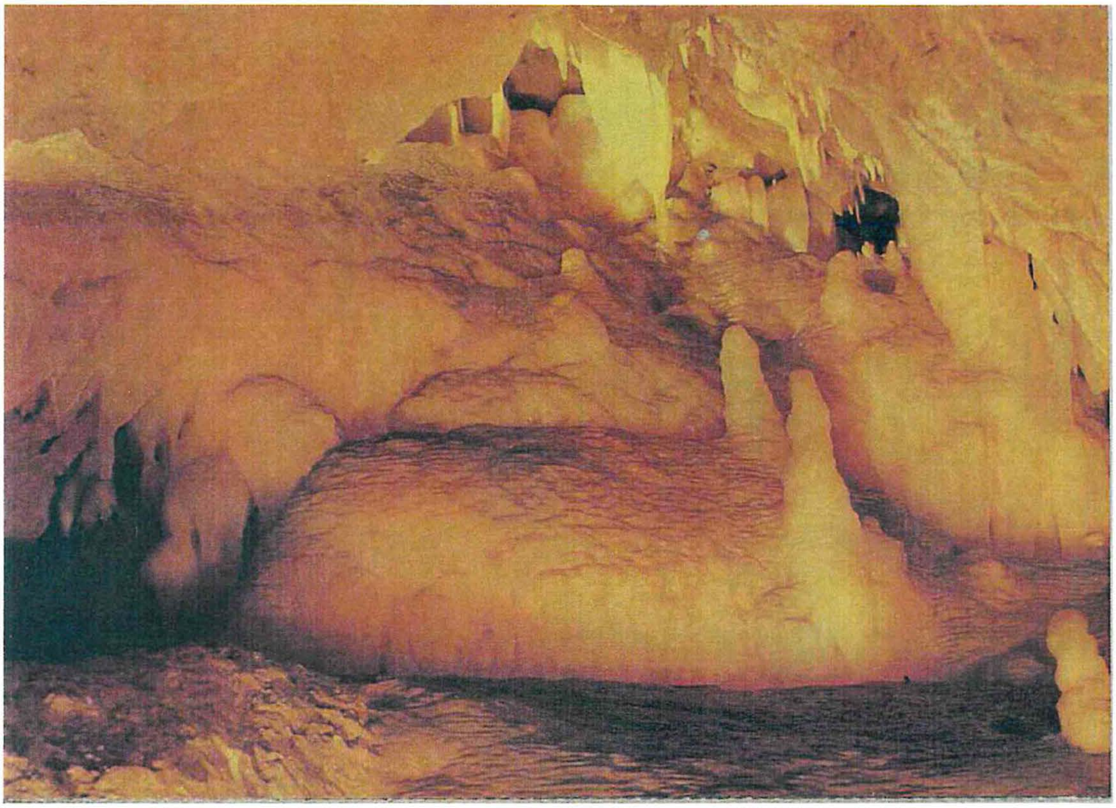
ASSESSMENT OF THE ARTIFICIAL MAINTENANCE OF GROUNDWATER IN YANCHEP CAVES

Groundwater Flow Modelling



by

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Contents

Figures

Tables

Summary

The Yanchep Caves contain a unique ecological system that is dependent on groundwater for its survival. Due to declining groundwater levels in the Gnangara Groundwater Mound since 1969 from reduced rainfall, from increased use of groundwater for public and private water abstraction and from pine plantations, the groundwater levels under these caves have declined considerably. The decline in groundwater levels has increased the stress on the groundwater dependent cave fauna since the mid 1990's.

Water levels were maintained for few years by an artificial sprinkler system that was recommended by the Recovery Team and implemented by the staff of the Yanchep National Park. However, in recent years, as water levels continue declining, the Department of Environment and Conservation (formerly Department of Conservation and Land Management and Department of Environment), Water Corporation and the Department of Water (formerly the Water part of the Department of Environment) are cooperating to design and trial a new emergency re-watering system for these caves. The objective of the system is to test the feasibility of re-hydrating the cave system by establishing and maintaining local groundwater mounds at seven of the faunal caves. These are the Crystal, Cabaret, Boomerang, Water, Car Park, Gilgi and Twilight Caves. The longer-term objective is to develop a permanent artificial system to reinstate and protect the threatened ecological invertebrate communities of Stygofauna associated with root mats. The artificial maintenance trial, which was carried out between December 2002 and September 2003, gave significant information on estimation of the required water to maintain the caves, and as the water level was raised and maintained above the floor of Crystal Cave at several discharge points, it was agreed between agencies that a permanent maintenance system could be accomplished.

To evaluate the amount of groundwater required for each of the seven caves and to determine the effects of pumping groundwater from the superficial aquifer, a three-dimensional groundwater flow model was constructed using Visual Modflow Pro 4.0 coupled with Modflow Surfact developed by Waterloo HydroGeoLogic, 2004.

It is estimated that a total discharge rate of up to total 3.5 GL/yr would maintain water in ponds in each priority cave in both summer and winter up to 2015. The effects of pumping on other water users and groundwater dependent environments were evaluated through the model. There are no groundwater dependent environments (GDE) in the vicinity that may be affected by pumping from the two bores located about 1 km south west of the Loch McNess Lake. The cone of depression resulting from pumping of these bores stabilizes in about two years and there may be a 0.5 m drawdown approximately 1 km west of the bores with zero impact on lake system towards the east after the second year of operations.

1 Introduction

The Yanchep Caves contain a unique ecological system that is dependent on groundwater for their survival. The caves are located within the Yanchep National park, which is about 45 km north of Perth (Figure 1). The National Park covers an area of 28.5 km^2 and contains about 300 caves. Seven of these caves previously had permanent streams and pools supporting cave root mat communities. Due to declining groundwater levels within the Gnangara Groundwater Mound, which started in 1969 resulting from reduced rainfall, from increased use of groundwater by public and private water abstraction and from pine plantations, the groundwater levels under these caves are also declining. The decline in groundwater levels increased the stress on the cave fauna since the mid 1990's as the fauna is dependent on groundwater for survival.

An artificial sprinkling system designed to protect the Yanchep Cave fauna, recommended by the Recovery Team and established by the staff of Yanchep National Park, appeared to work for a few years. In recent years, as water levels have continued to decline (groundwater levels have reduced on average by 0.75 m since monitoring began in 1991), it has become obvious that a more robust and generous provision of water is needed. Over the last two years, the Department of Environment and Conservation, Water Corporation and the Department of Water (formally part of the Department of Environment), have cooperated to design and trial a new emergency re-watering system for these caves. The objective of the system is to test the feasibility of re-hydrating the cave system by establishing and maintaining local groundwater mounds at seven of the faunal caves. The longer-term objective is to develop a permanent artificial system to reinstate and protect the threatened ecological invertebrate communities of Stygofauna associated with Tuart tree root mats. The artificial maintenance trial, which was carried out between December 2002 and September 2003, provided valuable information on estimation of the required water to maintain the caves, and as water was raised and maintained above the floor of Crystal Cave at several discharge points, it was agreed between agencies that a permanent maintenance system could be accomplished (Calvert and Yesertener, 2005).

To evaluate the amount of groundwater required for each of the seven caves and to determine the effects of pumping groundwater from the superficial aquifer, a three-dimensional groundwater flow model was constructed using Visual Modflow 4.0 and Visual Modflow Surfact that was developed by Waterloo Hydrogeologic in 2004.

The groundwater flow model estimates the recharge augmentation required to maintain water in one or more ponds in each priority cave in summer and winter from 2006 and up to 2015. The caves modelled are: Yanchep Cave, Cabaret Cave, Boomerang Cave, Water Cave, Car Park Cave, Twilight Cave and Gilgi Cave. Their locations are shown in Figure 1.

The effects of pumping on other water users and groundwater dependent environments were also evaluated through the groundwater model.

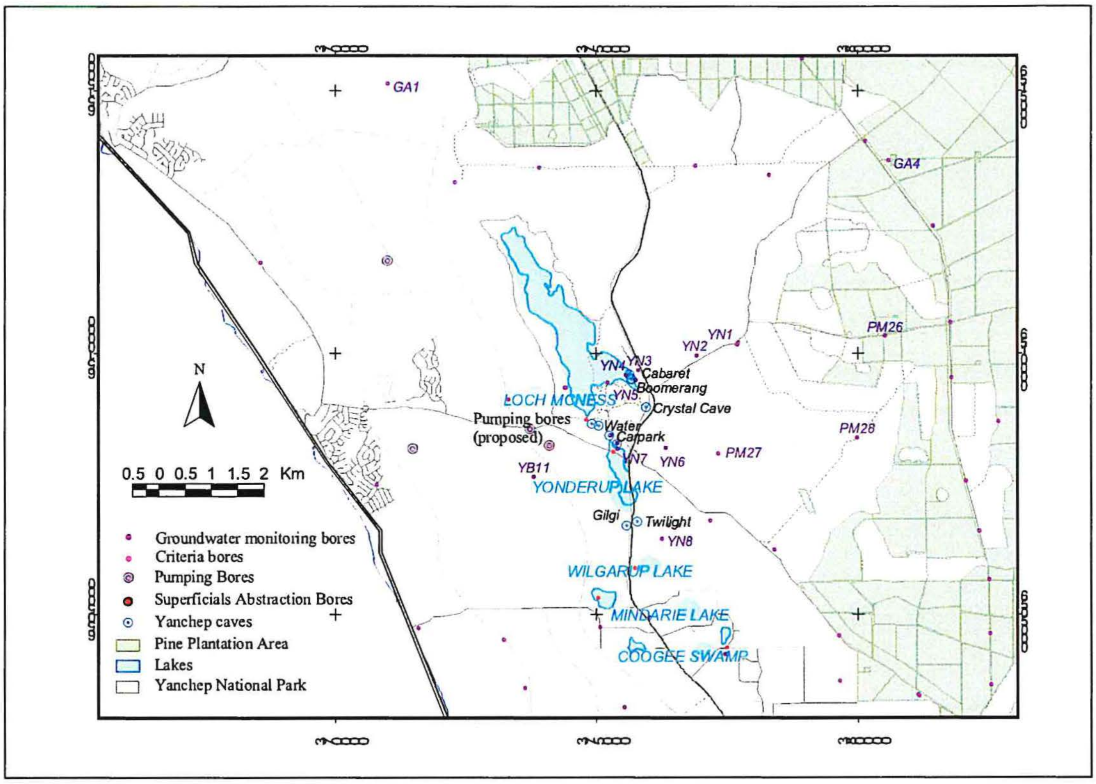


Figure 1 Yanchep Caves

2 Geology and Hydrogeology

2.1 Local Geology

The study area is covered by superficial formations, which are late Tertiary to Quaternary in age and consist of Bassendean Sand, Tamala Limestone and Safety Bay Sand (Figure 2).

Bassendean Sand covers the north east of the study area. It is present over most of the central Perth region and consists of fine to coarse-grained quartz sand. The unit varies in thickness to a maximum of about 80 m, depending on the topography. Tamala Limestone is the major superficial formation, which covers the most of the study area. It is a calcarenite and contains various proportions of predominantly medium grained quartz sand and minor clayey lenses. The limestone part of the unit contains numerous solution channels and karstic futures. Yanchep Caves occur in this formation. Depending on the location, this unit unconformably overlies the Leederville Formation or Bassendean Sand. Along the coastal margin it is unconformably overlain by the Safety Bay Sand. The Tamala limestone varies in thickness to a maximum thickness of 110 m. The Safety Bay Sand consists of calcareous fine to medium grained quartz sand and shell fragments and unconformably overlies the Tamala Limestone. Its thickness varies from a few metres to 24 m (Davidson, 1995).

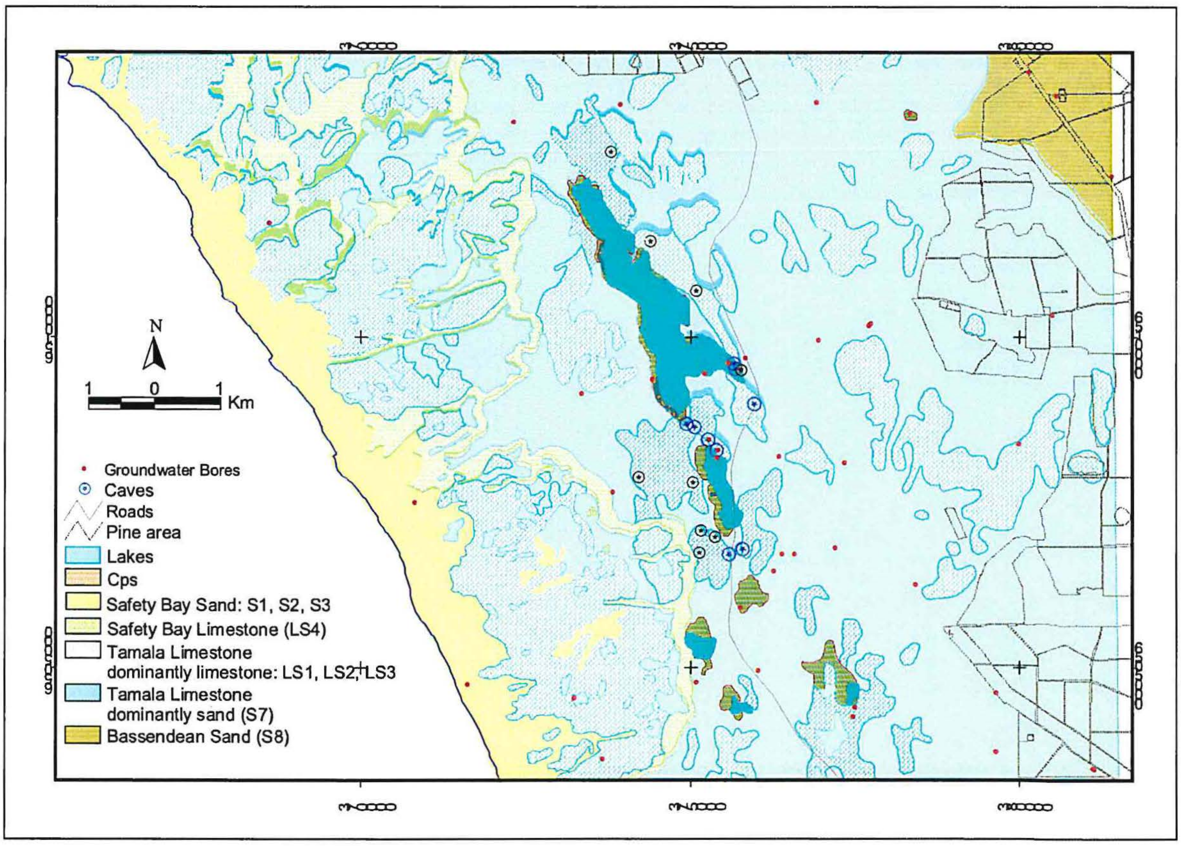


Figure 2 Geology of the Study Area (GSWA, 1985 with amendments by C Yesertener)

2.2 *Local Hydrogeology*

The Yanchep groundwater area is a part of the Gnangara Groundwater Mound, which is the major groundwater supply to Perth. Groundwater occurs in superficial formations, which are mainly Tamala Limestone, Bassendean sand and Safety Bay sand. Tamala Limestone, which covers most of the study area, is an extensive, karstic and highly productive unconfined aquifer (Figure 3). The permeable units are mainly sand decomposed from calcarenite on the east of the lake system, and mainly limestone in the west. The dashed line in Figure 3 separates a fissured aquifer on the west from a mainly intergranular aquifer on the east. The unconfined superficial aquifer is connected with underlying Leederville aquifer on the east of the dotted line in Figure 3. The Groundwater flow direction is southwest towards to the ocean. Hydraulic gradients generally change from an average of 0.005 within the sandy aquifer in the east to 0.0015 within the karstic limestone towards the west depending on hydraulic conductivity changes in the aquifers. Lake Loch McNess, Yonderup Lake, Wilgurup Lake, Pippidinny Swamp, Coogee swamp occur within the inter barrier depression with prominent karstic phenomena (Figure 3) and are located roughly on the eastern margin of the Tamala Limestone.

Loch McNess and Pippidinny Lake are permanent lakes, which are surface expressions of the groundwater table and are also considered as groundwater throughflow lakes. There are no pump test analysis done for the study area as far as known, however, Davidson (1995) provided some hydraulic conductivity values (K) modified from Hazel (1973). According to these values, in sandy parts of the superficial aquifers K values vary between 4 to 50 m/day depending on the grain sizes. Tamala limestone and calcarenite K values vary from 100-1000 m/day.

Recharge to the unconfined aquifer is mainly from rainfall percolation, even though some limited recharge from direct rainfall occurs through the lake system. Rainfall recharge estimations were conducted in a number of studies since 1970 (Davidson (1995). Recharge rates established by different studies, which relate to the study area, are given in Table 1.

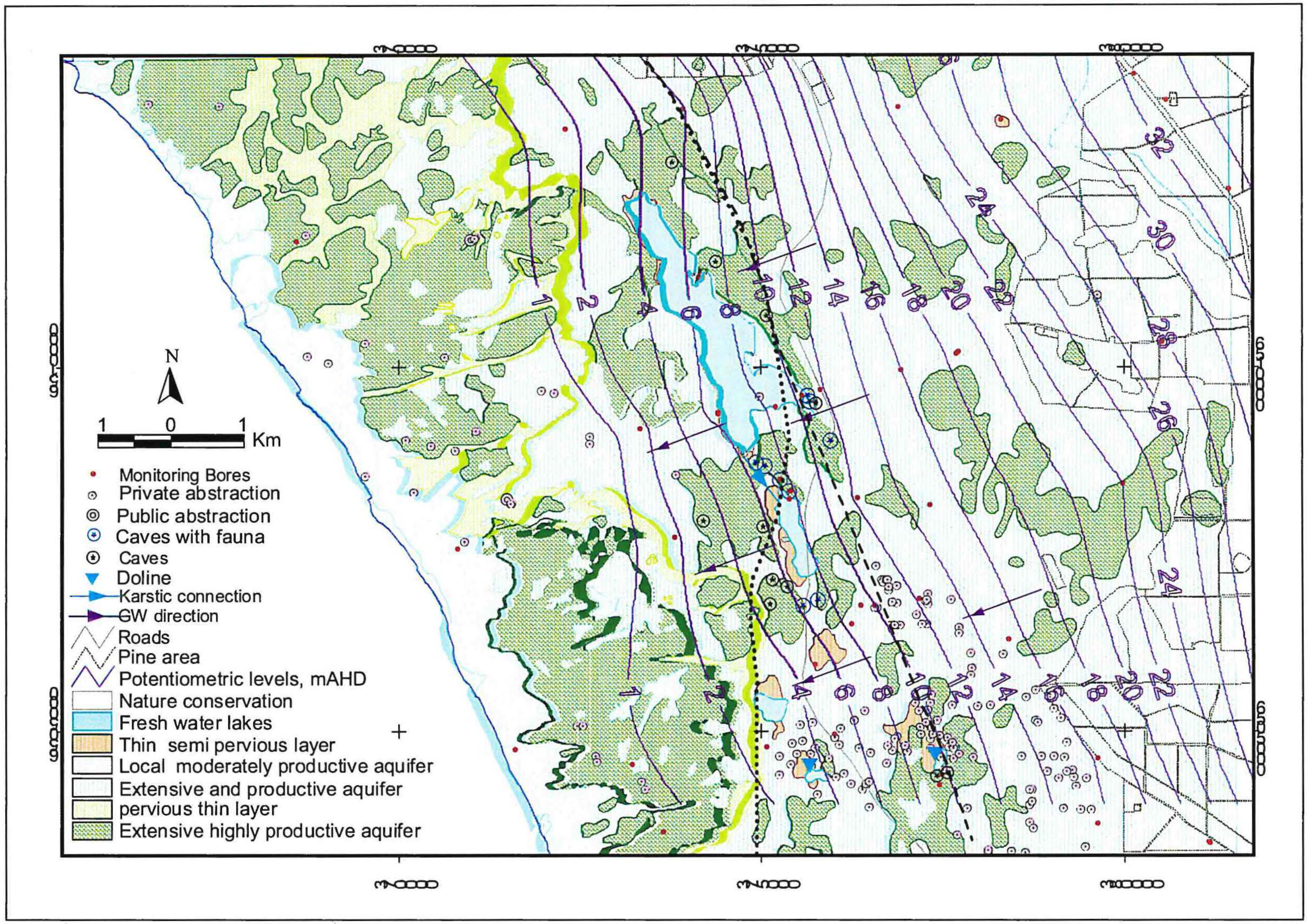


Figure 3 Hydrogeology map of the study area

Table 1 Estimated recharge to the superficial aquifer in Yanchep Area and vicinity

Study	Rainfall recharge estimated	Comments
Bestow, 1971	7.3% of the mean annual rainfall	From Davidson (1995)
Allen, 1976a	8.5% of the rainfall	From Davidson (1995)
Sharma and Pionke (1984)	12% of rainfall over native bush land 0% beneath a mature pine plantation	From Davidson (1995)
Davidson (1984a, 1987)	13% of rainfall	From Davidson (1995)
Sharma et al. (1988)	50-60% of rainfall on land used for posture	From Davidson (1995)
Thorpe (1989)	21% of rainfall near the crest of the Gnangara Mound	From Davidson (1995)
Farrington and Bartle (1989)	20-22% of rainfall for Banksia woodland area	From Davidson (1995)
Sharma et al. (1991b)	40% of the rainfall over the market garden area to the north of Perth	From Davidson (1995)
Davidson (1995)	11% of the annual rainfall over Gnangara Mound North	From Davidson (1995)
Davidson (1995)	15% of the annual rainfall beneath the relatively high limestone area	From Davidson (1995)
Hatton et al (2001)	Waves model: Banksia area 24%, Pine mature 8-12%, pasture 50% of rainfall.	Recharge estimated using WAVES Model
Salama et al (2002)	2-20% (10-150mm/yr) for the Spearwood sand under the Banksia, 12-25% (110-202mm/yr) for Bassendean Sand under Pine	Recharge has been estimated using short term water level fluctuations for the 1998-1999 season
Yesertener (2006, in preparation)	40% recharge from rainfall, of which 2.5% was surplus increased the groundwater storage in Yanchep rainfall zone in 1999, however it was 26% recharge from rainfall, and recharge - outflow difference was (-) 18% of rainfall, which taken from groundwater storage in 2001.	Recharge has been estimated using 1999 and 2001 deviation from mean rainfall between l907 and 2001annual rainfall.

Groundwater levels within the Yanchep Caves area have been declining for the last 35 years, as have water levels elsewhere in the Gnangara Groundwater Mound. The declining water table is attributed to reduction in rainfall, abstraction from the superficial and/or confined aquifers, and evapotranspiration losses from the nearby pine plantation in the Gnangara Groundwater Mound (Yesertener 2001, 2005). Hydrograph analysis shows that the major component of this decline within the Yanchep area is the reduction in rainfall (Figure 4a), however there is also some impact from local groundwater abstraction (Yesertener, 2005). Groundwater levels within the caves area has declined over 1.0 m within the last 10 years (Figure 4b and Figure 5)).

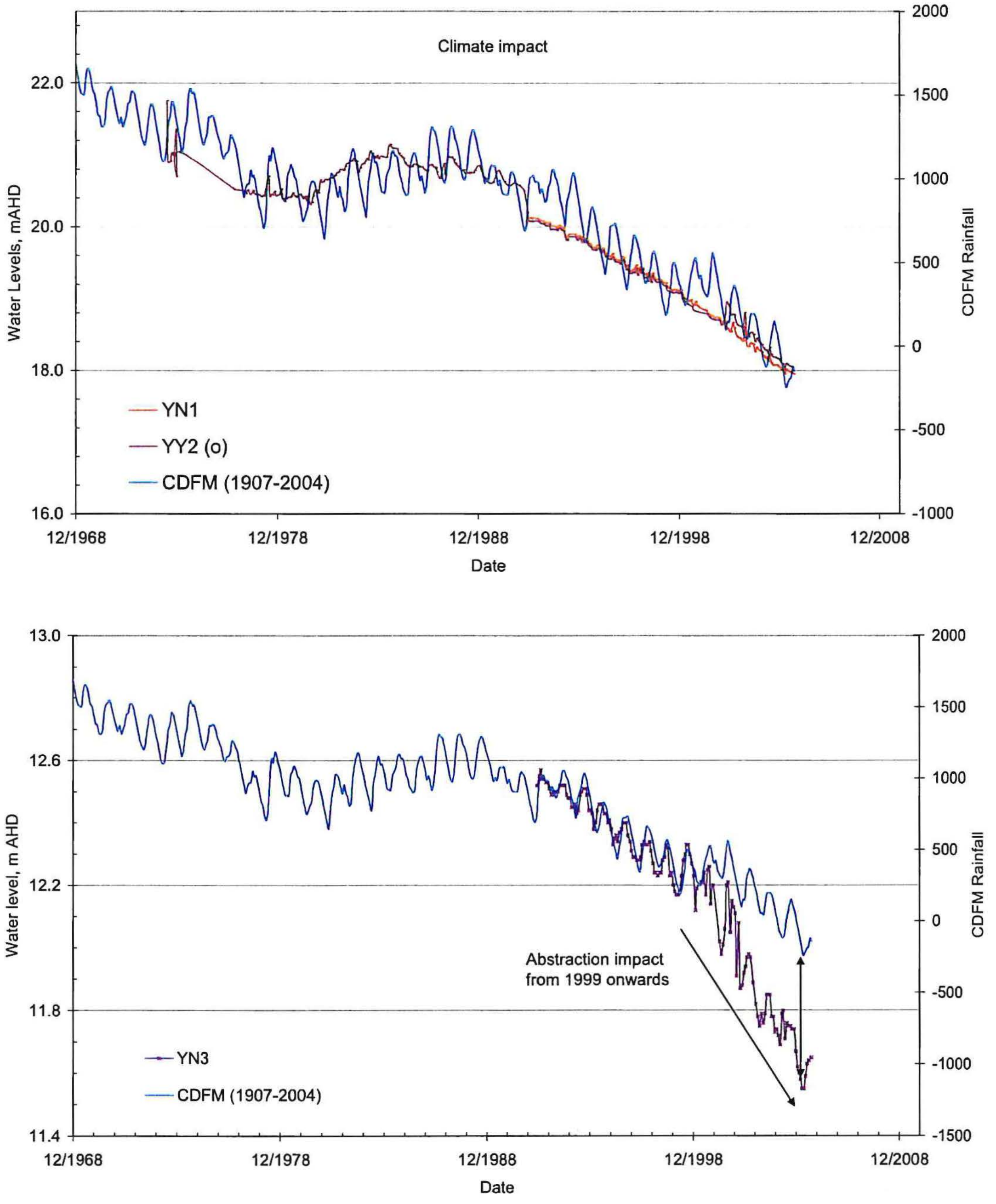


Figure 4 Groundwater Hydrographs: (a) YN1 & YY2, (b) YN3

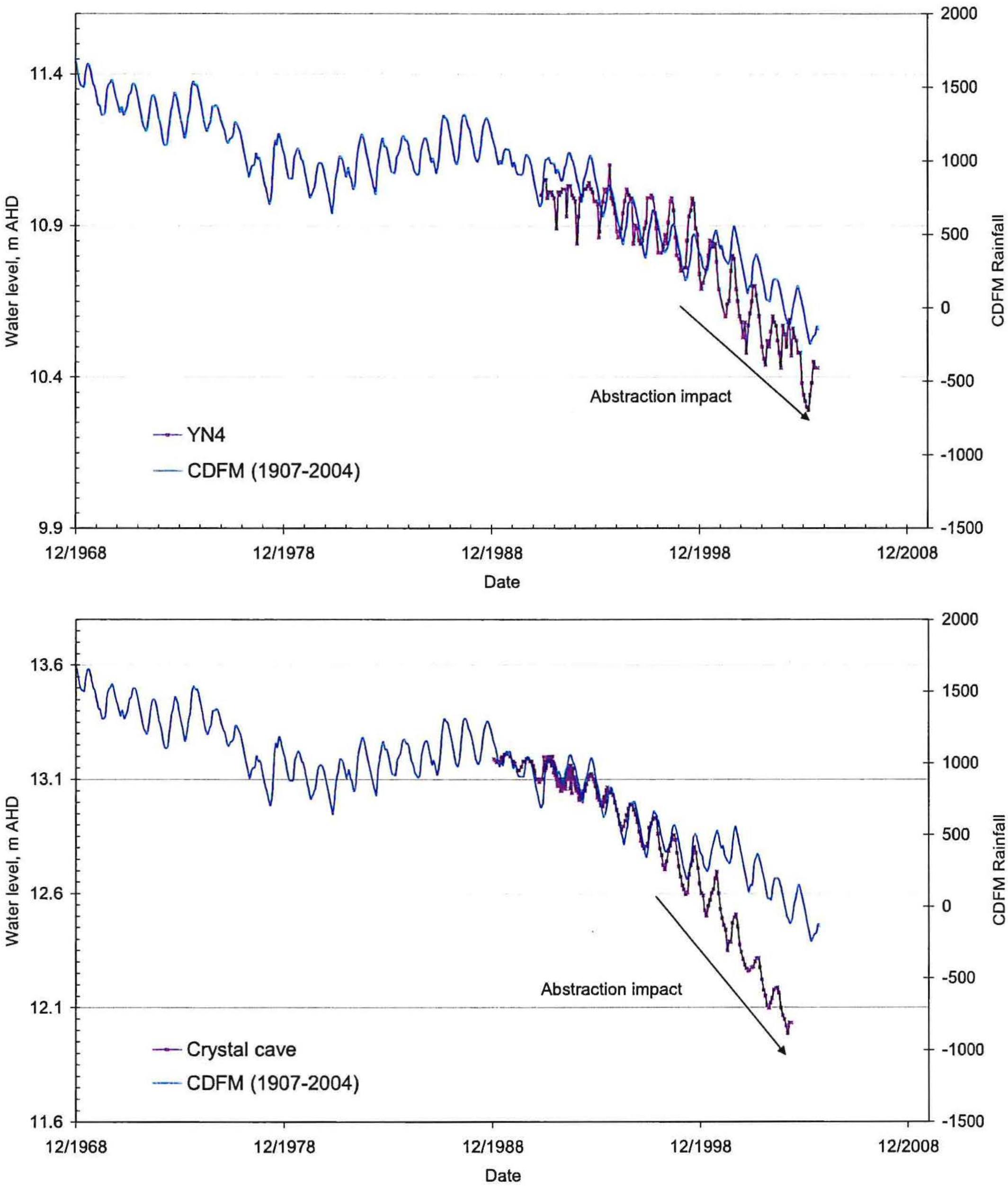


Figure 5 Groundwater Hydrographs: (c) YN4, (d) Crystal cave

Groundwater salinity of the superficial aquifer ranges from 170 mg/L (GA4) to 240 mg/L TDS (YN2) in the intergranular aquifer of mainly calcareous sands in the east, and from 300 mg/L (YN6) to 710mg/L TDS (YN8) in the mostly limestone aquifer west of the dashed line in Figure 3.

Physio chemical characteristics of the monitoring bores sampled in 2003 in the study area are given in Table 2. The pH values of groundwater vary within the different superficial aquifers. Within the intergranular aquifer (Bassendean sands and sands decomposed from calcarenite) groundwater at the top of the aquifer is acidic, with a range of pH 5.8 to 6.6. The carbonate aquifer, however, has groundwater with pH ranges from 7.0 to 8.0.

Table 2 Physio Chemical Characteristics of the groundwater across the study area (July, 2003)

Bore#	pH	T	TDS	Na	K	Mg	Ca	Cl	SO4	HCO3	Fe^{+}2	Aquifer
GA1	7.7	20.1	370	56	2.4	7.3	69	100	10	190	<0.05	Tamala Limestone
GA4	5.8	18.8	170	40	2.8	6.8	3.8	76	6	15	0.05	Bassendean Sand
PM26	6.0	18.1	180	40	3.2	6.6	12	67	13	50	<0.05	Sand decomposed from Tamala Limestone
YN2	6.6	17.8	240	48	1.9	5.4	31	85	10	90	<0.05	Sand decomposed from Tamala Limestone
YN3	6.6	19	180	41	2.4	8	19	76	9	65	<0.05	Sand decomposed from Tamala Limestone
YN5	8	18.6	980	190	3.1	17	100	420	33	230	0.35	Tamala Limestone
YN6	7	18.2	300	53	3.1	5.8	51	100	7	130	<0.05	Tamala Limestone
YN7	6.6	18.5	370	69	3	9.3	48	130	50	85	<0.05	Sand decomposed from Tamala Limestone
YN8	7	18	710	98	5.7	21	100	160	50	140	<0.05	Tamala Limestone
YB11	7.5	19.3	310	48	3.2	6.2	54	93	10	170	0.1	Tamala Limestone

Note: Chemical components units are mg/L.

Although Bassendean sands and Tamala sands, which are formed from decomposed calcarenite of Tamala limestone, have similar hydraulic properties, their hydrogeochemical characteristics are slightly different. The major ions concentrations are plotted as a Schoeller diagram in Figure 6 for the purpose of visualization of the comparative change in the concentrations to evaluate visually that the ratios of the solutes to each other are relatively similar. In a Schoeller diagram similar slope of lines connecting solute concentrations is indicative of groundwater from a similar source. Examination of the Schoeller diagram clearly indicates that groundwater is NaCl type within the Bassendean sand towards the east (GA4) and gradually mixes with a CaHCO3 type of groundwater while passing through the Tamala sands. The concentrations of Ca and HCO3 ions gradually increased within the Tamala sands and become dominant within the Tamala carbonate aquifer (YN5, GA1, and YN8).

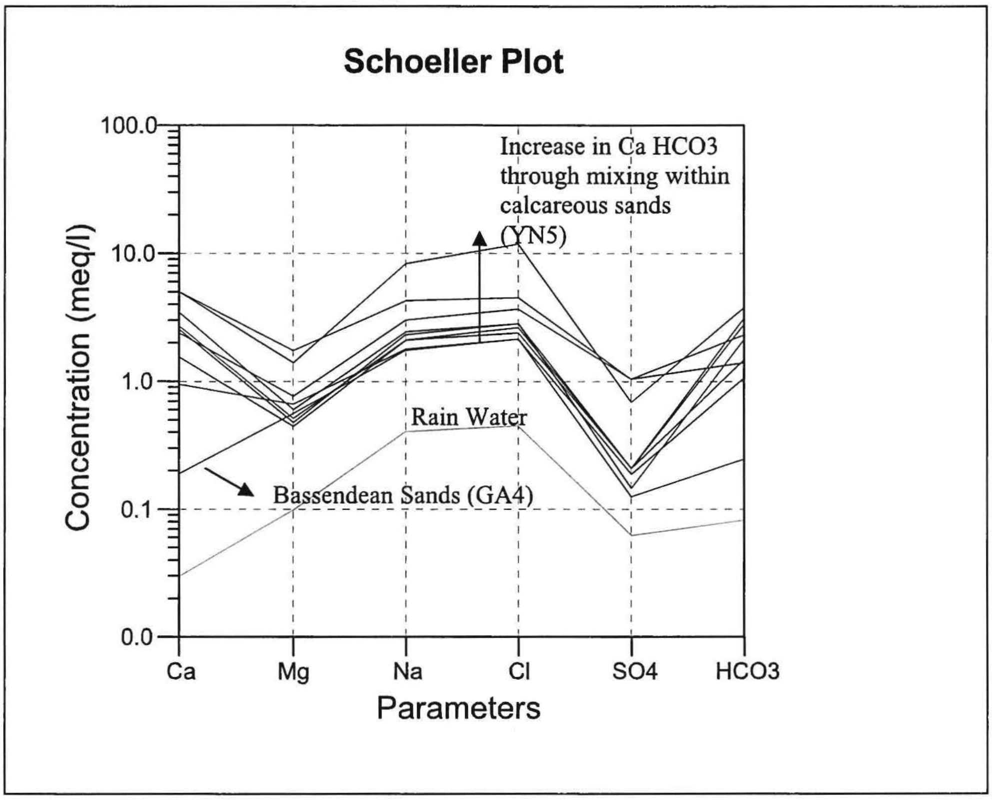


Figure 6 Schoeller plot showing the groundwater types

Groundwater is generally undersaturated with calcite within the carbonate aquifer except in GA1 and YN5 (Figure 7). Barber (2003) also showed that the carbonate aquifer under and in the vicinity of the cave system is undersaturated against calcite except in some ponds in Crystal cave.

Examination of the Ca saturation indexes in Figure 7 shows that groundwater within the calcareous sands is not saturated with calcite, however groundwater within the limestone is saturated or close to saturation. YB11 bore is near to the proposed production bores that will maintain the groundwater levels under the caves. The Calcite saturation index of the groundwater is –0.067, showing that groundwater is near saturation by calcite, therefore it is not aggressive water that would dissolve more limestone within the caves.

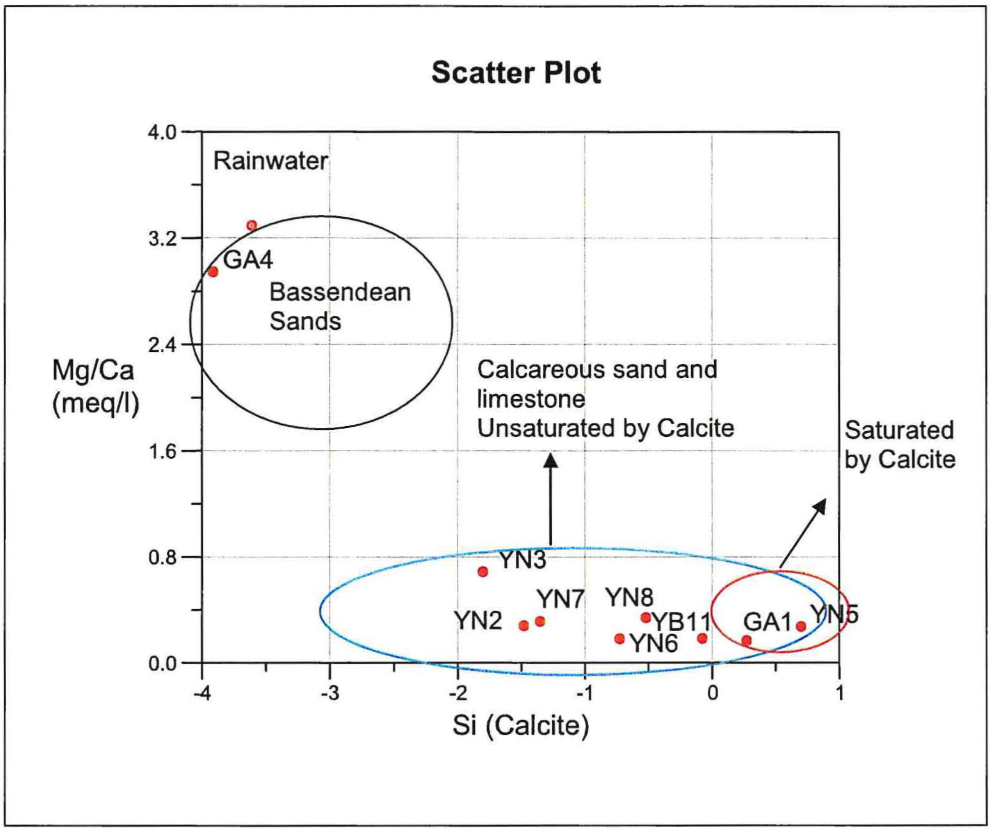


Figure 7 Ca Saturation indexes versus Mg/Ca ratio

3 Groundwater Flow Modelling

Visual MODFLOW Pro version 4.0 coupled with MODFLOW SURFACT, developed by HydroGeoLogic Inc., was used for the simulation of groundwater flow in the superficial aquifer. MODFLOW SURFACT is a fully integrated groundwater flow package based on the USGS MODFLOW code (McDonald and Harbaugh, 1988) and has the capability of modelling unsaturated moisture and air movement, which reduce the unsaturated flow problems, accurately delineate the water table elevations, and capture delayed yield response of an unconfined system to pumping and recharge. The details of the model form and characteristics are outlined in the following sections.

3.1 Model Construction

The model domain covers an area of 16 km from east to west and 12 km north to south. It is bounded by the Indian Ocean to the west and the pine plantation in the east and covers the whole Yanchep National Park (Figure 8). The northern and southern extents of the model were selected to ensure minimum boundary effects. The Indian Ocean is assigned as a constant head boundary along the coast, with inactive cells beyond it. The northeastern extent of the model is assigned as an inflow boundary and simulated as an infinite source of water (constant head). Regional decline of the groundwater level, which was calculated using CDFM techniques, is introduced to the inflow boundary at northeast. As a requirement to numerical modelling the model domain was divided into 160 x 120 uniform cells each measuring 100m x 100m and with 5 layers. A total of 96,000 model cells were generated. Inactive (no-flow) cells were assigned beyond the Indian Ocean. The top of the model corresponds to the surface topography.

Based on the conceptual model, five physical model layers were constructed to represent the hydrogeological units. The first three layers represent the superficial aquifers and the remaining two represent the Leederville aquifer and confining or semi confining layers in between the aquifers. The thickness of each layer varies according to the logged, interpreted and interpolated distribution of each of the hydrogeological units and has been adjusted where appropriate to compensate for layers pinching out.

The aquifer parameters assigned to each of the modelled hydrogeological units are the average values for each unit, even though they are known to vary locally (Table 3, Figure 9). The aquifer parameters assigned are very similar to the parameters used in the PRAMS model (Davidson and Yu, 2005).

Loch McNess, Yonderup, Wilgarup Lake, Pippidinny Swamp and Coogee Swamp were simulated using the river package from MODFLOW. This allows both inflows and outflows depending on the river stage and the surrounding groundwater levels. Monitored monthly water levels of these large surface bodies were assigned as their river stage levels and the rates of the inflow or outflows were governed by the conductance of the riverbed and river stages.

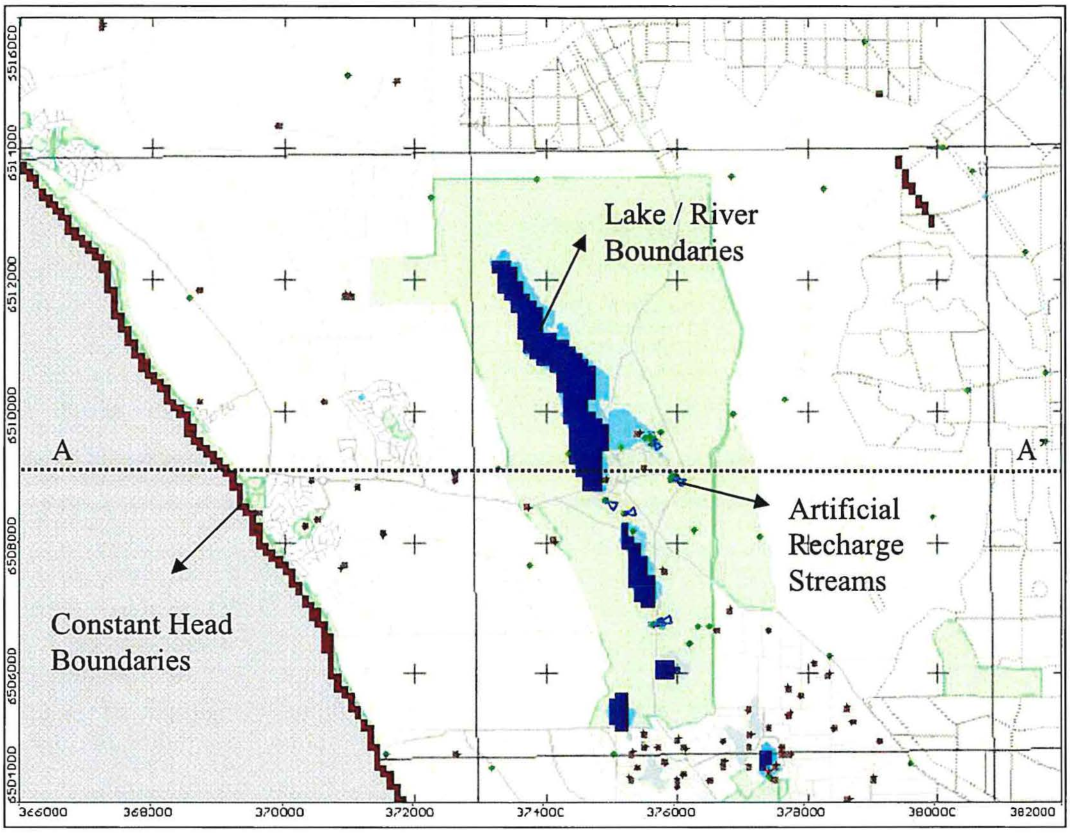


Figure 8 Model Domain, boundaries, observation bores (green squares), and abstraction bores (red circles)

Table 3 Aquifer parameters used in the model

Layers	K Zones	K_x	K_y	K_z	S_y/S_s
Bassendean sand	(3)	5-10	5-10	0.5-2.0	0.15-0.25
Tamala Calcareous sand	(4)	5-10	5-10	0.5-2.1	0.15-0.25
Tamala Limestone	(2 and 7)	20-300	20-300	2-7	0.2-0.35
Kardinya Shale	(6)	0.001	0.001	0.0001	1E-3-1E-5
Leederville	(7)	10-20	10-20	1-2	0.2-1E-5
Lancelin	(5)	1-5	1-5	0.1-1	0.1-0.01

K=Hydraulic conductivity, m/day: x, y and z show the directions in Cartesian coordinate system
Sy= Specific yield, Ss= Storage coefficient

A total of 70 licensed production bores in domain area (of which six are public abstraction bores) were simulated in the model as part of the steady state and transient calibration starting from 1996. Bores are represented as sinks with specified discharge rates, which can vary over time. Since the information on the abstraction rates for most private bores is lacking, annual allocated discharge rates have been used for these private bores. However public bores abstraction rates are supplied by Water Corporation, therefore monthly discharge rates of these bores have been used in model calibration and 2004 discharge rates have been applied to the model until 2015 for further predictions.

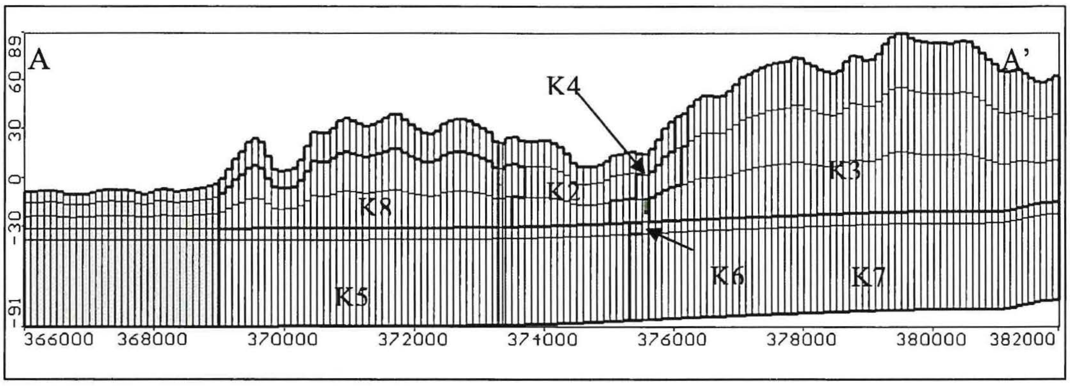


Figure 9 Cross-section (A-A') showing the hydraulic conductivity (K_x) zones

Groundwater levels in a total of 32 monitoring bores from 1996 onward were used in steady state and transient model calibrations. Six of the bores are located near the eastern constant head boundary and have been used to calculate the regional water level decline trend applied to the boundary.

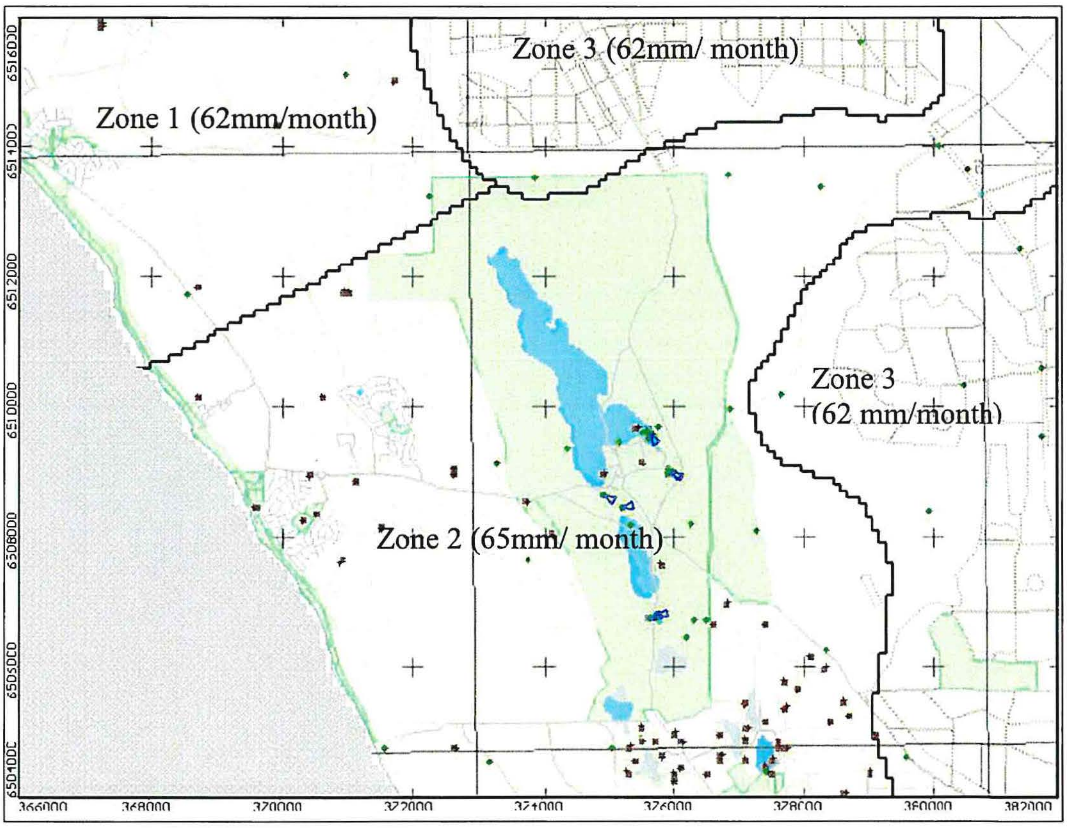


Figure 10 Recharge and Evaporation zones and threshold values of the individual zones

The 1996 minimum water levels were selected as the initial head and the model converged to a steady state solution. The converged and predicted head water levels were then used in transient model calibration.

The main source of recharge into the unconfined aquifer comes from rainfall infiltration. Comprehensive studies carried out by Water and Rivers Commission in 2001/2002 to separate the impacts on groundwater level decline in Gnangara area showed that the unconfined aquifer water levels have very high correlation with the cumulative deviation from the mean rainfall (CDFM) (Yesertener, 2002, 2005). The model used the monthly recharge rates and evapotranspiration rates calculated from the CDFM technique. The surplus monthly rainfalls above the long-term average (threshold value) are considered as net recharge to the groundwater and deficient rainfalls below the long-term average are considered as real evapotranspiration from the groundwater. The recharge zones and threshold values are given in Figure 10.

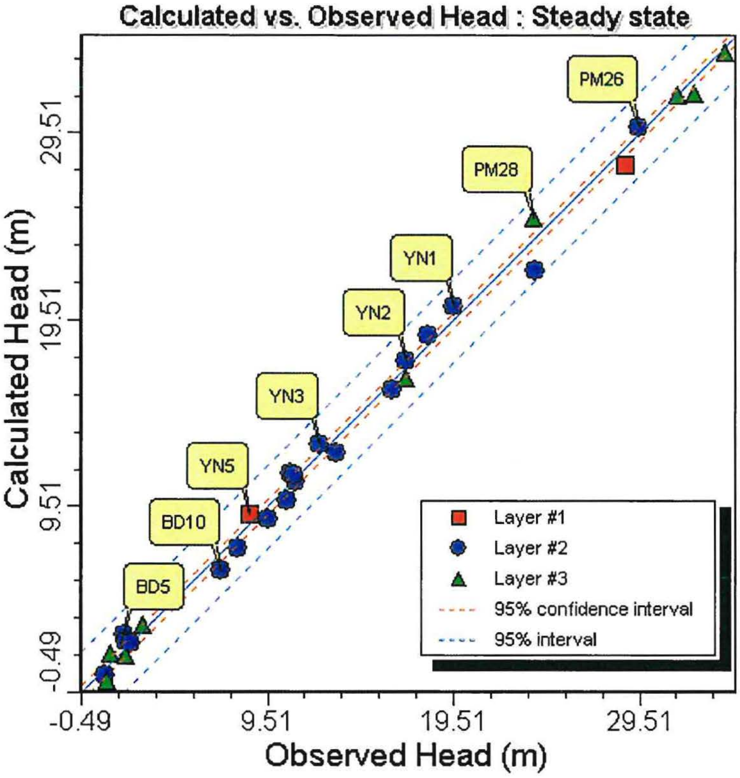
Recent Department of Water (DoW) studies show that mature pines, Zone 3 in the model, are reducing the groundwater recharge by approximately 30% (Yesertener, 2005). This reduced recharge has been included in the model. For example, assuming that we have 100mm rainfall in a certain month; recharge in that particular month will be 35 mm in zone 2 and only 24.5 mm in Zone 3. The recharge is applied to the highest active cell, to simulate water entering and recharging the water table aquifer.

3.2 Model Calibrations

The calibration process adopted for this project was conducted in two stages: steady state followed by transient state. The model was first calibrated in steady state to match the 1996 minimum water levels in the superficial aquifer in the domain area, and also considering the abstraction from private and public production bores. Once a satisfactory match was achieved, a second calibration was performed in transient mode by adjusting the storage parameters to match the transient data set between 1996 and 2003. The process was iterative, reverting to the steady state calibration to refine the hydraulic conductivity values and zones, and recharge and evaporation ratios in pine areas.

3.2.1 Steady – state calibration

Calibration of the steady state model was accepted with a correlation coefficient of 0.997. The standard error of the estimate was 0.135 m. The result of the sensitivity analysis and the calibration plot is given in Figure 11.



Num. of Data Points : 31
Max. Residual: 1.885 (m) at GA2/1
Min. Residual: 0.044 (m) at Y280/1
Residual Mean : -0.032 (m)
Abs. Residual Mean : 0.619 (m)

Standard Error of the Estimate : 0.135 (m)
Root Mean Squared : 0.74 (m)
Normalized RMS : 2.224 (%)
Correlation Coefficient : 0.997

Figure 11 Steady State calibration and statistical parameters

The best calibration was achieved with recharge rates of 280 mm/yr in Zone 3 and 380 mm/yr in Zone 2. These values are consistent with the recharge rates found by the CDFM method. The hydraulic conductivity (K) values and zones have been adjusted through the calibration processes within the ranges given in Table 3. The K values that achieve the best calibration were used in transient calibration (Table 4).

Table 4 Hydraulic conductivity values used in the model

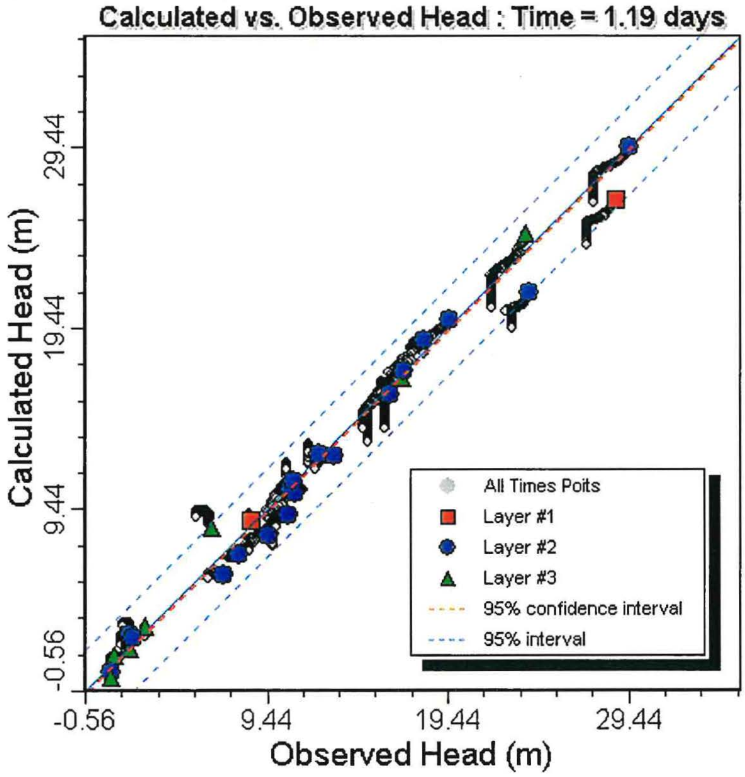
Layers	K Zone	K_x	K_y	K_z
Bassendean sand	3	9.8	9.8	0.2
Tamala Calcareous sand	4	5	5	0.5
Tamala Limestone	2	20	20	2
Tamala Limestone karstic	8	170	170	17
Kardinya Shale	6	0.001	0.001	0.0001
Leederville	7	12	12	1.2
Lancelin	5	5	5	0.5

K=Hydraulic conductivity, m/day

3.2.2 Transient Calibration

After having achieving a steady state run with high correlation, the model was run for transient state starting from January 1996 to end of 2015. The recharge values used in the model have been calculated based on the CDFM technique using the monthly rainfall data and from 2002 onwards recharge values are the average values of the 1996 and 2001 period. The same principles were applied for ET values. The transient data set for monitoring bores and abstraction bores is for the period 1996 and 2003. It has been assumed that the abstraction rate in 2003 will stay the same during the modelled period. There are small changes made for the hydraulic conductivities along the transition zone between the layers to increase the correlation coefficient. Recharge values for the pine area are reduced by about 25 to 30% of the recharge values applied outside of the pine areas, to get the best fit between the predicted and observed water level changes.

Best calibration is achieved with 0.016 m standard error of the estimate for all times. The correlation coefficient is 0.988, which shows that about 98% of the data can be predicted with high level of reliability. The calibration graph for all times is provided in Figure 12.



Num. of Data Points : 6188
Max. Residual: 3.839 (m) at GA2/1
Min. Residual: 0 (m) at YN6/1
Residual Mean : -0.162 (m)
Abs. Residual Mean : 0.904 (m)

Standard Error of the Estimate : 0.016 (m)
Root Mean Squared : 1.245 (m)
Normalized RMS : 4.315 (%)
Correlation Coefficient : 0.989

Figure 12 Transient calibration and statistical parameters

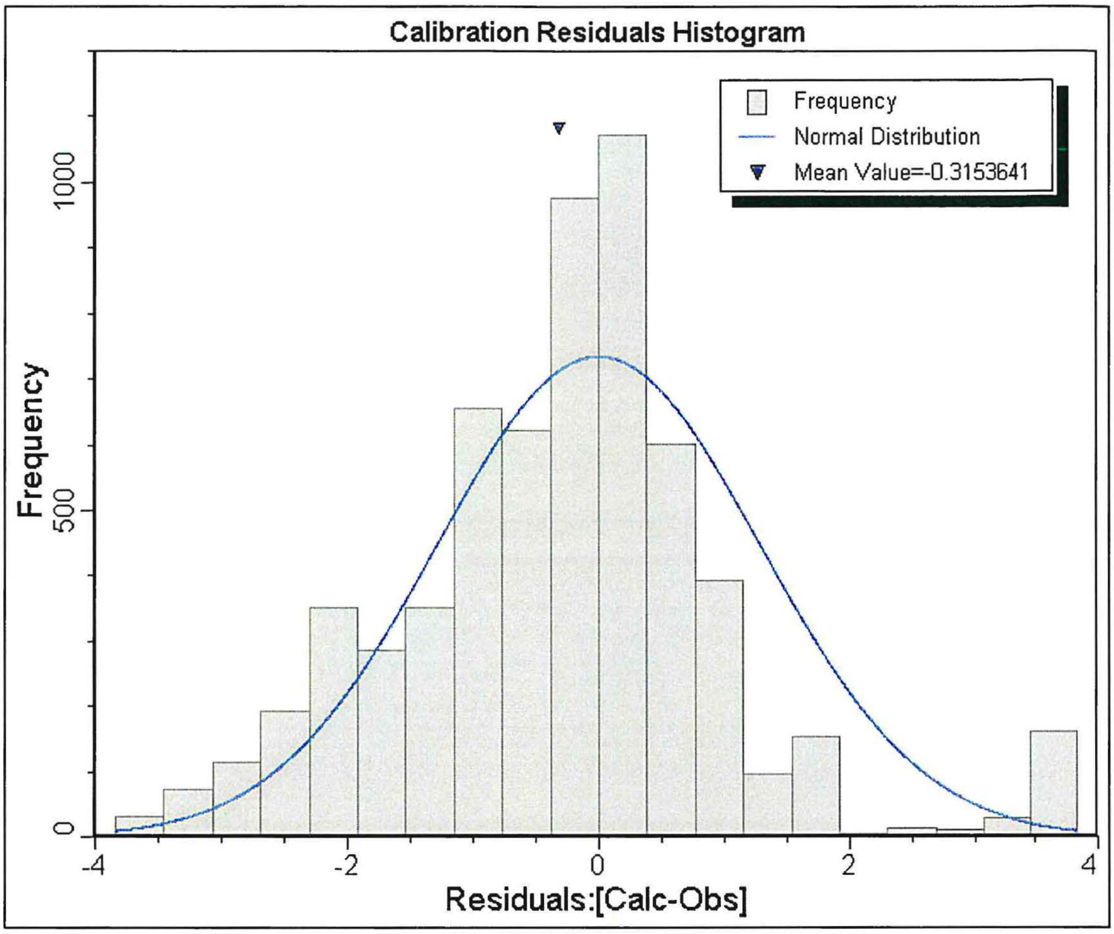


Figure 13 Calibration Residual Diagrams

Frequency analysis shows that residual values for all times in the transient run matches the normal distribution curve and mean value of the residual is –0.31 m for all times (Figure 13). This indicates that the model can be relied upon to conduct accurate predictions.

The calibrated model demonstrates that the predicted groundwater levels reasonably match the observed groundwater levels. The matches are especially good in caves areas, which are the primary area of interest of this study (Figure 14).

3.2.3 Model Verification

Verification, also called validation, is a test of whether the model can be used as a predictive tool by demonstrating that the calibrated model is an adequate representation of the physical system. The calibrated model demonstrated that the prediction reasonably matches the observations of the reserved data set, deliberately excluded from consideration during calibration (Murray-Darling Basin Commission, 2001). The Crystal cave monitoring data set is deliberately excluded from consideration during the calibration, however model prediction for Crystal Cave closely matches the observation of the Crystal Cave data set as seen in Figure 15.

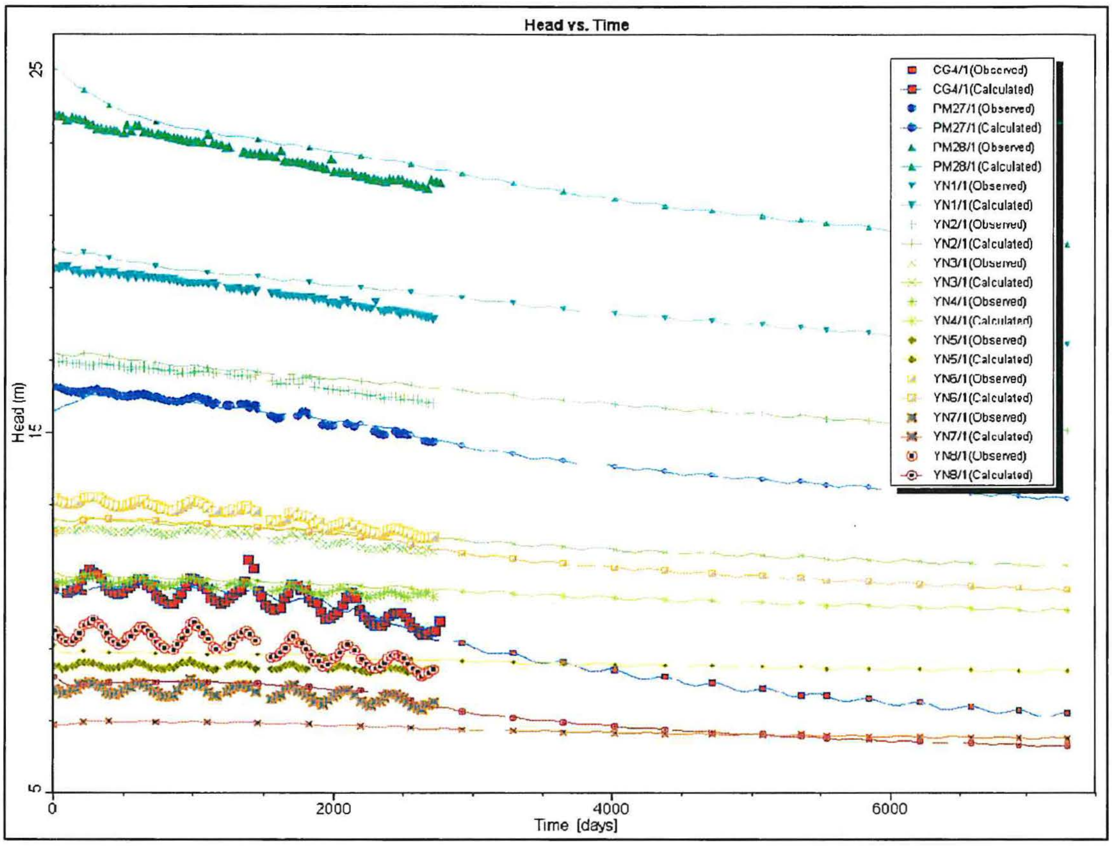


Figure 14 Predicted water levels versus observed water levels of the calibrated model around the Yanchep caves area

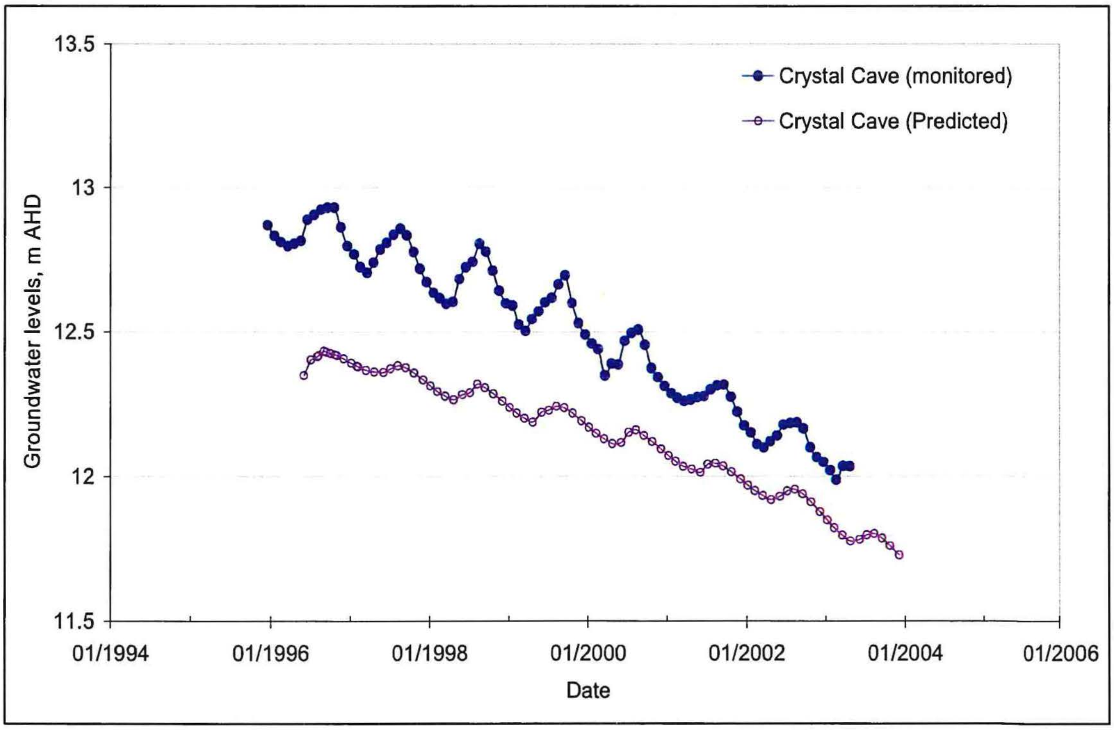


Figure 15 Crystal Cave groundwater level observations and model predictions in same location

3.3 Model Simulations

The Yanchep model has been developed to find out how much water is required for maintaining the groundwater levels in the selected seven caves, which originally had their groundwater levels above the cave floors. The management committee suggested constructing a groundwater flow model to simulate the groundwater levels around the caves area to predict the groundwater requirement to maintain the groundwater levels under the caves and evaluate the environmental impact of the discharge wells to the surrounding wetlands and ecosystems.

Four scenario runs were selected as follows:

- Scenario 1: Travel times of the groundwater within different aquifers
- Scenario 2: Long term water requirement (10 years)
- Scenario 3: Short term water requirement (3 years)
- Scenario 4: 1 day, 7 days and 30 days failure in operation to maintain the levels under the caves

Model results for these scenario runs are given in the following sections.

3.3.1 Scenario 1: Travel Times

The steady – state run shows that travel time of the groundwater is faster in limestone than in the granular sandy part of the aquifer. In general groundwater reaches Loch McNess Lake from the western border of the pine plantation in about 40 years (~80 m/yr). However it travels faster in the limestone aquifer and reaches the ocean in about 20 years (~200 m/yr) (Figure 16). Model transient runs show that the travel time of the groundwater within the sandy aquifer and limestone aquifer is about 65 m/yr and 150 m/year respectively, which is slower than the travel times achieved in the steady – state run (Figure 17).

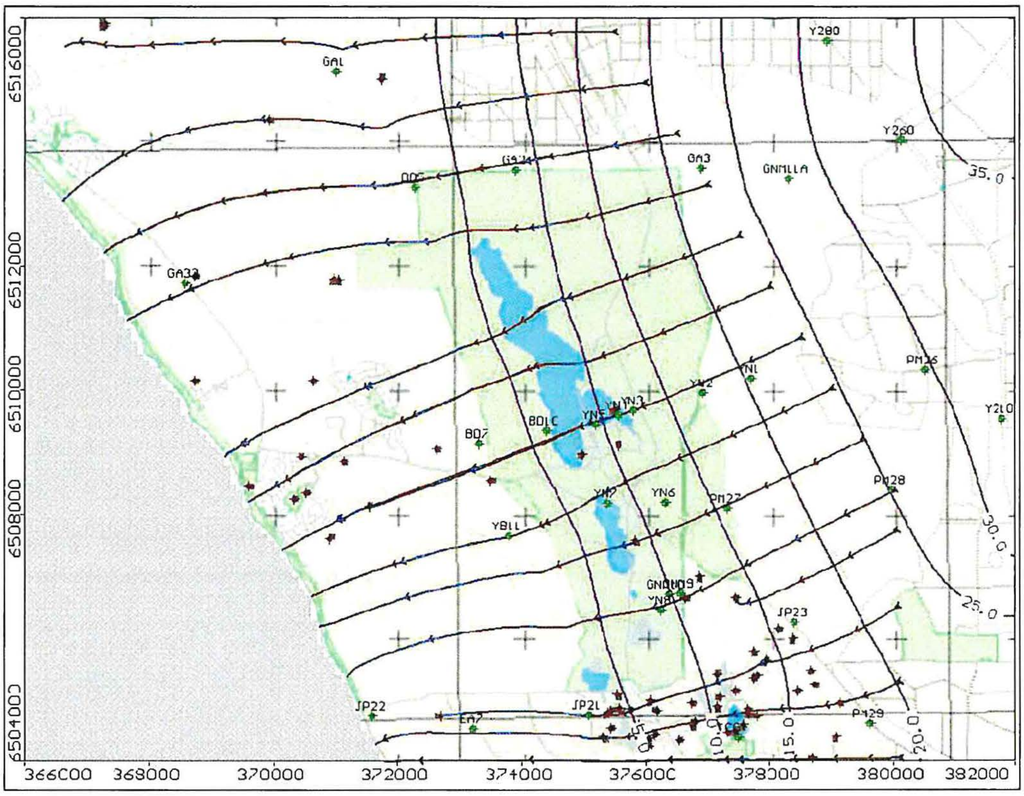


Figure 16 Shallow groundwater levels and travel times for the steady state calibrated model. (Time markers are at five yearly intervals)

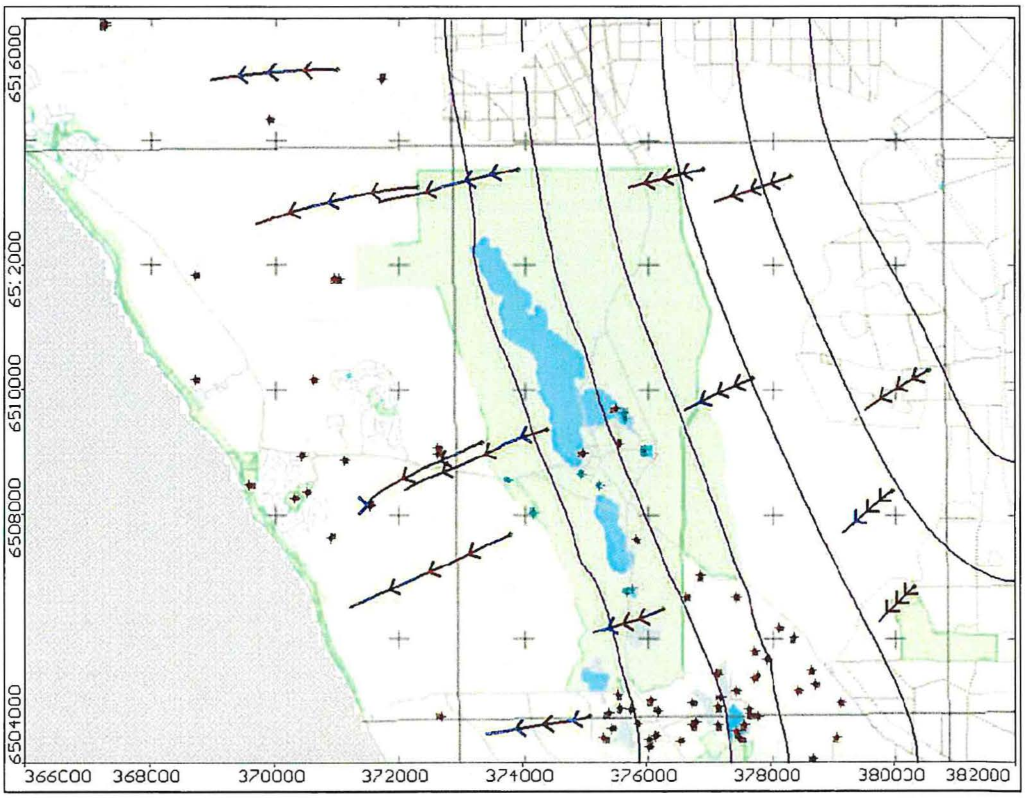


Figure 17 Shallow groundwater levels and travel times for the transient calibrated model (Time markers are at five yearly intervals)

3.3.2 Scenario 2: Long term water requirement

The model has been run to predict the water requirements for short-term (three years) and long-term (ten years). The caves project management committee wanted to know the optimum water requirements to maintain the groundwater levels under the caves in a year, and also the water requirements for a longer period, until 2015. To predict the water requirement for short-term and longer-term, it is needed to evaluate target minimum groundwater levels for each individual caves for 2005 and 2015.

Hydrograph analysis suggests that regional groundwater levels are declining approximately 10 cm per annum. The local groundwater decline under caves has been calculated for individual caves and given in Table 5. Model runs, for the do nothing scenario, also confirm the trend analysis given in Table 5.

Table 5 Local groundwater decline levels per annum

Cave	Name	Easting	Northing	Trend[1] m/yr	Trend[2] m/yr	Target 2005[1]	Target 2015[1]
Yn1	Crystal	375946	6508974	0.090	0.040	1.35	2.25
Yn5	Cabaret	375637	6509606	0.070	0.030	0.60	1.30
Yn11	Water	374999	6508634	0.030	0.020	0.60	0.90
Yn18	Carpark	375247	6508443	0.040	0.020	0.65	1.05
Yn27	Gilgi	375685	6506740	0.050	0.020	1.25	1.75
Yn99	Boomerang	375664	6509515	0.070	0.030	0.65	1.35
Yn194	Twilight	375780	6506795	0.050	0.020	1.25	1.75

[1] Target rise estimated using Hydrograph analysis; [2] Target rise estimated from the groundwater model runs

** All target levels are minimum groundwater levels rise calculated for summer period.*

The model was developed in 2004 and minimum water level targets for 2005 and 2015 have been estimated using the 2004 figures and trend analysis using hydrograph and model estimations (see Table 5). According to Table 5, target groundwater level, for example for Crystal Cave, is 1.35 m for year 2005. This means that groundwater levels under the cave should rise a minimum 1.35 m to fill the pools in the caves in year 2005. The target levels, however for year 2015 have two figures, one generated from modelling target level[2] and the other from hydrograph analysis (target level[1]).

Due to continuous artificial recharge to the caves has positive impact in reducing the magnitude of the declining trend of the groundwater as seen later in Figure 19, target level[2] for the year 2015 given at column 9 is less than the target level[1] given in column 8 in Table 5. These figures are 2.25 m and 1.75 m for Crystal caves, respectively.

Table 6 Modeled discharge estimates for seven caves for long-term water requirements

Caves	Discharge Point	Discharge Rates, (m^3/day)	Target Level[2] Rise, m	Prediction Rise, 2015, m
Crystal Cave	Crystal 1	1800	1.75	1.99
	Crystal 2	2000		1.99
Cabaret	YN6	1200	0.90	1.03
Boomerang			0.95	1.92
Water	Water Cave	1400	0.80	1.06
Car Park	Car park	800	0.85	1.05
Gilgi	Gilgi Cave	1100	1.45	1.60
Twilight	Twilight Cave	1300	1.45	1.70
Total Discharge Rate:		9600 (3.50 GL)		

The model was run a number of times for achieving the target groundwater levels including 2015, using a trial and error approach using different artificial recharge rates and recharge points (Figure 18) for each cave. The best result was achieved with the discharge rates and recharge points given in Table 6. Note that there are two discharge points in Crystal Cave, which are assumed to be upstream of Jewel City and in the Pantheon Cavern.

The model estimates artificial recharge required to maintain water in one or more ponds in each priority cave in summer and winter 2006 and up to 2015. A total discharge rate of up to 3.5 GL/yr should maintain ponds in the caves to 2015 (Table 6).

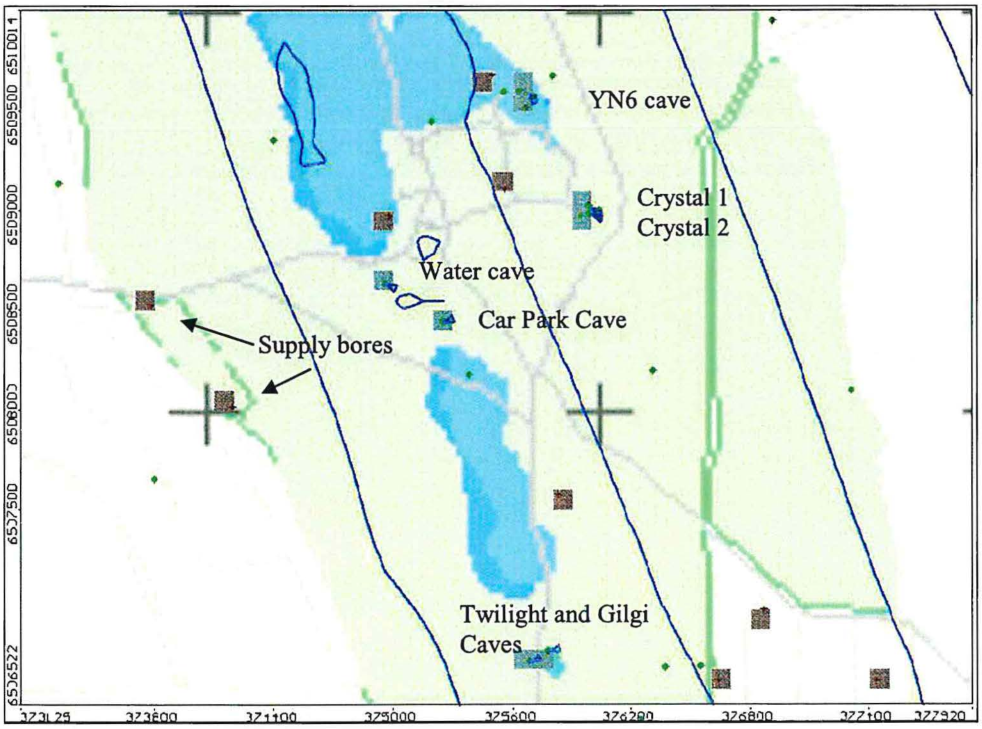
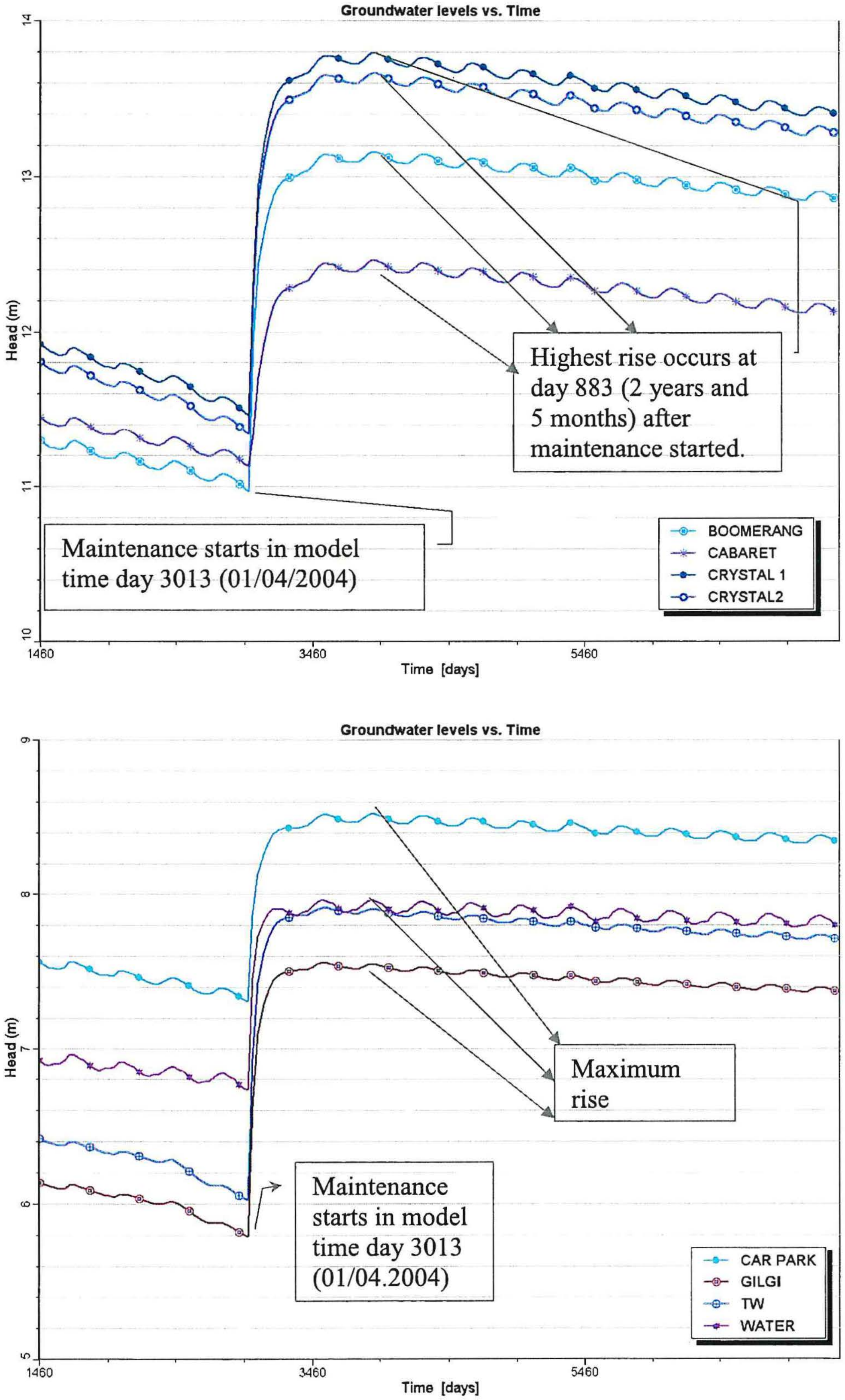


Figure 18 Cave artificial recharge streams (blue triangle symbols), red and green squares are production and monitoring bores respectively



Highest rise occurs at day 883 (2 years and 5 months) after maintenance started.

Maintenance starts in model time day 3013 (01/04/2004)

Maximum rise

Maintenance starts in model time day 3013 (01/04.2004)

Figure 19 Groundwater level changes under caves resulting from the long-term artificial maintenance program

Figure 19 shows the groundwater levels changes in m AHD under the individual caves as predicted from the long-term artificial maintenance program. Model results show that groundwater levels reach their maximum levels after 883 days, which is equivalent to 2 years and five months and establishes a new equilibrium with a declining trend due to the effect of the regional groundwater level decline. However, declining trends in a new equilibrium are better than the trends before the maintenance because a groundwater mound established under the caves reduces the declining trends (See also Table 5, trend²). The target groundwater levels for 2005 are reached in about two months with the estimated recharge rates for the caves (Figure 20) until 2015 maintain groundwater levels above the target level (Figure 21).

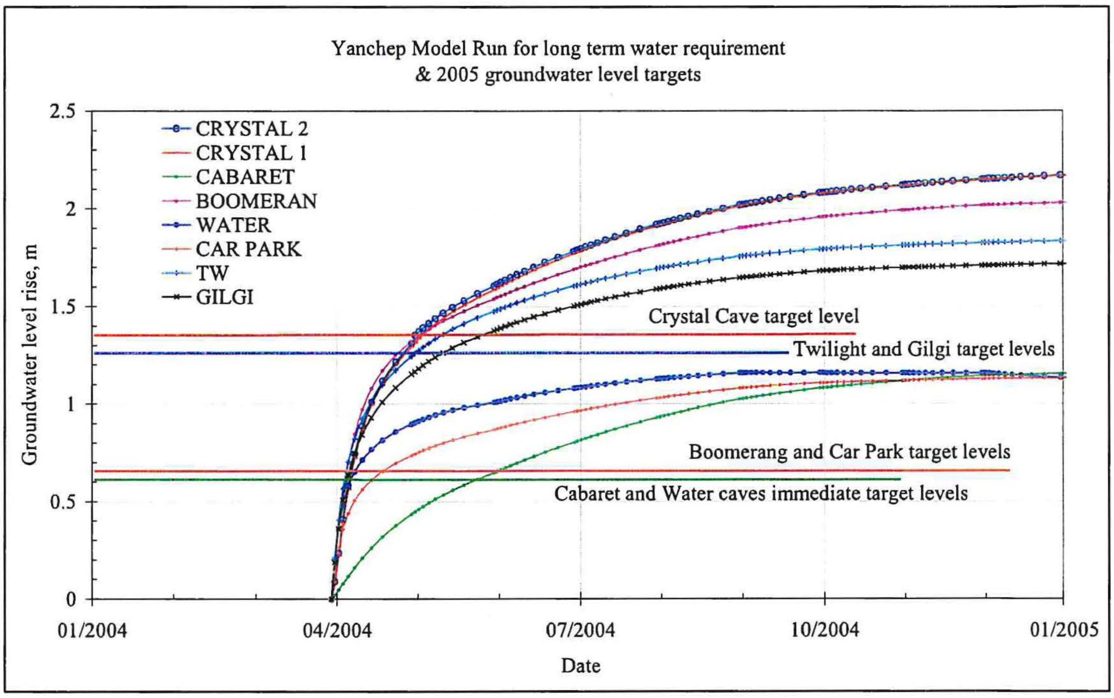


Figure 20 Groundwater level rise under caves in first year and 2005 target groundwater levels *(Model assumed that artificial maintenance started on 31st March 2004.*

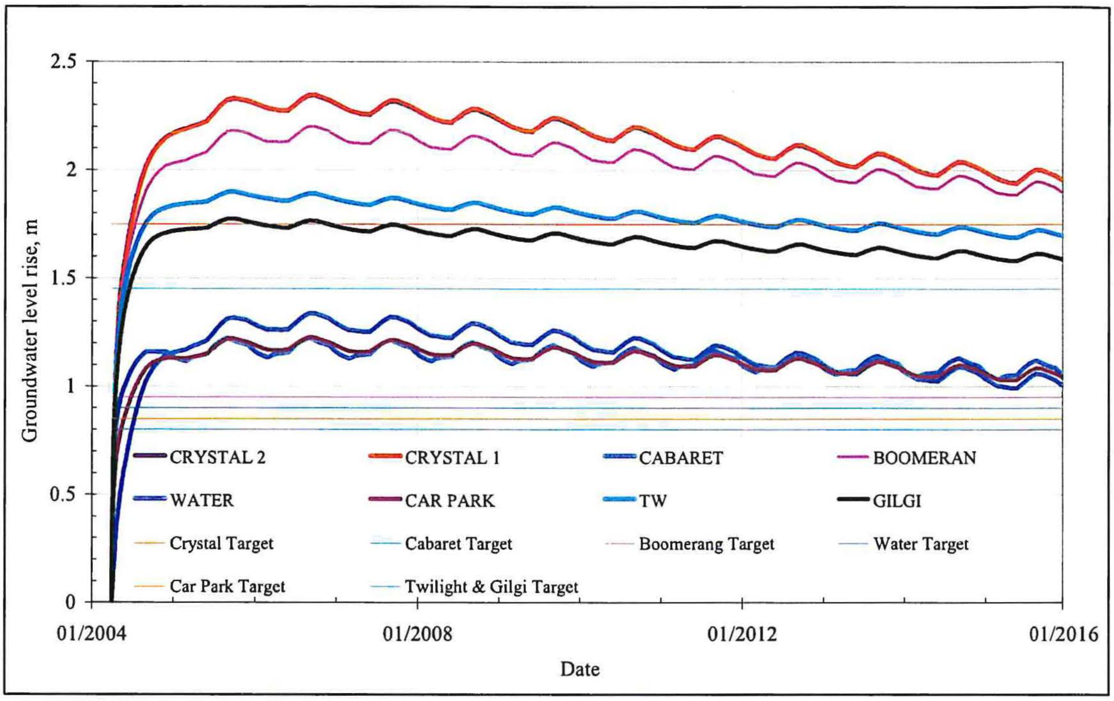


Figure 21 Water level changes during the modelled period ending 2015 and target groundwater levels

The estimated times required for individual caves to reach the immediate target levels for 2005 are given in Table 7.

Table 7 Target groundwater levels for 2005 and time required in reaching these targets

Caves	Target level rise (m) in 2005	Time required (days)	Maximum water level rise (m) (09/2006)
Crystal	1.35	35	2.34
Cabaret	0.60	55	1.33
Boomerang	0.65	7	2.2
Car Park	0.65	19	1.22
Water	0.60	8	1.22
Twilight	1.25	32	1.89
Gilgi	1.25	42	1.76

To show the environmental effects of the artificial recharge to Yanchep caves and the depression cone resulting from the supply bores, areal distribution of the rise and decline contours have been given for the maximum water level rise (883rd day ≈09/2006), and year 2015 (Figure 22).

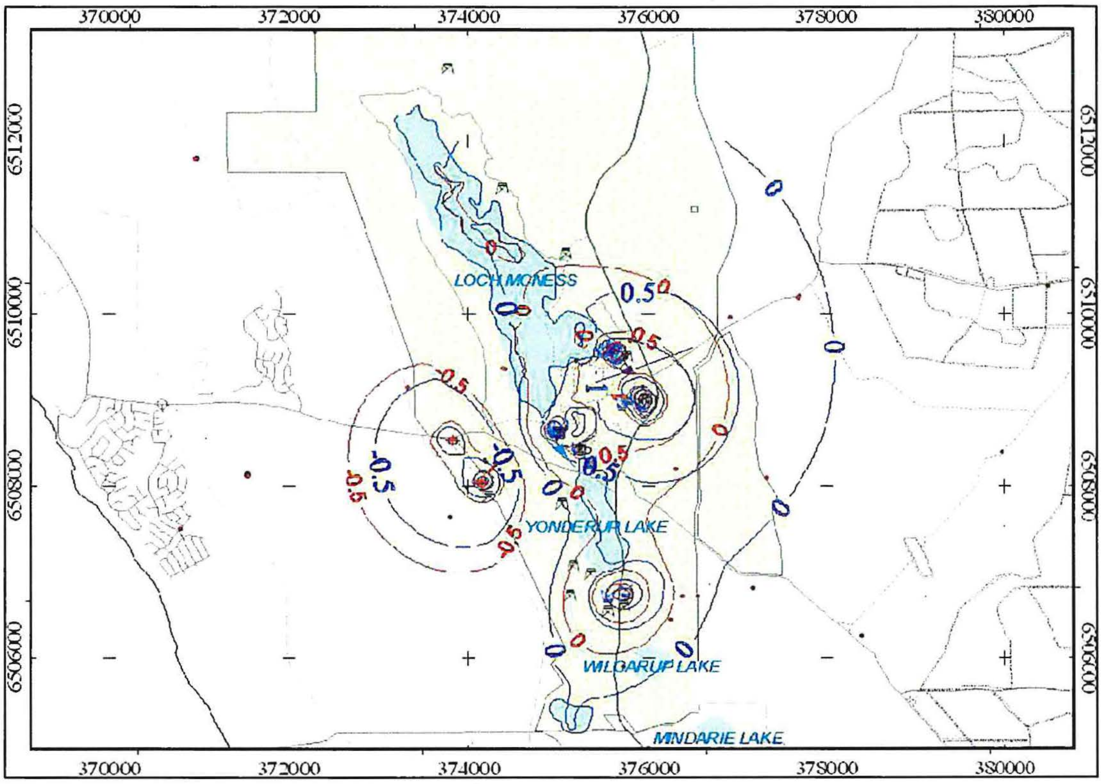


Figure 22 Artificial Recharge to Yanchep Caves- Maximum rising effects (883rd day- blue contours) and 10th year effect (red contours)

Groundwater will be pumped from two bores situated in the superficial aquifer west of the Yanchep Caves within the Yanchep National Park near the Yanchep Village. Groundwater will be piped to the caves on the eastern side of Loch McNess. The bores are located at; 0373780E, 6508526N (Northern bore) and 0374192E; 6508011N (Southern bore) (Figure 18; see also Figure 1).

The effects of pumping on other water users and groundwater dependent ecosystems (GDE) were evaluated through mathematical modelling. In respect to the environment, there are no GDEs other than Lake McNess that may be affected by pumping. The effect of pumping from the bores indicates that there may be a 0.5 m drawdown within approximately 1 km of the bores, particularly toward the west after the second and tenth year of operations, however there is no negative impact to Loch McNess (Figure 22).

3.3.3 Scenario 3: Short term water requirement

The regional groundwater level trend over the next decade is an important factor affecting recharge rates to maintain cave pools. The future regional trend will depend on rainfall variations, land use changes and the groundwater abstraction regime over the Gnangara Mound. If there is no further decline in regional groundwater levels, then groundwater levels under the caves will stay stable at current levels. Therefore in Scenario 3, the model has been run to predict the optimum water requirement to reach the target levels in short term without considering future groundwater trend changes.

The model run shows that 2.6 GL/yr of groundwater is sufficient to maintain water levels in one or more ponds in each priority cave in summer and winter next year and up to 2007 assuming that recharge started on 31st March 2004 (Figure 23). Because low recharge rates are required to reach the target levels in short term, this may also be the preferable engineering design for the maintenance system to carry out in order to meet of the demand for the first two of years and upgrade the system later.

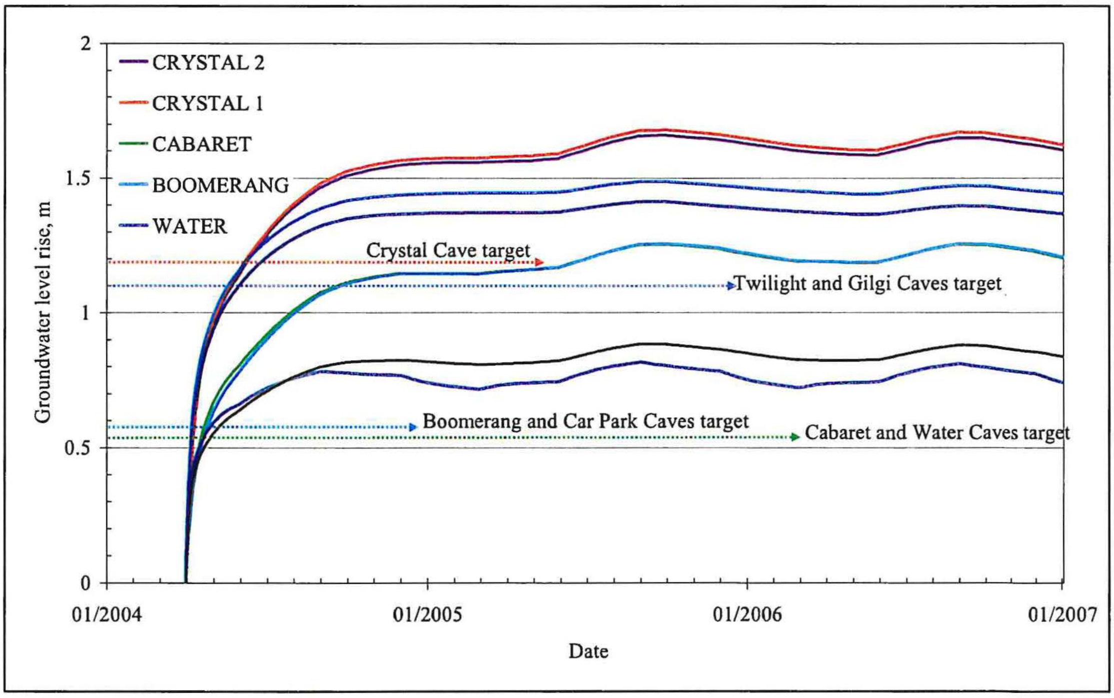


Figure 23 Groundwater level rise under caves in first year resulting from artificial recharge of 2.6 GL per year

The estimated recharge rates and times required for individual caves to reach the immediate target levels for 2005 are given in Table 8.

Table 8 The estimated recharge rates and times required for individual caves for immediate recovery for the short-term

Caves	Discharge Rates, (m³/day)	Target Levels (m) in 2005	Time requires (days)	Maximum water level rise (m) (day 883)
Crystal 1	1400	1.35	107	1.67
Crystal 2	1400		111	1.65
Cabaret	400	0.60	24	1.25
Boomerang	400	0.65	35	1.25
Water	900	0.60	35	0.81
Car Park	600	0.65	67	0.88
Gilgi	900	1.25	111	1.40
Twilight	1000	1.25	91	1.47
TOTAL	7000	(2.6 GL)		

Note that, in this Scenario run, Cabaret and Boomerang Caves both have individual recharge streams. YN6 cave is not used as a recharge point for both caves. This is because a greater increase in groundwater level is achieved with lower recharge rates to each cave.

If there is no trend change on regional groundwater levels and groundwater levels stay stable, then the predicted short term artificial recharge rate (2.6 GL/a) should be sufficient to maintain ponds in the caves indefinitely.

3.3.4 Scenario 4: Failures in operation for 1, 7 and 30 days

It is possible that artificial water supply into the groundwater system may fail for short periods of time due to power failure, pump failure or other factors. The model has been run to understand water level responses in such failures, and the water level recovery period after the problem is fixed. In this scenario, groundwater level changes have been examined at periods of 1, 7 and 30 days of no recharge after the system has operated for one year. A total recharge rate of 3.5GL/yr was the initial recharge rate used to evaluate the maximum impact of such failures.

Groundwater level changes under the caves resulting from 1, 7 and 30 days of failure in supply are given Figure 24. The results show that the decline of groundwater levels and duration required for recovery increase in proportion to the duration of failure. Individual groundwater responses under the caves and the duration required to recover the water levels are summarized in Table 9.

As can be seen in Figure 24, groundwater levels respond to such failures in a similar fashion, however the recovery periods to reach the same levels take longer than the failure periods. For example, for a 1-day failure in supply, which results in around 0.17 cm drop in groundwater levels, it requires approximately 30 days to recover. Similarly the average groundwater drop and recovery period for 7 days and 30 days failures are 0.60 cm / 69 days and 0.87 cm / 124 days, respectively (Table 9).

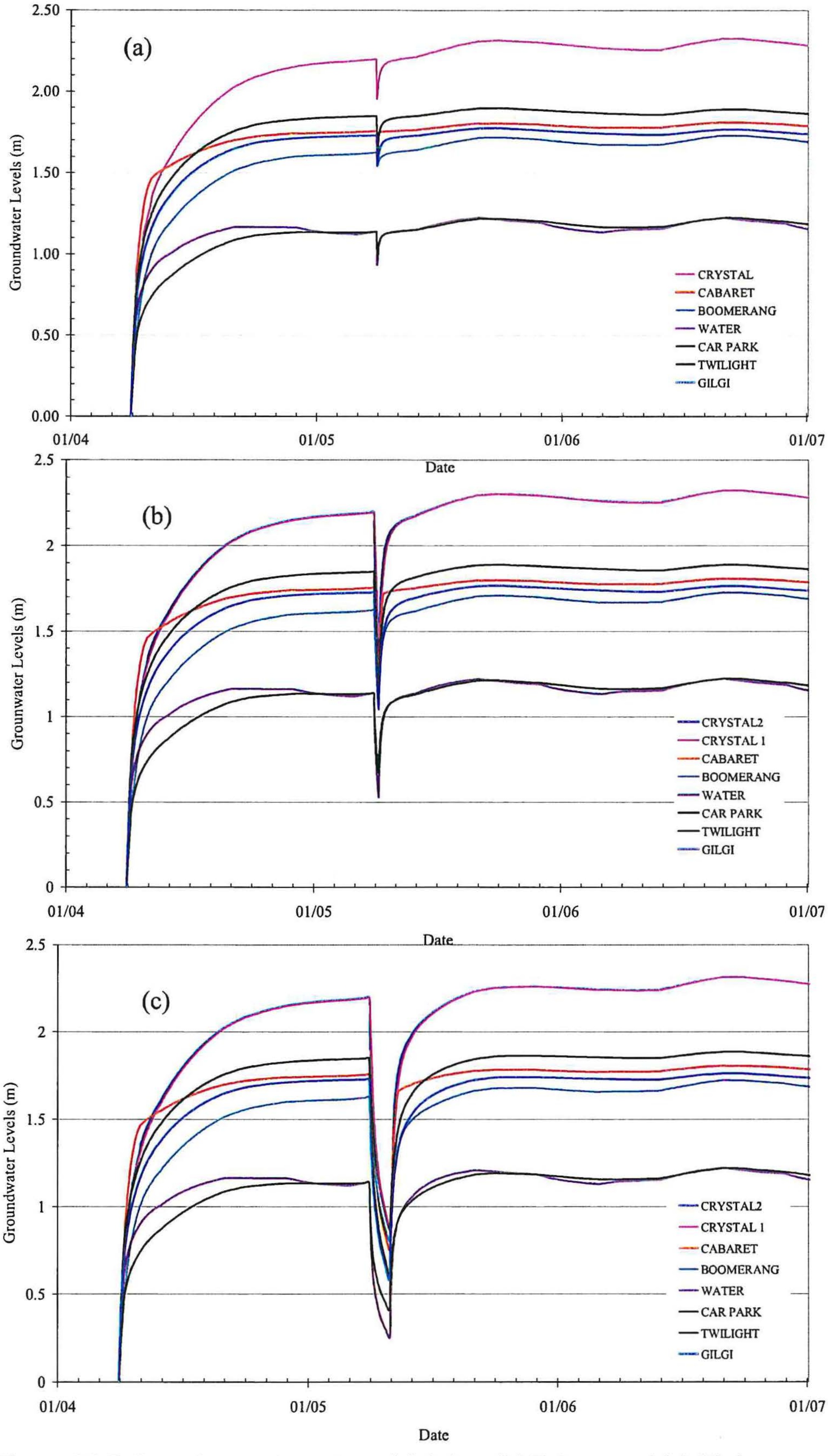


Figure 24 Failures in supply system; (a) 1 day, (b) 7 days, and (c) 30 days

Table 9 Groundwater level declines and recovery periods under the caves resulting from failures in operation

	1 Day Failure		7 Days Failure		30 Days Failure	
Caves	Drop in levels (m)	Recovery periods (days)	Drop in levels (m)	Recovery periods (days)	Drop in levels (m)	Recovery periods (days)
Crystal	0.24	32	0.80	70	1.24	131
Cabaret	0.13	10	0.51	41	0.83	106
Boomerang	0.08	15	0.40	61	0.74	115
Water	0.20	24	0.61	61	0.69	91
Car Park	0.14	30	0.47	65	0.59	111
Twilight	0.21	50	0.75	91	1.03	156
Gilgi	0.18	50	0.68	91	0.97	157
Average	0.17	30	0.60	69	0.87	124

3.4 *Model Limitations*

The Yanchep groundwater flow model is a local model, which is connected to the regional groundwater system via the inflow boundary parallel to the groundwater potentiometric line on the east, and outflow boundary along the coastline. The regional trends of groundwater levels are declining since 1969 (Yesertener, 2002), and the level of decline over the next decade is obviously an important factor affecting recharge rates to maintain cave pools (note the difference between rates for 2005 and 2015). Although the best possible estimate of the future regional groundwater trend has been done by a number of methods including CDFM techniques and has been considered on the inflow boundary in the model, it will depend on the rainfall trend and any changes in the land and water usage pattern across the Gnangara Mound. Because of the uncertainty in future trends, there is a risk that a system designed to meet the predicted recharge rates for 10 years will need to be modified to achieve the objectives.

The private licensed and Water Corporation bores are presented by a Well package in the Yanchep model. Although the Water Corporation provides details of their production bores and monthly water usage data, the private licensed data contains the latest licensed allocation amount. The model generated time series data for the private licensed bores for the modelling period using a scaling file, based on historical data with the assumption that most of the allocated water is used in the summer months. There are uncertainties in private bore data including record duplications, incomplete records and misallocation of bores in the wrong aquifer. These may affect the results used for predicting the required recharge rates.

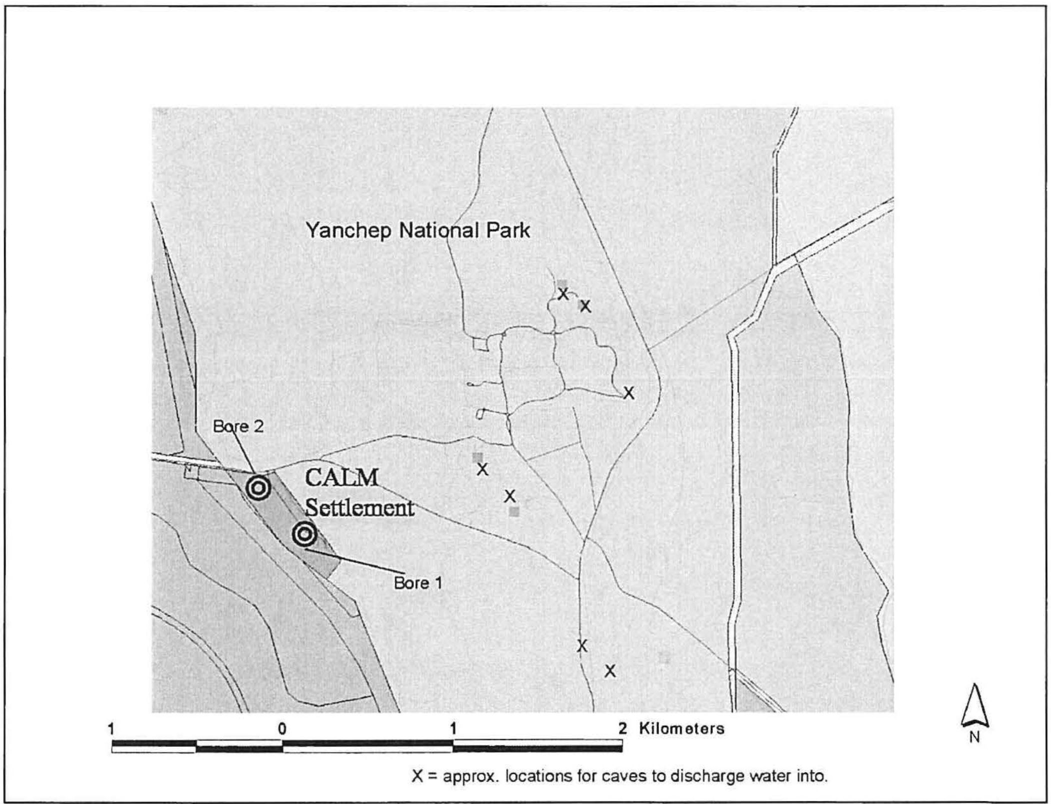
The model is not recommended to be used for prediction near the boundaries because of boundary effects.

4 Yanchep Caves Artificial Maintenance Scheme Operation and Management

4.1 Artificial Maintenance Scheme Operation

The model results show that total recharge rates of 9,600 m^3/day (~ 3.6 GL per year) for the suggested seven caves can maintain the groundwater levels under the caves for the 10 years to 2015 if water is pumped directly into each cave, except for the supply to Cabaret Cave and Boomerang Gorge, where water will be delivered to a nearby unused cave called YN6 (Table 6).

Two production bores will be drilled west of Loch McNess in the vicinity of the CALM Settlement (Figure 25). A water meter is needed on each bore to monitor the rate of draw to ensure pumping capacity does not exceed the licensed allocation for each bore.



X = approx. locations for caves to discharge water into.

Figure 25 Piping route to the caves through the Yanchep National Park (after Calvert and Yesertener, 2005)

A number of monitoring programs need to be continued, including the vegetation transect monitoring bores that are currently undertaken by the Department of Environment and Conservation, and Department of Water. Aquatic fauna and water quality in caves are monitored (conductivity, temperature and turbidity), analysed and reported annually. Cave water levels are monitored either continuously using a data logger, or monthly. In the initial stages of the scheme as groundwater levels rise under the caves, monitoring is required to be conducted on a daily basis, until discharge rates maintain water at the desired levels within the caves, and followed by weekly checks thereafter. Groundwater level monitoring at bores surrounding the caves and west of Loch McNess is also required to continue on a monthly basis.

All monitoring data will need to be assessed by a competent hydrogeologist who will provide relevant agencies a brief report and workbook containing all monitoring data and charts illustrating daily to weekly trends whilst a groundwater mounds develop in each cave and monthly trends thereafter. A more comprehensive report including analysis of groundwater response to the recharge and any impacts on Loch McNess should be submitted to the responsible Government agency. The report should include comments on the monitoring program with recommendations for any changes.

4.2 Management Plan for Failures in operation

In the event that water cannot be pumped to the caves (due to, for example, power cuts or pump failure), the model predicted the response of the groundwater levels in such failures for 1 day, 7 days and 30 days and results are given in Table 9. In such cases, small sprinkler systems already installed and used as an interim measure can be activated. The impact of pumping to the surrounding environment is considered negligible as there are no GDEs in the vicinity of the supply bores and most of the water discharged into the caves will return back through westerly groundwater flow. As previously indicated the predicted drawdown at the two supply bores is between 2 - 3.2 m and may impact the CALM Settlement bore. It is proposed that the 450 kL required per year is incorporated into the total requirement from the southernmost supply bore and diverted to the three houses. To ensure that there is no adverse impact on the environment and other groundwater users, groundwater levels are required to be monitored at a number of locations around the caves, Loch McNess, and in a westerly and southwesterly direction between the lake environment and supply bores (Figure 26).

While it appears that a large amount of water is required to artificially maintain water levels above the floor in seven caves at the Yanchep National Park, the model results indicate that with groundwater flow in the westerly direction the abstracted water will return back toward the abstraction sites. Water use efficiency is also achieved because discharging water directly into the caves will minimise evaporation.

The potential impact on water quality and cave wall dissolution of discharging water from Loch McNess and the Tamala limestone aquifer has been investigated (see section 2.2). Results from the investigation indicate that overall impact of artificial recharge using groundwater from the Tamala Limestone would not affect the caves in terms of additional weathering of limestone and nutrient status. It was also indicated that the groundwater from the Tamala Limestone contains similar water quality properties as that which naturally discharged into the caves in the past (Barber, 2003).

Physio-chemical characteristics of the water (electrical conductivity, turbidity, pH, Eh, temperature, major anions and cations) are required to be monitored on a regular basis inside the caves.

In relation to the potential that a salt-water wedge intrusion might occur due to pumping it is considered that this is unlikely due to the distance of approximately 4.5 km to the coast. It is also considered that the high hydraulic conductivity that occurs in Tamala Limestone aquifer systems would also prevent salt-water intrusion.

Figure 26 Loch McNess, surrounding monitoring bores and location of vegetation transects monitoring bores (after Calvert and Yesertener 2005).

5 Conclusions

This study presents a brief geology, hydrogeology, hydrochemistry, and a three-dimensional groundwater flow model constructed using Visual Modflow Pro 4.0 to investigate and evaluate artificial recharge of groundwater to maintain groundwater levels within key cave systems to protect cave fauna in the Yanchep National Park.

The model considers all current information about the hydrogeology of the Yanchep Area summarized in section 2.2, including private/public abstractions and nearby pine plantation areas. The best calibration is achieved with recharge rates of 280mm/yr in zone 3 to 380 mm/yr in zone 2 (see Fig 10). These values are consistent with the recharge rates found by CDFM method. The standard error of the estimate is 0.135 m in steady state and 0.016 m for all times in transient calibration. Correlation coefficient is 0.99, which shows that about 99% of the data can be predicted with a high standard of reliability in both calibrations.

The model is designed to use groundwater from two production bores situated in the superficial aquifer (Tamala limestone) west of the Yanchep Caves about one km south west of the Loch McNess within Yanchep National Park near Yanchep Village. Water will be discharged directly into the caves and will flow back in the westerly direction toward the supply bores.

The model takes into account the regional groundwater declines. Although the best possible estimate of the future regional groundwater trend has been carried out by a number of methods including CDFM techniques, and has considered on the inflow boundary in the model, the result depends on rainfall trend and any changes of land and water use pattern across the Gnangara Mound. Because of the uncertainty in future trends, there is a risk that a system designed to meet the predicted recharge rates for 10 years will need to be modified to achieve the objectives.

The model has estimated that a total recharge rate of up to 3.6 GL/yr would maintain water in ponds in each priority cave in both summer and winter up to 2015. In the area of Loch McNess and the caves, the artificial supplementation creates an artificial groundwater mound of approximately 18km^2 covering all targeted caves and Loch McNess and Yonderup Lake (Figure 22). The effects of pumping on other water users and GDEs were evaluated through the model. There are no other GDEs in the vicinity that would be affected by pumping from the bores. The cone of depression resulting from pumping of these bores stabilizes in two years indicating that there may be a 0.5m drawdown within approximately one km west of the bores with zero impact on lake system towards the east after the second year of operation.

The results of this study also indicate that groundwater within the calcareous sands is not saturated by calcite, however groundwater within the limestone are saturated or close to saturation by calcite. YB11 is nearest bore to proposed site for groundwater abstraction to maintain the groundwater levels under the caves. The Calcite saturation index of the groundwater sampled from this bore is –0.067, near the saturation by calcite, and less aggressive than groundwater under the caves (Figure 7), therefore weathering of limestone is probably less than weathering which occurs during natural discharge of groundwater within the cave systems.

Overall, it is concluded that artificial recharge using groundwater from the Tamala Limestone aquifer would have the least impact on the cave systems, in terms of additional weathering of limestone and nutrient status. The developed groundwater flow model is very effective in predicting the recharge rates for each cave to reach the target groundwater levels for 2005 until 2015 and also effective in predicting the time required for recovery in case of 1, 7 or 30 days failures in operation.

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