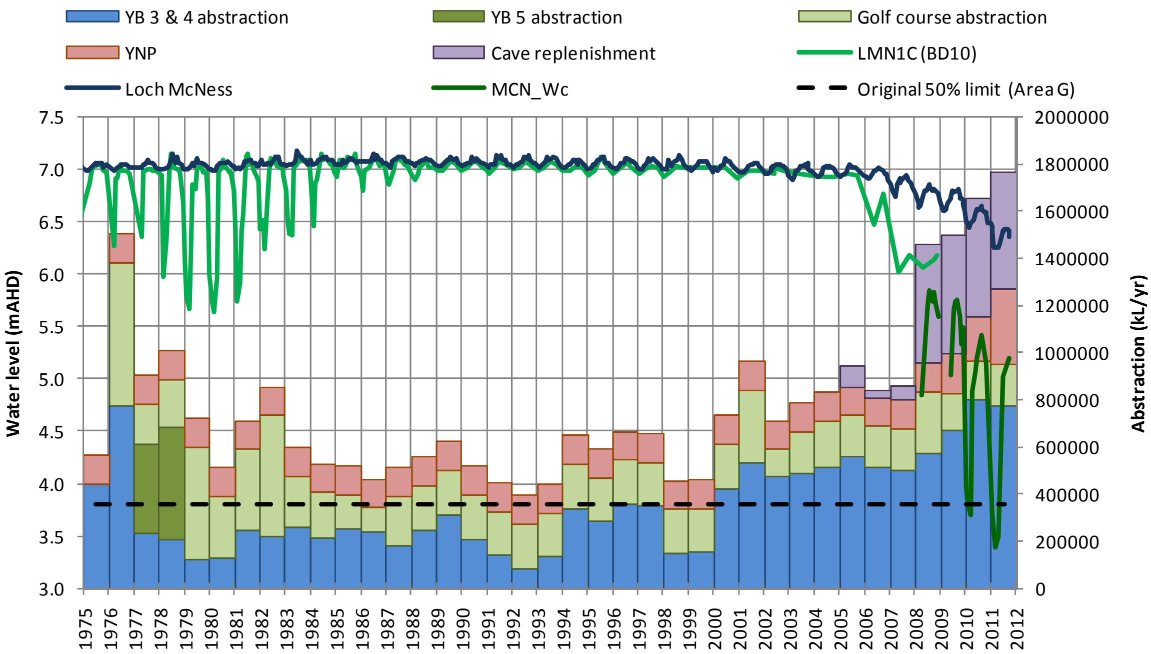


Figure 22 Superficial aquifer abstraction totals for the four major licences in the Yanchep Beach area with Loch McNess water level and LMN1c and MCN_Wc hydrographs

The large fluctuations in seasonal amplitude at LMN1c (on the lake's western shore) between 1975 and 1985 (Figure 22) were due to pumping from Superficial aquifer bores to the west (down-gradient of Loch McNess). Figure 22 shows there is a distinct pumping signal in the hydrograph of LMN1c between 1975 and 1985. During this period, the combined abstraction from the YB 3, 4 and 5 and golf course bores was greater than after 1985, so the pumping signal is most likely due to one or more of these bores. McPhar Geophysics (1973b) illustrated the potential for the drawdown from these abstraction points to lower groundwater levels on the western side of Loch McNess (Appendix B). However, these impacts were predicted at combined abstraction rates of around 1900 ML/year, which is more than is currently removed.

The timing of the pumping signal between 1975 and 1985 and Superficial aquifer abstraction volumes indicates the bores likely to be having the most impact were the golf course bores and YB 5. Although the highest pumping rates were in 1976 abstraction in this period due to large abstractions from YB 3 and 4, LMN1c did not show the greatest drawdown in this year. Annual reviews of the scheme indicate that much of the water abstracted from YB 5 was used for the golf course (Rockwater 1977a; 1979a), which would account for the smaller abstraction from the golf course bores in those two years. Groundwater demand from the golf course is very seasonal, which is likely to exacerbate the seasonal pumping signal. Water levels in LMN1c recovered once pumping from the golf course Superficial aquifer bores reduced from 1984 onwards – when the golf course transferred most of its groundwater abstraction to the Leederville aquifer.

From 2000 onwards, abstraction rates in the area rose after the Water Corporation stopped operating YB 6 and 7 and concentrated draw from YB 3 and 4. The volume from subarea G was then much higher than the recommended limit of 365 ML/year (dashed line on Figure

22) and there was visible effect on LMN1c in that its seasonal signal was dampened. When additional pumping for cave supplementation started in 2005, LMN1c's water level fell dramatically. This provides clear indication that adhering to the previously estimated abstraction limit of 365 ML/year for subarea G would minimise impacts on the lake.

In May 2006 the water level in the shallow monitoring bore LMN1c showed a sudden decline of 0.47 m from its September 2005 level, despite 2005 having the third-highest rainfall recorded since 1975 (817 mm) at Yanchep rainfall station 9045. The timing of the water-level decline coincided with the start of pumping from the cave supplementation bore 1.0 km west of LMN1c (800 m west of the south-west corner of Loch McNess, Figure 20).

Assembling a disjointed record of pumping information recorded for the cave supplementation trial shows that:

- 18/07/2005 – pumping runs at 4 ML/day for 10–14 days (40 ML total)
- 11 to 30/11/2005 – pumping runs at ~2.3 ML/day for 21 days (48 ML total)
- 19/05/2006 to 11/07/2006 – filtration trial, various rates (estimate 30 ML total)
- 2007 – little abstraction until treatment system completed (estimate 60 ML total)
- 2008–11 – approximately 500 ML/year.

Note that these volumes are approximate and exclude water lost via the pressure regulator overflow pipe near the bore. This would account for additional losses.

Initial modelling indicated the pumping was unlikely to affect the water level in Loch McNess. The modelling also indicated that up to 3600 ML/year would need to be removed from cave supplementation bores and pumped into the Yanchep Caves to sustain water levels within the caves to protect the stygofauna (DoW 2006). However, examination revealed that the model was inadequate to represent water-level changes in Loch McNess, so any predictions of lake water level based on the model are invalid.

Most of the cave supplementation water was pumped to Crystal and Carpark caves. Although the water pumped into Crystal Cave may have flowed back to the lake, water pumped to Carpark Cave would have followed the regional hydraulic gradient (Figure 3) and flowed south of Loch McNess. In addition, the water that supplemented Crystal Cave that flowed towards Loch McNess may have then been intercepted by the national park's ring-main and irrigation supply bores. A better outcome may have resulted if the supplementation water had instead been pumped into Cabaret Cave, from where it would have helped maintain inflows into Loch McNess to accommodate the additional drainage losses caused by the abstraction.

The large pumped volumes for cave replenishment between 2008 and 2011 inclusive align with the large drawdown observed in MCN_Wc. However, there was additional abstraction from Yanchep National Park's domestic supply bore to make up for losses from the park's ring-main during these years.

Groundwater-level decline is also seen in all other monitoring bores near the western edge of Loch McNess (Appendix E) but it is more difficult to establish the influence of abstraction on bores BH_LM1, BH_LM2 and the MCN bores due to the relatively short length on monitoring records (2005 onwards).

Summary:

The main Superficial aquifer effects to the west of Loch McNess can be attributed to:

- Golf course Superficial aquifer bores (3.2 km west of Loch McNess): These appear likely to have affected LMN1c during 1975–85. The golf course now gets most of its water from the Leederville aquifer (west of the Badaminna Fault) and the direct influence of these bores is no longer seen.
- Cave supplementation trial: Abstraction for the cave supplementation trial contributed to a rapid decline in groundwater levels adjacent to Loch McNess (and water level in the lake) during 2005–11. Cave supplementation ended in January 2012.
- Yanchep Beach superficial abstractions: Although the effects of steadily rising abstraction rates from other Superficial aquifer bores to the west of Loch McNess (Yanchep Beach area) are not acutely evident, abstraction will have increased hydraulic head gradients between the lake and areas to the west. This would have increased water leakage through the bed of the lake.

Recommendations:

- Maintain future allocation from the Superficial aquifer to the west of Loch McNess at less than 50 per cent of discharge to the ocean for each subarea, to avoid groundwater decline on the western side of Loch McNess and protect against seawater intrusion. This allocation approach is consistent with previous approaches applied in the 1980s by Rockwater and the GSWA, which stated that total allocation should be less than 50 per cent of the total flow through. The previously-determined allocation limit of 365 ML/year needs to be reviewed to take into consideration decreased rainfall and changed land uses.

6.2 Land-use impacts and Superficial aquifer abstraction to the east of Loch McNess

Pine plantations on the central part of the Gnangara Mound are thought to cause groundwater decline through the interception of recharge (Yu 2003; DoW 2008). Modelling to assess the likely recharge response from clear-felling pines indicated a potential 0.1 m increase at monitoring bore YN4 (90 m east of Crystal Spring) within three years if 900 ha was cleared to the east (Yu 2003).

Since 2002, the pines east of Loch McNess have gradually been cleared. In 2002, the 150 ha of pines closest to Loch McNess were cleared in an attempt to increase recharge and water flow into the Yanchep Caves to protect endemic stygofauna. A much larger area of pines was cleared during 2009 after an extensive area east of Loch McNess was burnt in early 2009. In the summer of 2010/11 many pines died following a low-rainfall year. These deaths have resulted in a higher rate of clear-felling. Between 2002 and August 2011, approximately 2800 ha of pines to the east and north of Loch McNess were cleared.

The emergence of a recharge response as a result of pine removal is taking longer than predicted. Up until 2011, a rise in water level was not be seen in any of the YN monitoring bores east of Loch McNess, even in those close to the plantations. This could in part be due to the effects of drier years and ongoing pumping on the Gnangara Mound limiting the magnitude of any groundwater rise. However, in 2011 the hydrograph for monitoring bore Y240, 6 km east of Loch McNess in the middle of the pines removed in 2009, showed a slight recharge response for the first time in nearly 20 years (Appendix E). It may take several more years with at least average rainfall for water levels to rise as more pines are progressively removed. However, more than 3500 ha of the pine plantations still remain to the east of Loch McNess and future removal of these would be expected to result in increased recharge to groundwater.

The effects of pumping from the Superficial aquifer bores to the east of Loch McNess have not been observed in Superficial bores close to Loch McNess. Pumping of generally less than 122 ML/year from the bores in the national park to the east of the lake (prior to the cave supplementation trial) does not appear to have influenced water levels in bore YN5 nearest to the pumping, whose hydrograph has a similar appearance to the hydrograph of YN7 located to the south (Appendix E). Superficial aquifer abstraction bores located in the Pinjar borefield, which is the closest IWSS Gnangara Mound borefield to Loch McNess, are more than 11 km east of the lake. As groundwater-level decline induced by abstraction from Superficial aquifer borefields is generally only apparent within 6 km of the borefields (DoW 2008), the impact of the Pinjar borefield abstraction is unlikely to be seen at the lake.

Three kilometres south-east of Loch McNess is the northern end of the Carabooda irrigation district. In the northern 3 km of the district the licensed Superficial aquifer groundwater allocation is approximately 2500 ML/year, which is drawn from many bores. Groundwater modelling would be required to accurately quantify the extent and amount of drawdown from the district that affects the Superficial aquifer around Loch McNess and the lake's water levels. Empirical methods generally assume homogenous aquifer properties and do not account for bore drawdown interference.

Despite this, as modelling is not within the scope of this project, empirical methods have been used to obtain an order-of-magnitude estimate of the district's influence on the lake. A simple Theis calculation was used, for a bore 4.5 km south of Loch McNess, in a homogenous aquifer with a storage coefficient of 0.15 and a transmissivity of 330 m^2/day, assuming 2500 ML/year abstraction. After 730 days (two years) the drawdown at Loch McNess was estimated be 0.02 m. Thus, within the inherent prediction uncertainty, it can be inferred that the Carabooda irrigation district is unlikely to cause significant drawdown in the vicinity of the lake.

Summary:

Pine plantation clearance and pumping from the Superficial aquifer east of Loch McNess did not appear to be affecting the watertable height east of the lake.

- A recharge response in monitoring bores east of Loch McNess was not evident following removal of pines east and north of Loch McNess during 2002–11. However, more than 3500 hectares of the pine plantations still remained to the east of Loch

McNess in 2011 and future removal of these would be expected to result in increased recharge to groundwater.

- Pumping from the Superficial aquifer in the national park (to the east of the lake) does not appear to have influenced water levels of bores closest to Loch McNess.
- The impacts of Superficial aquifer abstractions from the IWSS Gnangara borefields are not apparent in monitoring bores east of Loch McNess.
- Using empirical modelling, potential watertable drawdown in the vicinity of Loch McNess from Superficial abstraction in the Carabooda horticultural district was estimated to be very small.

6.3 Leederville aquifer impacts

There is evidence that water levels in the Superficial aquifer are responding to hydraulic head changes in the Leederville aquifer. In the Loch McNess area, the Superficial and Leederville aquifers are hydraulically connected (no confining layer). Data from LMN1a and LMN1c shows a reversal in the hydraulic head gradient in 1999; that is, since 1999 there has been downward flow from the Superficial aquifer to the Leederville aquifer (recharging; Figure 12 and earlier discussion in this section). These changes also correspond with the greater rate of decline observed in water levels in the Leederville aquifer at AM13A (Figure 24; Appendix E).

Pumping from the Leederville aquifer has been steadily increasing during the past 35 years to meet demand from population growth and reduced water availability from Perth's water supply dams (Figure 23). From the Pinjar Leederville aquifer bores (east of Loch McNess; Figure 24) there was a step increase in abstraction from 4 GL in 1996–97 to 7 GL in 1998–99. In addition, in 1998–99 5 GL abstraction began from Leederville aquifer bores in the Quinns borefield to the south. This increased to nearly 10 GL in 1999–2000, before stabilising at 8–9 GL/year over the period 2001–11. Abstraction from the Whitfords borefield began in 1999–2000, but this borefield is smaller than Quinns and its location is considered too distant to affect groundwater levels around Loch McNess.

The impact of Leederville aquifer abstraction on Superficial aquifer groundwater levels has previously been demonstrated elsewhere on Gnangara Mound where the Leederville is in hydraulic connection with the Superficial aquifer. In the Pinjar Superficial aquifer monitoring bore PM6 (Figure 24), the cumulative impacts of abstraction on groundwater levels was estimated to be 1.8 m, representing approximately 44 per cent of the decline between 1979 and 2005. Abstraction from the Leederville aquifer bore P105, 2.4 km away, started in 1997 (DoW 2008).

The Leederville abstraction impacts on several Superficial bores are discussed in the next section.

Summary:

- Declines in water levels in the Leederville aquifer are likely to be influencing water-levels in the Superficial aquifer at Loch McNess.
- The timing of greater declines in water levels (hydraulic heads) in the Leederville aquifer at and to the east and north of Loch McNess corresponds with the onset of pumping from the Leederville aquifer at Pinjar and Quinns.

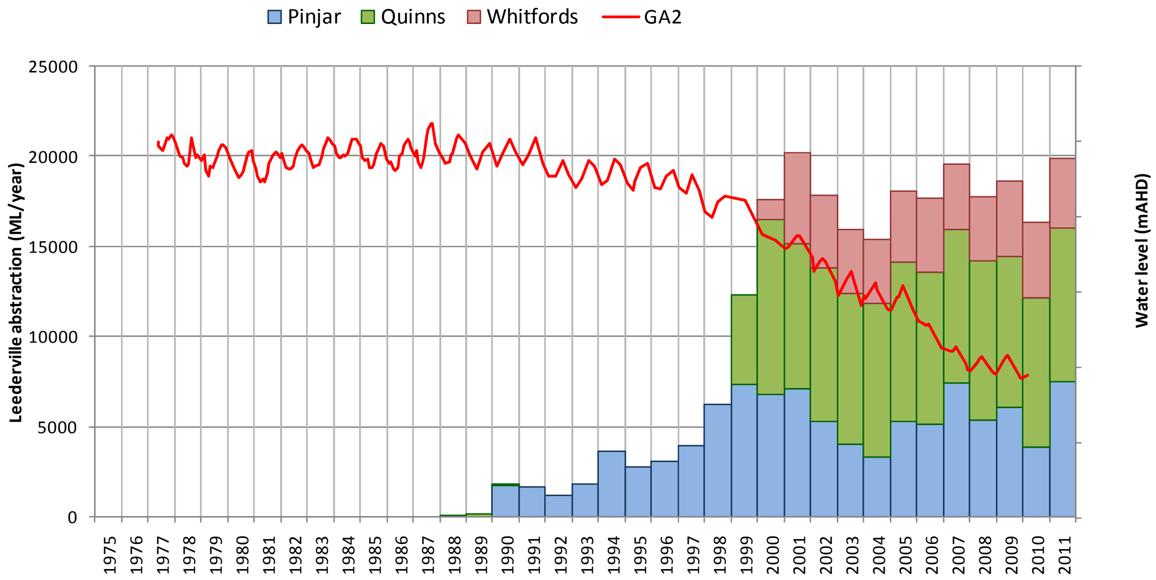


Figure 23 Abstraction from Leederville aquifer water supply borefields nearest Loch McNess and the hydrograph of Superficial aquifer monitoring bore GA2

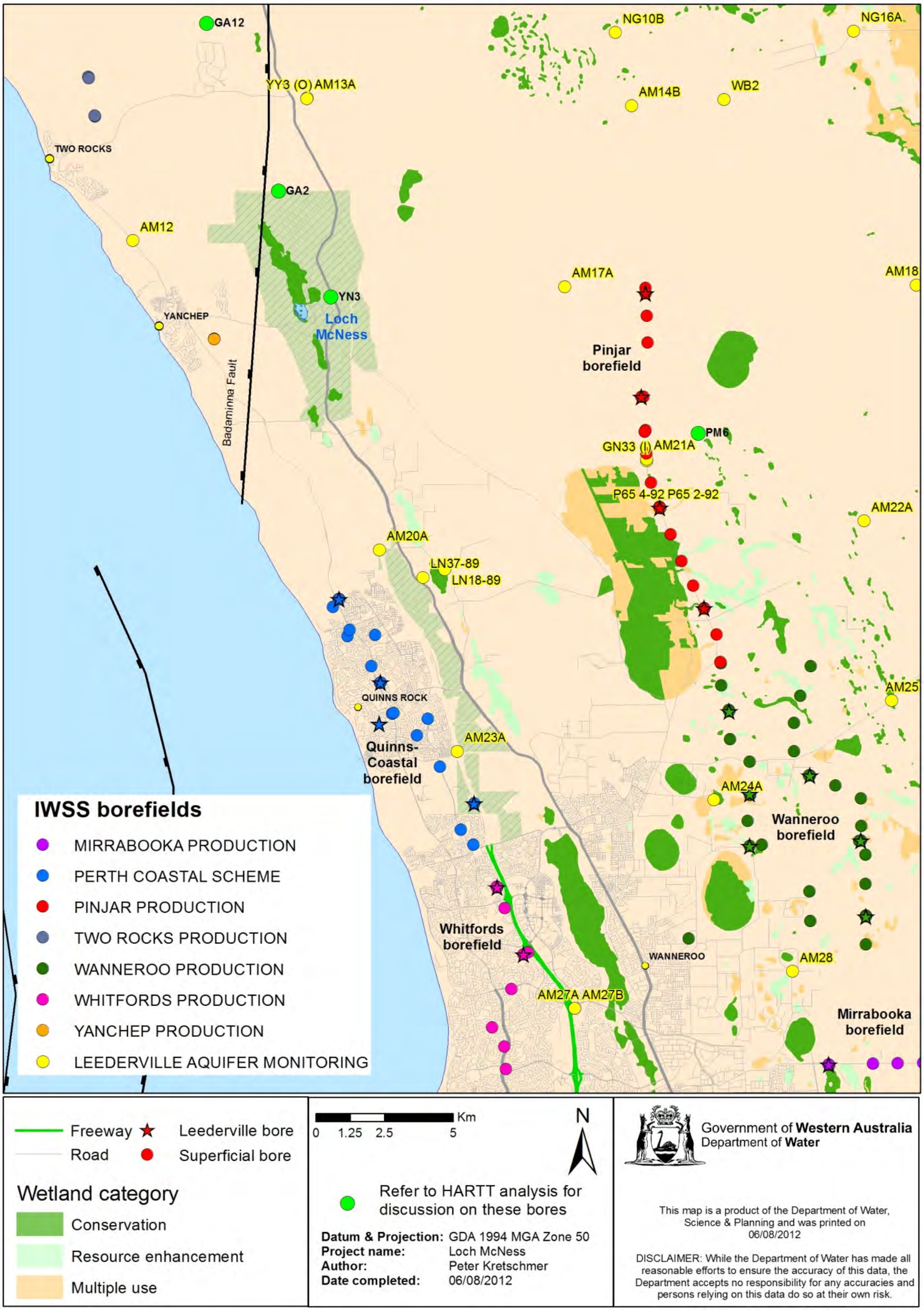


Figure 24 Public water supply borefields and Leederville aquifer monitoring bores north-west of Perth

6.4 HARTT analysis

In this study, HARTT (Hydrograph Analysis: Rainfall and Time Trends) was used to analyse trends in groundwater levels to attribute the causes of groundwater-level change to climate, abstraction or land-use changes. HARTT (Ferdowsian et al. 2001) uses multiple regression analyses to estimate the relative impacts of climate and the other variables. HARTT is available as a download from the Department of Agriculture and Food Western Australia website www.agric.wa.gov.au.

The Superficial aquifer bores used in the analysis are GA2, GA12 and YN3 (Figure 24). A detailed description of the analysis is included in Appendix F. These bores were chosen to demonstrate Superficial aquifer response to different drivers: rainfall, Leederville aquifer abstraction and pine plantations. YN4 and YN5, which are closer to Loch McNess, were not used due to their close proximity to the Crystal Spring discharge point which would have buffered groundwater levels over time.

East of Loch McNess, the possible causes of groundwater-level decline are decreasing rainfall, Superficial aquifer abstraction, pine plantations and Leederville aquifer abstraction, which are discussed below. Only those variables likely to significantly influence water levels are included in the HARTT analysis.

6.4.1 Decreasing rainfall impact

The effect of rainfall is represented by the cumulative deviation from mean (CDFM) rainfall variable (Ferdowsian et al. 2001; Yesertener 2008). CDFM is calculated by subtracting the actual rainfall over a defined period from the long-term mean rainfall of the same period. The deviations are plotted cumulatively and thus show periods of above-mean rainfall as an upward-tending graph and below-mean rainfall as a downward-tending graph.

Rainfall data were obtained from a SILO data drill for Yanchep rainfall station 9045. SILO is a rainfall database maintained by the Queensland Department of Environment and Resource Management.

Changing rainfall trends are evident in the cumulative deviation from mean rainfall plot for site 9045 (Figure 25). Rainfall was above average for a number of consecutive years in the early 1980s but since then the annual rainfall has mostly been below the long-term average and so the plot deviates downwards. Clearly, decreasing rainfall will affect groundwater recharge on the Gnangara Mound. Therefore, CDFM rainfall is included as an independent variable in the HARTT analysis for GA2, GA12 and YN3.

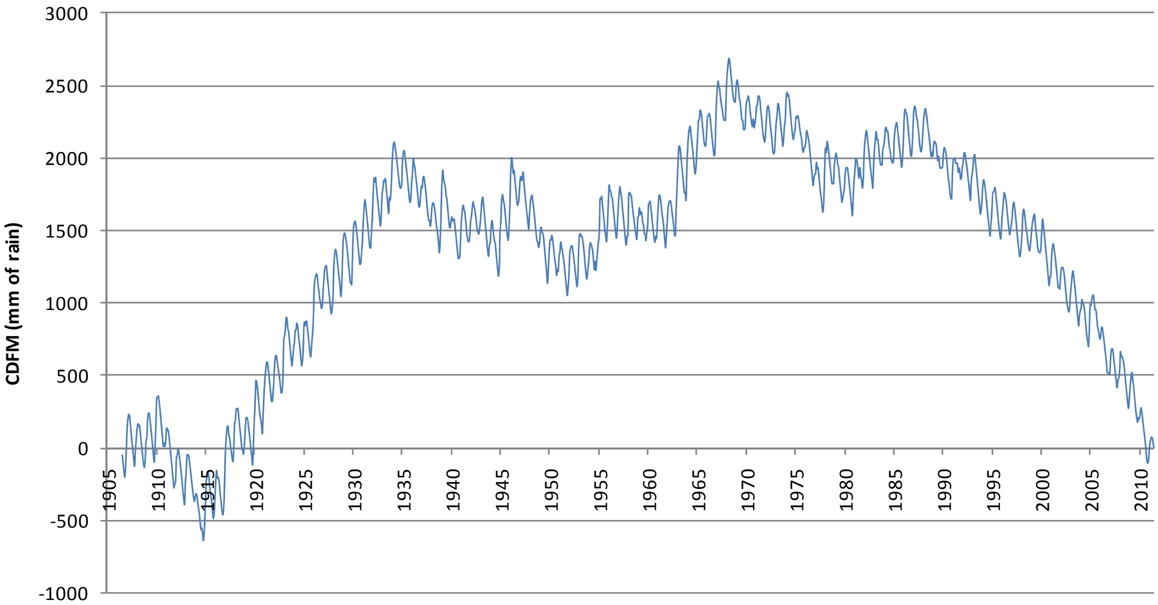


Figure 25 Cumulative deviation from mean rainfall for the period 1907 to 2011 (site 9045)

6.4.2 Superficial aquifer abstraction

Superficial aquifer abstractions that could affect monitoring bores GA2, GA12 and YN3 (Figure 24) are those from the Pinjar borefield on the Gnangara Mound, the Sun City golf course, Yanchep National Park and Carabooda irrigation district bores.

The nearest major Superficial aquifer abstractions to the monitoring bores are in the Carabooda irrigation district, which is 3 km south of YN3, 7 km south of GA2, and 13.5 km south of GA12, and the IWSS Pinjar borefield more than 12 km to the east. As discussed previously, none of these are likely to affect the monitoring bores. Impacts from Superficial aquifer bores on the Gnangara Mound are only evident within about 6 km (DoW 2008). The earlier Theis assessment of Carabooda irrigation district drawdown indicates that drawdown from this location is not likely to be noticeably affecting water levels around Loch McNess or YN3 (and GA2 and GA12, which are further north).

The golf course bores induced drawdown in LMN1c, 3 km to their east during 1975–85 (Figure 2). However, a similar impact was not evident in GA2, GA12 or YN3. During this period the changes in the annual hydrograph of GA2 and YN3 (decrease during 1977–81 and increase during 1982–88) can be explained by rainfall variation. GA12 is too far from the golf course (9 km north) to be affected.

The Yanchep National Park bores, located close to the lake's south-east corner, are unlikely to have affected GA2 or GA12. Their drawdown cone would have been limited by the constant head of Loch McNess for most of the period. YN3 is closer (1 km up-gradient), but there was no apparent change in YN3 water levels in response to all oval irrigation being turned off in early 2005 (destroyed in a bushfire [A Pritchard, pers. com.]), nor to more recent (2009–11) over-abstraction from the park's ring-main supply bore. Based on the available evidence, Superficial aquifer abstraction for Yanchep National Park is not thought to be affecting YN3.

Due to the lack of available evidence indicating Superficial aquifer abstraction impacts on the water levels of GA2, GA12 and YN3, Superficial abstraction will not be included in the HARTT analysis.

6.4.3 Pine plantations

Land-use changes with the potential to affect water levels in GA2 relate to growth and harvesting of the pine plantation 430 m north of the bore. The pines, planted in 1966, were not influencing the GA2 hydrograph during 1975–90; the variations are explained by climate (Figure 26). It is possible that for some time between 1966 and 1975 the pines did affect groundwater levels at GA2 but by 1975 the water levels were in equilibrium with the plantation’s water usage. Furthermore, water levels in GA2 did not respond to 260 ha of the same plantation being cleared between 1992 and 1994.

As pine plantation water usage is not observable in the GA2 hydrograph, pine plantation growth and harvesting will not be included in its HARTT analysis.

GA12 is 1400 m directly down-gradient of a large area of pine plantation which was planted in 1969/1970. The drawdown caused by pine plantations in the vicinity of GA12 has previously been recognised (DoW 2008; Xu 2008). As the water level in GA12 did not trend upwards in the 1980s despite above-average rainfall it is reasonable to conclude the pines were having a drawdown influence during this period. Therefore, pine plantations will be included in the HARTT analysis for GA12.

YN3 is a relatively new bore (installed in 1991). Since then, 150 ha of pines 2.6 km east of YN3 were cleared in 2002. However, to 2011 there was no recharge response in YN3 or in bores YN1 and YN2 which are closer to the cleared pines. As there is no evidence that water levels in this bore were affected by pine plantations, they will not be included in the HARTT analysis for YN3.

6.4.4 Leederville aquifer abstraction

Hydraulic head decline is evident in many Leederville bores on the Gnangara Mound as discussed by Salama et al. (2002) and shown in Appendix E for bore AM13A 3.5 km north of GA2 (Figure 24).

Changes in the rate of water-level decline in GA2 correspond with abstraction from the Pinjar borefield (Figure 23). Pinjar pumping started in 1990 and GA2 water levels showed a step-down response in 1992. Pinjar pumping increased in 1997 and GA2 water levels showed another step down in 1998 and subsequently a faster rate of decline was evident. Large volumes pumped in 1998–2001 coincide with a diminished seasonal recharge signal in the GA2 hydrograph (Figure 23). A similar increase in the rate of water-level decline can be seen in YN3 after 1998 (Figure 27).

Abstraction from the Quinns borefield may also be affecting water levels at GA2 and YN3. Abstraction began in 1998/99 when 5022 ML was withdrawn from the borefield. Although 1999/2000 abstraction was 9683 ML, during the period 2000 to 2011 it operated steadily at

8000–9000 ML/year. These steady abstraction rates make it difficult to identify inter-annual influences on these two bores. However, the increased rate of water-level decline in GA2 and YN3 from 1998 onwards may be a response to the combined impacts of the Pinjar and Quinns borefields. Therefore, Leederville aquifer abstraction is included as a variable in the HARTT analysis for GA2 and YN3. Whitfords Leederville aquifer borefield abstraction is not included in this analysis as it is further away and less water was removed than from the Pinjar and Quinns borefields (Figure 24).

GA12 does not show the same rise in the rate of water-level decline after 1998 as GA2 and YN3. GA12 is screened in the Superficial aquifer west of the Badaminna Fault. In this location it is currently accepted that the Superficial aquifer is underlain by an aquiclude which separates the Superficial and Leederville aquifers (Leyland 2011). So it is reasonable to expect that changes of Leederville aquifer hydraulic head will have little effect on the superficial aquifer water level in this location. Therefore, Leederville aquifer abstraction is not included as a variable in the HARTT analysis for GA12.

The independent variables used in the HARTT analyses of GA2, YN3 and GA12 are listed in Table 2.

Table 2 Independent variables used in HARTT analyses of Superficial bores GA2, YN3 and GA12

Bore	CDFM rainfall	Superficial aquifer abstraction	Pine plantation growth/clearance	Leederville aquifer abstraction
GA2	Yes	No	No	Pinjar & Quinns
YN3	Yes	No	No	Pinjar & Quinns
GA12	Yes	No	Yes	No

6.4.5 Results of HARTT analysis

The above assessment shows the major influences on water-level decline in the Superficial aquifer bores GA2 and YN3 appear to be the drying climate and abstraction from the Pinjar and Quinns Leederville aquifer borefields. For GA12 the major influences on water-level decline appear to be the drying climate and pine plantations (Table 2).

For GA2 and YN3, the modelled water levels were determined with HARTT using CDFM rainfall and cumulative monthly Leederville aquifer abstraction as the independent variables and groundwater level as the dependent variable. Regression analysis was done for the period 1976–2010. Similar analysis was done for GA12, using CDFM rainfall and a linearly-increasing variable for pines as the independent variables.

The modelled groundwater levels for GA2 are shown in Figure 26 and the regression analysis statistics are given in Appendix F. The R^2 *coefficient of determination* was 0.99 (that is, 99 per cent of the variation was explained by the regression model) and the modelled groundwater levels visibly fit the measured groundwater levels.

Although the individual impacts of pumping from the Pinjar and Quinns borefields cannot be determined using this method due to their similar timing, the water-level decline due to reduced rainfall and abstraction can be separated. Figure 26 shows the modelled GA2 water levels due to (a) both abstraction and varying rainfall (red line) and (b) only varying rainfall (green line). Between May 1991 and May 2010, water-level fell by about 1.5 m. The drying climate contributed approximately 0.5 m of the decline and abstraction from the Leederville aquifer borefields approximately 1.0 m (see Figure 26).

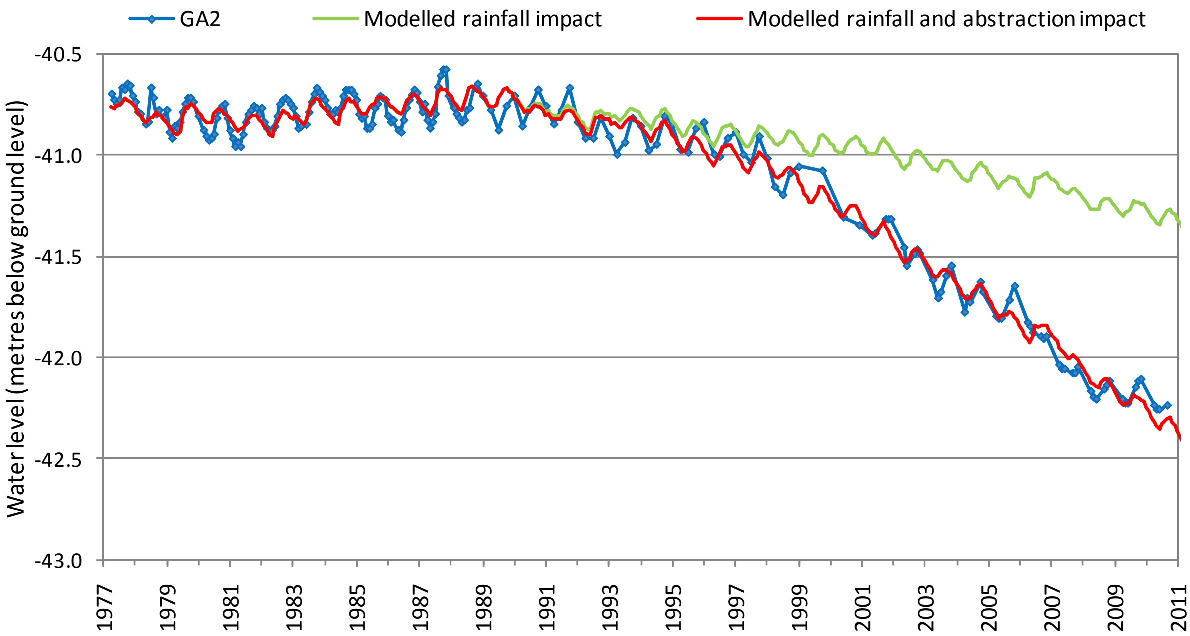


Figure 26 *Modelled and observed water levels for GA2. The modelled water level (red plot) includes CDFM and cumulative abstraction from the Pinjar and Quinns borefields as independent variables. The green plot indicates the modelled rainfall impact.*

A similar analysis was done for Superficial aquifer bore YN3 (Appendix F & Figure 27). Again, the regression model included CDFM rainfall and cumulative Pinjar and Quinns abstraction as independent variables. The R^2 *coefficient of determination* was 0.99 and the modelled water levels had a good visible fit to the measured values (Figure 27). In YN3 the modelled water-level decline between May 1991 and May 2010 was approximately 1.47 m. The drying climate contributed approximately 0.5 m, and abstraction from the Leederville aquifer approximately 0.97 m.

The modelled groundwater levels for GA12 are shown in Figure 28 and the regression analysis statistics are given in Appendix F. The R^2 *coefficient of determination* was 0.98 and the modelled groundwater levels visibly fit the measured groundwater levels. The analysis of GA12 found that pines affected groundwater levels until about mid-1990. After this, the water level changes were influenced by the CDFM rainfall variable only. This indicates that the water levels in GA12 reached equilibrium with the pine plantations in 1990 and since then water levels have only been affected by rainfall.

The results show that the decline in groundwater level in the Loch McNess area (bores GA2 and YN3) for the period 1991–2010 was approximately 1.5 m, and of this approximately two-thirds was a consequence of Leederville aquifer abstraction and one-third due to declining rainfall.

Pine plantations were seen to affect groundwater levels in GA12 until 1990. From 1991–2010 water-level decline of approximately 0.7 m can be attributed solely to rainfall. The analysis infers that Leederville aquifer abstraction does not affect the Superficial aquifer water levels in this location where the two aquifers are separated by an aquitard.

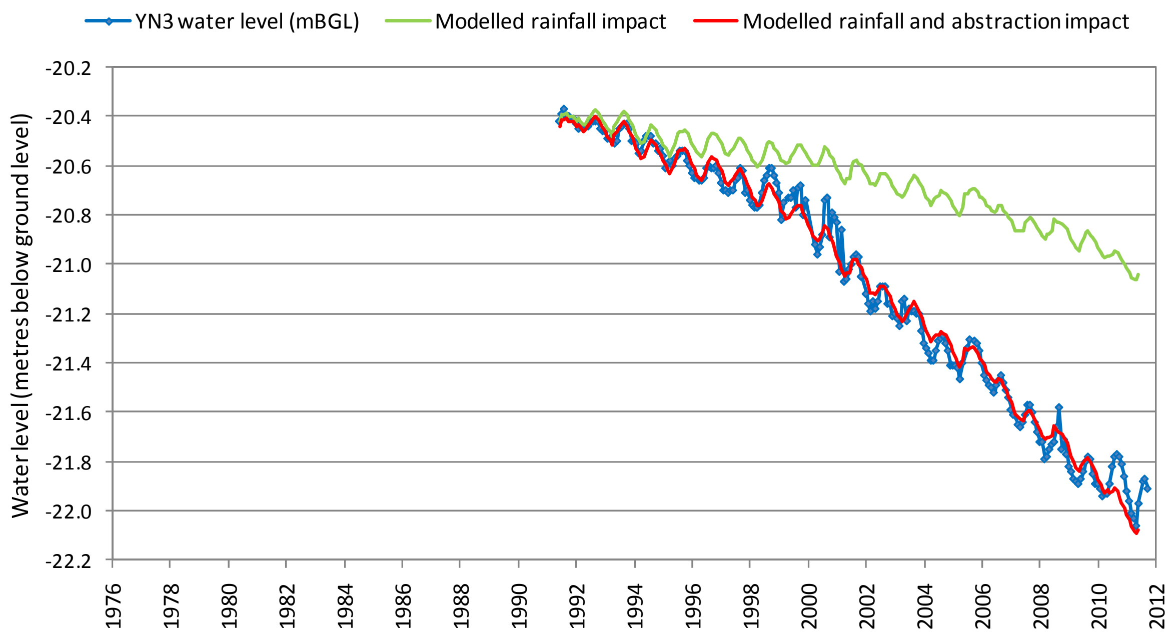


Figure 27 YN3 modelled and observed water levels. The modelled water level (red plot) includes rainfall (as CDFM) and cumulative abstraction from the Pinjar and Quinns borefields as independent variables. The modelled green plot indicates modelled rainfall impact.

Summary:

- The decline in groundwater level east of the Loch McNess area for the period 1991–2010 was approximately 1.5 m, and approximately two-thirds of this was a consequence of Leederville aquifer abstraction and one-third due to declining rainfall.
- Bore GA12, which is west of the Badaminna Fault, is not affected by Leederville aquifer abstraction. Pine plantations affected GA12 water level up until 1990. From 1991–2010 GA12 water-level decline of approximately 0.7 m is attributed mainly to decreasing rainfall.

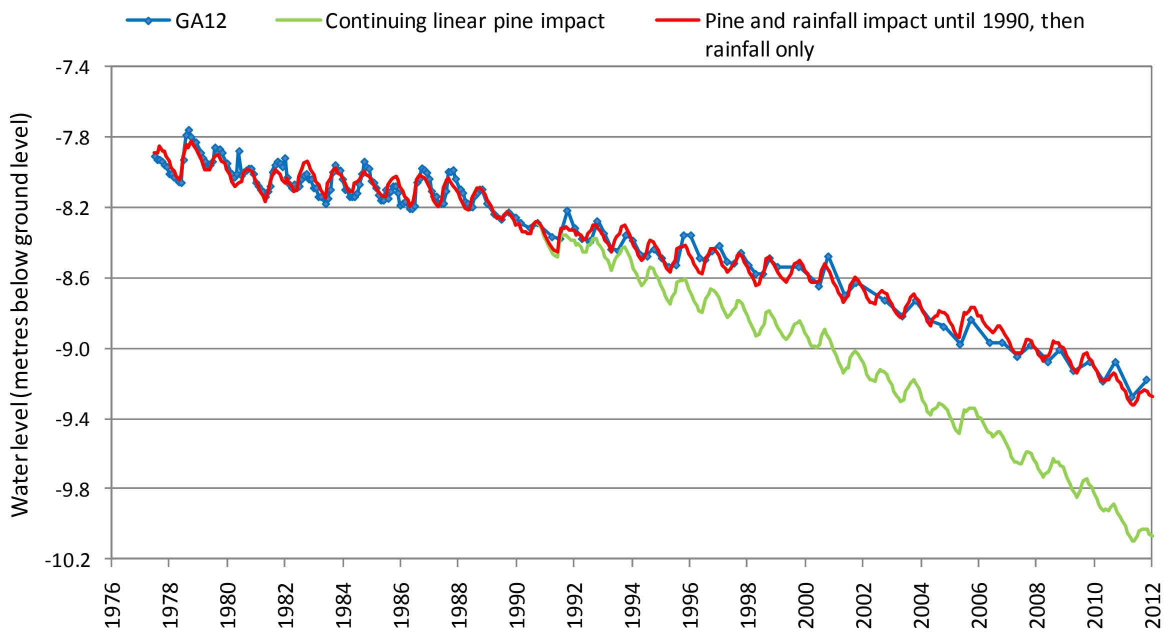


Figure 28 GA12 modelled and observed water levels. The modelled water level (red plot) includes rainfall (as CDFM) and pine plantation effects until 1990 as independent variables. The modelled green plot indicates modelled effects if the influence of pine plantations was assumed to be constant.

Recommendations:

- Pumping from the Leederville aquifer at the Pinjar and Quinns borefields affects groundwater levels in the Superficial aquifer and thus inflow into Loch McNess.
  - Pumping from the Leederville aquifer at Pinjar should be reviewed with the aim of reducing to the pre-1998 pumping rate (preferably less than 3 GL/year).
  - The relative impacts of pumping from the Quinns and Pinjar Leederville aquifer borefields on groundwater levels in the Loch McNess region (where Leederville and Superficial aquifers are in hydraulic connection) should be investigated.
- Data from other lakes to the south of Loch McNess, in particular Lake Yonderup, should be reviewed to assess relative effects of pumping from the Superficial and Leederville aquifers and land-use changes to the west and east of the lakes.
- To increase groundwater recharge pine plantations should be removed and not replanted. Water-level responses may take some time to appear but this land-use change will increase the groundwater recharge and so increase inflows to Loch McNess.

7 Conclusions and revised conceptual hydrogeology of Loch McNess

Loch McNess has changed from being a permanently-full flow-through lake before 2006 to a seasonally-dry wetland. At the end of the 2011/12 summer shallow, turbid and poor quality water covered less than one-third of the lake area. Inflow from the Superficial aquifer to the east is through the lake bed and springs. Outflow to the west is via caves and leakage through the lake bed.

Beneath Loch McNess there is no aquitard separating the Superficial and Leederville aquifers, and in 1999 the declining hydraulic head in the Leederville caused the hydraulic head gradient at LMN1a/LMN1c to reverse from upward (flow from Leederville to Superficial) to downward (flow from Superficial to Leederville). As the watertable around Loch McNess progressively dropped, inflows to the lake decreased, water levels in the caves fell and spillover into the caves west of the lake decreased.

Before 2006, the lake's water level was reasonably constant and the maximum height was controlled by the spillover into the caves. In early 2006, a critical point was reached – the inflows to Loch McNess were no longer greater than the outflows due to evaporation and leakage through the lake bed – and the water level in the lake began to drop.

Watertable decline in the Loch McNess area since the 1970s is the result of drying climate and pumping from the Superficial and Leederville aquifers. Of these, the HARTT analysis of bores GA2 and YN3, east and north of Loch McNess, showed the decline in the watertable east of Loch McNess for the period 1991–2010 was approximately 1.5 m; approximately 1.0 m of this can be attributed to Leederville aquifer abstraction. The remaining watertable decline (~0.5 m) was due to decreasing rainfall. The impacts of pine plantations and Superficial aquifer abstraction at the Pinjar borefield and in the Carabooda horticultural area were minor.

During this study, DEC became aware that Loch McNess and the Yanchep Caves were being adversely affected by its over-abstraction for the Yanchep National Park ring-main and cave water supplementation, and ended the pumping in December 2011.

To restore watertable heights around Loch McNess, in addition to the steps that DEC has taken, abstraction from the Leederville aquifer will also need to be reduced.

Abstraction for public water supply from the Yanchep Beach bores YB 3 and 4 at rates higher than those recommended by Rockwater and GSWA (after detailed groundwater investigations in the 1980s) is likely to be causing seawater intrusion into the aquifer and contributing to increasing groundwater gradients to the west of Loch McNess.

Lake Yonderup is likely to be facing threats similar to Loch McNess and an investigation which recommends the necessary actions required to preserve this lake is needed.

The conceptual hydrology of Loch McNess and surrounding areas is illustrated in Figure 29. Information relating to the labels (A–J) in the figure is given below.

A) **Declining hydraulic heads:** In the Loch McNess area the Superficial aquifer is in hydraulic connection with the Leederville aquifer. Before 1999, the Leederville aquifer discharged into the Superficial aquifer (A_1). Since 1999, the Superficial aquifer has, at one set of nested bores, been draining into the Leederville (A_2). Weak upward gradients may still exist at the MCN_E monitoring bores.

B) **Declining up-gradient inflow and watertable decline:** The watertable at YN3 dropped by 1.5 m during 1991–2010. About two-thirds of this is attributed to abstraction from the Leederville aquifer, with decreasing rainfall explaining the remaining one-third of the decline.

C) **Inflow:** Aquifer hydrochemical investigations (MCN_E a, b, c) indicate that most of the inflow to Loch McNess comes from the upper half of the Superficial aquifer.

D) **Inflow:** Additional inflow comes from Crystal Spring via a culvert and minor seeps along the lake's banks. Groundwater discharge to Crystal Spring causes the watertable gradient to flatten as it approaches Loch McNess.

E) **Outflow:** Head pressures and hydrochemistry (MCN_W a, b, c) show that water from Loch McNess is leaking towards the upper and middle half of the Superficial aquifer. Leakage on the lake's western side would have been less before 1999, as water spilling through the caves and upward gradients from the Leederville aquifer would have meant the hydraulic gradient between the lake and shallow Superficial aquifer would have been smaller.

F) **Outflow and inflow:** Depending on the year, between 0.5 and 0.8 m/year of rain falls directly onto Loch McNess. Evaporation from Loch McNess is approximately 1.4 m/year on average (when the lake is full).

G) **Outflow:** The invert level of the spillover caves controlled the maximum water level in Loch McNess until 2006. Since 2006, leakage and evaporation exceeded inflows, the lake water level no longer reached the invert level of the caves, and water no longer spilled into the caves.

H) **Karst aquifer to the west:** Pump tests have indicated that to the west of Loch McNess the Tamala Limestone is semi-confined. Due to the karstic nature of the limestone, conductivity may be up 10 000 times greater in the horizontal direction than the vertical. Calculations of horizontal hydraulic conductivity from pump tests range from 35 to 200 m/day in bores to the lake's west.

I) **Tamala sand formation:** The Tamala sand formation is likely to have a horizontal hydraulic conductivity of about 10 m/day.

J) **Karst/sand aquifer interface:** Although the location of the interface between the sand aquifer and the Tamala Limestone is uncertain, it is likely to be an important hydrogeological factor due to the development of watertable slots and dissolution of the limestone where slightly acidic water from the east has intersected the limestone.

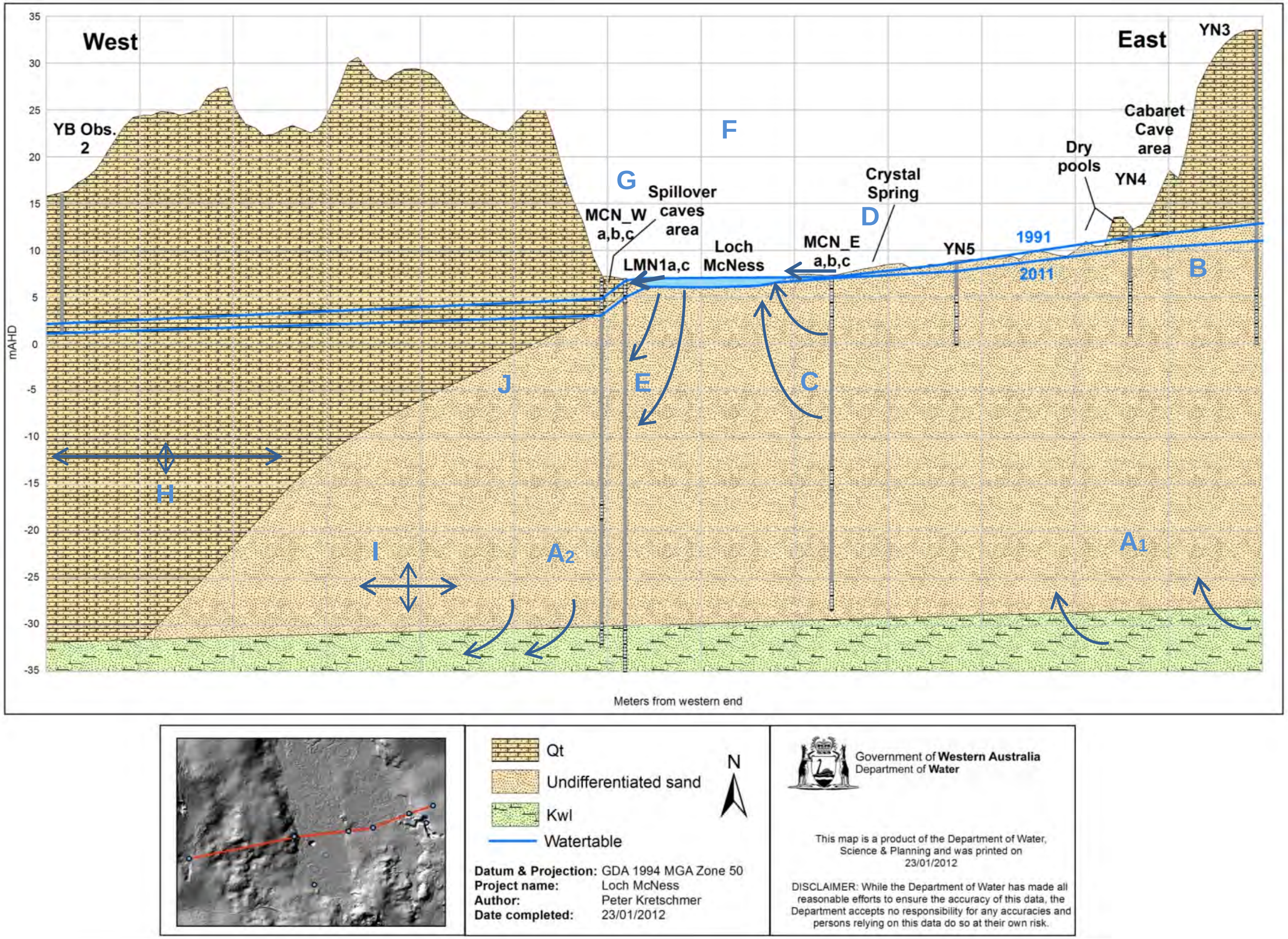


Figure 29 Close-up east-west cross-section of Loch McNess showing the watertable elevation in 1991 and 2011. Note the spillover caves to the west of the lake are the karst features that have controlled the maximum water level.

8 Recommendations

Watertable decline in the Loch McNess area during the period of this study (1975–2011) was the result of abstraction from the Superficial and Leederville aquifers, drying climate, and the presence of the pine plantations. The following management recommendations are intended to assist with restoring and maintaining water levels at Loch McNess, and potentially, also restoring flows to some of the Yanchep Caves.

Managing licensed pumping:

- Do not resume pumping from the cave supplementation bore and relocate pumping away from the lake and caves in Yanchep National Park.
- Review pumping from the Leederville aquifer at Pinjar and consider progressively reducing this to the average pumping rate pre-1998 (preferably less than 3 GL/year). Pumping from the Leederville aquifer at the Pinjar and Quinns borefields affects groundwater levels in the Superficial aquifer and also inflow into Loch McNess. Over the two decades prior to 2011, the effect of Leederville aquifer pumping was greater than the effect of declining rainfall.

Allocation planning:

- Ensure future allocation in the Yanchep groundwater area is spread across subareas A–G to avoid concentration of pumping to the west of Loch McNess.
- Maintain future allocation from the Superficial aquifer to the west of Loch McNess at less than 50 per cent of discharge to the ocean for each subarea, to avoid groundwater decline on the western side of Loch McNess and protect against seawater intrusion. This allocation approach is consistent with previous approaches applied in the 1980s by Rockwater and the GSWA, which stated that total allocation should be less than 50 per cent of the total flow-through. The previously-determined allocation limit of 365 ML/year for subarea G needs to be reviewed to take into consideration the decreased rainfall and changed land use.
- To increase groundwater recharge pine plantations should be removed and not replanted. Water-level responses may take some time to appear but this land-use change will increase groundwater recharge and so increase the inflows to Loch McNess.

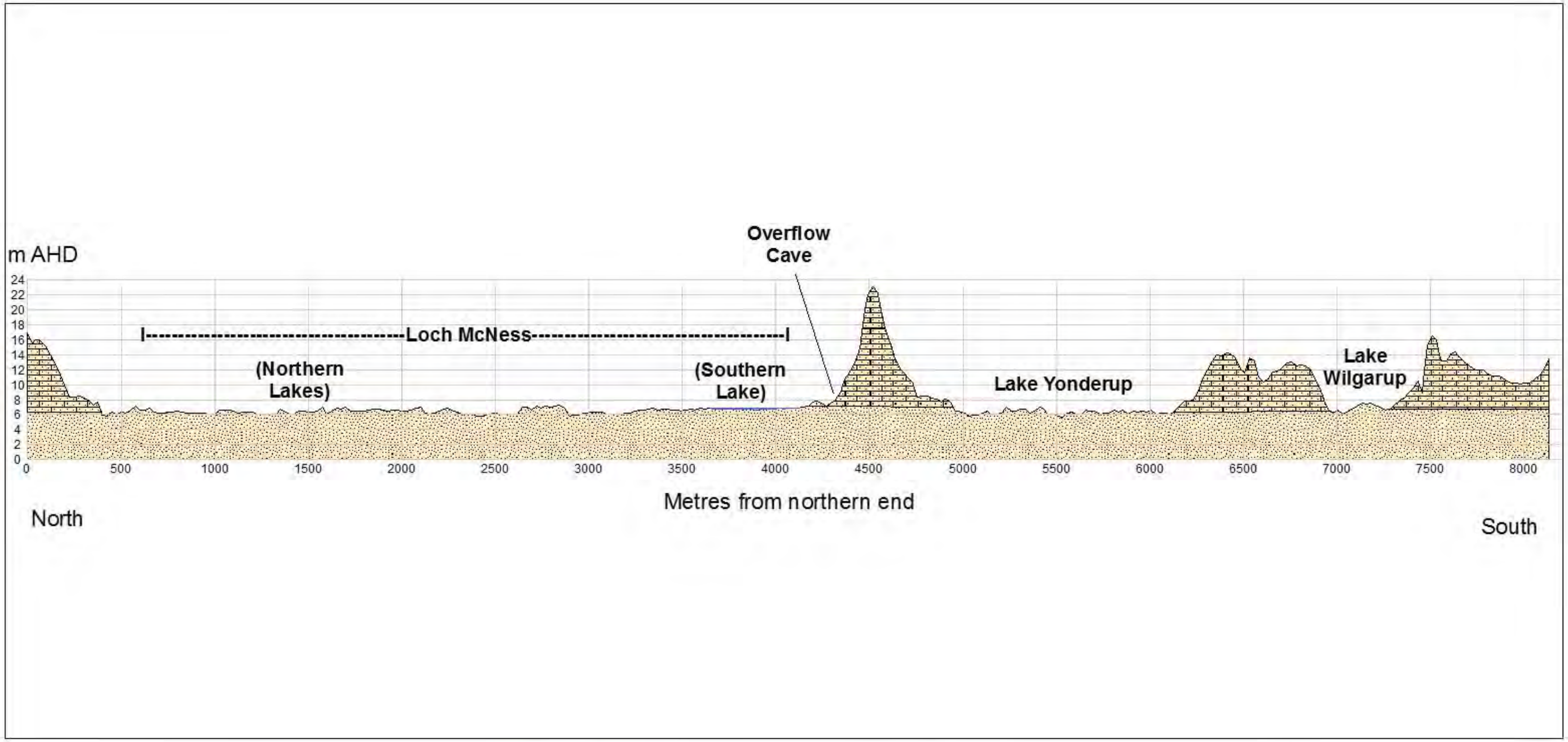
Measurement, monitoring and assessment:

- Undertake water-level monitoring in nested bores close to Loch McNess. This would enable assessment of the impact of Superficial aquifer abstraction close to the lake for the national park’s water supply.
- Consider installing and monitoring additional seawater interface bores at Yanchep Beach.
- Calculate where the seawater interface will stabilise at current pumping rates and develop management and monitoring criteria for this.

- Investigate the relative impacts of pumping from the Quinns and Pinjar, Leederville aquifer borefields on groundwater levels in the Loch McNess area (where the Leederville and Superficial aquifers are in hydraulic connection).
- Review data from other lakes to the south of Loch McNess to assess relative impacts of pumping from the Superficial and Leederville aquifers, and of land-use changes to the west and east of the lakes. For instance, Lake Yonderup is closer to the Carabooda horticultural district, so Superficial aquifer abstractions at Carabooda as well as Leederville aquifer abstractions may be having an impact.
- The conceptual hydrogeological interpretation developed in this project should be included in future groundwater modelling of the Loch McNess area, where possible. When models have insufficient resolution to incorporate this complex hydrogeology, the model inaccuracies should be acknowledged and taken into account when the model is used for allocation planning.

Appendices

Appendix A – North-south geological cross-section



Qt

Undifferentiated sand

Vertical datum: mAHD
Horizontal scale: metres

Datum & Projection: GDA 1994 MGA Zone 50
Project name: Loch McNess
Project code: ####
Author: Peter Kretschmer
Date completed: 23/01/2012

N

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

This map is a product of the Department of Water, Science & Planning and was printed on 23/01/2012

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 accuracies and persons relying on this data do so at their own risk.

Appendix B — Yanchep Beach – Two Rocks water supply investigations 1972–90

From 1972 to 1990 the region to the west of Loch McNess was the subject of some very detailed groundwater investigations. The investigations were essentially undertaken to establish maximum sustainable abstraction limits for groundwater licences. The scheme was initially developed by the Bond Corporation Pty Ltd to supply water to the Yanchep Beach and Two Rocks townships, as well as to the Yanchep Sun City development.

In the Yanchep Beach area the water-supply scheme development resulted in the installation of seven public drinking water supply bores, 11 abstraction bores for a golf course and public open space, and 22 water-level and seawater intrusion monitoring bores. The investigations included pump testing several abstraction bores, seawater intrusion assessments and the collection of water-level, rainfall and metered abstraction data.

This section provides a brief outline of the key findings from a selection of these reports (Table B1), including the reviews by GSWA (1972–1983). This information supports the understanding of the hydrogeology to the west of Loch McNess.

- Aug–Nov 1972: McPhar Geophysics Pty Ltd for the Bond Corporation, *Report on drilling and testing at Yanchep Beach, WA* (found in GSWA 1972–1983):
    - Covers the 1972 drilling and test pumping of Superficial aquifer water supply bores Yanchep Beach 3 and 4 (YB 3 and 4), 1.5 km from the coast, and screened between 48.8 m and 57.9 m BGL.
    - Reports results of step-drawdown pump tests between 42.7 and 159 m^3/h, and a constant rate test on YB 4 at 159 m^3/h (NB. metric conversion conducted).
    - Test pumping at YB 4 finds that a local aquifer boundary or low-permeability layer was encountered 720 minutes into the step-drawdown test when the pumping rate was 159 m^3/h.
- July 1973: McPhar Geophysics Pty Ltd for the Bond Corporation, *Regional groundwater resources preliminary evaluation – Yanchep Beach – Two Rocks, WA* (Accession report 90):
    - Notes the limestone outcrops on the western margin of Loch McNess, and theorises there is a low-permeability area on the lake's western side which explains the steep hydraulic gradients from the lake water level (~7 m AHD) to the eastern boundary of the Bond Corporation property (~2 m AHD).
    - Estimates transmissivity at YB 4 to be 3300 m^2/day, and 3000 m^2/day in Golf Course no. 1 bore located 1900 m north; however, throughflow estimates are made with a regional average transmissivity of 9000 m^2/day.
    - Estimates regional drawdown assuming abstraction rates of 4.55 ML/day at YB 3 and 4, and 1.64 ML/day at Golf Course no. 1, as well as abstraction at several sites closer to Two Rocks. To calculate drawdown, theoretical impermeable image boundaries were positioned along the western side of

Loch McNess and at the coastline (Figure B1). The boundaries were designed to represent the constant head boundary of the coastline to the west, and the significant change in transmissivity at the sand/limestone interface to the east.

GSWA reviewed the findings from the McPhar Geophysics (1973) report (GSWA 1972–1983). It was calculated that the proposed abstraction from YB 3 and 4 and Golf Course no. 1 would likely result in seawater intrusion into the coastal aquifer as far as the scheme abstraction bores YB 3 and 4. It was also reasoned that, based on the information made available, the transmissivity for the purpose of calculating sustainable supply should be 3300 m^2/day near Yanchep Beach and 15 000 m^2/day near Two Rocks.

- April 1974: McPhar Geophysics Pty Ltd for the Bond Corporation Pty Ltd, *Shallow groundwater resources Yanchep Beach – Two Rocks, WA* (Accession report 111):
  - Reports on a second pump test of YB 3 and 4, in which they were simultaneously pumped for 27 days: estimates of transmissivity varied between 4500 and 13 000 m^2/day, and the storage coefficient was calculated to be 0.15 (The test pumping indicated that the horizontal conductivity may be 'many times' higher than the vertical conductivity. Evidence of low vertical conductivity was also supported by the fact that the seawater interface was encountered immediately below a clay layer in the aquifer. The report reaffirmed that transmissivity values are higher in the Two Rocks region than at Yanchep Beach. The report used an average value of 13 000 m^2/day for its throughflow calculations.).
  - Estimates rainfall recharge to be 9.5 per cent of total rainfall in the Yanchep Beach area.
  - Describes the water level in Loch McNess as being controlled by overflow into cavernous limestone on its western side: notes that as the lake's water level rose it discharged rapidly though cavities in the limestone at about the watertable level.
  - Predicts that excess draw to the west of Loch McNess would be met by winter recharge from sandy sediments east of the lake.
  - Requests a 4.5 ML/day allocation from the Yanchep Beach area.

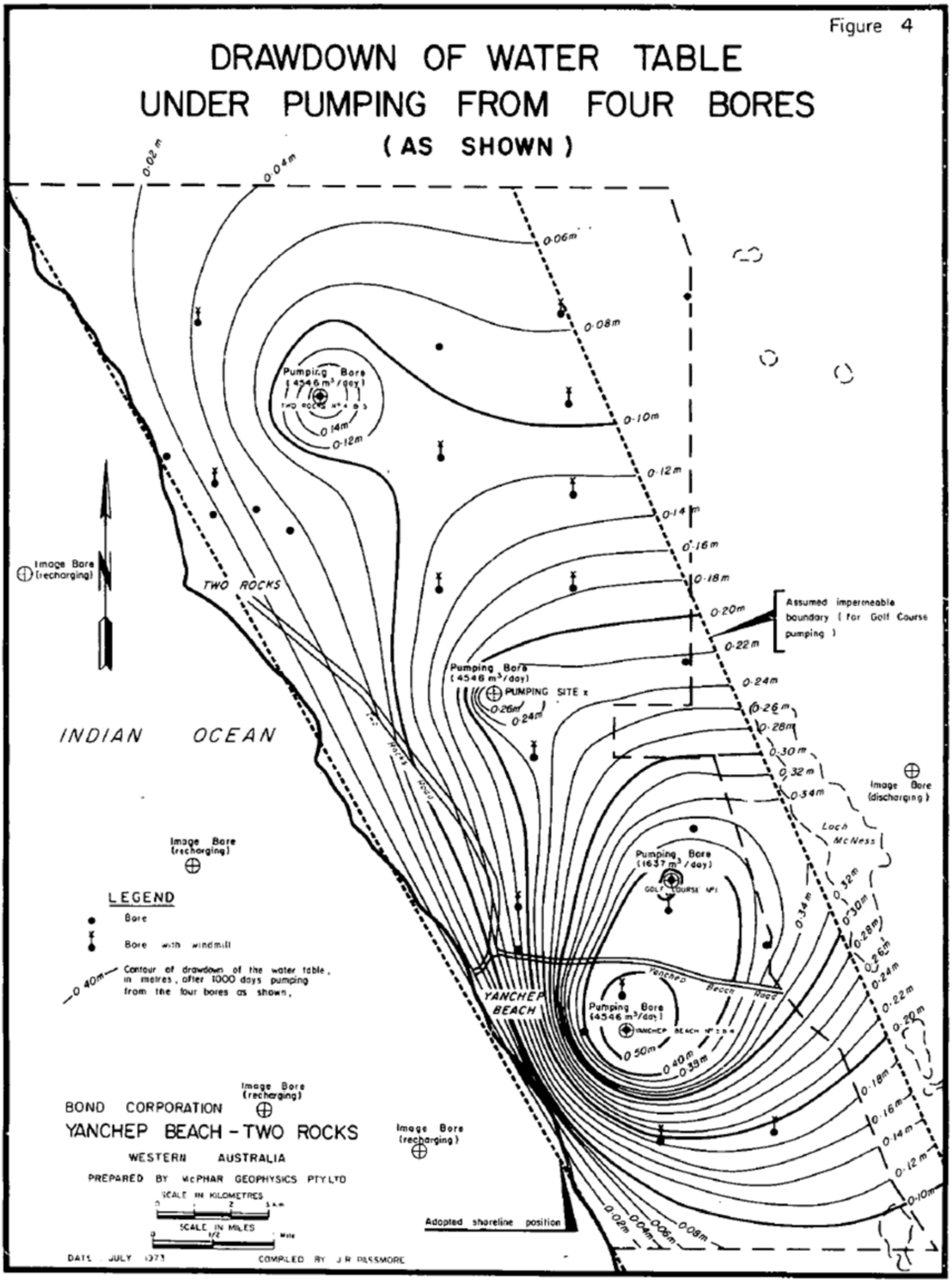


Figure B1 *Drawdown contours for the Yanchep Beach – Two Rocks region. Note the theoretical impermeable boundary to the west of Loch McNess*

The GSWA review noted that the 27-day pump test on YB 3 and 4 indicated a strongly anisotropic aquifer, with a horizontal to vertical conductivity of 10 000:1 (GSWA 1972–1983). The review suggested the whole aquifer probably consisted of multiple horizontally-flowing aquifers that could be considered separate from each other. The review also stated that on available evidence Loch McNess should not be significantly affected by pumping at Yanchep Beach if there was no pumping to the east and abstraction rates at Yanchep Beach were within the rates GSWA recommended. The GSWA proposed that abstraction at Yanchep Beach be limited to 0.5 ML/day (total from both YB 3 and 4), plus a further 0.5 ML/day from further south (GSWA 1972–1983). Another reason the rates were set lower than requested was due to the possibility of seawater intrusion at YB 3 and 4 given their close proximity to the coast (1.5 km) and the high rate of proposed abstraction from these wells.

The subsequent letters exchanged between Rockwater Pty Ltd and GSWA, and the GSWA reviews are held in the file associated with GSWA (1972–1983; Accession report 11/1973) and for succinctness are not listed or referenced individually.

A written reply from Rockwater in October 1974 suggested the allocation was too conservative. It appears some concessions were made and abstraction from YB 3 and 4 bores was doubled to 1 ML/day.

In a letter dated November 1974, GSWA recommended abstraction be limited to less than 50 per cent of estimated total throughflow to protect against seawater intrusion and impacts on Loch McNess. It also reinforced that abstraction near Yanchep Beach, including both private and scheme abstraction, should remain limited to less than 1 ML/day, or 365 ML/year. Notably, a later review of groundwater reserves at Yanchep also recommended allocation be limited to 50 per cent of calculated throughflow in an effort to protect the lakes and wetlands in Yanchep National Park (WAWA 1992) though its method of calculating throughflow was flawed.

The Metropolitan Water Board accepted these recommendations in December 1974 and subsequently the first Yanchep – Two Rocks allocation map was published (Figure B2).

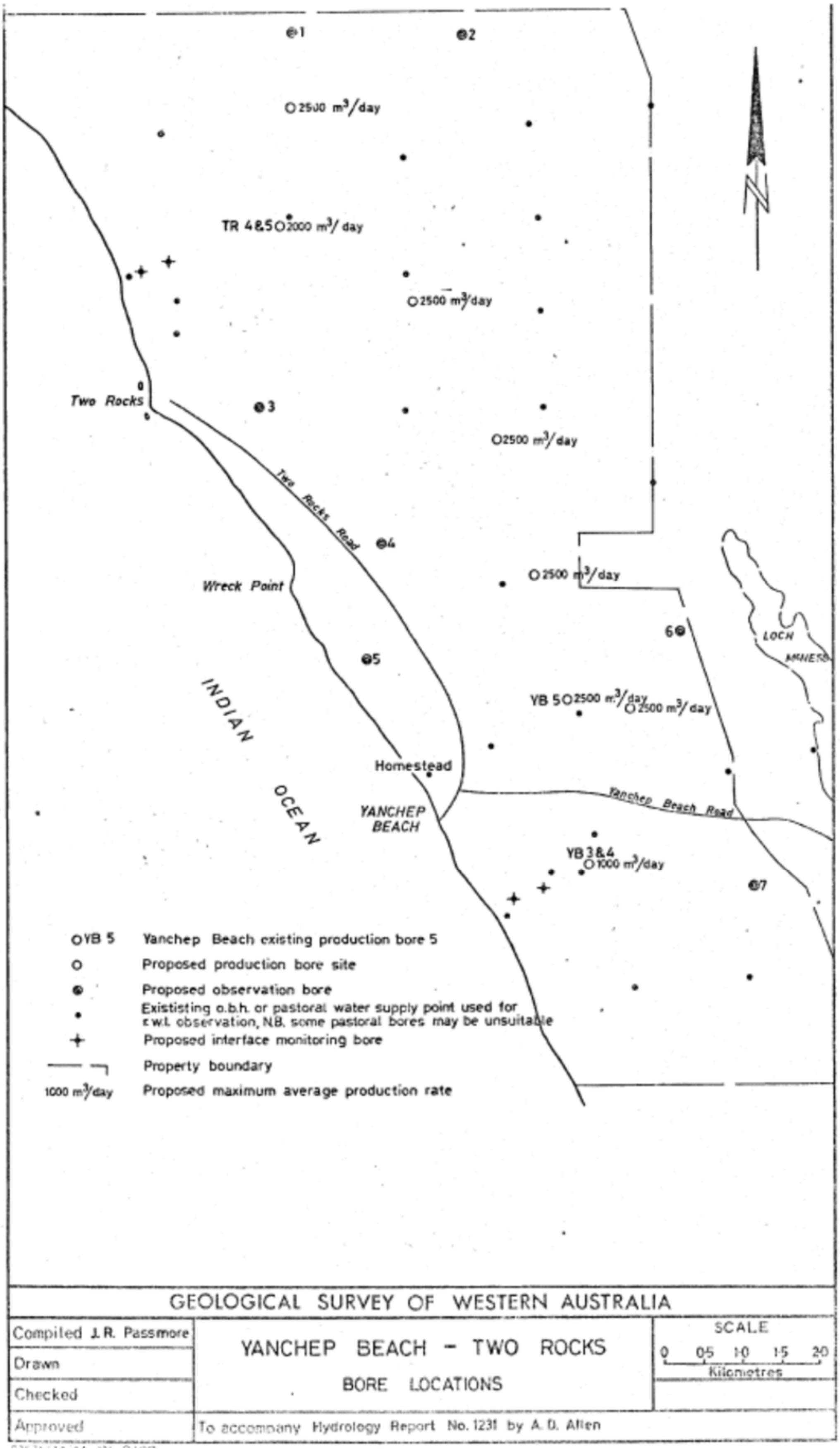


Figure B2 Recommended spread of abstraction from the Yanchep Beach – Two Rocks region. Note that the highlighted abstraction near YB 3 and 4 is limited to less than 1000 m³/day (1 ML/day).

The Metropolitan Water Board requested that every year the Yanchep Beach – Two Rocks scheme operators submit annual reports of scheme operation, including scheme and private abstraction rates, water levels, information on bore installation, pump testing and water chemistry. The reports found are listed with their Accession database number in Table B1 below. These reports document several aquifer thoughflow recalculations based on revised transmissivity estimates, regional potentiometric surface contours and observations of the seawater interface. As a result, revised sustainable abstraction figures were published in Rockwater (in 1976, 1979, 1980 and 1983).

Table B1 Yanchep Beach – Two Rocks water supply scheme groundwater investigations and reviews from 1972 to 1985

Author	Published	Title	Accession Number
McPhar Geophysics Pty Ltd	March 1973	Groundwater investigation and results of test-pumping at Two Rocks, W.A.	ACC82
McPhar Geophysics Pty Ltd	July 1973	Regional groundwater resources preliminary investigation, Yanchep Beach - Two Rocks W.A.	ACC90
McPhar Geophysics Pty Ltd	April 1974	Shallow groundwater resources Yanchep Beach - Two Rocks W.A.	ACC111
Rockwater Pty Ltd	March 1976	Yanchep Sun City Bore No. 1 drilling and testing report	ACC201
Rockwater Pty Ltd	Spetember 1976	Shallow groundwater monitoring programme Yanchep Beach - Two Rocks	ACC215
Rockwater Pty Ltd	September 1976	Shallow Aquifer Monitoring Programme Annual Summary	ACC216
GSWA	1972 - 1976	Various correspondance	11/1973
Rockwater Pty Ltd	November 1976	Yanchep Sun City Bore No. 2 drilling and testing report	ACC214
Rockwater Pty Ltd	November 1977	Shallow groundwater monitoring report Yanchep Beach -Two Rocks Volume 1	ACC251-01
Rockwater Pty Ltd	November 1977	Shallow groundwater monitoring report Yanchep Beach -Two Rocks Volume 2, Appendix II	ACC251-02
Rockwater Pty Ltd	June 1979	Monitoring bore construction Yanchep Beach - Two Rocks	ACC1694
Rockwater Pty Ltd	January 1979	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 1	ACC286-01
Rockwater Pty Ltd	January 1979	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 2, Appendix II	ACC286-02
Rockwater Pty Ltd	January 1980	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 1	ACC1612
Rockwater Pty Ltd	October 1980	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 1	ACC362-01
Rockwater Pty Ltd	October 1980	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 2, Appendix II	ACC1603
Rockwater Pty Ltd	October 1980	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 2, Appendix II & III	ACC362-02
Rockwater Pty Ltd	December 1980	Monitoring bore construction Yanchep Beach - Two Rocks	ACC343
Rockwater Pty Ltd	August 1981	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 1	ACC1614
GSWA	1980	Various correspondance	244/1980
Rockwater Pty Ltd	May 1981	Construction of YB Obs. 13B and installation of tide gauge	ACC1617
Rockwater Pty Ltd	August 1982	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 1	ACC425
Rockwater Pty Ltd	August 1982	Shallow groundwater monitoring report Yanchep Beach - Two Rocks Volume 2, Appendix V	ACC2457
Rockwater Pty Ltd	December 1982	Construction and testing report - Two Rocks production bores TR6 & TR7	ACC1616
Rockwater Pty Ltd	August 1983	Shallow groundwater monitoring report Yanchep Beach - Two Rocks	ACC466
John Ewing & Assoc. Pty Ltd	August 1984	Yanchep/Two Rocks Shallow aquifer extraction	ACC566
John Ewing & Assoc. Pty Ltd	August 1985	Yanchep/Two Rocks Shallow aquifer extraction records	ACC631

In October 1976, GSWA published a map (Figure B3) showing the Yanchep Beach – Two Rocks allocation area divided into seven subareas labelled A to G from north to south. The relevant subarea located directly down-gradient of Loch McNess was subarea G. The maximum abstraction in this subarea (immediate vicinity of Yanchep Beach and YB 3 and 4) was set at 1 ML/day (365 ML/year).

The Rockwater (1983) report was the last time the sustainable abstraction limits for the Yanchep Beach – Two Rocks area were stated (Figure B3). After nearly 10 years of investigation and discussion, the sustainable abstraction limit for subarea G remained at just 1 ML/day (365 ML/year), reflecting the lower transmissivity, seawater intrusion risk and the proximity to Loch McNess in the southern area.

In July 1985, the Yanchep Beach – Two Rocks water supply scheme was taken over by WAWA (WAWA 1987). Subsequently, abstraction limits were increased. A 1992 review of allocation limits did not reference the above-mentioned publications and recommended (using a flawed calculation of throughflow) a total abstraction limit of 41 700 ML/year for subareas A–G, an eight-fold increase (WAWA 1992).

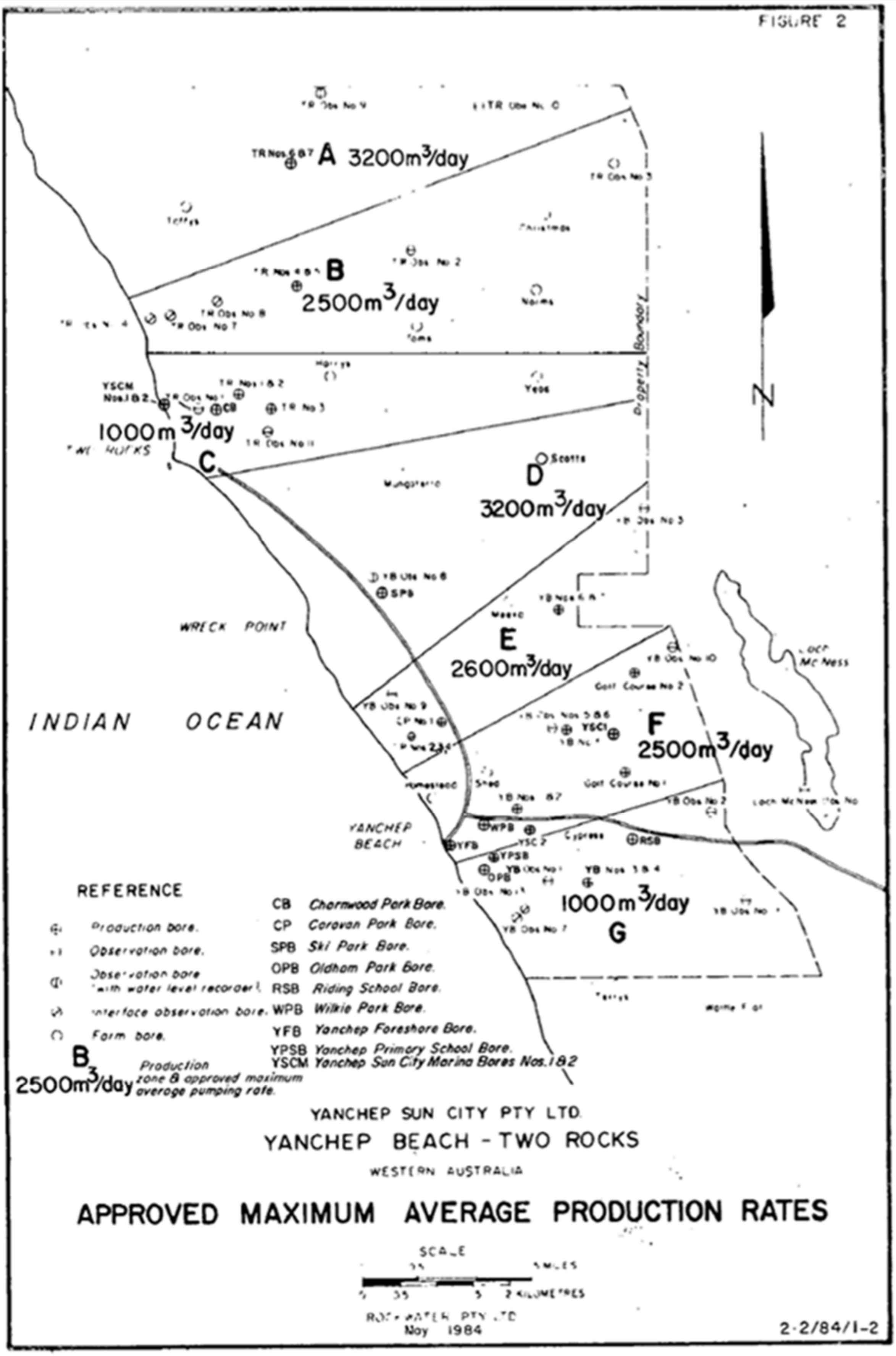


Figure B3 *Yanchep Beach – Two Rocks groundwater scheme final published map of agreed maximum abstraction rates for both private and scheme use in the region (Rockwater 1983)*

Appendix C — Groundwater abstraction

Year	Golf course 1 and 2	YB 3 and 4	YB 5	YB 6 and 7	Yanchep National Park	Cave supplementation	YSC1 (Leederville)
12/1975	0	442042	0	0	121610	0	0
12/1976	608461	772414	0	115635	121610	0	95576
12/1977	169360	234450	377031	551676	121610	0	455225
12/1978	204960	208270	474058	60585	121610	0	547349
12/1979	474806	124037	0	383824	121610	0	?
12/1980	261649	130388	0	169311	121610	0	536364
12/1981	343556	245000	0	68077	121610	0	340892
12/1982	511133	220667	0	102736	121610	0	265892
12/1983	217103	257401	0	70140	121610	0	637102
12/1984	192427	214381	0	81359	121610	0	546472
12/1985	143016	255669	0	88309	121610	0	510472
12/1986	101859	240000	0	10000	121610	0	287938
12/1987	209379	180000	0	10000	121610	0	129807
12/1988	188300	249400	0	32500	121610	0	279100
12/1989	188300	311700	0	138600	121610	0	279100
12/1990	188300	207210	0	114986	121610	0	279100
12/1991	188300	139235	0	258619	121610	0	279100
12/1992	188300	83300	0	244849	121610	0	279100
12/1993	188300	132600	0	210936	121610	0	279100
12/1994	188300	337996	0	47415	121610	0	279100
12/1995	188300	282525	0	211334	121610	0	279100
12/1996	188300	355642	0	24033	121610	0	279100
12/1997	188300	347851	0	77062	121610	0	279100
12/1998	188300	147322	0	277509	121610	0	279100
12/1999	188300	152510	0	262808	121610	0	279100
12/2000	188300	423723	0	4420	121610	0	279100
12/2001	306800	533820	0	0	121610	0	279100
12/2002	115500	474515	0	0	121610	0	278000
12/2003	180200	484940	0	0	121610	0	268900
12/2004	194200	516570	0	0	121610	0	277900
12/2005	174600	557867	0	0	121610	20000	200100
12/2006	174600	512848	0	0	121610	117300	235800
12/2007	173900	503440	0	0	121610	60000	319700
12/2008	263900	571700	0	0	121610	500000	303100
12/2009	154900	672132	0	0	169292	500000	326300
12/2010	160100	803401	0	0	190613	500000	294400
12/2011	172700	774474	0	0	319533	500000	287500

Yellow squares indicate estimated volumes. Golf course – average for 2002–11; YB 3 and 4, 6 and 7 – estimated from graph in WAWA (1990); Yanchep National Park – estimated from predicted demand for irrigated areas; cave supplementation trial – see text in document; YSC1 – average for 2002–11. NB. As different licences have different annual reporting dates, all annual data have been aligned to the end of the calendar year that the meter usage was reported to make it easier to plot and analyse.

Appendix D — Regional monitoring bores and notable abstraction bores

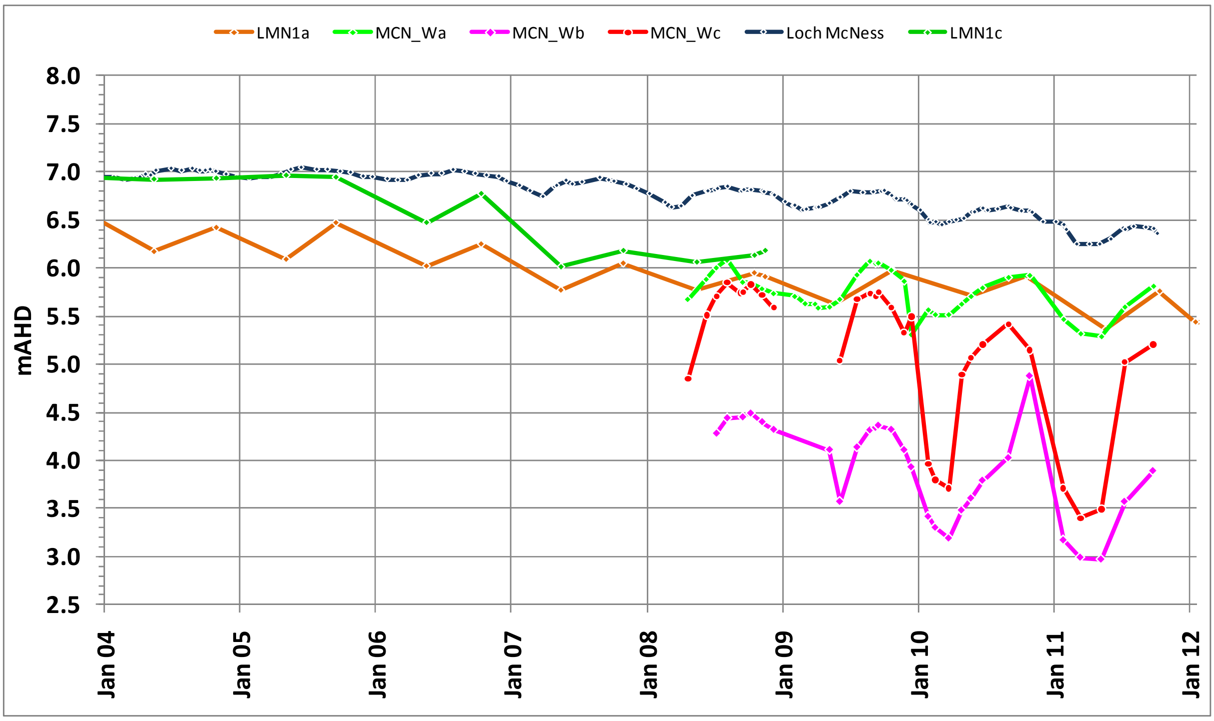
AWRC number	Common name	Easting	Northing	Commenced	Drilled depth	Top screen (mBGL)	Bottom screen (mBGL)	TOC (mAHD)	GL (mAHD)	Well purpose	End date	Comments
61612100	YN1	377693	6510183	31/05/1991	63	55.3	61.3	73.675	72.995	Monitoring	Ongoing	Gnangara Monitoring
61612101	YN2	376914	6509957	30/05/1991	45	36	45	52.928	52.248	Monitoring	Ongoing	Gnangara Monitoring
61612102	YN3	375804	6509679	24/05/1991	33.12	27.12	33.12	33.68	32.94	Monitoring	Ongoing	Gnangara Monitoring
61612103	YN4	375558	6509599	24/05/1991	10.69	4.69	10.69	12.501	12.501	Monitoring	Ongoing	Gnangara Monitoring
61612104	YN5	375197	6509449	24/05/1991	8.96	2.94	8.96	8.841	8.841	Monitoring	Ongoing	Gnangara Monitoring
61612105	YN6	376311	6508194	28/05/1991	21.51	15.51	21.51	26.124	25.586	Monitoring	Ongoing	Gnangara Monitoring
61612106	YN7	375379	6508177	24/05/1991	15.22	9.22	15.22	11.837	11.06	Monitoring	Ongoing	Gnangara Monitoring
61612107	YN8	376244	6506452	25/05/1991	17.88	11.88	17.88	18.42	11.88	Monitoring	Ongoing	Gnangara Monitoring
61710028	LMN1a (BD9)	374437	6509358	18/04/1974	42.4	37.5	42	8.155	*7.3*	Monitoring	2009	Yanchep water scheme
61710029	LMN1c (BD10)	374437	6509356	18/04/1974	3	0	3	7.77	*7.3*	Monitoring	Ongoing	Yanchep water scheme
61611845	MCN_Ea	374945	6509404	21/04/2008	39	34.3	36.3	8.174	8.127	Monitoring	Ongoing	SGS Monitoring
61611846	MCN_Eb	374945	6509403	21/04/2008	23.8	21.6	23.6	8.212	8.148	Monitoring	Ongoing	SGS Monitoring
61611847	MCN_Ec	374945	6509402	21/04/2008	5.85	0.79	5.79	8.236	8.174	Monitoring	Ongoing	SGS Monitoring
61611841	MCN_Wa	374418	6509330	7/04/2008	49	39.6	41.6	9.135	9.121	Monitoring	Ongoing	SGS Monitoring
61611842	MCN_Wb	374416	6409332	21/04/2008	28.5	26.3	28.3	8.968	*9.121*	Monitoring	Ongoing	SGS Monitoring
61611843	MCN_Wc	374418	6509331	21/04/2008	11.55	5.45	11.45	8.848	*9.121*	Monitoring	Ongoing	SGS Monitoring
61611844	MCN_SWc	374597	6508858	21/04/2008	8.9	1.13	6.13	7.73	7.687	Monitoring	Ongoing	SGS Monitoring
61640107	BH_LM1	373275	6511920	1/10/2004	-	-	-	8.516	-	Monitoring	Ongoing	Ministerial condition related?
61640108	BH_LM2	374607	6508850	1/10/2004	*6.011*	*0.5*	*6*	8.364	7.655	Monitoring	Ongoing	Ministerial condition related?
NA	Bore 3/04	373827	6508523	17/09/2004	78	20	44	-	*19.9*	Pumping	Ongoing	Cave Replenishment
NA	Bore 01/04	373845	6508520	4/11/2004	56	24	48	-	*20.1*	Monitoring	Ongoing	Cave Replenishment
61710030	GA2	373904	6513543	19/04/1977	57	45	57	47.19	46.44	Monitoring	Ongoing	Gnangara Monitoring
61710123	GA12	371277	6519680	30/06/1977	21.4	9	21	15.172		Monitoring	Ongoing	Gnangara Monitoring
61619405	Golf Course 1	372052	6510017	10/03/1973	40.9	34.5	40.9	-	*19.1*	Pumping	Ongoing	Golf Course North Bore (scndry)
61606968	Golf Course 2	372171	6509453	11/03/1973	47.4	39	47.4	-	*23*	Pumping	Ongoing	Gulf Course South Bore (main)
NA	YB Obs. 1	370960	6507974	1973				24.86		Monitoring	Uncertain	Yanchep water scheme
61710025	YB Obs. 2 (BD7)	373319	6509134	18/04/1974	21.3	-	-	17.18	-	Monitoring	Ongoing	Yanchep water scheme
61710026	YB Obs. 3 (BD5)	372283	6513260	18/04/1974	-	-	-	5.375	-	Monitoring	Ongoing	Yanchep water scheme
NA	YB Obs. 4	371515	6508014	-	-	-	-	33.33	-	Monitoring	Uncertain	Yanchep water scheme
NA	YB Obs. 5	371140	6510170	9/10/1973	65	30.5	59.8	31.5	-	Monitoring	Uncertain	Yanchep water scheme
61619409	YB Obs. 6	371143	6510176	12/01/1974	68	29	61	31.10	-	Monitoring	Uncertain	Yanchep water scheme
NA	YB Obs. 7	370593	6507496	21/11/1973	58	36	39	18.49	-	Monitoring	Uncertain	Yanchep water scheme
NA	YB Obs. 8	368398	6512150	-	-	-	-	19.53	-	Monitoring	Uncertain	Yanchep water scheme
61607042	YB Obs. 9	368711	6510644	-	-	-	-	10.82	-	Monitoring	Uncertain	Yanchep water scheme
61606977	YB Obs. 10	372576	6511757	17/12/1974	36.57	30.9	32.9	31.56	-	Monitoring	11/08/1975	Yanchep water scheme

AWRC number	Common name	Easting	Northing	Commenced	Drilled depth	Top screen (mBGL)	Bottom screen (mBGL)	TOC (mAHD)	GL (mAHD)	Well purpose	End date	Comments
61610582	YB Obs. 11	376799	6507649	11/08/1975	18.3	14.76	16.76	12.27	-	Monitoring	Ongoing	Yanchep water scheme
NA	YB Obs. 12	371048	6507775	10/09/1975	60	28	58	30.07	-	Interface	Uncertain	Yanchep water scheme
NA	YB Obs. 13	370640	6507616	25/09/1975	60.5	26	57.6	26.80	-	Interface	Uncertain	Yanchep water scheme
NA	YB Obs. 13A	370678	6507583	1/05/1980	50.3	44	45	26.63	-	Interface	Uncertain	Yanchep water scheme
NA	YB Obs. 13B	370669	6507606	10/04/1981	60.9	56	58	28.12	-	Interface	Uncertain	Yanchep water scheme
NA	YB Obs. 14	370842	6507761	29/06/1979	62	55	60	31.22	-	Interface	Uncertain	Yanchep water scheme
NA	YB Obs. 15	370770	6507630	9/05/1980	64	57.5	62.5	32.62	-	Interface	Uncertain	Yanchep water scheme
61607004	YB Obs. 16	371163	6510460	20/06/1979	34	30	34	31.88	-	Monitoring	Uncertain	Yanchep water scheme
61607009	YB Obs. 17	371540	6507808	5/07/1979	38	34	38	35.765	-	Monitoring	Uncertain	Yanchep water scheme
61607011	YB Obs. 18	371011	6511744	26/06/1980	31	27.5	31	28.871	-	Monitoring	Uncertain	Yanchep water scheme
61607007	YB Obs. 19	371200	6511530	15/05/1980	31	27.5	31	28.73	-	Monitoring	Uncertain	Yanchep water scheme
61607006	YB Obs. 20	370572	6510163	29/07/1980	41.5	38	41.5	39.34	-	Monitoring	Uncertain	Yanchep water scheme
61607005	YB Obs. 21	370138	6511336	20/07/1980	31	27.5	31	29.00	-	Monitoring	Uncertain	Yanchep water scheme
61607010	YB Obs. 22	372238	6510482	29/08/1980	29.5	25.5	29.5	26.62	-	Monitoring	Uncertain	Yanchep water scheme
61606973	Yanchep Beach 1	370488	6509020	-	-	-	-	-	-	Pumping	1977	Yanchep water scheme
61606974	Yanchep Beach 2	370475	6509005	-	-	-	-	-	-	Pumping	1977	Yanchep water scheme
61619401	Yanchep Beach 3	371542	6508136	24/08/1972	57.9	48.8	57.9	34.321	34.1	Pumping	Ongoing	WaterCorp
61619402	Yanchep Beach 4	371549	6508123	25/08/1972	57.9	48.8	57.9	34.594	34.1	Pumping	Ongoing	WaterCorp
61606972	Yanchep Beach 5	371163	6510193	26/10/1973	60	38	60	31.5	-	Pumping	1978	Yanchep water scheme
61619403	Yanchep Beach 6	371041	6511799	1/04/1976	49	40	49	28.27	-	Pumping	2000	Yanchep water scheme
61619404	Yanchep Beach 7	371051	6511807	30/06/1975	48	39	48	28.14	-	Pumping	2000	Yanchep water scheme
61641302	Backup for ring-main	375444	6509776	-	-	-	-	-	*11.79*	Pumping	Ongoing	Yanchep National Park
61641303	Backup for Yanchep Inn	374998	6509285	-	-	-	-	-	*11.96*	Pumping	Ongoing	Yanchep National Park
61641305	Fairway No. 1	374913	6509773	-	-	-	-	-	*9.25*	Pumping	Ongoing	Yanchep National Park
61641306	Fairway No. 3	375361	6510010	-	-	-	-	-	*12.13*	Pumping	Ongoing	Yanchep National Park
61641307	Lakeside - irrigation	374990	6508967	-	-	-	-	-	*9.65*	Pumping	Ongoing	Yanchep National Park
61641308	Lakeside - ring-main	374990	6508969	-	-	-	-	-	*9.65*	Pumping	Ongoing	Yanchep National Park
61606989	Wilkie Park	370106	6508982	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
999	Oldham Park	370184	6508293	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
61606990	Yanchep Primary	370523	6508421	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
61607039	Caravan Park 1	369522	6510290	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
61607040	Caravan Park 2	369051	6510068	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
61607037	Caravan Park 3	368972	6510099	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS
61607038	Caravan Park 4	368990	6510068	-	-	-	-	-	-	Pumping	Uncertain	Irrigation POS

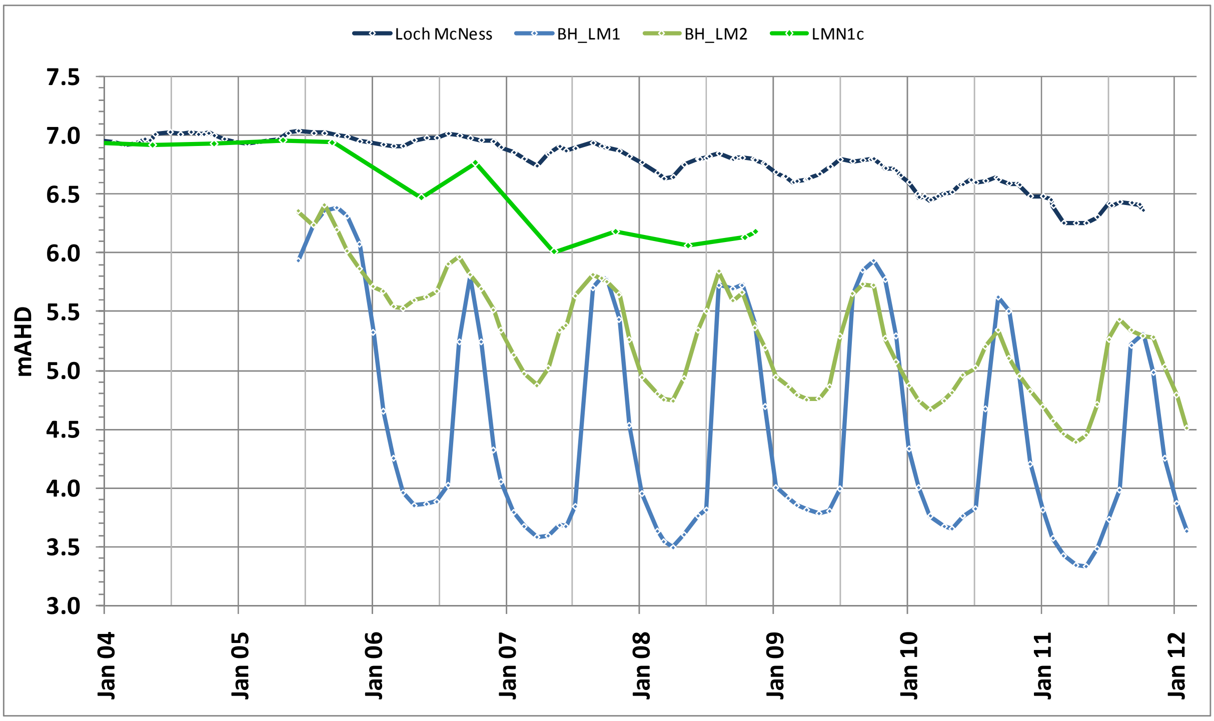
NB. Italicised values are estimated from various secondary sources of information.

Appendix E — Monitoring bore hydrographs

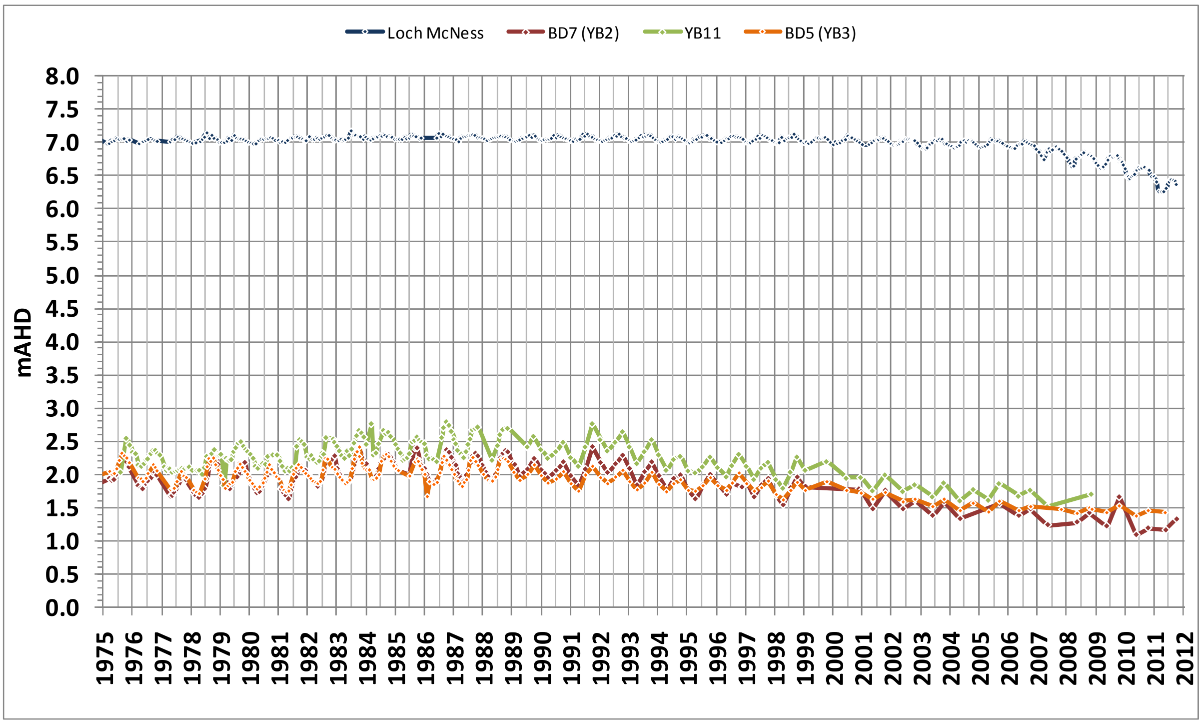
Bore locations provided in Figures 1 and 2.



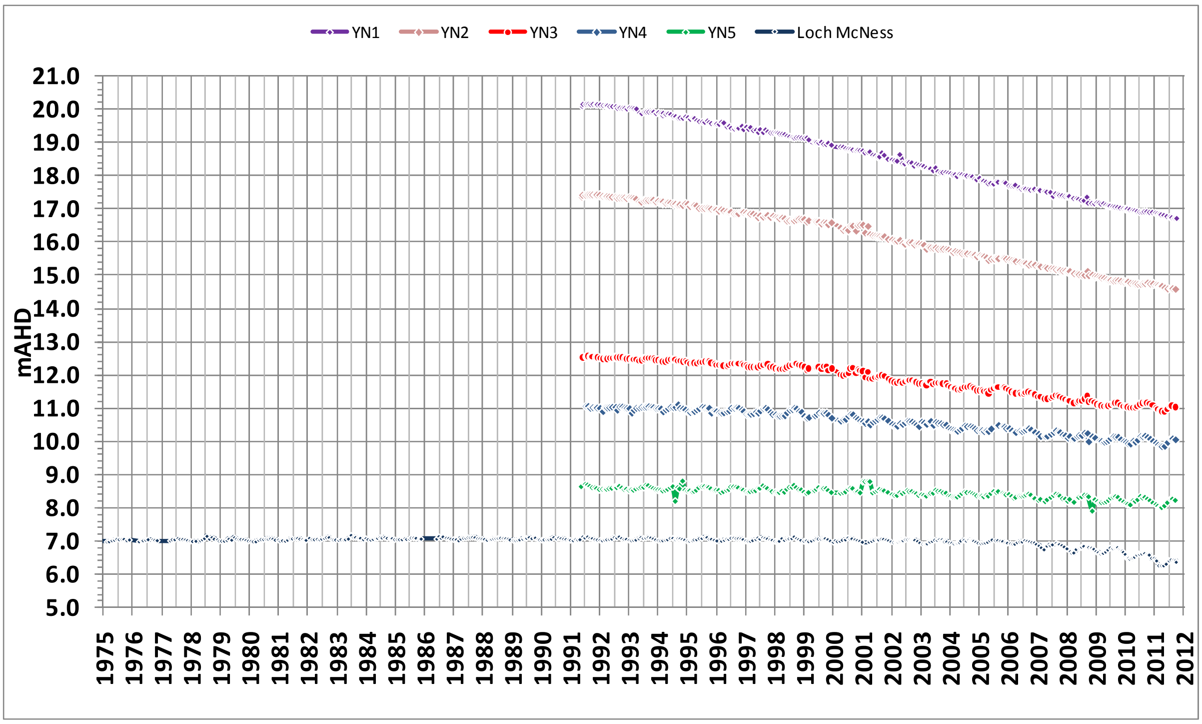
Loch McNess, LMN1a, MCN_Wa, MCN_Wb, MCN_Wc



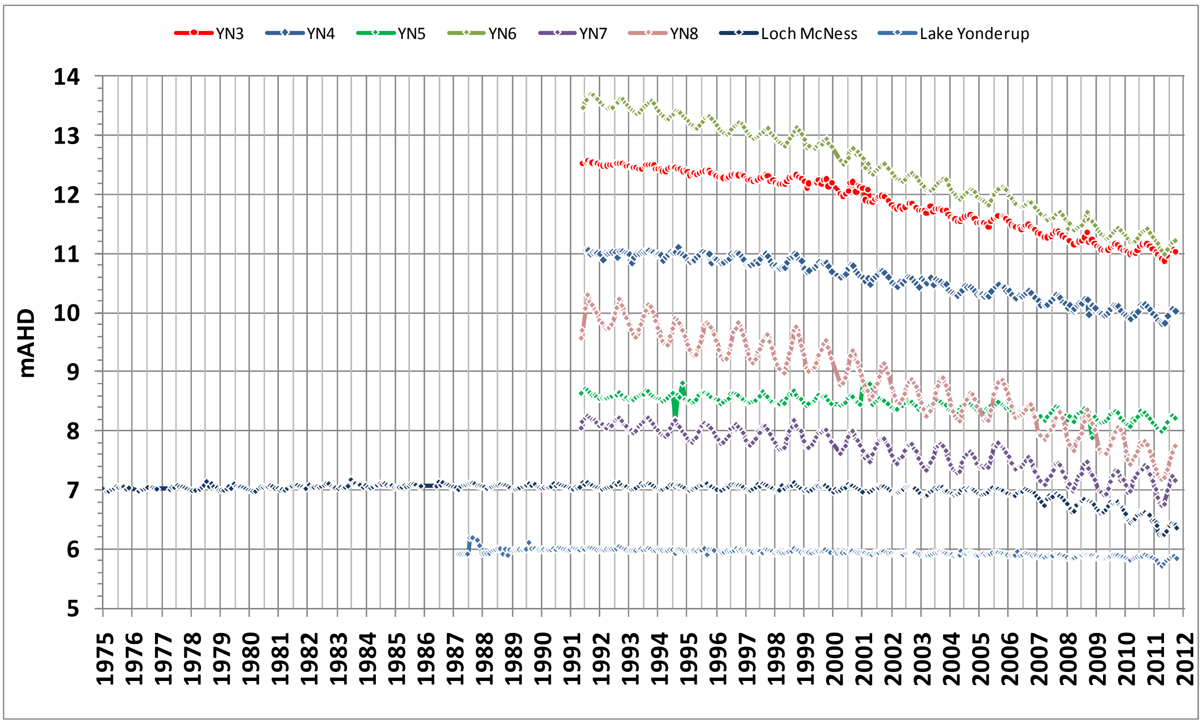
Water levels: Loch McNess, BH_LM1, BH_LM2 & LMN1c



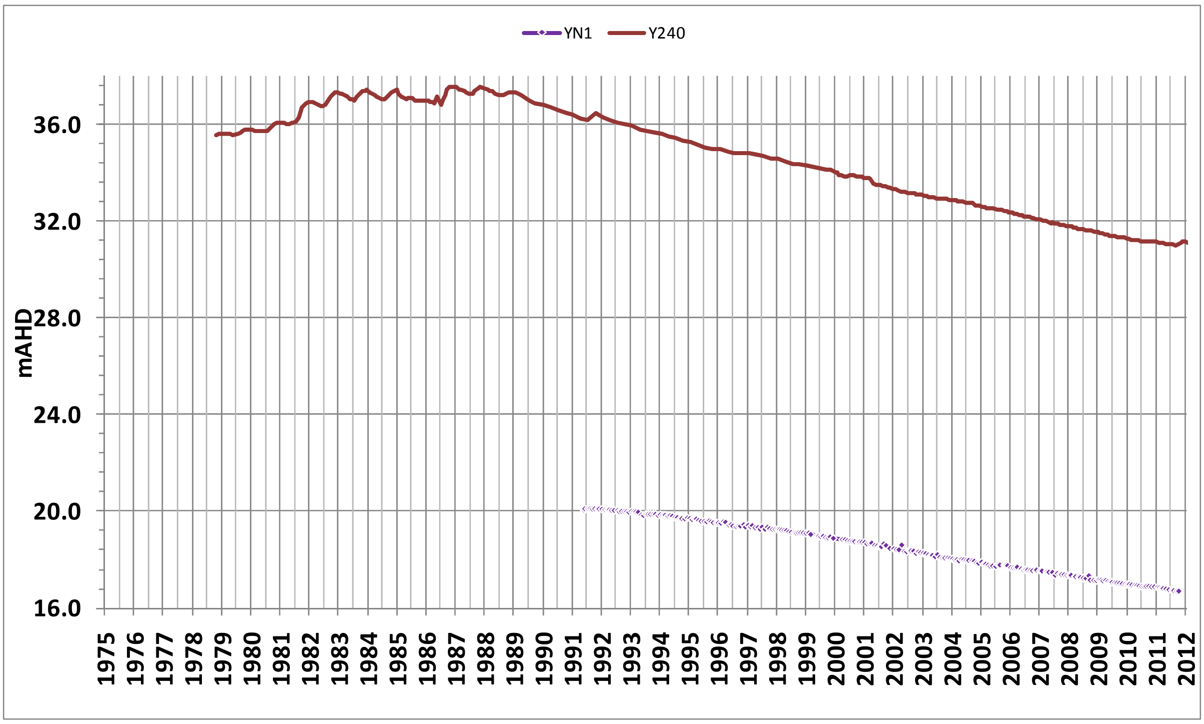
Water levels: YB Obs. 2 (BD7), YB Obs. 3 (BD5), YB Obs. 11 (YB11)



Water levels: Loch McNess, YN1, YN2, YN3, YN4, YN5

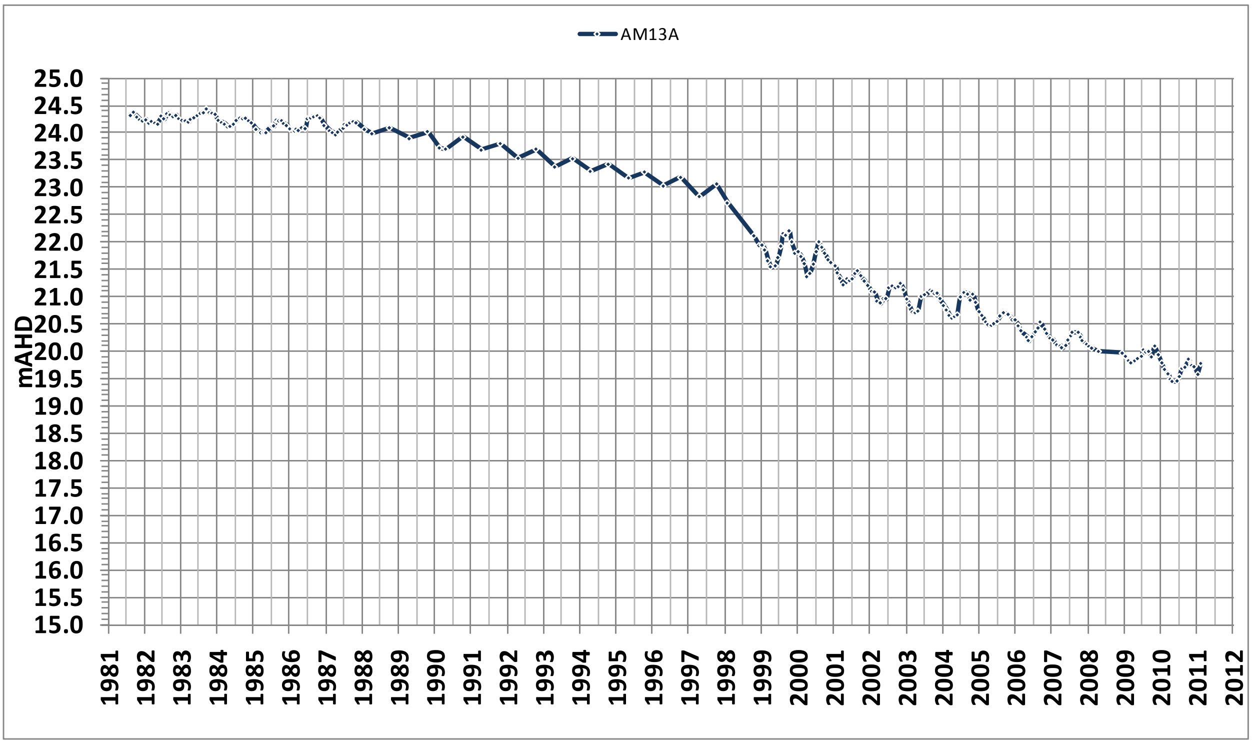


Water levels: Loch McNess, Lake Yonderup, YN3, YN4, YN5, YN6, YN7, YN8



Water levels: Y240 and YN1

Leederville aquifer bores



Hydraulic head: AM13A

Appendix F — HARTT analysis for bores GA2, YN3 and GA12

HARTT was developed by the Department of Agriculture and Food to analyse the impacts on groundwater levels of land clearing where deep-rooted native vegetation was replaced with annual cereal crops. It uses the regression tool in Excel's data analysis pack to solve the formula

Equation 1 $Y = c + (k_1 * \text{“CDFM”}) + (k_2 * t)$

Y is the water level.

C is a constant (usually a similar value to the first water-level reading).

CDFM is the cumulative deviation from mean rainfall (HARTT automatically calculates this for the period of rainfall it is provided [1907–2011 in this case]).

t is time since a change has occurred, such as the planting or clearing of a deep-rooted crop (e.g. legumes or pines). HARTT automatically includes this variable as 1, 2, 3, 4 etc., representing the time in months. **IMPORTANT** – effectively, HARTT assumes that the land-use change (e.g. clearing) has already occurred at the start of the time series, and the watertable is not in equilibrium with the new land use. This does not apply to many areas of the Gnangara Mound, and so this variable needs to be removed where it is not applicable, or shifted in time so that it represents real planting or abstraction dates.

k_1 and **k_2** are the variables calculated by the regression.

In other words, HARTT's central premise is:

Water level = beginning water level + (k_1 * CDFM) + (k_2 * time since land use changed)

If the hydrograph was for an area with no land-use change (or an area that is unaffected by land-use change) or abstraction, then only rainfall should influence the water level. Therefore, the equation is simplified to:

Equation 2 $Y = c + (k_1 * \text{“CDFM”})$

The ideal situation for establishing the relationship between CDFM and water levels is where there are several years of water-level monitoring before there are any land use or abstraction impacts. This is rare east of the Yanchep National Park, as many plantations were established in the 1960s, while most bores were installed in the 1970s. However, in locations where the water levels have reached equilibrium with the plantations' effects on recharge, then again a reliable relationship between CDFM and water levels can be established. Note that this assumption holds while the land-use remains unchanged.

If groundwater abstraction is likely to be affecting the groundwater hydrograph, then a further variable can be added to the equation in a similar way to the linear time trend, with the variable beginning at the start of the abstraction. For the analysis in this report, cumulative abstraction from the Leederville aquifer was included individually for the Pinjar and Quinns borefields.

The regression analysis automatically provides statistics on the fit between the modelled hydrograph and measured hydrograph, such as R^2 and p-values.

The following discussion describes the components of HARTT.

Mean annual rainfall for the period 1907–2011 (site 9045, see Figure 5) is 758 mm. The cumulative deviation from mean annual rainfall (CDFM) is shown in Figure F2. The major Leederville aquifer borefield abstractions are shown in Figure F2.

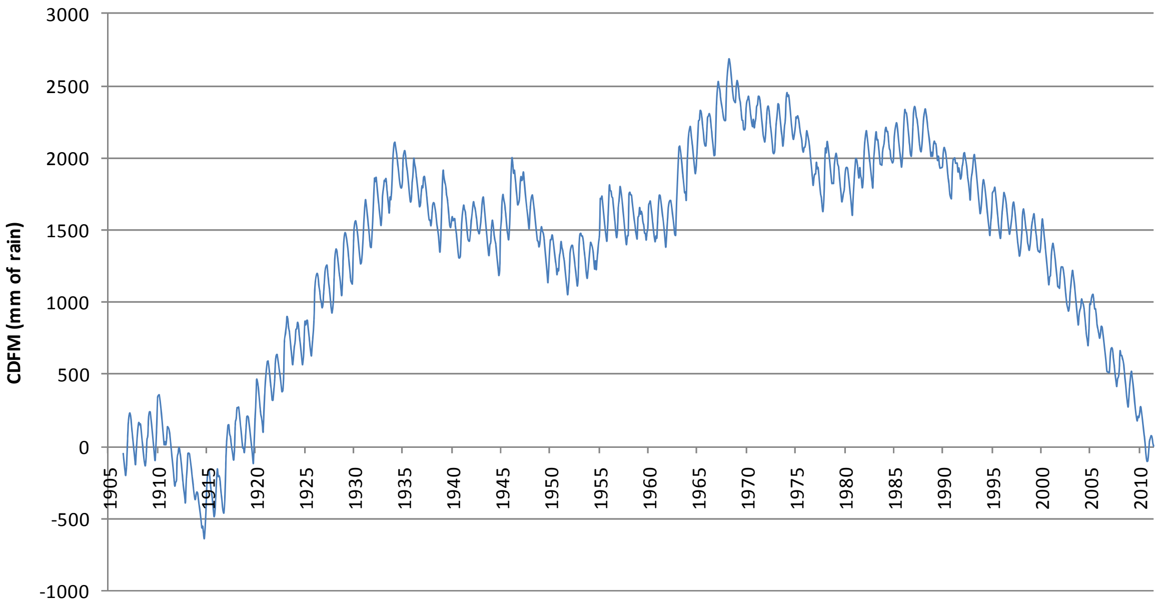


Figure F 1 Cumulative deviation from mean rainfall for the period 1907 to 2011

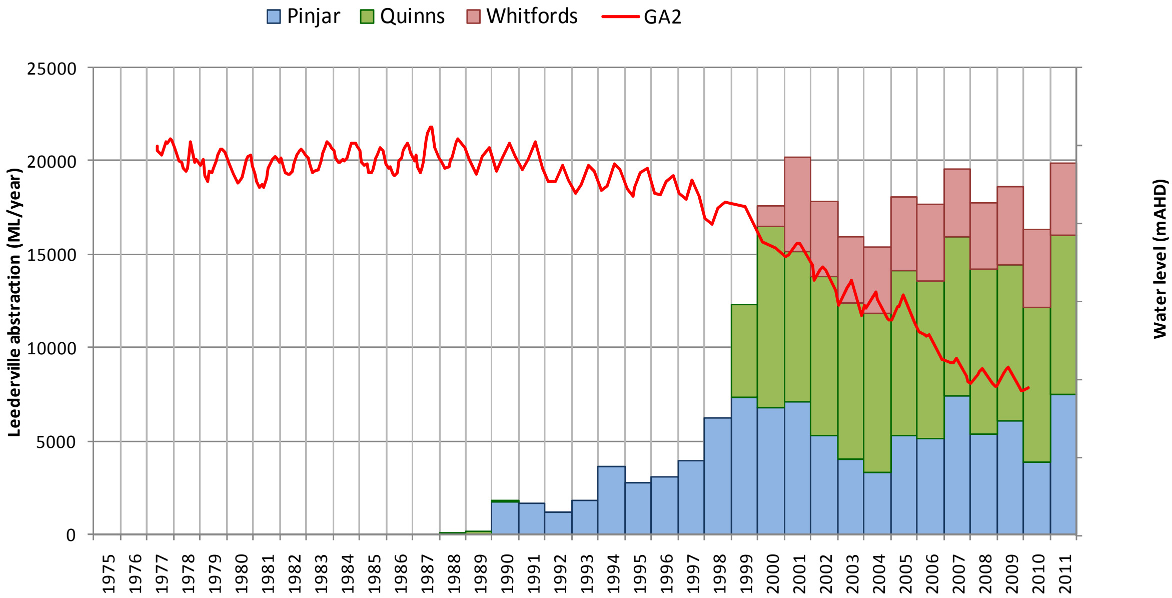


Figure F2 Abstraction from Leederville aquifer water supply borefields and the hydrograph of Superficial aquifer bore GA2

GA2 and YN3

Three variables were used in the HARTT regression analysis to represent rainfall and abstraction impacts on monitoring bores GA2 and YN3 with corresponding coefficients k1, k2 and k3:

k1 Cumulative deviation from mean rainfall (1907–2011)

k2 Cumulative Leederville aquifer abstraction from the Pinjar borefield –January 1990 to September 2010

k3 Cumulative Quinns Leederville aquifer abstraction from the Quinns borefield – July 1998 to September 2010

The statistical output for the regression analysis and the plots of modelled and observed water level for each bore are presented below:

GA2:

Regression Statistics	
Multiple R	0.993
R Square	0.985
Adjusted R Square	0.985
Standard Error	0.057
Observations	230

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	50.417	16.806	5096.869	3.4E-207
Residual	226	0.745	0.00330		
Total	229	51.162			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-41.44	0.05	-827.85	0.0	-41.54	-41.34
CDFM	3.28E-04	2.49E-05	13.14	1.12E-29	2.79E-04	3.77E-04
Pinjar	-6.57E-03	6.14E-04	-10.70	7.16E-22	-7.77E-03	-5.36E-03
Quinns	-4.03E-03	5.38E-04	-7.50	1.46E-12	-5.09E-03	-2.97E-03

All variables are statistically significant. However, the similar timing of large increases in abstraction from Pinjar and Quinns makes it difficult to separate these variables.

YN3:

Regression Statistics	
Multiple R	0.995
R Square	0.990
Adjusted R Square	0.990
Standard Error	0.050
Observations	233

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	3	58.779	19.593	7795.948	3.54E-230
Residual	229	0.576	0.00251		
Total	232	59.354			

	Coefficients	*Standard Error*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-21.03	0.05	-409.88	0.0	-21.13	-20.93
CDFM	3.21E-04	2.69E-05	11.96	6.46E-26	2.68E-04	3.74E-04
Pinjar	-6.58E-03	5.42E-04	-12.16	1.41E-26	-7.65E-03	-5.52E-03
Quinns	-3.53E-03	3.97E-04	-8.90	1.79E-16	-4.31E-03	-2.75E-03

Again, all variables are statistically significant and each of the variables has similar coefficient values to GA2.

GA12

Two variables were used in the HARTT regression analysis to represent rainfall and pine plantation impacts on monitoring bores GA12, with corresponding coefficients k1 and k2:

k1 Cumulative deviation from mean rainfall (1907–2011)

k2 Pine plantation induced drawdown represented as a linearly increasing value calculated as the number of months since the first water level observation (1977–1990) (This is applied in the same way as the *t* variable in standard HARTT analysis).

GA12:

Regression Statistics	
Multiple R	0.99
R Square	0.98
Adjusted R Square	0.98
Standard Error	0.048
Observations	194

ANOVA

	df	*SS*	*MS*	*F*	*Significance F*
Regression	2	19.019	9.51	4132.862	6.18E-158
Residual	191	0.4395	0.002		
Total	193	19.459			

	Coefficiem	*dard Er*	*t Stat*	*P-value*	*Lower 95%*	*Upper 95%*
Intercept	-8.792	0.0186	-472.601	5.44E-295	-8.83E+00	-8.76
CDFM	0.0005	8E-06	5.974E+01	1.53E-125	4.64E-04	0.00050
Pine	-0.003	7E-05	-43.302724	1.05E-100	-3.22E-03	-0.00294

Shortened forms

CDFM	cumulative deviation from mean rainfall
DoW	Department of Water
GSWA	Geological Survey of Western Australia
HARTT	Hydrograph Analysis: Rainfall and Time Trends
m AHD	metres Australian Height Datum
m BGL	metres below ground level
ML/year	megalitres per year
PRAMS	Perth Regional Aquifer Modelling System
WAWA	Water Authority of Western Australia

Glossary

Abstraction	the extraction of groundwater from an aquifer
Allocation limit	the maximum volume of groundwater a person may abstract from an aquifer over a given period
Anisotropic	the degree of variation of hydraulic conductivity between the vertical and horizontal directions at a point in an aquifer
Aquiclude	a geological formation or group of formations unable to transmit significant quantities of water
Aquifer	a geological formation or group of formations able to receive, store and transmit significant quantities of water
Borefield	a collection of bores used for the abstraction of groundwater
Cave supplementation scheme	the scheme operated to abstract groundwater from a bore and use it to replenish water levels in nearby caves in Yanchep National Park with the aim to protect stygofauna
Confined aquifer	a permeable aquifer overlain and underlain by impermeable geological formations
Constant head boundary (model)	a setting in a model that prevents the simulated water level varying from a specified level
Electrical conductivity	a measure of a material's ability to conduct an electrical conductivity: in groundwater, it is usually used to represent water salinity
Fault	a fracture in rocks or sediments along which there has been an observable displacement of the geology
Flow-through lake	a lake through which groundwater can flow in on one side and flow out on the other side
Hydraulic conductivity	a measure of how easily water can pass through rock or soil.
Hydraulic gradient	the rate of change of hydraulic head per unit distance of flow at a given point and in a given direction
Hydraulic head	the height with which the free surface of a body of water will rise relative to a given reference point – usually observed in monitoring wells
Hydrochemistry	the chemical constituents of the water / the science of the chemical composition of natural waters and the laws governing the changes

	in composition as a result of the chemical, physical, and biological processes occurring in the surrounding environment.
Invert level	the minimum height at which water will begin to flow into a feature such as a cave or a pipe
Isopotential	a line of equipotential: in groundwater it often refers to a line of equal hydraulic head
Karst	a type of geology that is formed in limestone by chemical weathering and dissolution of the limestone due to slightly acidic groundwater – usually characterised by caves, sink holes, dolines and solution channels
Labyrinthine cave	a cave with a complicated structure including interconnected corridors and sub-caves
Limestone	a sedimentary rock usually composed largely of the minerals calcite and aragonite: in the context of the Tamala Limestone, it is formed from the collection of the remnants of seashells and bioforms mixed with quartzite sand
Lithology	the description of a geological unit's physical characteristics
Model (modelling system)	a simplified numerical version of a hydrogeological system that approximately simulates the response and relationships of the real system
Recharge (groundwater)	all water reaching the saturated part of an aquifer (artificial or natural)
Seawater intrusion	the process by which seawater flows into an aquifer to replace fresh water that has been removed from the aquifer
Spring	a point where groundwater freely flows to the surface
Storage coefficient	the volume of water that a confined aquifer releases from storage per unit area of an aquifer per unit decline in hydraulic head normal to the surface
Stygofauna	a type of aquatic fauna that live within groundwater systems such as caves and aquifers, usually macroinvertebrates
Throughflow (groundwater)	groundwater that flows through a given area within an aquifer
Transmissivity	the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient

Unconfined aquifer	an aquifer with an upper boundary formed by a free watertable at atmospheric pressure
Watertable	the surface water level in an unconfined aquifer at which the pressure is equal to that of the atmosphere

References

Anderson, R, Clarke, J & Cockram, C 2005, *Dredge wrecks in Loch McNess / Wagardu Lake*, Yanchep National Park, Report 229, Department of Maritime Archaeology – Western Australian Museum and Maritime Archaeology Association of Western Australia.

Bastian, L 1996, 'Speleogenetic controls at Yanchep', *The Western Caver*, 36, pp. 13–19.

—1999, 'Loch Overflow Cave', *The Western Caver*, 39, p. 31.

—2008, 'Yanchep – Yanchep Summary', *The Western Caver*, 48, pp. 39–41.

Barber, C 2003, *Investigation of potential impacts of artificial recharge to maintain water levels in key cave systems for protection of cave fauna – evaluation of water quality impacts and cave wall dissolution*, a report for the Department of Conservation and Land Management, Crisalis International Pty Ltd.

Bekesi, G 2007, unpublished Loch McNess notes by G. Bekesi.

Bridge, PJ 1968, 'Wanneroo-Yanchep field excursion notes', *The Western Caver*, 8, 6, pg 119.

Cook, BA & Janicke, BG 2005, *Environmental monitoring and investigations for Gnangara Mound – Yanchep cave stream invertebrate monitoring, Egerton and Edgecombe Spring monitoring 2004*, report 03/05, Centre of Excellence in Natural Resource Management, University of Western Australia.

Crisalis International Pty Ltd 2005, *Investigation of source of iron in water recharging the Yanchep Caves systems*, prepared for Department of Conservation and Land Management, Crisalis International Pty Ltd, Western Australia.

English, V, Jansinska, E & Blyth, J 2003, *Aquatic root mat community of caves of the Swan Coastal Plain, and the Crystal Cave crangonyctoid interim recovery plan 2003–2008*, Department of Conservation and Land Management, Western Australia.

Davidson, WA 1995, *Hydrogeology and groundwater resources of the Perth region, Western Australia*, Geological Survey of Western Australia, Department of Minerals and Energy, Bulletin 142.

Department of Water 2006, *Assessment of the artificial maintenance of groundwater in Yanchep Caves – groundwater flow modelling*, Hydrogeological record series, report HG 13, Department of Water, Perth, Western Australia.

—2008, *Assessment of the declining groundwater levels in the Gnangara Groundwater Mound*, Hydrogeological record series, report HG 14, Department of Water, Perth, Western Australia.

—2009a, *Perth Regional Aquifer Modelling System (PRAMS) model development: application of the vertical flux model*, Hydrogeological record series, report HG27, Department of Water, Perth, Western Australia.

—2009b, *Gnangara groundwater areas allocation plan*, Water resource allocation and planning series, report 30, Department of Water, Perth, Western Australia.

—2011, *Perth shallow groundwater investigation – Loch McNess*, Hydrogeological record series, report HG 43, Department of Water, Perth, Western Australia.

Drilling Consultancy 2004, *Yanchep National Park – groundwater recharge to cave system, construction, development and pump testing of Yanchep Cave bore 3/04*, drilling report.

Environment Australia 2001, *A directory of important wetlands in Australia,* third edition, Environment Australia, Canberra.

Ferdowsian, R, Pannell, DJ, McCarron, C, Ryder, A & Crossing, L 2001, 'Explaining groundwater hydrographs: separating atypical rainfall events from time trends', *Australian Journal of Soil Research*, vol. 39, pp. 861–875.

Ferdowsian, R & Pannell, DJ 2009, *Explaining long-term trends in groundwater hydrographs*, conference paper submitted for the 18th World IMACS/MODSIM Congress, July 2009.

Geological Survey of Western Australia 1972–1983, untitled (letters and reviews related to the Yanchep Beach – Two Rocks water scheme).

—1974, *Comments on McPhar Geophysics report of April 1974, 'Shallow groundwater resources of Yanchep Beach – Two Rocks, WA'*, Hydrology report 1204.

John Ewing & Associates Pty Ltd 1984, *Yanchep/Two Rocks shallow aquifer extraction records*.

—1985, *Yanchep/Two Rocks shallow aquifer extraction records*, for Yanchep Sun City Pty Ltd.

Knott, B, Storey, AW & Chandler, L 2006, *Yanchep Cave streams and East Gnangara (Lexia) – Egerton Spring and Edgecombe Spring: invertebrate monitoring*, unpublished report prepared for the Department of Environment by School of Animal Biology, University of Western Australia.

Knott, B, Storey, AW & Tang, D 2008, *Yanchep Cave streams and East Gnangara (Lexia) – Egerton Spring and Edgecombe Spring: invertebrate monitoring*, unpublished report prepared for the Department of Water by School of Animal Biology, University of Western Australia.

Leyland, L 2011, *Hydrogeology of the Leederville Aquifer, Central Perth Basin, Western Australia*, PhD thesis to the University of Western Australia School of Earth and Environment.

Leyland, L 2012, *Reinterpretation of the hydrogeology of the Leederville aquifer, Gnangara groundwater system*, Hydrogeological record series, report HG59, Department of Water, Perth, Western Australia.

McPhar Geophysics Pty Ltd 1973a, *Groundwater investigation and results of test-pumping at Two Rocks, WA,* for Bond Corporation Pty Ltd.

—1973b, *Regional groundwater resources preliminary investigation, Yanchep Beach – Two Rocks, WA*, for Bond Corporation Pty Ltd.

—1974, *Shallow groundwater resources Yanchep Beach – Two Rocks, WA,* for Bond Corporation Pty Ltd.

Perriam, J, Tapsuwan, S, Burton, M & Schilizzi, S 2008, *Value of the Yanchep Caves: assessing Yanchep National Park visitors' willingness to pay for environmental improvement to the caves*, CSIRO Land and Water.

Rockwater Pty Ltd 1976a, *Shallow groundwater monitoring programme Yanchep Beach – Two Rocks*, for Yanchep Sun City Pty Ltd.

—1976b, *Yanchep Sun City Bore no. 1 drilling and testing report*, for Yanchep Sun City Pty Ltd.

—1976c, *Shallow aquifer monitoring programme annual summary*, for Yanchep Sun City Pty Ltd.

—1976d, *Yanchep Sun City Bore no. 2 drilling and testing report*, for Yanchep Sun City Pty Ltd.

—1977a, *Shallow groundwater monitoring report Yanchep Beach –Two Rocks Volume 1*, for Yanchep Sun City Pty Ltd.

—1977b, *Shallow groundwater monitoring report Yanchep Beach –Two Rocks Volume 2*, *Appendix II*, for Yanchep Sun City Pty Ltd.

—1979a, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 1*, for Yanchep Sun City Pty Ltd.

—1979b, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 2, Appendix II*, for Yanchep Sun City Pty Ltd.

—1979c, *Monitoring bore construction Yanchep Beach – Two Rocks*, for Yanchep Sun City Pty Ltd.

—1980a, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 1*, for Yanchep Sun City Pty Ltd.

—1980b, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 2*, for Yanchep Sun City Pty Ltd.

—1980c, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 2, Appendix II*, for Yanchep Sun City Pty Ltd.

—1980d, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 2, Appendix II and III*, for Yanchep Sun City Pty Ltd.

—1980e, *Monitoring bore construction Yanchep Beach – Two Rocks*, for Yanchep Sun City Pty Ltd.

—1981a, *Construction of YB Obs. 13B and installation of tide gauge*, for Yanchep Sun City Pty Ltd.

—1981b, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 1*, for Yanchep Sun City Pty Ltd.

—1982a, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 1*, for Yanchep Sun City Pty Ltd.

—1982b, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks Volume 2, Appendix V*, for Yanchep Sun City Pty Ltd.

—1982c, *Construction and testing report – Two Rocks production bores TR6 & TR7*, for Yanchep Sun City Pty Ltd.

—1983, *Shallow groundwater monitoring report Yanchep Beach – Two Rocks*, for Yanchep Sun City Pty Ltd.

—2003, *Report for the investigation of groundwater-wetland water level relationships study – Gnangara & Jandakot Mounds*, report for the Department of Environment.

—2005a, *Hydrological investigation of the Tamala Limestone/Gnangara Sans Contact, Joondalup to Two Rocks – Draft*, a report for Water Corporation.

—2005b, *Yanchep Caves production bore completion report*, a report for Water Corporation.

Salama, RB, Bekele, E, Hatton TJ, Pollock, DW & Lee-Steere, N 2002, *Sustainable yield of groundwater of the Gnangara Mound*, Perth, Western Australia CSIRO Floreat, WA.

Salama, RB, Silberstein, R & Pollock, D 2005, 'Soils characteristics of the Bassendean and Spearwood sands of the Gnangara Mound (Western Australia) and their controls on recharge, water level patterns and solutes of the Superficial Aquifer', *Water, Air and Soil Pollution: Focus*, vol. 5, pp. 3–26.

Sommer, B & Horwitz, P 2011, *Physio-chemical and biological consequences of lower ground- and surface water levels at Loch McNess, Yanchep National Park: a desktop study*, report to the Department of Environment and Conservation, report CEM2011-07, Edith Cowan University, Western Australia

Water Authority of Western Australia 1987, *Groundwater scheme review, Yanchep – Two Rocks*, report WG 70, Water Authority of Western Australia.

—1990, *Yanchep Beach – Two Rocks groundwater scheme review*, report WG 101, Water Authority of Western Australia.

—1992, *Perth north-west corridor groundwater management plan*, Water Resources Directorate, Groundwater and Environment Branch, report WG 145, Water Authority of Western Australia.

—1995, *Review of proposed changes to environmental conditions: Gnangara Mound groundwater resources (Section 46)*, Water Authority of Western Australia.

West Australian 1935, '£1,000 for Yanchep, dredging of lake proposed', article in the *West Australian* newspaper, 21 December 1935.

WorleyParsons Services Pty Ltd 2009, *Perth region Superficial aquifer source review, IWSS source review 1995 to 2008*, a report published for Water Corporation

Xu, C 2008, *Effects of rainfall, pines and abstraction in Gnangara Mound level decline*, Water Corporation.

Yesertner, C 2008, *Assessment of the declining groundwater levels in the Gnangara Groundwater Mound*. Department of Water, Hydrogeological report series, report HG14, Perth, Western Australia.

Yesertener, C 2009, *Hydrochemical assessment of superficial aquifers – Perth metropolitan area*, Department of Water, Hydrogeological report series, report HG279, Perth, Western Australia.

Yu, X 2003, *Evaluation of pine tree management impacts on groundwater levels around Yanchep Caves using PRAMS 2.1*, Hydrology report 206, Water and Rivers Commission, Western Australia.

Department of **Water**
168 St Georges Terrace, Perth, Western Australia
PO Box K822 Perth Western Australia 6842
Phone: 08 6364 7600
Fax: 08 6364 7601
www.water.wa.gov.au

12504 20 0516