Conservation and Land Management WA

Lake Toolibin Numerical Groundwater Model

Project Report - Final

October 2000

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Contents

1. Executive Summary **1**
1.1 Introduction 1
1.2 Model Calibration 1
1.3 Predictive Models 2
1.3.1 No Pumping 2
1.3.2 Continuous Pumping 2
1.3.3 Non-Continuous Pumping 3
1.3.4 Water Level Recession Following Inundation 4
1.4 Sensitivity Studies 5
1.5 Conclusions 7
1.6 Recommendations 7

2. Introduction **9**

3. Objectives **10**

4. Conceptual Model **11**

5. Hydrogeological Observations and Records **14**
5.1 Groundwater Hydrographs 14
5.2 Lake Inundation 16
5.3 Rainfall 16

6. Numerical Groundwater Model **18**
6.1 Model Modifications 18
6.2 Model Domain and Discretisation 18
6.3 Boundary Conditions 20
6.4 Aquifer Properties 20
6.5 Applied Stresses 21
6.6 Inundation 22

7. Methodology **23**
7.1 Calibration 23
7.2 Predictions 25
7.2.1 No Pumping 25
7.2.2 Continuous Pumping 25
7.2.3 Discontinuous Pumping 25
7.2.4 No Inundation 25
7.3 Sensitivity Studies 26

8. Results **28**
8.1 Calibration 28
8.2 Predictions 31
8.2.1 No Pumping 31
8.2.2 Continuous Pumping 34
8.2.3 Non-Continuous pumping 38
8.3 Sensitivity Analyses 42
8.3.1 Base Case 42
8.3.2 Sensitivity Models 43

9. Discussion 46

10. Conclusions 49

11. Recommendations 50

12. References 51

Appendix A - Calibration Results 52

Appendix B - Vector Diagrams for Selected Models 55

Appendix C - Pumping Test Results 56

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1. Executive Summary

1.1 Introduction

Lake Toolibin is a small, shallow ephemeral lake in the Northern Arthur River drainage system about 200 km southeast of Perth. It is one of a few relatively fresh water lakes in the region and provides an important breeding area for a wide variety of water birds. The importance of the lake to the wildlife ecosystem has been recognised.

In terms of hydrogeology the lake represents a centre of groundwater discharge, predominantly through evapotranspiration. Salinisation of the lake is observed and is believed to be the result of upward fluxes of saline groundwaters.

A three dimensional three layer groundwater model of Lake Toolibin was developed by SKM in 1998. This model included a relatively simple distribution of aquifer properties with little or no detailed representation of hydrogeological features of the area.

The present study has included the modification of the existing model in order to include additional geological and physical details believed to be important in the description of the hydrogeology of the area. Most of the model parameters were defined by CALM (the Department of Conservation and Land Management) and its Technical Advisory Group.

1.2 Model Calibration

Calibration procedures, consisting of matching model results to observed groundwater levels, were carried out to refine model parameters and to demonstrate the accuracy of model results. The quality of the calibration process is expressed in terms of the root mean square error (RMS) of the prediction relative to observed groundwater levels. The target of an RMS error of 0.3m was only achieved within a limited period of the calibration model. Most of the calibration interval has an RMS error between 0.3 and 0.5m. The difficulty in obtaining the target RMS error arises from:

- The available pumping record is incomplete and does not include pumping that was carried out prior to 1997
- Erroneous observation data

- Inadequate definition of lake surface topography such that depth dependant evapotranspiration is not accurately represented.

Despite these problems the calibrated model is believed to accurately represent groundwater response to various applied stresses such as pumping, rainfall recharge, evapotranspiration and lake filling episodes.

The calibrated model includes recharge at a level of 8% of measured rainfall. This recharge rate resulted from trial and error calibration simulations and provides the best match to observed groundwater hydrographs. The calibrated model includes average seasonal evapotranspiration rates applied during summer and winter respectively. The model also includes the effects of lake inundation as enhanced recharge periods representing the infiltration of water through the lake bed whenever the lake is full.

1.3 Predictive Models

Predictive simulations were conducted in order to assess the likely future trends in groundwater heads under various pumping scenarios.
Models were run to determine the impact of different pumping options on the water levels and evapotranspiration rates beneath the lake bed. For the purpose of this study it is assumed that if the water table falls to a level that is more than 2m below the surface then evapotranspiration effectively ceases and the processes giving rise to salinisation are interrupted.

1.3.1 No Pumping

The first predictive simulation involved the no-change scenario in which there is no pumping and groundwater simply responds to recharge, evapotranspiration and lake filling processes. This model shows how the groundwater heads are expected to vary over the next 20 years provided rainfall and evapotranspiration continue at average seasonal rates. It is assumed that lake filling episodes will follow the same pattern as the observed record over the last 20 years. The result suggests that groundwater levels will remain close to the surface between lake inundation episodes and will rise to above ground level within the lake during inundation. Between inundation episodes the groundwater levels below the lake are predicted to remain within 2m of the surface and the lake will continue to act as a centre for groundwater discharge through evapotranspiration. Under such conditions salinisation of the lake bed and its vegetation can be expected to continue unabated.

1.3.2 Continuous Pumping

The first pumping scenario considered in this study utilised the same input parameters as that used in the no-pumping case described above, except that all existing wells are pumped continuously at their maximum tested (or assumed maximum) rate. Results of this model show that pumping can depress the water table to more than 2m below ground level for much of the 20 year model period over a significant portion of the lake. Pumping cannot prevent water table rise during the lake filling episodes. However once the water recedes from the lake the pumping acts rapidly to depress the water table.

1.3.3 Non-Continuous Pumping

The second pumping scenario considered was a case where the pumps are operating continuously except for the lake filling episodes when they are turned off. Depression of the water table in this case was also effective although the time taken for water levels to fall to 2m below the surface is slightly greater than in the continuous pumping scenario. The principal difference between the continuous and non-continuous pumping results is the fact that the continuous pumping scenario reduces the duration and water level of lake filling episodes. Under the continuous pumping scenario the lake will be inundated less often and to lower water levels than in the no-pumping and non-continuos pumping scenarios.

Both pumping scenarios are effective in reducing evapotranspiration and accompanying salinisation effects beneath the lake surface as shown in Figure 1.1. The reduction in cumulative evapotranspiration over the area of the lake for twenty years of pumping is presented in Table 1.1.

Figure 1.1: Percentage of Lake Bed in Which Depth to Water Exceeds 2m Under Pumping

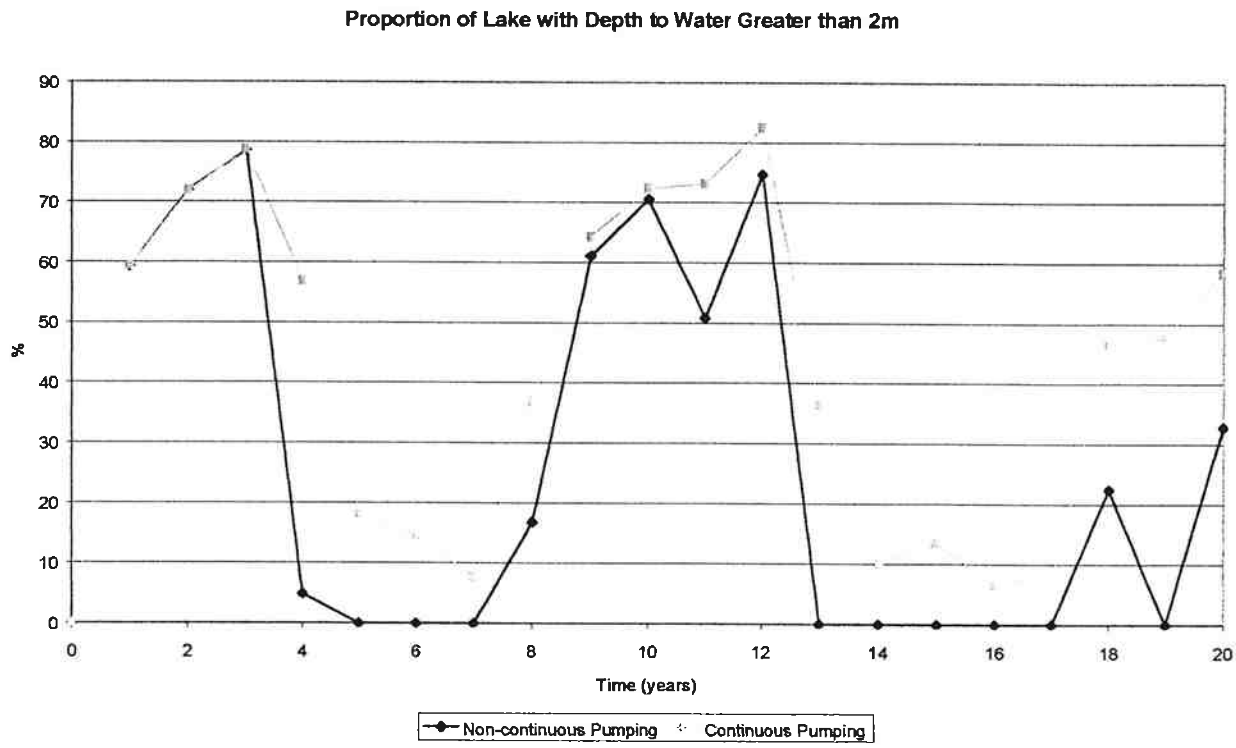


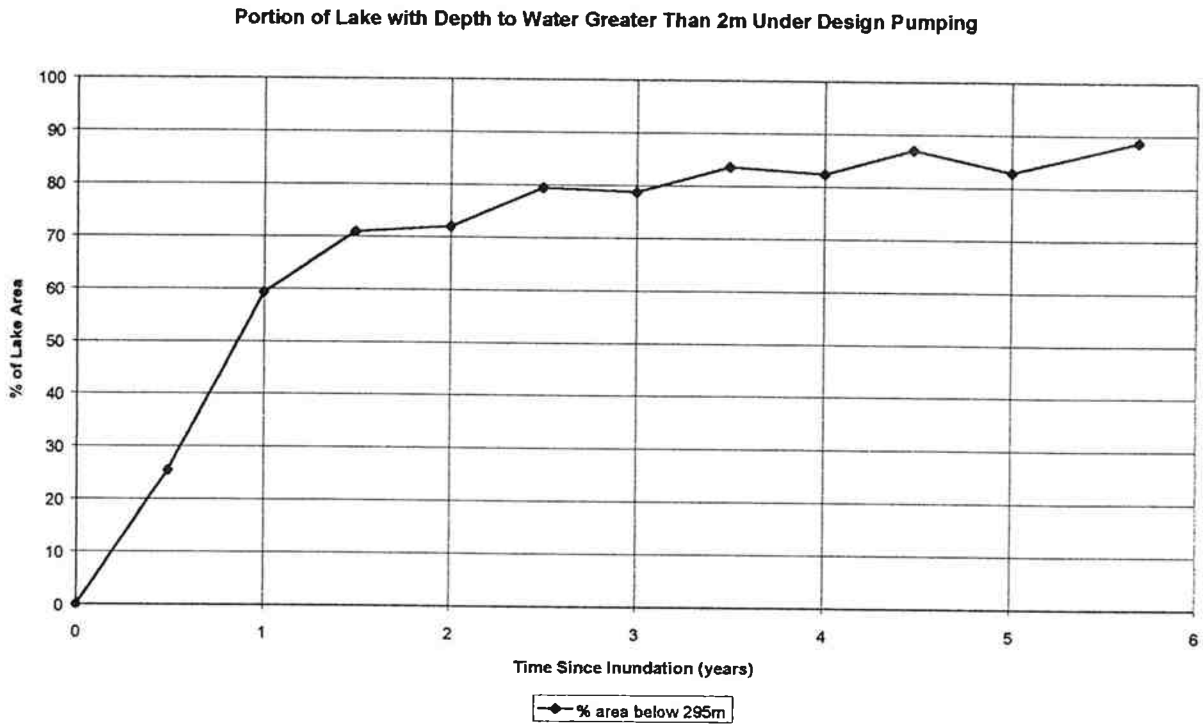
Table 1.1: Predicted Evapotranspiration Within the Area of the Lake

Model	Evapotranspiration (million m^3)	Evapotranspiration (mm/yr)	% Reduction
No Pumping	5.75	37.7	-
Continuous Pumping	1.22	8.00	79
Non-Continuous Pumping	3.07	20.12	47

1.3.4 Water Level Recession Following Inundation

The fourth scenario considered in this study was the case that corresponds to the period immediately following a lake filling episode. In this model the initial conditions correspond to the time when the lake makes the transition from a state of inundation to being dry and the groundwater level is at the surface. The model was run with no lake inundation episodes and simply investigates the rate at which the water table recedes under the pumping scenario following a lake filling episode. The result indicates that 80% of the lake area will have a water table more than 2m below the surface after 2.5 years of pumping. The result of this model is shown in Figure 1.2 as a plot of the percentage of lake bed with depth to water exceeding 2m against time since inundation.

Figure 1.2: Percentage of Lake with Depth to Water Exceeding 2m



1.4 Sensitivity Studies

A series of twelve additional models were run to determine the sensitivity of the results to variation in parameters used in the model. The reason for running these models is to provide an indication as to the relative importance of some the principal input variables in the model and to address the impact of including detailed geological information. The models addressed the following:

- An increase and decrease in the horizontal hydraulic conductivity throughout the entire model (Sens01 and 02 respectively).
- An increase and decrease in the vertical hydraulic conductivity throughout the entire model (Sens03 and 04 respectively).
- An increase and decrease in the hydraulic conductivity within the eastern half of the lake (Sens05 and 06 respectively). These models were

used to assess the impact of possible variability in the conductivity and thickness of aeolian deposits found at the surface on the eastern margin of the lake.

- A decrease in the horizontal conductivity at the margin of the palaeochannel that bisects the lake (Sens07). This model investigates the impact of possible sealing of the margin of the palaeochannel.

- A decrease in horizontal hydraulic conductivity associated with dykes that are believed to exist beneath the lake (Sens08).

- Pumping rates from all bores reduced to 90%, 80% and 60% of the target rates (Sens09, Sens10 and Sens11).

- Removal of the northwestern "arm" of the palaeochannel (Sens12).

Results of these models shown in Table 1.2 suggest that varying the horizontal and vertical hydraulic conductivities throughout the entire model has a measurable impact on the rate at which the water table recedes under pumping conditions. Higher horizontal conductivities results in poorer dewatering efficiency due to the fact that drawdown associated with the pumping is reduced in the vicinity of the wells. Conversely reduced vertical conductivity results in a poorer dewatering efficiency because drainage from shallow levels to the deeper pumping levels is retarded by the low hydraulic conductivity.

Sensitivity models involving reduced pumping rates suggest that there may be a significant impact on dewatering efficiency if the bores are unable to be pumped at their target rates. Table 1.2 indicates that if pumping rates fall to 60% of the designed rates then only about 20% of the lake will have depth to water table exceeding 2m compared to about 80% when pumps operate at their target rates.

The inclusion of thick aeolian deposits, sealing at the margin of the palaeochannel, removal of the northwestern arm of the palaeochannel and the inclusion of dykes beneath the lake have little impact on the rate and magnitude of groundwater recession under pumping. The result suggests that in terms of long term dewatering performance, aquifer transmission properties considered on a large scale outweigh the impact of small scale variations in this parameter.

Table 1.2: Results of Sensitivity Analyses - Percentage of Lake with Depth to Water >2m

Model	Description	1 year	2 years	3 years	4 years
Calibrated	Calibrated model	59.4	72.0	78.8	82.4
Sens01	K_h doubled	22.9	36.6	31.8	40.2
Sens02	K_h halved	68.2	82.6	90.2	93.6
Sens03	K_v increased 10 times	63.8	77.3	84.5	88.0
Sens04	K_v decreased 10 times	21.2	55.8	63.0	67.4
Sens05	K_h doubled in eastern half of lake	59.4	73.1	78.9	82.3
Sens06	K_h halved in eastern half of lake	58.9	72.0	78.8	83.5
Sens07	K_h halved at palaeochannel edge	60.2	73.1	80.0	82.9
Sens08	K_h doubled in dykes and faults	59.2	72.5	79.9	83.5
Sens09	90% pumping rates	51.2	64.4	68.9	71.9
Sens10	80% pumping rates	31.1	54.5	58.7	60.9
Sens11	60% pumping rates	9.8	14.3	16.4	17.0
Sens12	Revised palaeochannel shape	59.7	72.2	78.2	81.6

K_h = horizontal hydraulic conductivity, K_v = vertical hydraulic conductivity

1.5 Conclusions

The modelling study has shown that evapotranspiration processes beneath the lake cannot be completely prevented as lake-filling episodes will always result in periods when the groundwater levels are close to the surface. Evapotranspiration can however be arrested in the periods following inundation by the designed pumping scheme. It is further implied that salinisation can be substantially reduced by the implementation of the scheme.

1.6 Recommendations

The groundwater model, in its present form, can be used with confidence to predict the groundwater response to pumping. As such it is a powerful groundwater management tool that can be used to evaluate various dewatering and water level control schemes. At this stage further refinement of the model is considered unnecessary. However monitoring is recommended in order to support future model refinement. Detailed recommendations include:

- Monitoring of observation bore water levels and individual well pumping rates continue on a monthly basis.

- The model calibration be reviewed in the future after the full scale pumping scheme has been operational for at least 12 months. The additional stress on the aquifer corresponding to widespread pumping will provide a further insight to the aquifer and its response to artificial stresses.

- Monitoring of water levels in the lake during inundation is recommended.

- Water level monitoring in all observation bores during inundation should be attempted.

The pumping scheme that has been designed appears to be effective in reducing evapotranspiration beneath the lake and operational pumping should proceed as soon as practicable.

2. Introduction

Groundwater models of Lake Toolibin were originally developed by SKM in 1998 and are described in SKM (1998). The models described in this report have been developed as stage 2 of the project in accordance with the contract between SKM and the Department of Conservation and Land Management (CALM).

Lake Toolibin is a small, shallow ephemeral lake in the Northern Arthur River drainage system about 200 km southeast of Perth. It is one of a few relatively fresh water lakes in the region and provides an important breeding area for a wide variety of water birds. The importance of the lake to the wildlife ecosystem has been recognised. In terms of hydrogeology the lake represents a centre of groundwater discharge, predominantly through evapotranspiration. Clearing of native vegetation for dry land agriculture has led to increased water table levels and associated appearance and spread of salinized land. Salinisation of the lake is believed to be the result of salt concentration at the water table arising from evapotranspiration of near surface groundwaters and the resultant upward flux of deeper saline groundwater.

The currently proposed method of salinity remediation for Lake Toolibin is to install and operate a network of production bores capable of depressing the groundwater level to more than 2 m below the lake surface where evapotranspiration effects are believed negligible. To this end a number of production bores have been drilled and tested and a number of observation bores have been drilled in and around the lake and have produced water level records of varying length.

The objective of the stage 2 modelling is to incorporate additional geological and physical information in the model to more accurately reflect the hydrogeology of the area.

Details of the hydrogeology and the conceptualisation developed prior to the current study are presented in Martin, (1990) and SKM, (1998). This report describes in detail the modifications made to the original SKM model, the modelling procedures carried out and the results that have been obtained.

All models described in this report have been generated and run in Visual Modflow, a three dimensional, finite difference groundwater flow modelling package.

3. Objectives

- To develop a numerical groundwater model of the lake that can be used with confidence to predict groundwater response to externally applied stresses including evapotranspiration, rainfall recharge, lake inundation and pumping.
- To assess the impact of proposed pumping schemes on groundwater levels beneath the lake.
- To review the planned dewatering scheme to assess its efficacy in maintaining groundwater levels more than two metres below the lake surface.

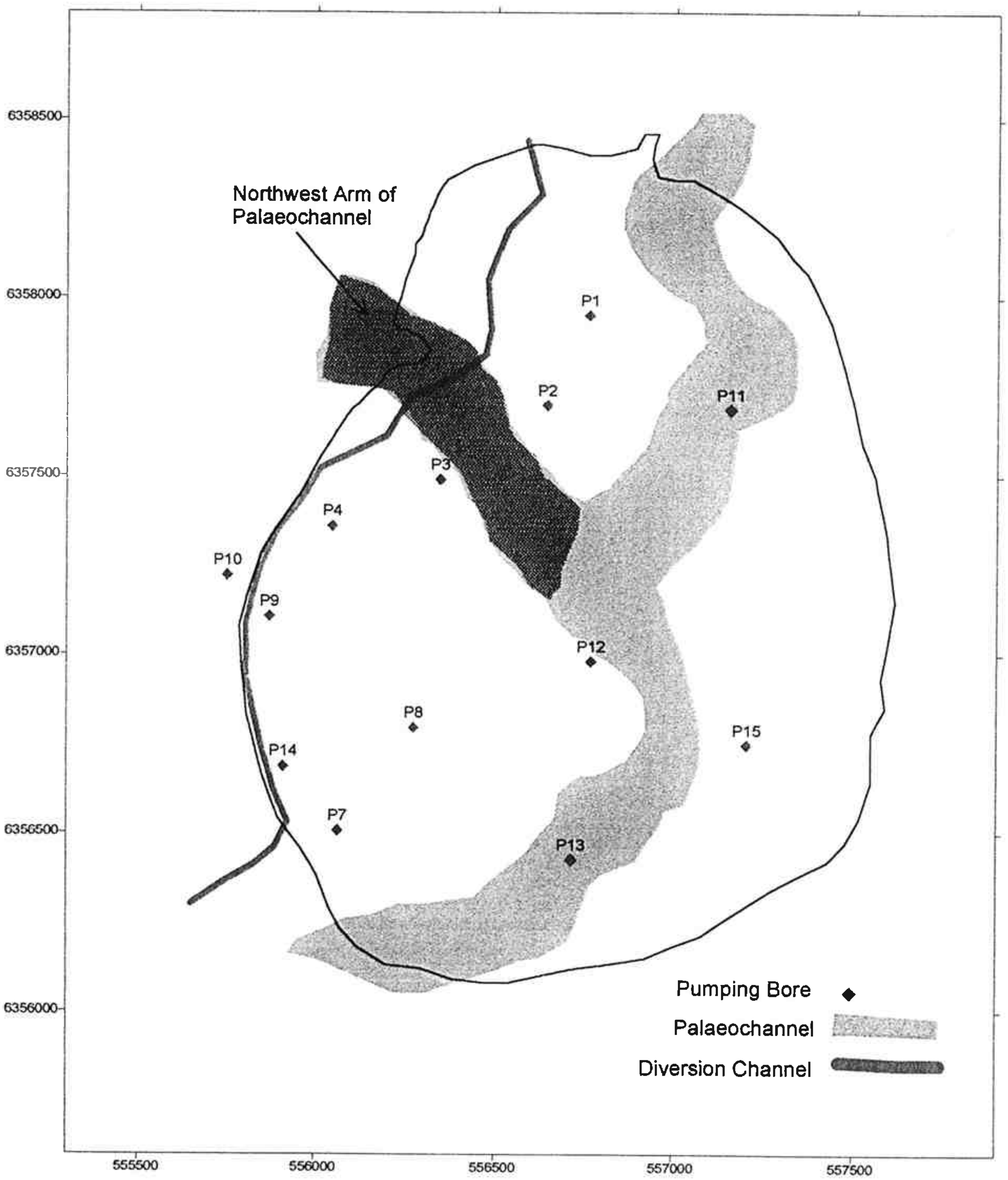
4. Conceptual Model

A detailed description of the hydrogeology of the area and the model conceptualisation are presented in Martin (1987 and 1990) and George and Bennett (1995). Features of the local hydrogeology that are of particular importance to the numerical model development are described herein.

Lake Toolibin is located in a topographic depression and is a region of natural groundwater discharge where geology and evapotranspiration effects have combined to create a natural sink in the local hydrogeological domain. A distinct depression in the local equipotential surface reflects this phenomenon. Water levels rise close to the surface from where evapotranspiration effects result in groundwater discharge and associated concentration of salt beneath the surface of the lake. Increasing salinity levels may eventually lead to the death of most vegetation in the lake. It has been postulated that reducing the water levels beneath the lake between the inundation events will arrest salinisation by reducing the effects of evapotranspiration. Salinity remediation has involved the construction of a network of pumping wells aimed at reducing the water table below the lake to levels at which evapotranspiration effects are minimal.

Martin (1990) reports that the first production bore was drilled in 1988 (referred to as bore 1/88) and has been pumped on an intermittent basis since its completion. Located near the western margin of the lake, this bore is now referred to as P10. Since then additional drilling has resulted in a total of 13 pumping wells that have been used in extensive dewatering trials since 1997. The location of the pumping wells is presented in Figure 4.1.

Figure 4.1: Location of Lake Toolibin Pumping Wells



Lake Taarblin, to the south west of Lake Toolibin, is also a groundwater discharge site and the regional groundwater flow is from north east to south west. Geology and pump test results indicate an unconfined hydrogeological domain with poor transmission and storage characteristics that limit the extraction rates possible from the pumping wells. Interpretation of geophysical surveys has revealed a buried palaeochannel dissecting the lake that recent studies show to be a localised region of increased hydraulic conductivity (George and Dogramaci, 1999). The location of the palaeochannel is shown in Figure 4.1.

An inflow diversion channel (refer to Figure 4.1) constructed on the western margin of the lake as part of the salinity remediation plan is believed (by SKM) to act as a line of groundwater discharge during periods of high groundwater level.

Groundwater levels between periods of inundation primarily respond to evapotranspiration and rainfall recharge with evapotranspiration rates generally exceeding direct rainfall recharge. The predominance of evapotranspiration results in the gradual recession of groundwater levels during such periods. Low hydraulic conductivity of the sediments beneath and surrounding the lake inhibits lateral flow of water away from the lake between inundation events. During inundation, the lake acts as a recharge source and groundwater levels respond accordingly. Groundwater levels recorded in observation wells drilled in the lake floor demonstrate groundwater response to evapotranspiration, recharge and pumping from 1992 to the present day.

5. Hydrogeological Observations and Records

5.1 Groundwater Hydrographs

Records of groundwater head at several locations in and around the lake are available. The locations of bores for which reliable long term records are available are shown in Figure 5.1. The groundwater hydrographs obtained from these bores, many of which extend back to 1992, have been used for model calibration as described in more detail in sections 7.1 and 8.1

Figure 5.1: Location of Observation Bores

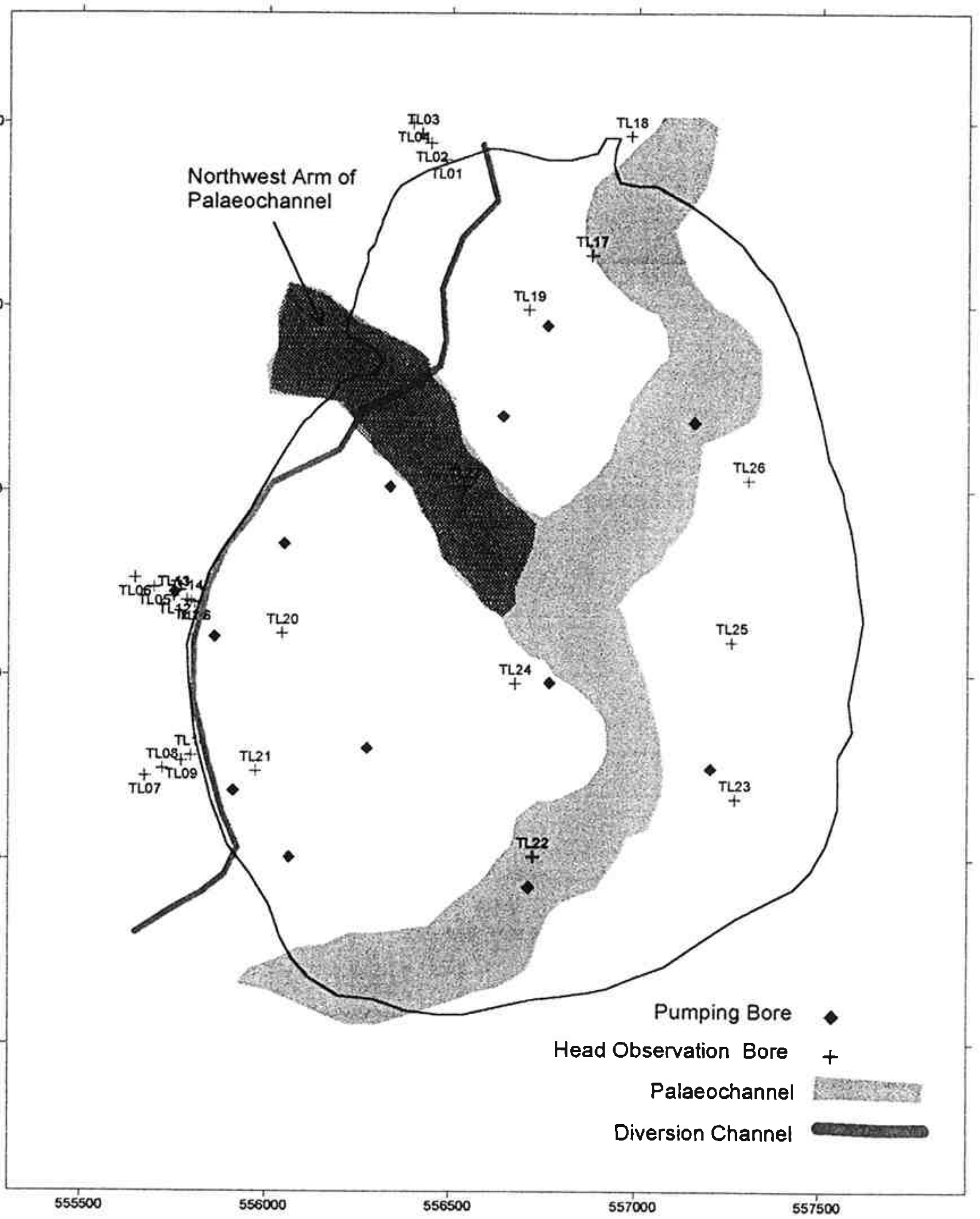
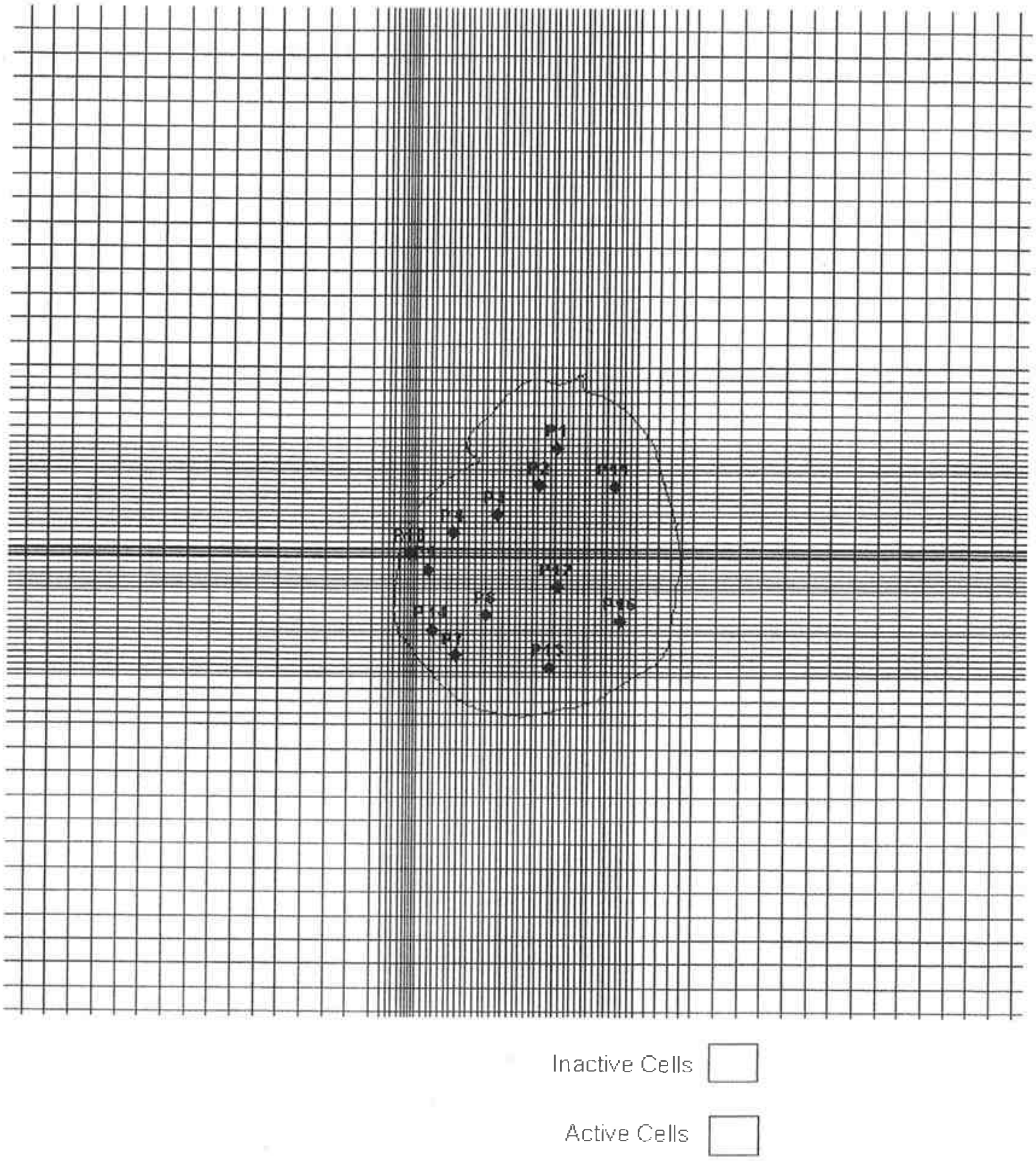
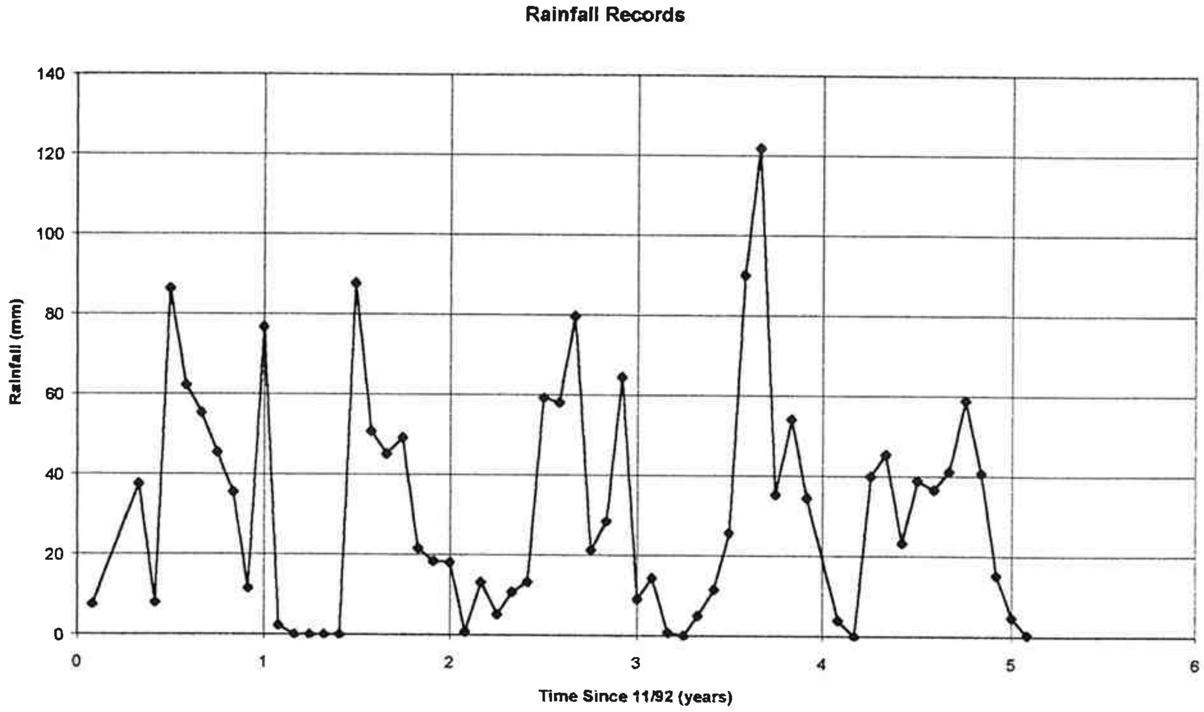


Figure 6.1: Model Grid



The model boundary is set at the location of the 300m AHD equipotential as defined by Martin (1990) with all cells outside this contour rendered inactive. To the south west the model extends to Lake Taarblin. The top of the model is defined as ground level and the base of the model is set at an elevation of 260m AHD. All four layers are 10m thick except for the uppermost layer which is variable according to ground level elevation.

Figure 5.3: Wickepin Rainfall From November 1992



6. Numerical Groundwater Model

6.1 Model Modifications

The basic groundwater model used in this project is described in SKM (1998). Modifications to the original model are listed below:

- The palaeochannel has been introduced as a region of greater hydraulic conductivity that dissects the lake. The location and relative hydraulic conductivity of the palaeochannel have been incorporated in the model in accordance with information supplied by George and Dogramaci (1999). An additional layer has been introduced to the model to enable the incorporation of the palaeochannel hydraulic conductivity in accordance with George and Dogramaci (1999).

- A shallow region of relatively high hydraulic conductivity has been incorporated in the model to represent aeolian deposits on the eastern margin of the lake.

- The diversion channel located on the western margin of the lake that intercepts groundwater and discharges it to Lake Taarblin, has been included in the model as an appropriate boundary condition ("drain cells").

- Additional pumping wells have been included in accordance with the latest drilling activities. Pumping rates for the new wells have been set at levels indicated by George and Dogramaci (1999).

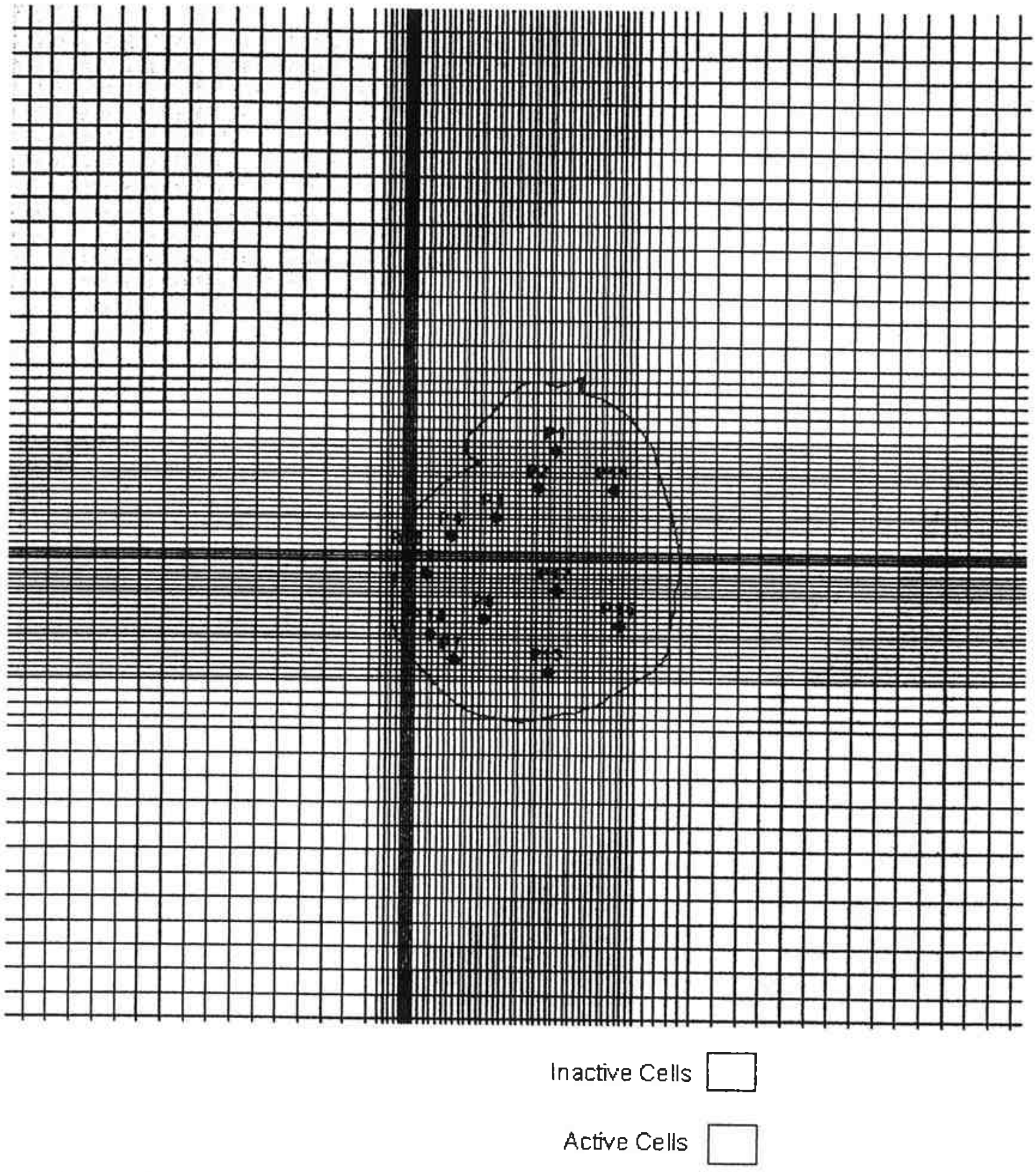
- Hydraulic conductivities and storage parameters for each of the important hydrogeological units were initially set at levels described by George and Dogramaci (1999).

- Evapotranspiration rates and extinction depths were incorporated in the model to more accurately represent variations in vegetation.

6.2 Model Domain and Discretisation

The model consists of a three dimensional rectangular grid in four layers. Horizontal grid spacing is approximately 150m with added refinement (to a spacing of about 40m) in the vicinity of each of the production wells. The model is presented in Figure 6.1

Figure 6.1: Model Grid



The model boundary is set at the location of the 300m AHD equipotential as defined by Martin (1990) with all cells outside this contour rendered inactive. To the south west the model extends to Lake Taarblin. The top of the model is defined as ground level and the base of the model is set at an elevation of 260m AHD. All four layers are 10m thick except for the uppermost layer which is variable according to ground level elevation.

6.3 Boundary Conditions

Boundary conditions applied to the model include:

- A general head boundary coincident with the 300 m equipotential as indicated by Martin (1990) defines the outward extent of the model. This type of boundary condition provides a specified boundary head with a user defined conductance term between the boundary and the model. Mass transport into or out of the model depends on both the hydraulic gradient at the boundary and the conductance term.

- A constant head boundary representing Lake Taarblin in the south west.

- No flow boundary at the base of the model.

- Variable elevation, constant, atmospheric pressure at the top of the model except for periods of inundation when heads are set to follow observed water levels within the lake.

- During inundation the lake elements in the top layer are defined as river boundary elements (head equal to river stage with a conductance term between the boundary and model) with river stage equal to the observed water level in the lake as presented in Figure 5.2.

- Drain boundary conditions (specified head element with conductance term) applied to elements coincident with the diversion channel.

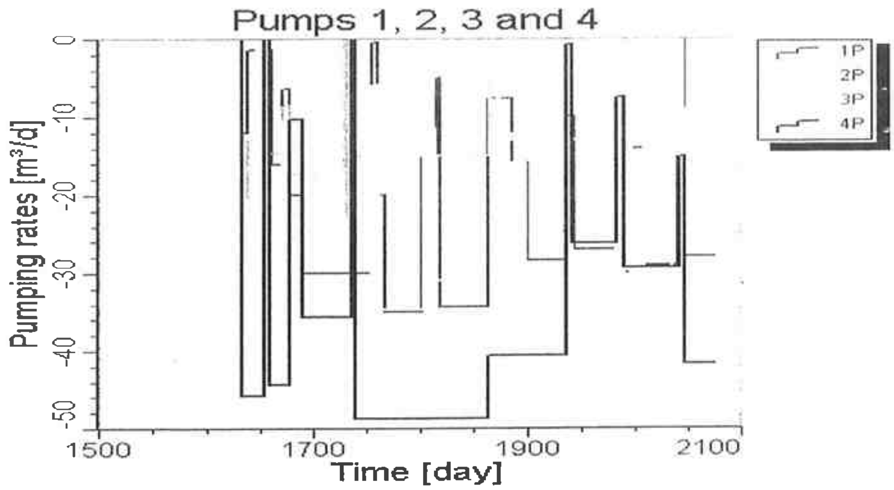
6.4 Aquifer Properties

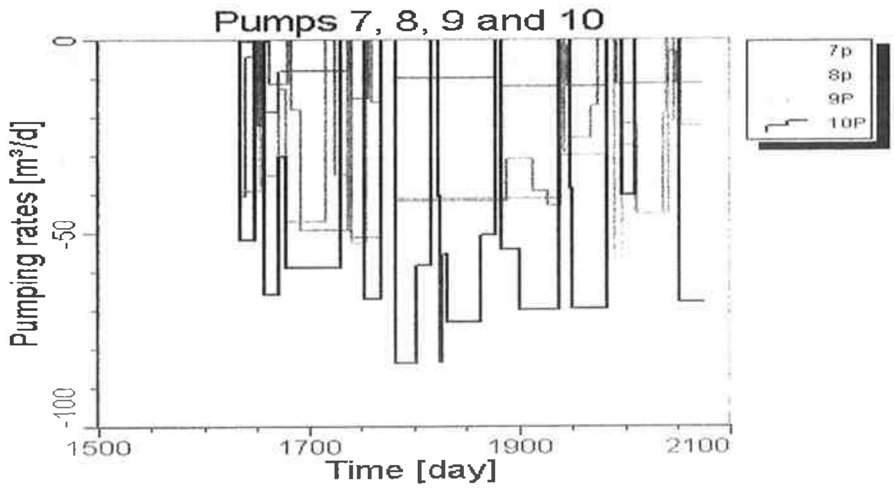
The initial distribution of hydraulic conductivity in the model followed that described by George and Dogramaci (1999) with enhanced conductivity in the palaeochannel at depth. Minor modification of the conductivity and storage parameters was required during calibration.

6.5 Applied Stresses

The model includes the effects of evapotranspiration and rainfall recharge. It should be noted that evapotranspiration used in the MODFLOW model represent that water withdrawn from the saturated aquifer by the combined action of evaporation and transpiration. It

Figure 7.1: Pumping Rates Used in Calibration Model





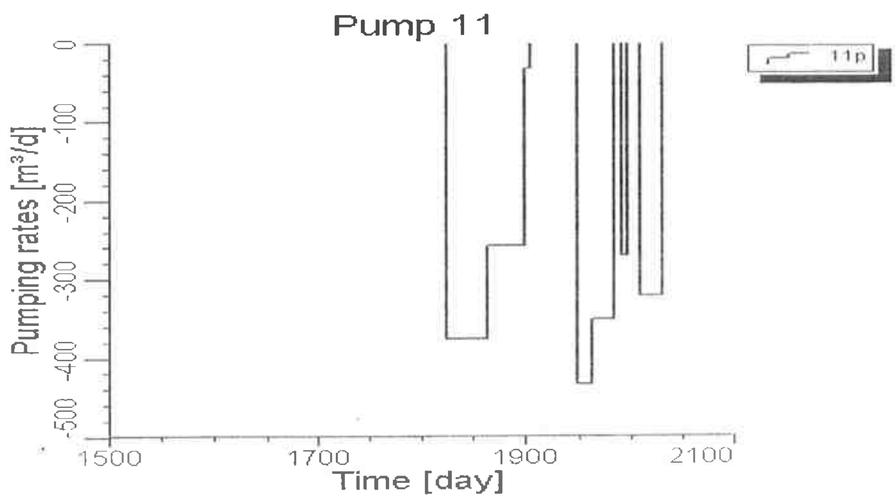
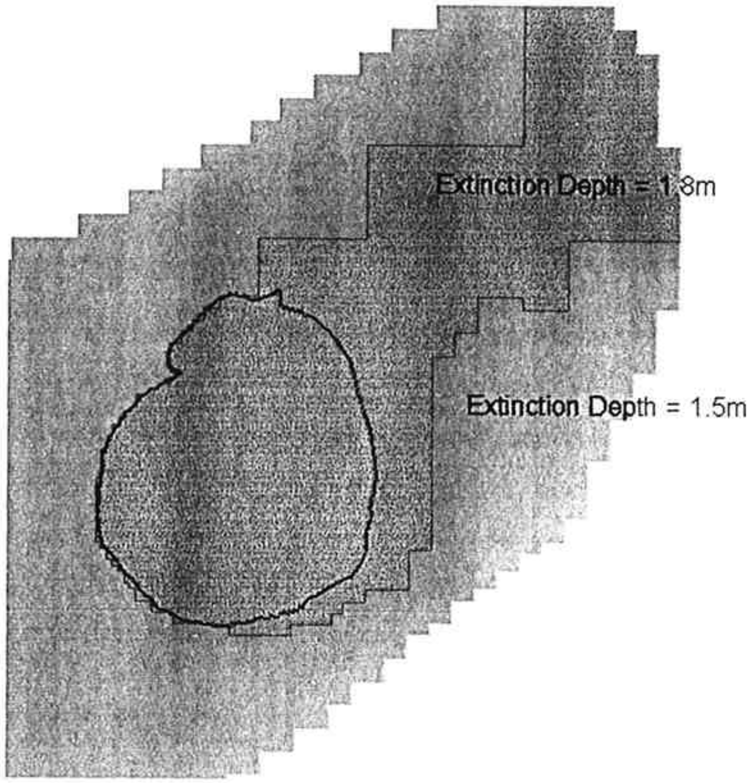


Figure 6.2: Evapotranspiration Extinction Depth



Rainfall recharge is input to the model at a rate that is proportional to recorded rainfall. The ratio of recharge rate to rainfall rate was adjusted during the calibration process.

6.6 Inundation

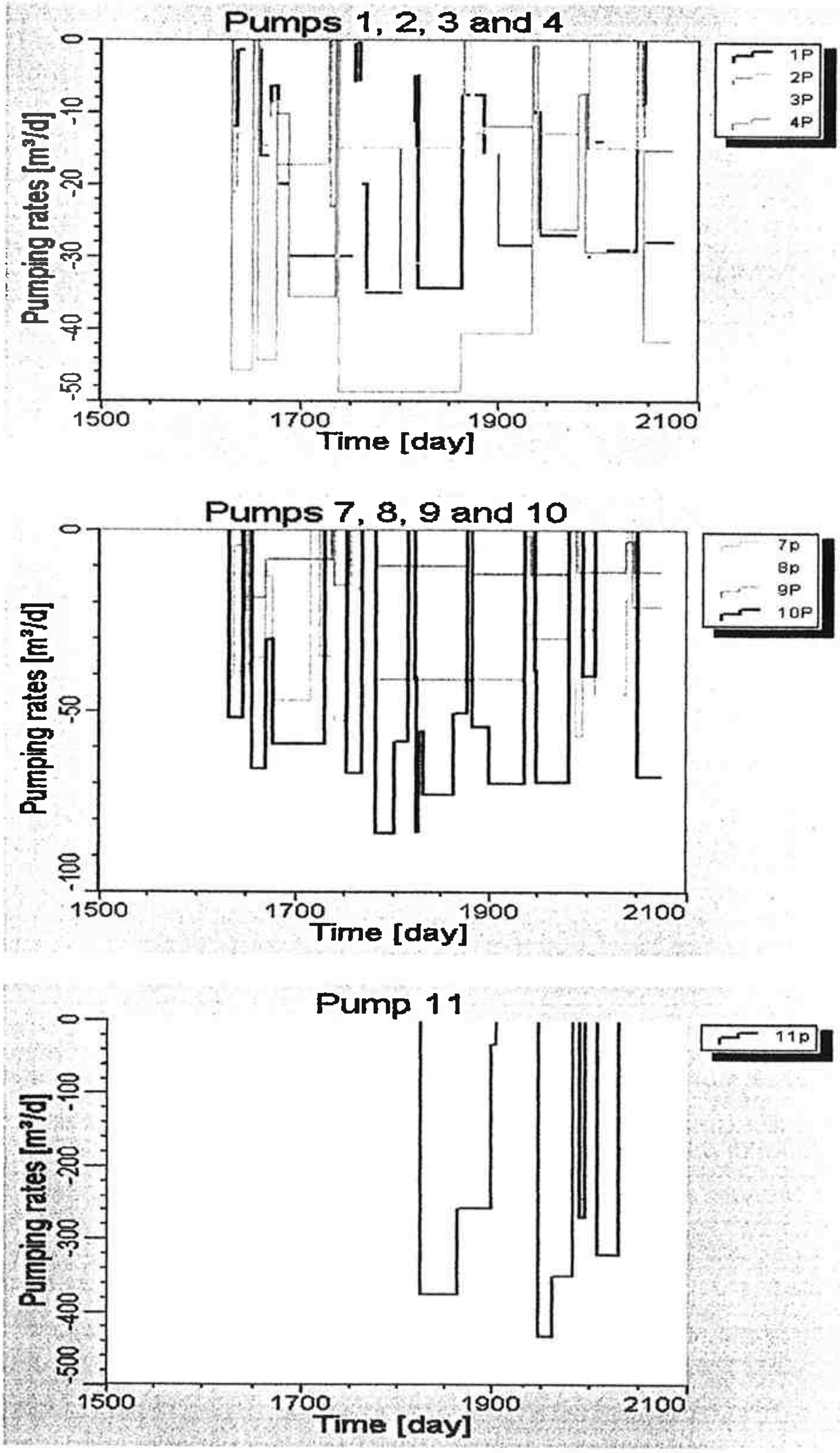
Lake inundation is represented in the model as a river type boundary condition for each of the elements within the lake. This boundary condition has a specified river boundary head with a conductance between this head and the model cells to which the boundary is connected. During periods of inundation the specified boundary head is determined from records of lake water level as shown in Figure 5.2.

7. Methodology

7.1 Calibration

Model calibration involves setting stress conditions that are consistent with historical observations over a period in which the groundwater response has been recorded. Variables within the model are then iteratively refined in an effort to adequately reproduce the observed groundwater response. For this project calibration models were run over a period of approximately seven years, starting November 1992, in which detailed records are available. The first five years of the models were run with no pumping and groundwater heads respond to the effects of rainfall and evapotranspiration with enhanced recharge during periods of lake inundation. Pumping was introduced to the model at locations and rates that correspond to the actual pumping recorded during the calibration period.

Figure 7.1: Pumping Rates Used in Calibration Model



The quality of the calibration can be evaluated in terms of the root-mean-square of the deviations for each observation point. In this case a target root mean square error of 0.3m has been specified.

7.2 Predictions

Following calibration the model was used to assess the impact of the proposed pumping scheme on groundwater heads beneath the lake. Three prediction runs were conducted as follows:

7.2.1 No Pumping

The control prediction scenario was run to determine the groundwater heads that can be expected in the absence of any further pumping. The model was run for 20 years with applied stresses including;

1. Evapotranspiration of the same pattern (both temporal and spatial) and rate as that used in the calibrated model.
2. Rainfall was entered as average summer and winter values calculated from the Wickepin Rainfall Station record from 1913 to 1998 using the same proportion of rainfall to recharge as that included in the calibrated model.
3. Lake inundation heads were taken directly from the available lake level record over the 20 year period between 1977 and 1997.

7.2.2 Continuous Pumping

This model was run with the same input data as used in the no pumping scenario described above (refer to Section 7.2.1). In addition pumping was included from existing bores located in the lake. The location of the pumping bores are shown in Figure 4.1 and the pumping rate assigned to each bore is presented in Table 7.1. The rates presented in Table 7.1 are observed maxima and assumed rates for bores that have yet to be fully tested.

7.2.3 Discontinuous Pumping

This scenario is identical to the continuous pumping scenario except for the fact that all pumping is stopped when the lake is inundated.

7.2.4 No Inundation

This scenario includes no inundation recharge episodes for a model time of 2000 days duration with continuous pumping from all bores. The model was run to determine the groundwater level response in the period following an inundation episode to indicate the time taken for pumping to depress the water level after an inundation episode. The no inundation scenario was subsequently used for all sensitivity study models (as described below) because the absence of inundation recharge simplifies comparisons and evaluation of pumping results.

Table 7.1: Pumping Rates Used in Model Predictions

Bore	Pumping Rate m3/day
P1	-35
P2	-23
P3	-46.6
P4	-48.8
P7	-56.9
P8	-51.4
P9	-20
P10	-60
P11	-300
P12	-10
P13	-300
P14	-15
P15	-70

7.3 Sensitivity Studies

The no inundation model described in Section 7.2.4 was used to evaluate a series of sensitivity cases. The continuous pumping, average seasonal recharge/evapotranspiration and no inundation assumptions of the no inundation model were used for all sensitivity study models (as described below). Comparisons between various cases and the base case (no-inundation model) are simplified by the fact that inundation recharge episodes are not included.

A number of simulations were performed in order to assess the impact of possible variation or inaccuracy in some of the input variables. A total of twelve sensitivity models were run as described below:

1. Horizontal hydraulic conductivity in all elements increased by a factor of two (referred to as Sens01).
2. Horizontal hydraulic conductivity in all elements decreased by a factor of two (referred to as Sens02).

3. Vertical hydraulic conductivity increased by a factor of ten (referred to as Sens03).
4. Vertical hydraulic conductivity decreased by a factor of ten (referred to as Sens04).
5. Hydraulic conductivity in all elements within the eastern half of the lake increased by a factor of two (referred to as Sens05)
6. Hydraulic conductivity in all elements within the eastern half of the lake decreased by a factor of two (referred to as Sens06)
7. Hydraulic conductivity at the palaeochannel margin reduced by a factor of two (referred to as Sens07).
8. Hydraulic conductivity in major dykes and faults decreased by a factor of two (referred to as Sens08).
9. Pumping rates in all bores reduced to 90% of the rates shown in Table 7.1.
10. Pumping rates in all bores reduced to 80% of the rates shown in Table 7.1
11. Pumping rates in all bores reduced to 60% of the rates shown in Table 7.1
12. Removal of the northwestern arm of the palaeochannel.

8. Results

8.1 Calibration

The calibration match for each of the observation wells is presented in Appendix A

The matches can be quantified statistically in terms of the root mean square of the variations between the observed and calculated groundwater hydrographs. A plot of root mean square deviations against model time is presented in Figure 8.1.

The calibration process resulted in a number of modifications to boundary conditions and aquifer parameters in order to obtain a reasonable match to the observed groundwater hydrographs. The hydraulic conductivity distribution in each layer of the calibrated model is shown in Figure 8.2.

Figure 8.1:RMS Error of Calibration Plotted Against Model Time

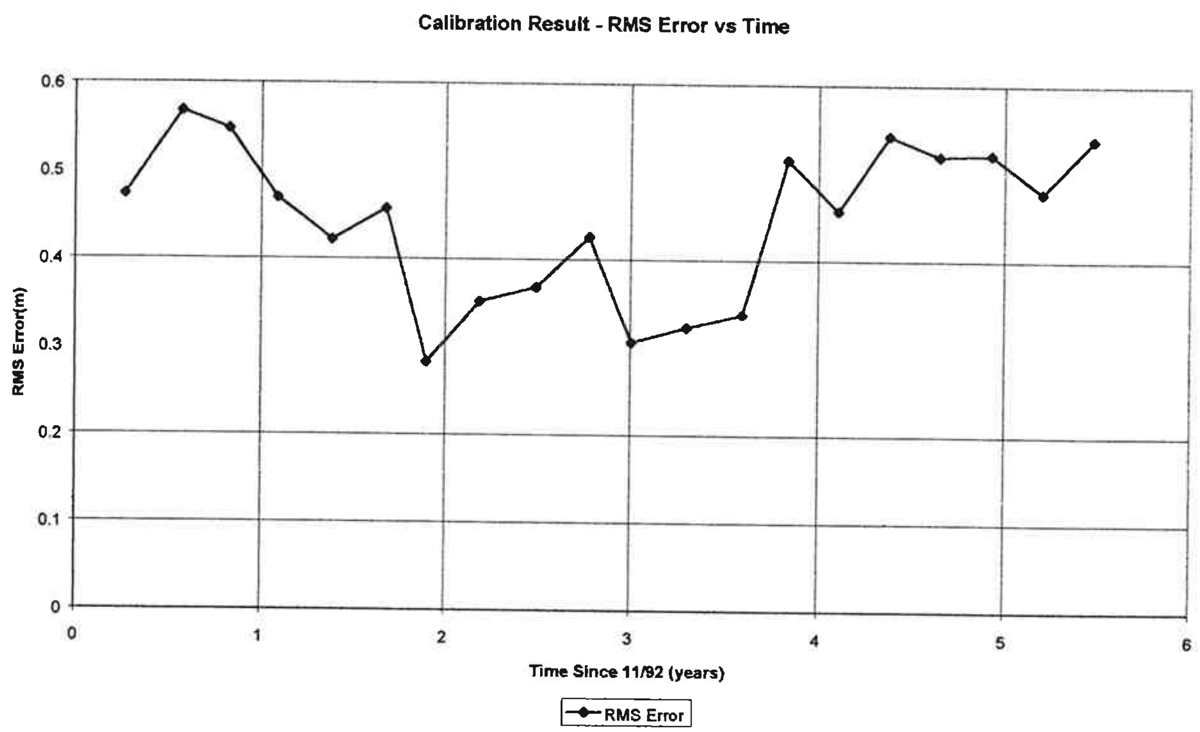
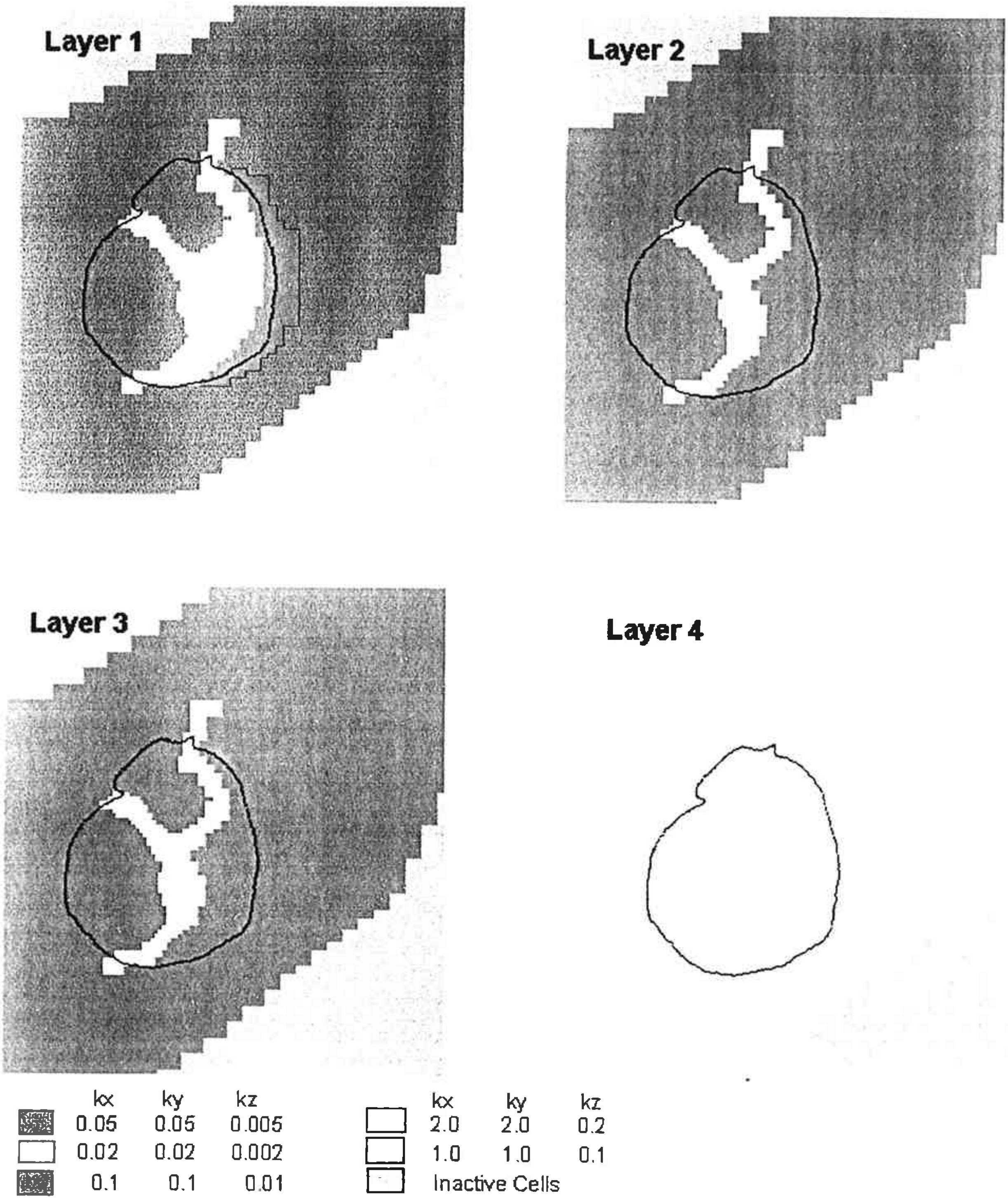


Figure 8.2: Hydraulic Conductivity Distribution in the Calibrated Model



Although the target root mean square error was 0.3m, this was not achieved for all model times. In fact Figure 8.1 suggests that the root mean square error is typically between 0.3 and 0.5m. Although this level of precision is considered adequate and appropriate for the accuracy of the observations and measurements from which the model has been developed, a better match to the observed groundwater hydrographs may be possible if the following problems can be resolved:

1) An accurate history of pumping from all bores was not available. This problem is particularly obvious in the responses recorded in those observation bores in the vicinity of pumping well P10. Figure A1 in Appendix A shows the matches for observation bores TL5, 11, 12, 13, 14 and 15 model consistently over-estimates the water table in these observation bores and that the difference between predicted and observed hydrographs increases in the vicinity of well P10. Martin (1990) indicates that a pumping well was in fact drilled in 1988, originally referred to as bore 1/88, this bore is probably the bore currently known as P10. Martin (1990) further suggests that this bore was tested prior to 1990 and that pumping was more or less continuous at that time. Without an accurate record of pumping rates and pumping times for this bore it will not be possible to improve the calibration statistics for those wells located in the south western sector of the lake.
2) The record for some bores is clearly inaccurate. For example the record for TL13 shows a lengthy period of constant head that may well indicate faulty instrumentation, water levels that are below a measurement threshold or that the bore is dry.
3) The hydrogeological conceptualisation used to develop the model, including the hydraulic conductivity distribution, has been provided by George and Dogramaci (1999). The options for improving the calibration are limited by the requirement to preserve the hydraulic conductivity distribution thus defined. A better match might well be possible if changes were made to the hydraulic conductivity distribution.
4) The topographic data for the lake and surrounding land surface provided for the study is too coarse to be able to incorporate an accurate surface topography in the model. The subsequent mismatch between actual and model elevations introduces an error in the application of depth-dependant evapotranspiration rates in the model.

A mass balance for the lake is presented in Table 8.1. Fluxes into the lake are made up of rainfall recharge, lateral flow from the area surrounding the lake and recharge during inundation. Recharge arising from lake inundation and from rainfall are reported separately here because they are treated differently in the model (ie. as third type transfer and second type flux boundary conditions respectively). The model is not in steady state and as such water entering and leaving storage must be accounted for in the volumetric balance. The largest single flux entering the groundwater beneath the lake is the lateral flow from the surrounding aquifers. This can be explained by the fact that between inundation events evapotranspiration results in a large discharge of water from the lake bed that creates a depression in the piezometric surface beneath the lake. The lake becomes a groundwater sink with lateral hydraulic gradients forcing water to flow towards the lake from the surrounding aquifer.

The importance of evapotranspiration on the volumetric balance of water within the lake bed can be seen in Table 8.1. It represents the single largest flux within the model. Other fluxes that extract water from the lake bed include pumping, lateral flow from the lake, flow to the diversion channel and flow to the lake during inundation. This latter flux is relatively small and it appears briefly during lake level recession at the completion of an inundation event when heads in the aquifer surrounding the lake exceed lake level and as a result, groundwater is discharged to the lake. Table 8.1 also indicates that lateral flow away from the lake is relatively small. This observation can be explained by the low hydraulic conductivity of the sediments beneath the lake and the short period when hydraulic gradients act to disperse water from beneath the lake.

Table 8.1: Volumetric Balance for the Lake Area of Calibrated Model

Flux	Volume In (m^3)	Equivalent Flux In Through Lake Surface (mm/yr)	Volume Out (m^3)	Equivalent Flux Out Through Lake Surface (mm/yr)
Evapotranspiration	0	0	1,562,823	72.0
Rainfall Recharge	517,501	23.9	0	0
Pumping	0	0	142,433	6.6
Lateral Flow	620,317	28.6	7,380	0.3

Across Boundary				
Flow to Drain	0	0	13,382	0.6
Flow to/from Lake During Inundation	511,934	23.6	6,936	0.3
Change in Storage	428,380	19.7	345,119	15.9
Total	**2,078,131**	**95.8**	**2,078,074**	**95.7**

8.2 Predictions

For the purpose of evaluating the efficiency of any pumping scenario (including the no pumping option) it is assumed that the target for water level depression is 2m below ground level and that within the lake that target is equivalent to a water level at or below 295m AHD.

8.2.1 No Pumping

The no-pumping scenario indicates the water levels that would be expected beneath the lake in the absence of any dewatering attributable to pumping. The results of this scenario are presented Figure 8.3 that shows water table variation with time in selected observation bore locations. The water table appears to fluctuate between 296m and 298m AHD with a clear seasonal pattern that corresponds to the seasonally averaged evapotranspiration and recharge model boundary conditions. Periods of lake inundation are also apparent as intervals when the head in the observation bores exceeds 297m AHD. Figure 8.4 displays the equipotential groundwater contours in the model at a time of 4000 days. As expected the water table beneath the lake does not decline to more than 2m below the ground surface to any appreciable extent. Under this condition groundwater discharge through evapotranspiration of near surface waters can be expected.

Figure 8.3: Predicted Heads in Selected Observation Bores - No Pumping Scenario

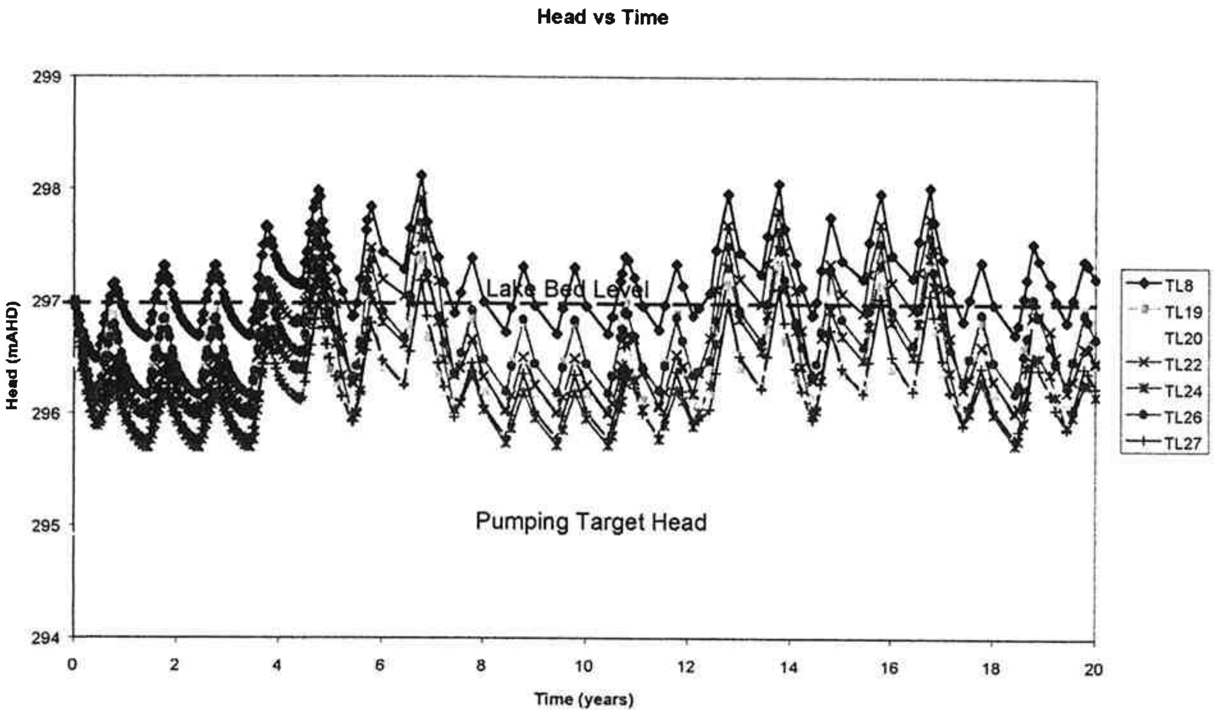
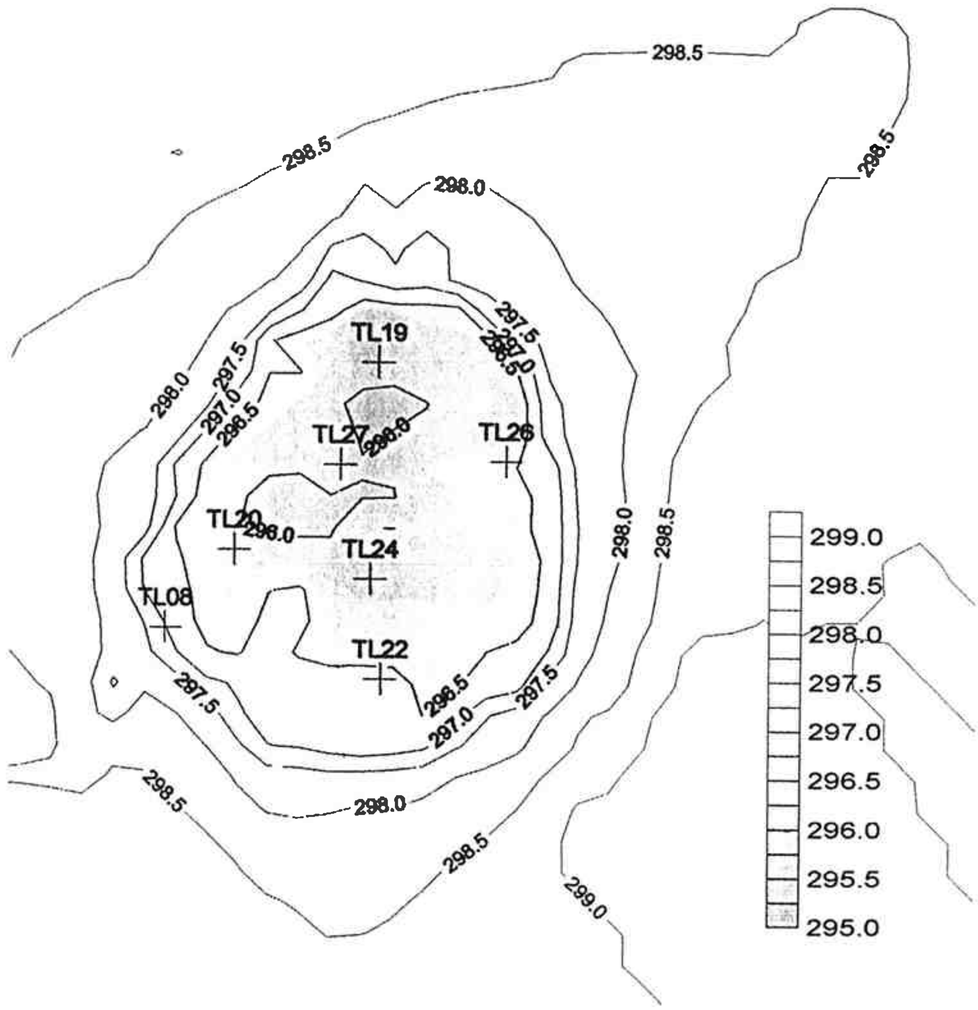


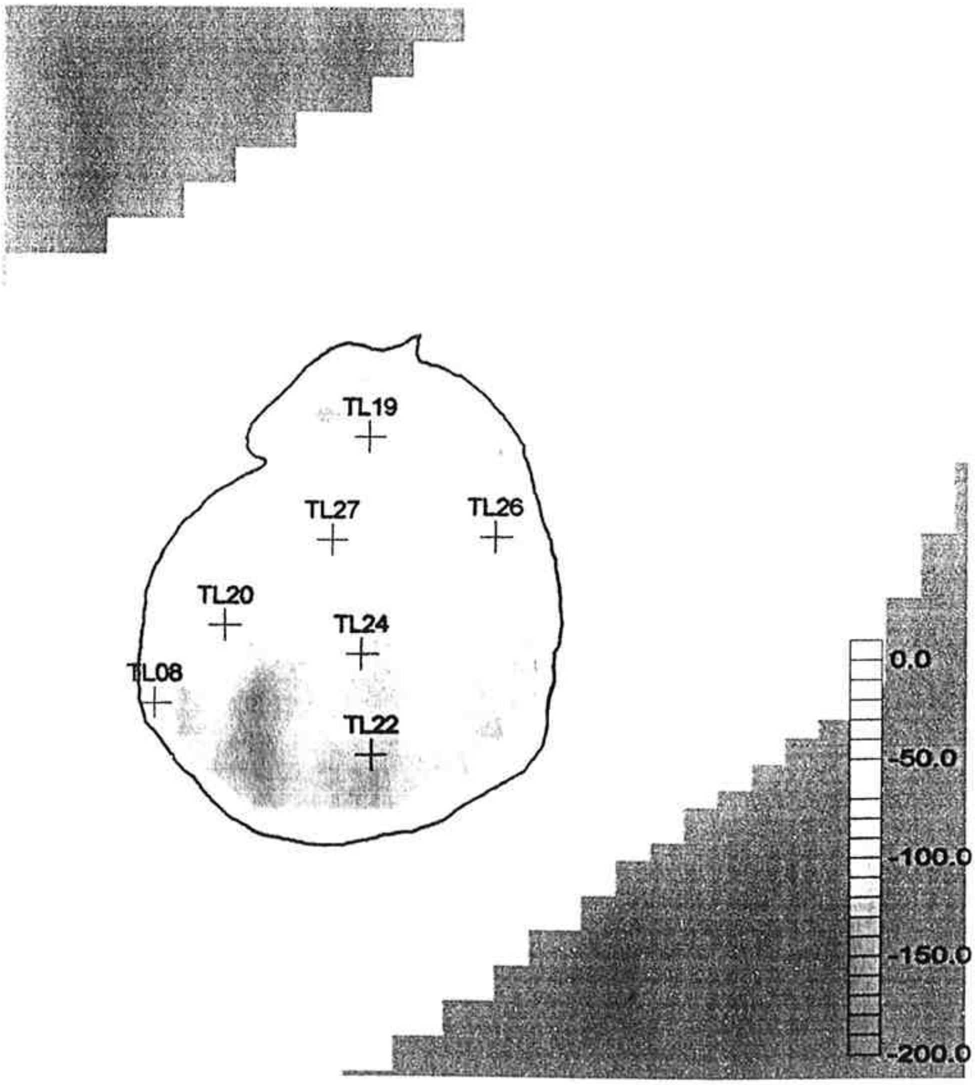
Figure 8.4: Groundwater Levels at 4000 Days (11 years)



The model result expressed in terms of net recharge in mm/year at 4000 days model time is shown in Figure 8.5. Here negative recharge indicates discharge from the model. In this case discharge is due to evapotranspiration effects. It can be seen that the lake represents a local sink for the aquifer where large volumes of water are discharged through evapotranspiration. A summation of fluxes in the model over the entire 20 years of model time indicates that a total of 5.75 million cubic metres of water has been removed from the area beneath the lake surface as evapotranspiration. This equates to an average annual evapotranspiration rate of about 38 mm for the lake area.

A velocity vector plot at 4000 days presented in Figure B1 of Appendix B demonstrates the lateral flow system generated under the no-pumping scenario. The inward flux of water towards the centre of the lake is a direct consequence of evapotranspiration that is most pronounced at the low ground elevations of the lake bed.

Figure 8.5: Net Recharge at 4000 Days - No Pumping Scenario



Note Coloured contours represent region in which evapotranspiration exceeds recharge (units mm/year)

8.2.2 Continuous Pumping

The results of this scenario are presented in Figure 8.6 that shows water table variation with time in selected observation bore locations. Figure 8.7 displays the proportion of the lake in which the water level is below 295m AHD at a time of 4000 days (approximately 11 years). Here it can be seen that most of the lake area has water table depressed to below 295m AHD (ie. depth to water table in excess of 2m). It should be noted that the selected time of 4000 days corresponds to a time of relatively low groundwater levels being some 4 to 5 years after a lake inundation episode. The water table elevation is strongly influenced by lake inundation and water levels are expected to rise above the surface during such events. After inundation ceases the water table appears to decline rapidly. The rate or groundwater recession following inundation is described in more detail in Section 8.3.

The differences in water table elevation predicted at the observation bore locations of Figure 8.6 generally arises out of the proximity of the individual observation bore to the pumping bores, the pumping rates in the relevant bores and the hydraulic conductivity.

Figure 8.8 shows the predicted drawdown at day 4000 (approximately 11 years) of the pumping scenario compared to the non-pumping scenario at the same time. Drawdowns of up to 5m are expected in the lake with drawdown reducing in the region of the lake boundaries.

Figure 8.6: Water Table Variations in Selected Observation Bore Sites - Continuous Pumping Scenario

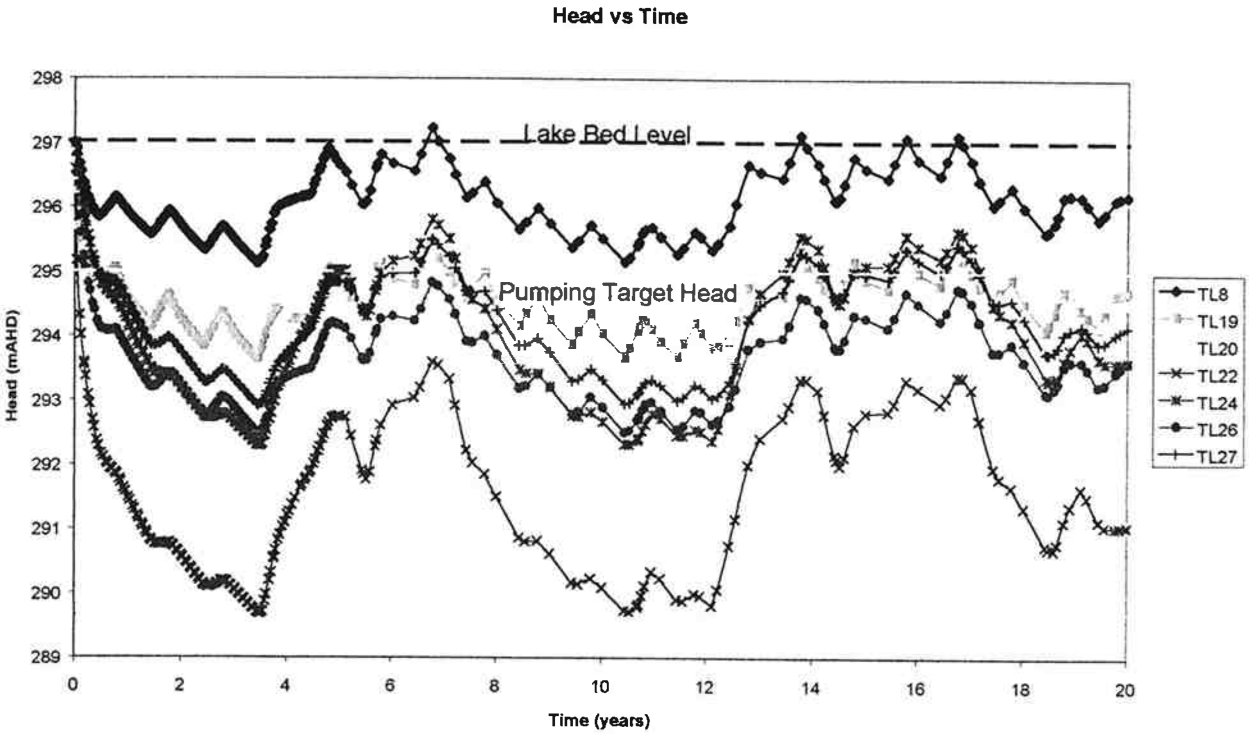


Figure 8.7: Proportion of Water Table Below 295m AHD at 4000 days - Continuous Pumping Scenario

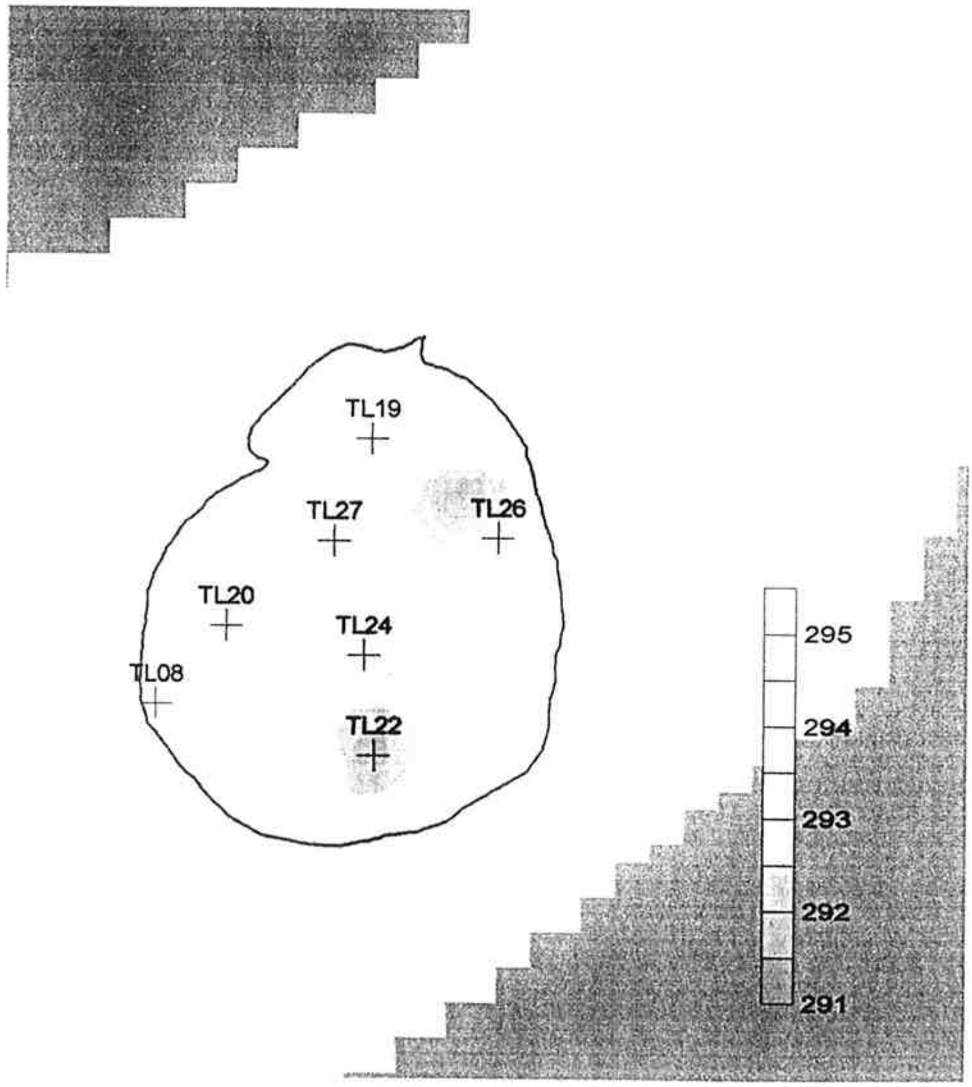
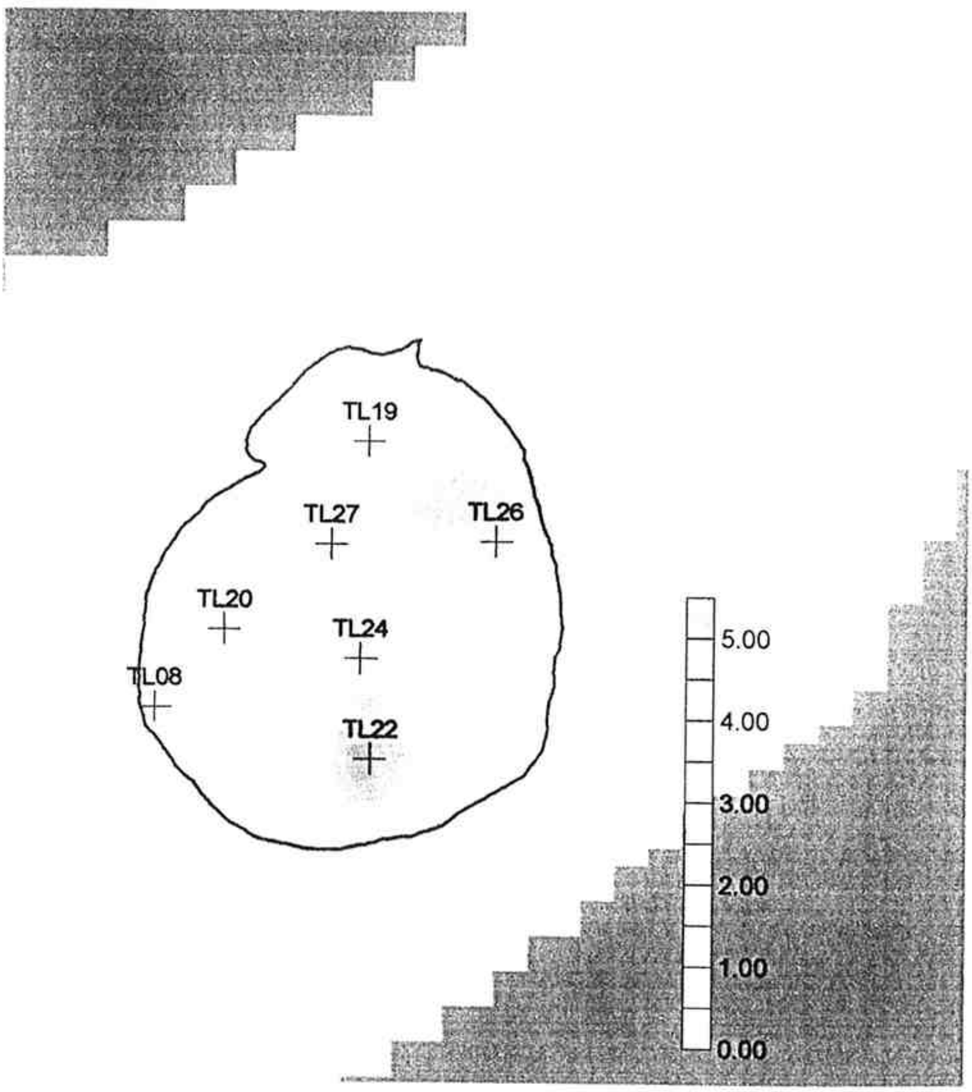


Figure 8.8: Drawdown (m) for the Continuous Pumping Scenario Compared to the No-Pumping Case - Time = 4000 Days

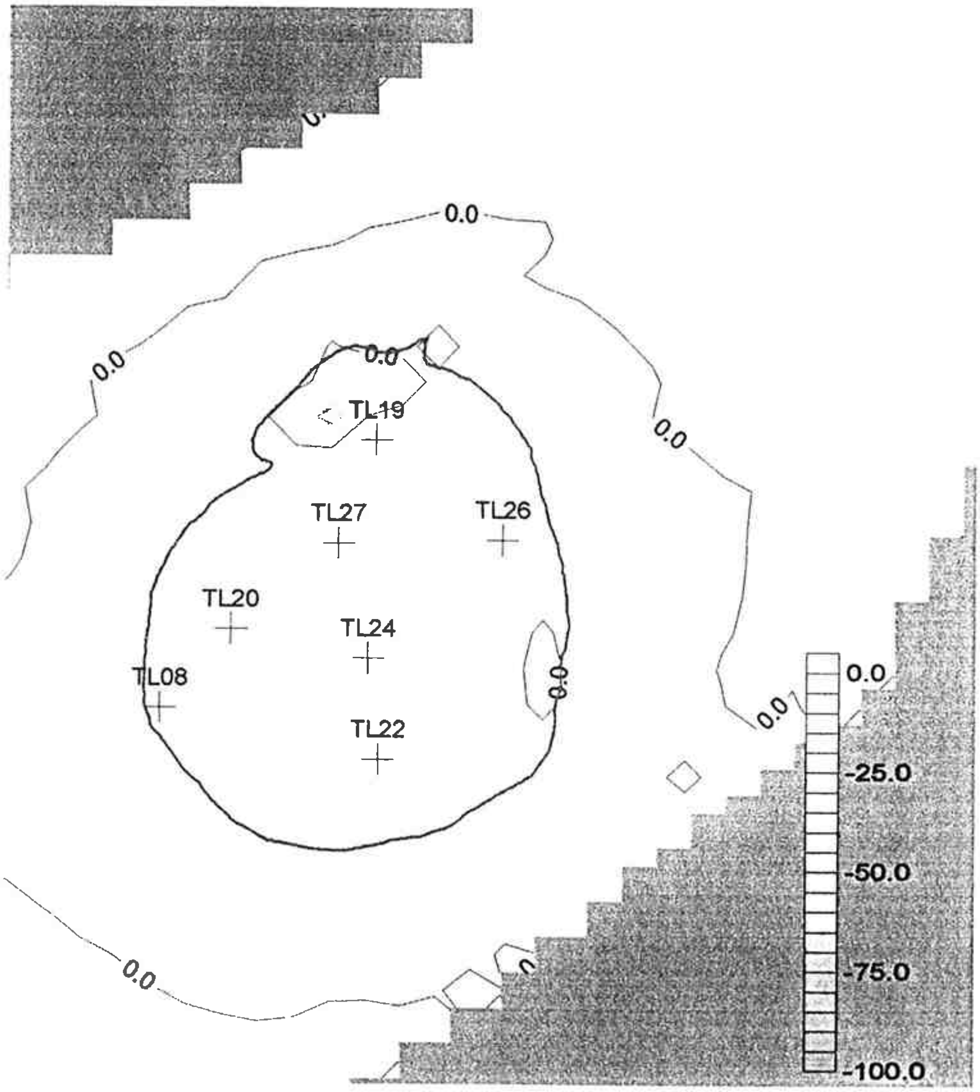


The impact of pumping on the model's net recharge is shown in Figure 8.9. Net recharge is defined as the rate of recharge in excess of evapotranspiration and is negative when evapotranspiration exceeds recharge. Here it can be seen that most of the lake is now under net recharge as the water table has been depressed to below the evapotranspiration extinction depth by the effects of pumping. It suggests that the continuous pumping scenario can effectively reduce discharge through evapotranspiration within the area of the lake. In fact model results indicate that the total cumulative evapotranspiration volume from the lake is

1.22 million cubic metres, or an average annual rate of about 8.0 mm.

Velocity vectors after 4000 days of pumping are presented in Figure B2 of Appendix B. Attention should be drawn to the fact that vector scaling factors are not the same for Figures B1 and B2 and that groundwater velocities calculated in the pumping scenario (Figure B2) far exceed those in the no-pumping model of Figure A1.

Figure 8.9: Net Recharge after 4000 Days - Continuous Pumping Scenario



Note: Coloured contours represent region in which evapotranspiration exceeds recharge. White region shows area where recharge exceeds evapotranspiration (units mm/year).

8.2.3 Non-Continuous pumping

This scenario is the same as the continuous pumping model except that pumping stops during lake inundation episodes. The results of this scenario are presented in Figure 8.10 showing the predicted heads in selected observation bores. It is clear that this scenario is also effective in reducing heads beneath the lake and in reducing the amount of evapotranspiration. The total volume of evapotranspiration from the area of the lake for the entire model period has been calculated as 3.07 million cubic metres or an average annual rate of about 20 mm per year.

Differences in the groundwater head responses between the continuous and non-continuous pumping scenarios can be seen in Figure 8.6 and Figure 8.10 respectively. The continuous pumping case appears to be more effective in suppressing heads both during and between inundation episode. This phenomenon is more clearly shown in Figure 8.11 which is a comparison between the head response in the continuous and non-continuous pumping scenarios for TL24. Here it can be seen that under the continuous pumping scenario heads are depressed during all inundation episodes. It is also apparent that the duration of inundation is reduced in the continuous pumping scenario.

Figure 8.12 is a comparison of the areas within the lake that have water levels more than 2m below the ground surface for the continuous and non-continuous pumping scenarios. The improvement in dewatering efficiency of the continuous pumping case is apparent at most times and appears to become more pronounced with time.

Figure 8.10: Predicted Heads in Selected Observation Bores - Non-Continuous Pumping Scenario

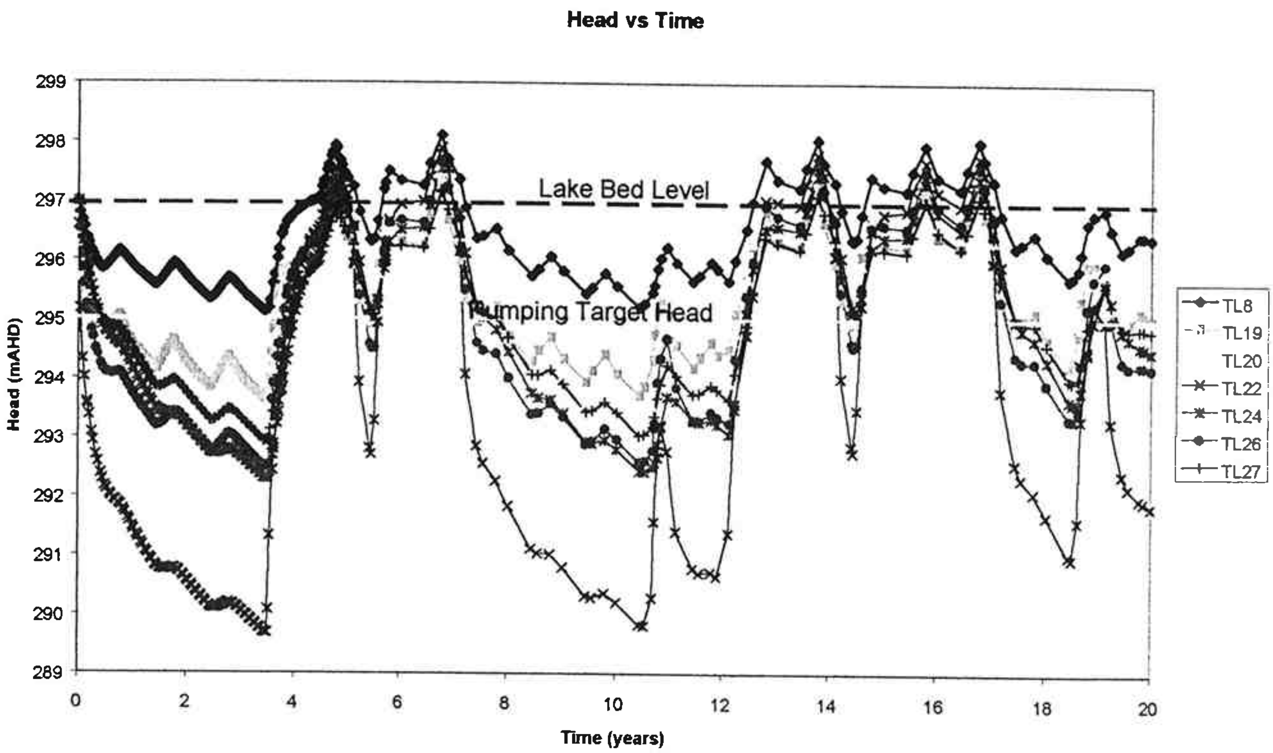


Figure 8.11: Comparison Between Continuous and Non-Continuous Pumping Scenarios - Heads at Observation Bore TL24

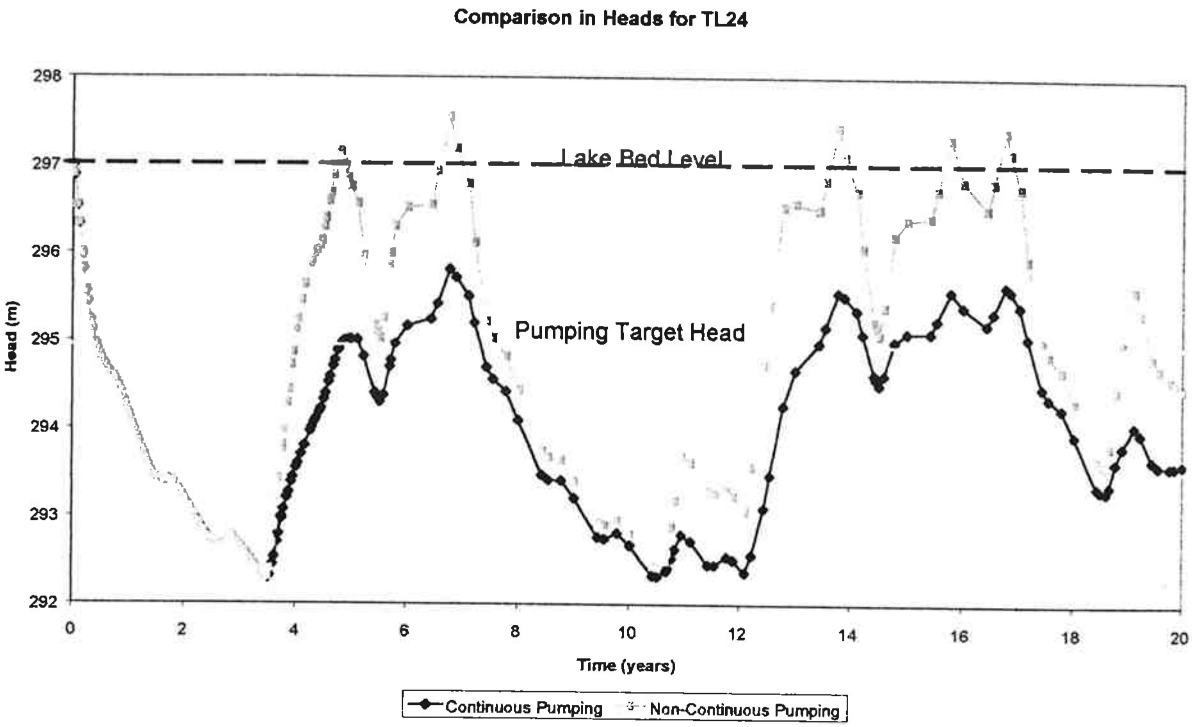
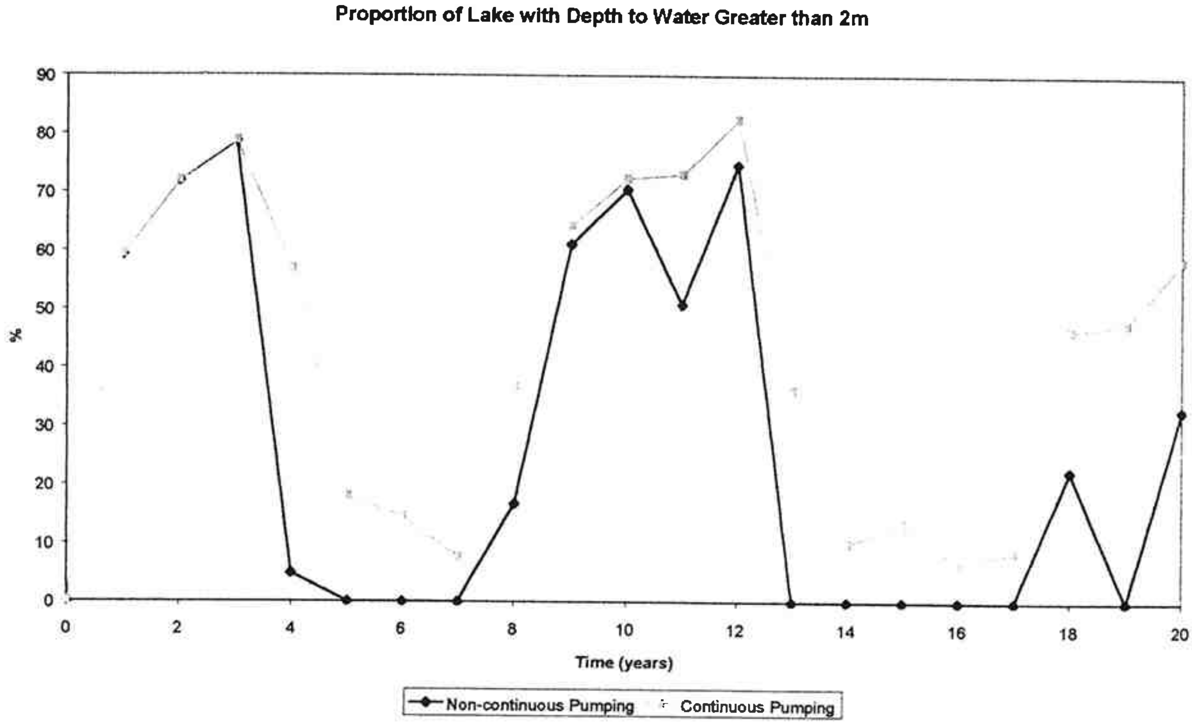


Figure 8.12: Percentage of Lake Surface With Depth to Water Exceeding 2m for Continuous and Non-Continuous Pumping



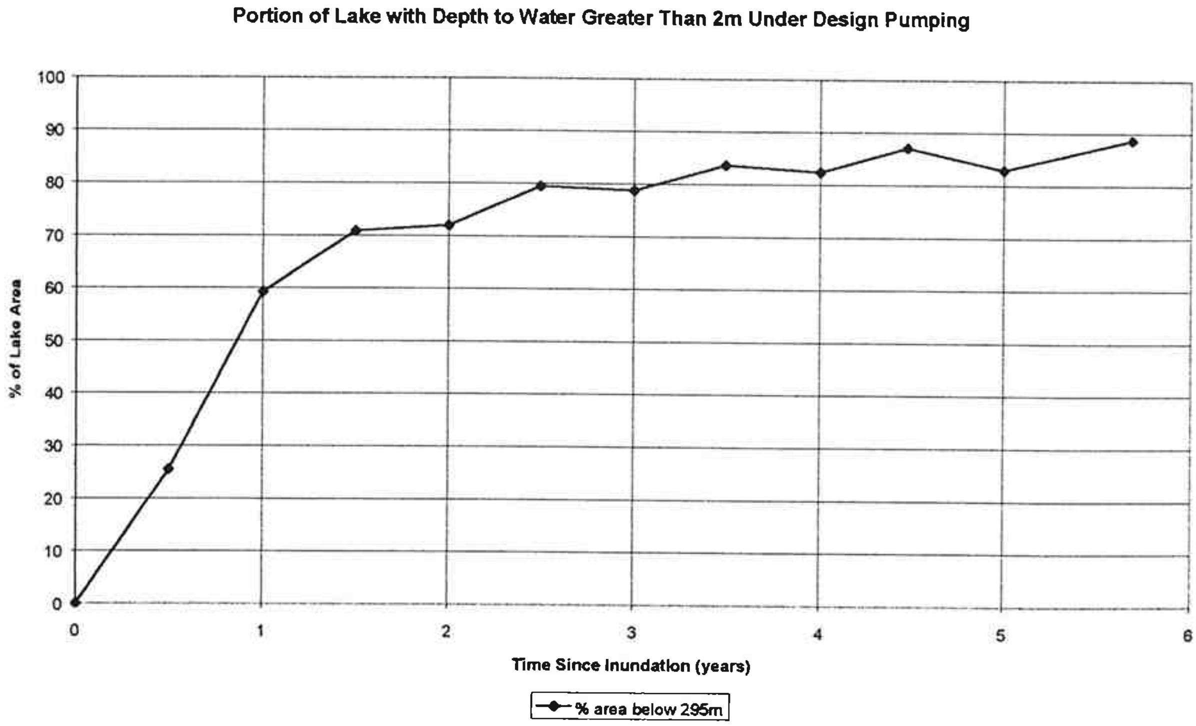
8.3 Sensitivity Analyses

Results of all the sensitivity analyses are presented in terms of the proportion of lake bed that has a depth to water table in excess of two metres. Of particular relevance is the rate at which this proportion changes with time. Sensitivity scenarios all used an initial head of 297m AHD distributed throughout all elements of the model. This condition corresponds to the situation that would arise at the end of an inundation episode when the last of the surface water has drained from the lake and the water table is at the surface. The sensitivity models described herein investigate the rate at which the water table would recede under average seasonal evapotranspiration and recharge and assuming no further inundation. Pumping is assumed continuous and all models were run for 2000 days.

8.3.1 Base Case

The base case for all comparisons is the calibrated model case. This scenario corresponds to the continuous pumping model described in Section 8.2.2 and describes the rate at which the water table will decline if there is no further inundation and assuming average climatic conditions. Results for this scenario are presented in Figure 8.13. The "saw-tooth" fluctuations apparent in this figure results from the fact that data are plotted at half yearly intervals and the evapotranspiration and rainfall recharge are represented as seasonally averaged values.

Figure 8.13: Proportion of Lake with Depth to Water Greater than 2m Plotted Against Time for Design Pumping and Calibrated Model



8.3.2 Sensitivity Models

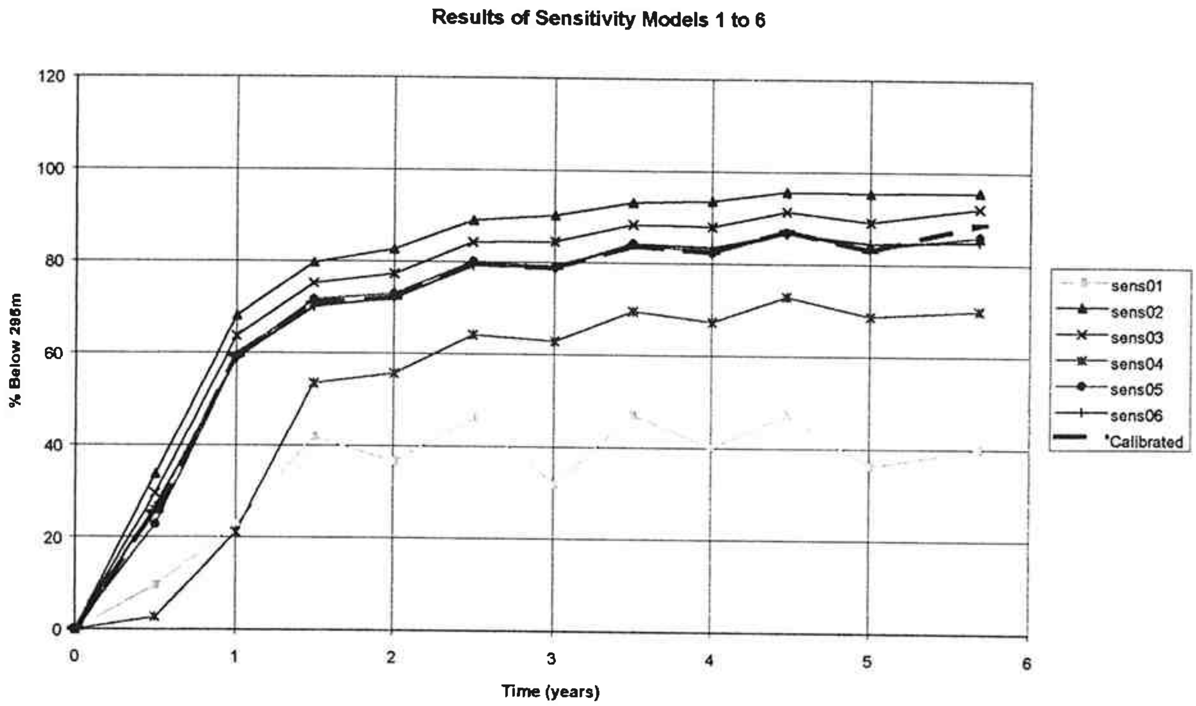
Results from all twelve sensitivity model simulations are presented in Figure 8.14. Results are presented as the area of lake that has a water table below 295m AHD (equivalent to 2m depth to water table) plotted against time since lake inundation. Figure 8.14 suggests that sensitivity cases 5, 6, 7, 8 and 12 have little impact on the rate at which the water table recedes under the design pumping condition. In other words model results are almost insensitive to small scale variations in hydraulic conductivity arising from the inclusion of geological detail in the model.

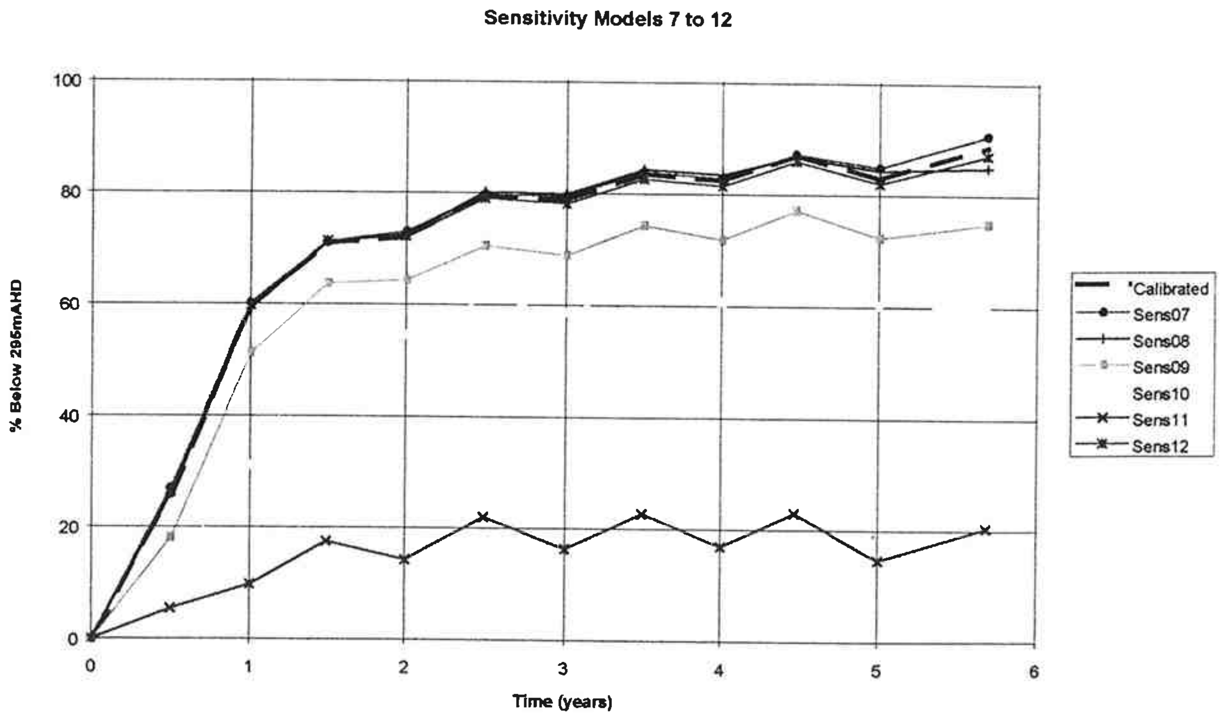
Variations in results for sensitivity cases 1, 2, 3 and 4 suggest that the model results are sensitive to global scale changes in the hydraulic conductivity. Increasing the horizontal hydraulic conductivity by a factor of two results in relatively shallow, and widespread cones of depression around each pumping well. As a result a smaller proportion of the area has a water table below 2m. Conversely decreasing the horizontal hydraulic conductivity by a factor of two creates greater drawdown and steeper hydraulic gradients within the cones of depression that surround each pump and dewatering efficiency is improved.

Results for sensitivity cases 3 and 4 suggest that increasing the vertical hydraulic conductivity by a factor of ten has little impact on the result but that a ten fold decrease in vertical hydraulic conductivity will result in poorer dewatering efficiency. This result can be explained by the fact that restricted vertical conductivity results in water being extracted from the screened model layer only with little contribution from shallower or deeper layers. In this case most of the pumping wells extract water from the model's bottom layer. Pumping causes an immediate drawdown in this layer with the formation of non-hydrostatic vertical hydraulic gradients that create a potential for water to descend from shallow layers. The low vertical hydraulic conductivity prevents water from draining immediately from the shallow layers of the model. As pumping persists water is slowly drained from the shallow layers. In other words the low vertical hydraulic conductivity in this model gives rise to a delay in vertical drainage that reduces the efficiency of dewatering. This delayed yield effect results in the water table responding slowly to the deep pumping. Delayed yield from shallow layers may eventually lead to dewatering results of similar magnitude as the calibrated case, but at much longer pumping times.

Models 9, 10 and 11 investigate the sensitivity of dewatering and water table recession to the rate at which the wells are pumped. Figure 8.14 suggests that model results are strongly dependant on pumping rate and that a substantial reduction in dewatering efficiency can be expected if pumping falls to 60% of the assumed rates. Although it is considered unlikely that the bores will be capable of pumping rates substantially lower than those assumed (refer to Table 7.1), it is contended that additional drilling could be used to rectify any such future shortfall. Of particular importance in this regard are the pumping rates in wells P11 and P13. These two wells are both assumed to be capable of pumping as much as 300 m^3/day thereby representing almost 60% of the combined extraction rate for all wells. Well P11 has recently been tested at a pumping rate of 270 m^3/day over approximately three days (refer to Appendix A for test observations and results). The well has yet to demonstrate that it is capable of sustaining the assumed 300 m^3/day. Similarly P13 has been subjected to a brief step drawdown test and its ability to sustain high pumping rates over long periods has yet to be confirmed.

Figure 8.14: The Percentage of Lake Bed With Depth to Water Table Exceeding 2m for all Sensitivity Cases





9. Discussion

The model calibration procedure has highlighted the fact that the historic pumping data provided for this study is not necessarily a complete and accurate record of all pumping activities throughout the duration of the calibration period (from November 1992 to June 1998). In particular, the information supplied for pumping from well P10 (and possibly from well P9) is not complete. While this discrepancy has been recognised in the course of calibration it has not been rectified because the record in question is not available. The net effect of such discrepancies is to influence the statistics used to quantify the calibration matching to observed data. Irrespective of this problem, the calibration procedure has demonstrated that the model faithfully predicts groundwater response to pumping and to rainfall and evapotranspiration stresses.

Given that the designed pumping scheme is aimed at reducing evapotranspiration that occurs within the lake bed, it is of interest to compare the amount of evapotranspiration predicted for each of the pumping scenario models. This comparison is presented in Table 9.1 which presents the cumulative evapotranspiration in each model. It should be noted that the data included in Table 9.1 relates to evapotranspiration from the area of the lake only. Reductions in evapotranspiration of between 50 and 80% can be expected over a twenty year period if pumping is carried out.

Table 9.1: Comparison of Evapotranspiration from Lake Bed for Pumping Models

Model	Evapotranspiration (million m^3)	Evapotranspiration (mm/yr)	% Reduction
No Pumping	5.75	75.5	-
Continuous Pumping	1.22	16.0	79
Non-Continuous Pumping	3.07	40.2	47

The results described in Section 8 suggest that the dewatering system that has been designed will be effective in reducing the water table beneath the lake. It is however recognised that not all of the dewatering wells have been tested and the assumed pumping rates for some of these wells may exceed the final pumping rate that is possible from the well. In particular the relatively effective dewatering results depend on the ability of both pumps P11 and P13 to produce 300 m^3/day.

While P11 has been tested for an extended period and is believed to produce slightly less than 300 m^3/day, P13 has yet to be fully tested and a somewhat poorer dewatering result would be obtained if this well proves to be less productive than anticipated.

The results presented in Figure 8.11 are important and require some comment. This figure shows the expected head variation in one observation bore (TL24) under continuous and non-continuous pumping. In the continuous pumping case pumping continues throughout all lake full episodes, while in the non-continuous case the pumps are turned off during all inundation episodes. The result suggests that the continuous pumping scenario will reduce the duration of each inundation episode and will also reduce lake levels during each episode. Although further discussion on this matter is outside the scope of this study, it is important to recognise the fact that lake inundation episodes will be influenced by pumping, particularly by the continuous pumping scenario.

It should be noted that the continuous pumping model has predicted that a small area around wells P11 and P13 will have a depth to water in excess of 2m during periods of inundation. In other words the calibrated model indicates that the lake will become perched above the shallow groundwaters during inundation and that the sediments beneath the lake in the vicinity of P11 and P13 will become desaturated as a result of intensive pumping in these bores. This result arises from the fact that pumping rates in these two bores (300 m^3/day) exceed the rate at which water can infiltrate and drain through the shallow sediments to the depth of the well screens. It is an interesting phenomenon and is one that could be tested by appropriate measurements during operation of the pumping scheme.

Sensitivity models indicate that variation in hydraulic conductivity on a global scale is particularly important in determining the efficiency of dewatering. It is acknowledged that if the model underestimates the horizontal hydraulic conductivity of the region then the results presented herein will provide an overestimation of the dewatering efficiency of the designed pumping scheme. It is however unlikely that the model has grossly underestimated hydraulic conductivity as the calibration procedure carried out and described above provides some confidence that the hydraulic conductivities in the model are reasonably close to reality. Of further comfort is the fact that pumping tests recently conducted on well P11 provide support for the hydraulic conductivities used in the model. Preliminary assessment of recent long term pumping tests performed on well P11 suggests that the hydraulic conductivity of the palaeochannel is in the order of 35 m^2/day. The transmissivity of the model layer 4 is 40 m^2/day in the palaeochannel and 10 m^2/day elsewhere. Results of the pumping test are presented in Appendix C.

Sensitivity models also suggest that small scale variation in hydraulic conductivity associated with the detailed geology of the area has little or no impact on the model result. This can be seen in the results for sensitivity cases 5, 6, 7, 8 and 12 that investigate the effect of varying the hydraulic conductivity in small regions of the model. Cases 5 and 6 considered increased and decreased (by a factor of 2) the hydraulic conductivity in the eastern half of the lake. Case 7 included a thin margin of increased hydraulic conductivity at the margins of the palaeochannel and Case 8 included reduced hydraulic conductivity in faults and dykes that cross the lake. All of these cases resulted in water table recessions that closely mirrored that of the base case scenario. Sensitivity case 12 investigated the impact of removing the northwestern arm of the palaeochannel. The resultant decline in water table level under pumping closely follows that of the base case. In other words if the northwestern arm of the palaeochannel had been removed from the predictive model scenarios, the results would have been almost unchanged from those presented in Section 8.2. These results indicate that the dewatering process involves the flow of water throughout large volumes of aquifer to the pumping wells and that small scale changes of aquifer properties within this large volume have little impact on the overall dewatering performance.

10. Conclusions

A three dimensional groundwater flow model has been formulated that can be used to predict the groundwater response to various applied stress conditions including the assessment of head response to pumping.

Results of predictive simulations suggest that both continuous and non-continuous pumping schemes will be effective in increasing the depth to water table over much of the lake. It is predicted that 80% of the lake area will have a depth to water of more than 2m after 1000 days of pumping following a lake-full episode. Provided evapotranspiration does not occur when the water table is deeper than 2m then it is further implied that evapotranspiration and salt concentration will not occur over 80% of the lake area after 1000 days of pumping. This result can be compared with the no-pumping scenario in which net discharge through evapotranspiration is predicted to occur over the entire lake area at all times.

The model results are sensitive to global changes in hydraulic conductivity (both horizontal and vertical) and to bore pumping rates, but are reasonably insensitive to small scale changes in hydraulic conductivity that may arise out of the inclusion of detailed geological structure within small regions of the model. However the model appears to be well calibrated and significant error in the applied values of hydraulic conductivities is unlikely. Accordingly the model is expected to provide reasonably accurate results. Sensitivity studies also suggest that the dewatering efficiency is strongly dependant on bore pumping rate and the ability of the scheme to reduce groundwater levels below the lake will be impaired if pumping rates are for any reason, less than the target rates.

11. Recommendations

The groundwater model, in its present form, can be used with confidence to predict the groundwater response to pumping. As such it is a powerful predictive tool that can be used to evaluate dewatering and other lake management schemes. At this stage further refinement of the model is considered unnecessary. However continued water level and pump rate monitoring is recommended in order to support future modelling. Detailed recommendations include:

- Monitoring of observation bore water levels and individual well pumping rates continue on a monthly basis.

- The model calibration be reviewed in the future after the full scale pumping scheme has been operational for at least 12 months. The additional stress on the aquifer corresponding to widespread pumping will provide a further insight to the aquifer and its response to artificial stresses.

- Monitoring of water levels in the lake during inundation is recommended.

- Water level monitoring in all observation bores during inundation should be attempted.

The pumping scheme that has been designed appears to be effective in reducing evapotranspiration beneath the lake and operational pumping should proceed as soon as practicable.

12. References

SKM Sinclair Knight Merz (1998) Project report groundwater model the effects of pumping on Lake Toolibin - Unpublished report submitted to CALM October 1998.

Martin (1987) Lake Toolibin dewatering investigation, Western Australia Geological Survey, Hydrogeology Report 2797.

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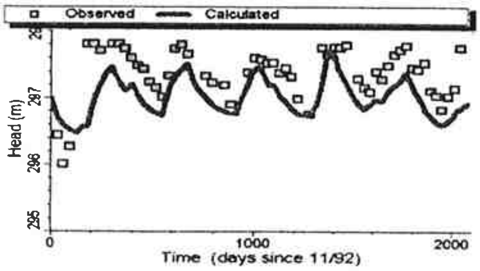
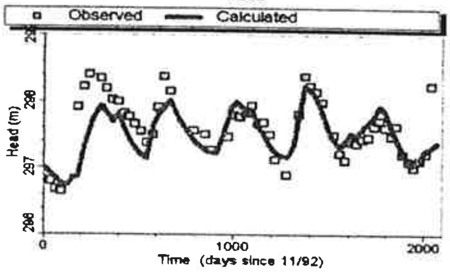
Appendix A - Calibration Results

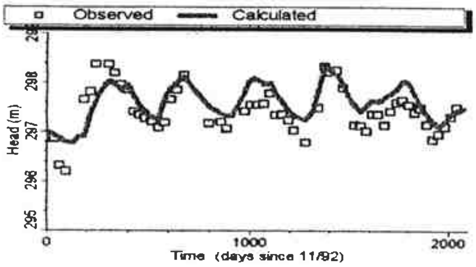
TL01



TL02



TL03



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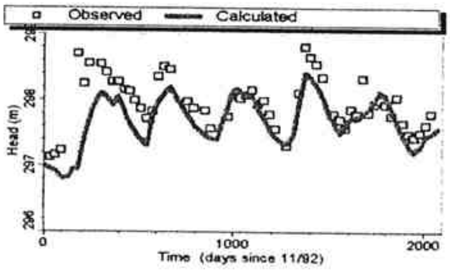

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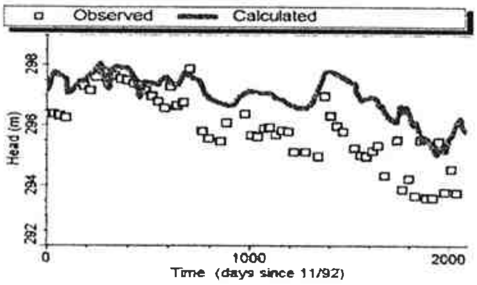

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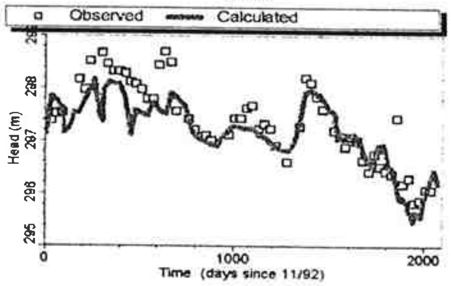

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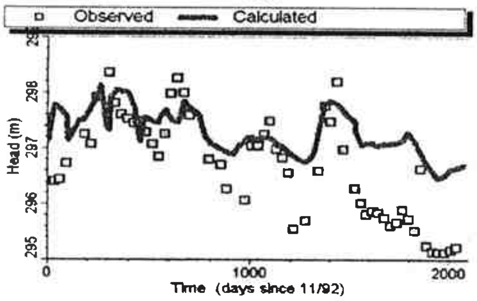

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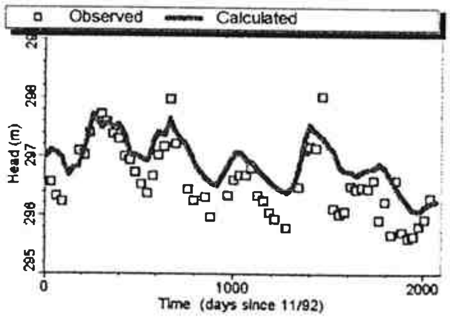

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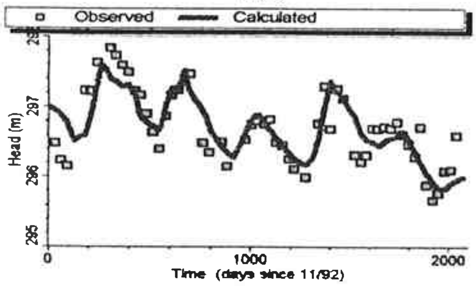

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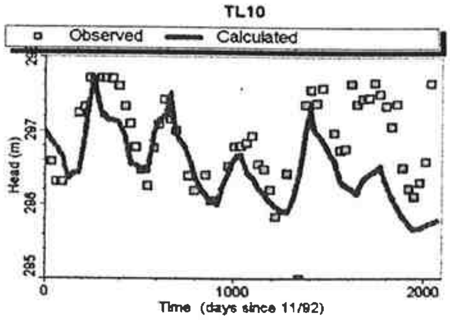

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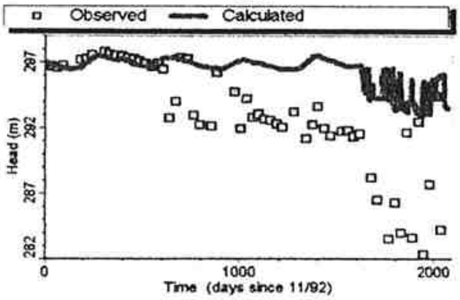

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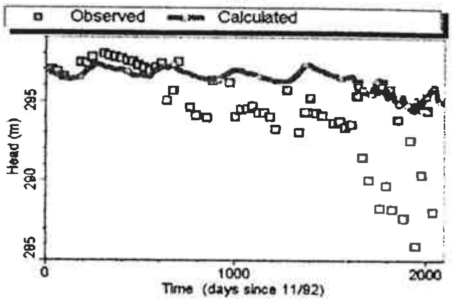

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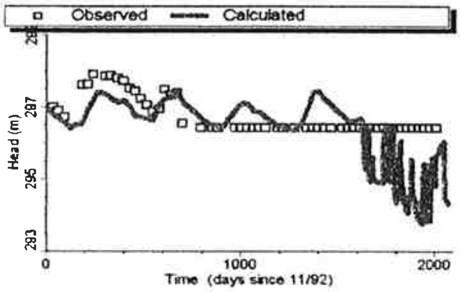

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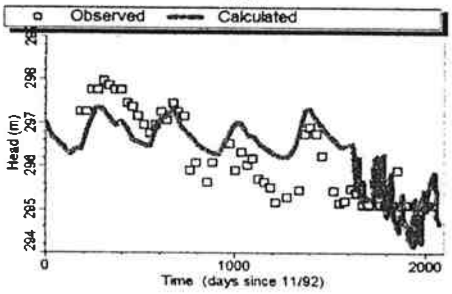

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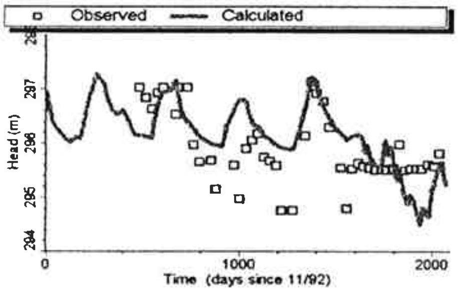

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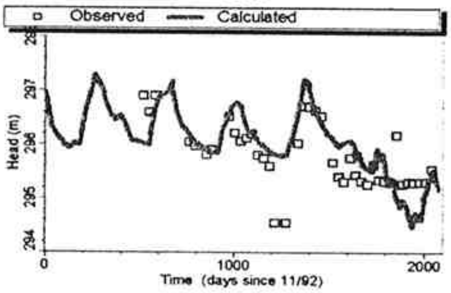

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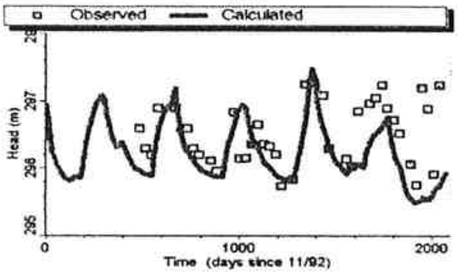

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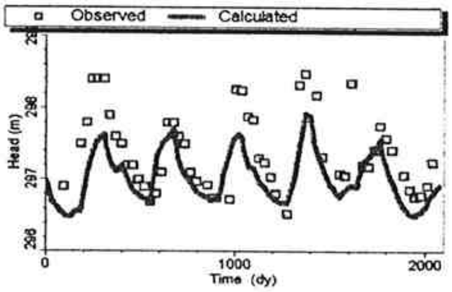

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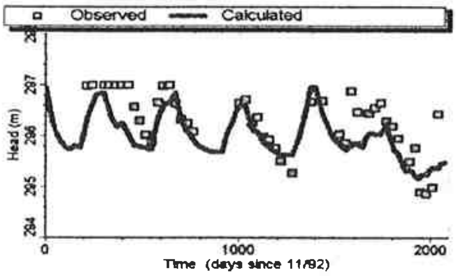

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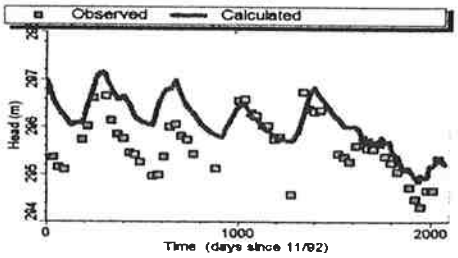

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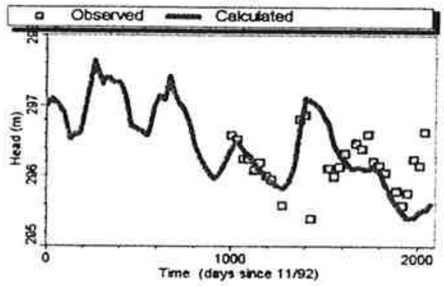

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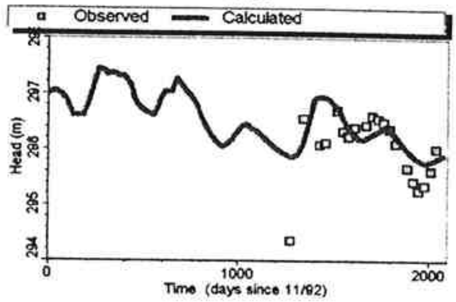

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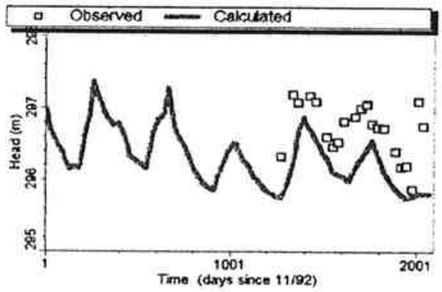

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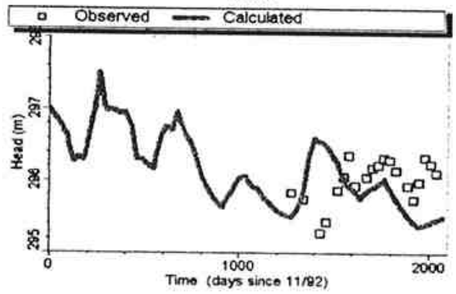

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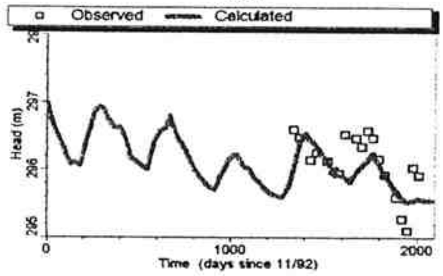

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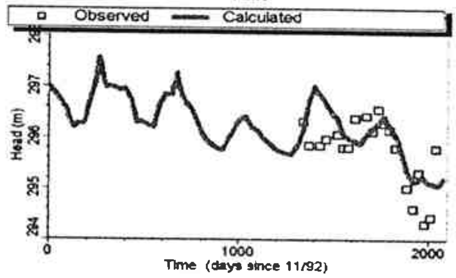

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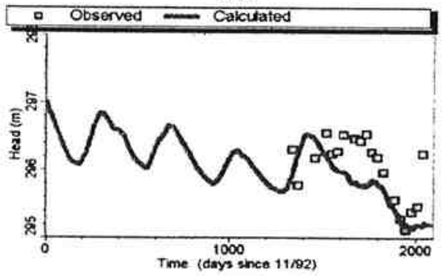


Appendix B - Vector Diagrams for Selected Models

Figure B 1: Flow Vectors for No-Pumping Model T=4000 days

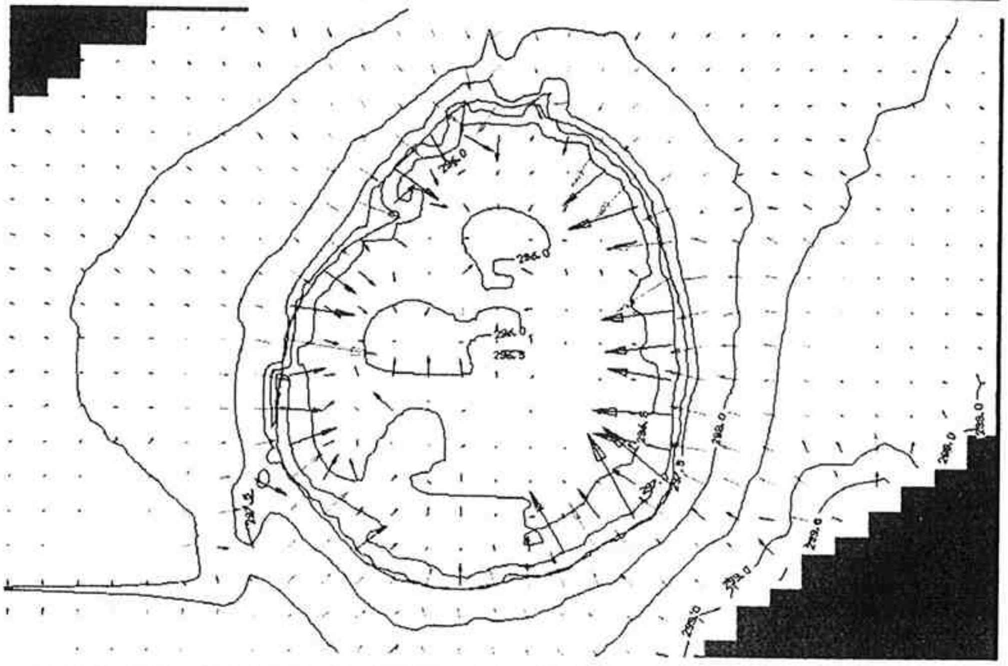
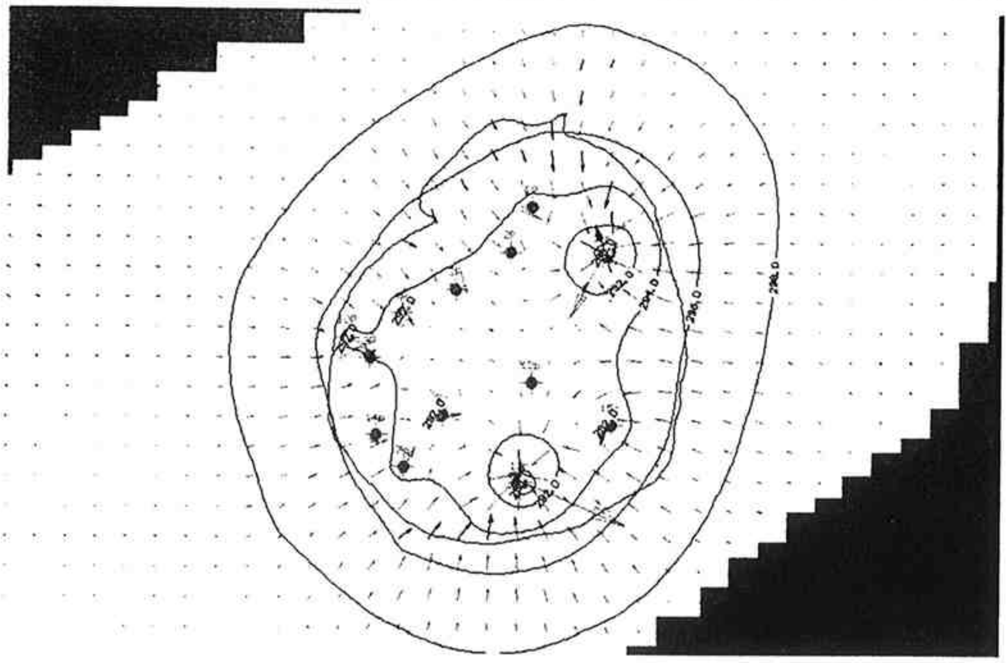


Figure B 2: Flow Vectors for Continuous Pumping Model T=4000 days



Appendix C - Pumping Test Results

Pumping Bore P11 has recently been subjected to a series of pumping tests aimed at confirming aquifer properties in and around the palaeochannel and at determining long term sustainable pumping rates. The bore was pumped for about 35 days from 12 April 2000 at a rate of approximately 250 m^3/day. Heads were observed in the pumping bore itself, in observation bores, TL28, TL29 and TL30 and in bore P15. Observation bores TL28, 29 and 30 are located in the palaeochannel approximately 200 m, 15 m and 30 m from P11 respectively. Pumping well P15 was used as an observation point in this test. It is located some 940 m due south of P11.

Plots of observed drawdown are presented in Figures C.1 and C.2. Figure C.1 shows that the drawdown measured well P11 appears to stabilise at approximately 16 to 18 m. In this bore the static water level is close to the surface and the pump has been set at 32 m below the surface. Given the depth of the pump and the observed drawdown response, it is apparent that P11 can probably sustain greater pumping rates than the 250 m^3/day as used in the test.

Figure C.1: Drawdown Measured in P11

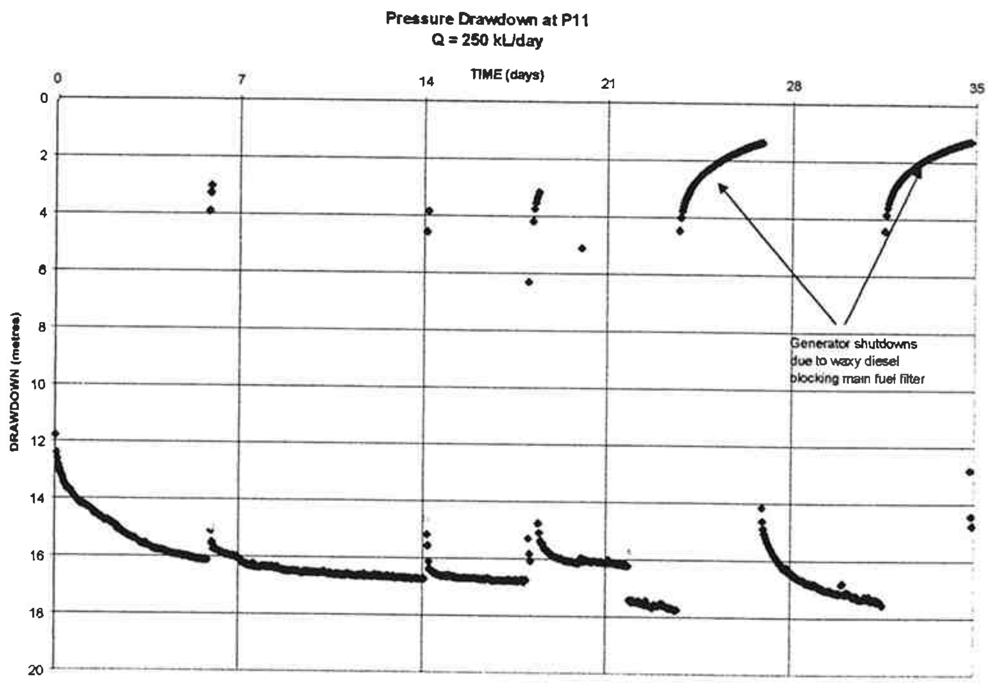
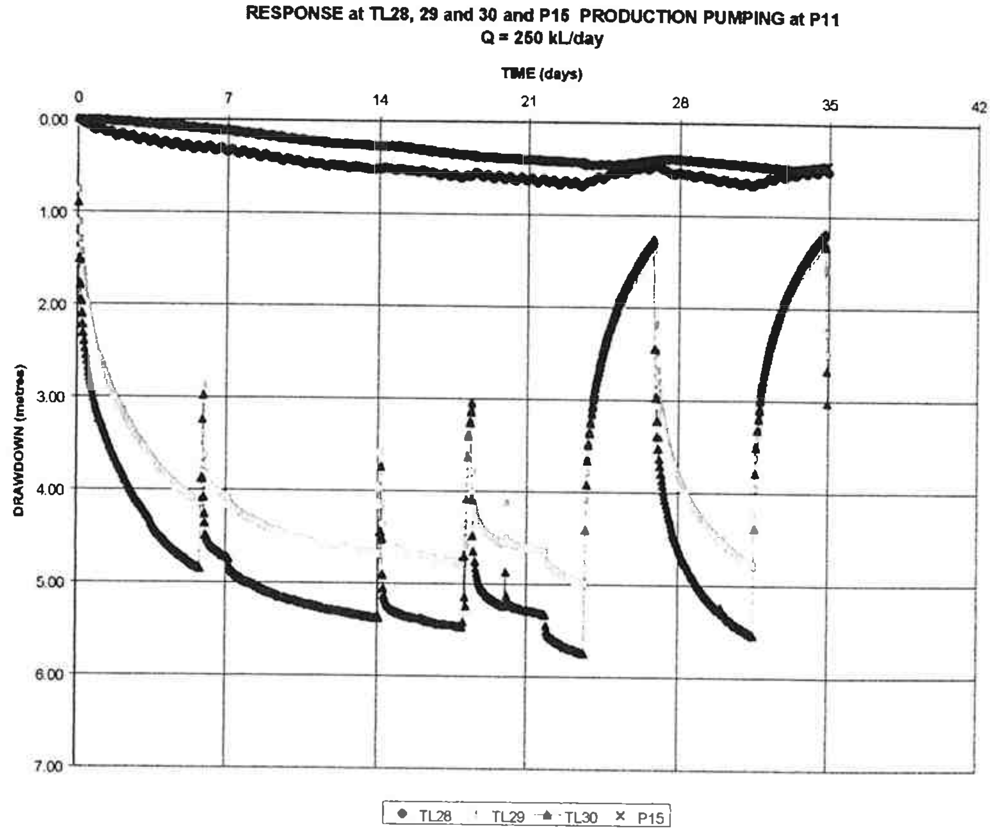


Figure C.2: Drawdown Records in all Observation Bores



Drawdown measured in the pumping bore, P11, (refer to Figure C.1) indicates several interruptions to pumping including relatively long stoppages to clear blocked fuel filters in the pump. Although the pumping rate is stated as 250 m^3/day, it should be noted that variation in pumping rate is indicated by the record of drawdown. Variable rates are obvious in the pumping steps between day 18 and 24. Figure C.2 shows that the nearby observation bores, TL29 and 30, display strong and immediate responses to both pumping and recovery phases in the pumping record. The more distant observation bores (P15 and TL28) present a more subdued response to pumping.

Preliminary graphical analysis of the observed drawdown records has been undertaken and results are presented in Figures C3 to C7. It should be noted that no attempt has been made to account for variable pumping rates in the analysis. Results are reasonably consistent and suggest a transmissivity of 35 m^2/day. This value is consistent with the numerical model that has a value of 40 m^2/day in the palaeochannel. Calculated values of storage coefficient are variable but suggest some degree of aquifer confinement. In fact this may be caused by the lower permeable sediments that infill the palaeochannel at shallow depths.

Figure C.3: Type Curve Analysis for P11

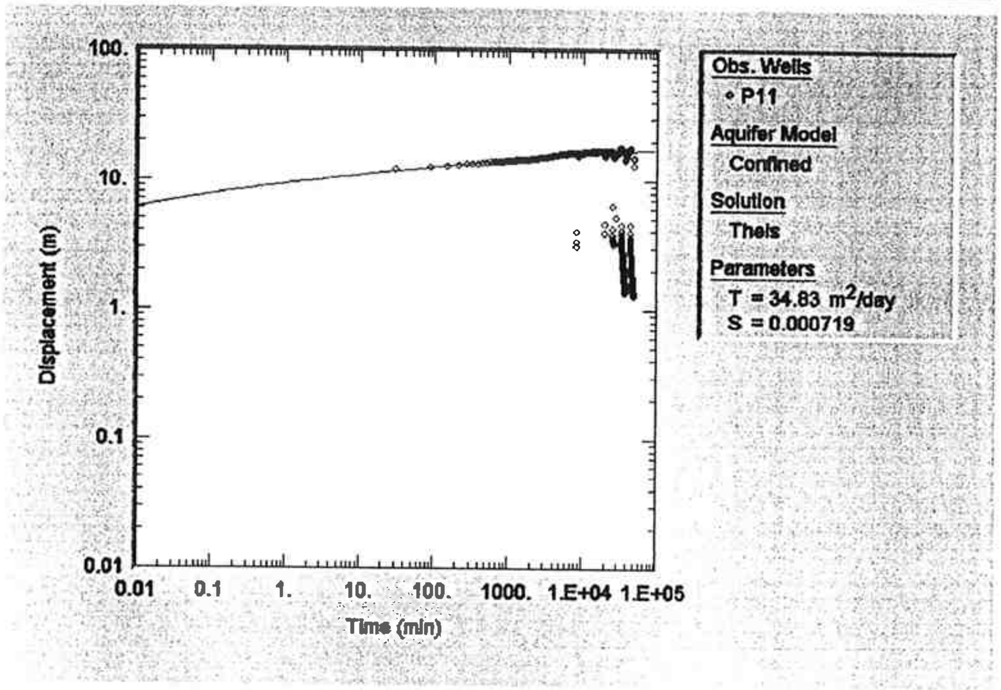


Figure C.4: Type Curve Analysis for P15

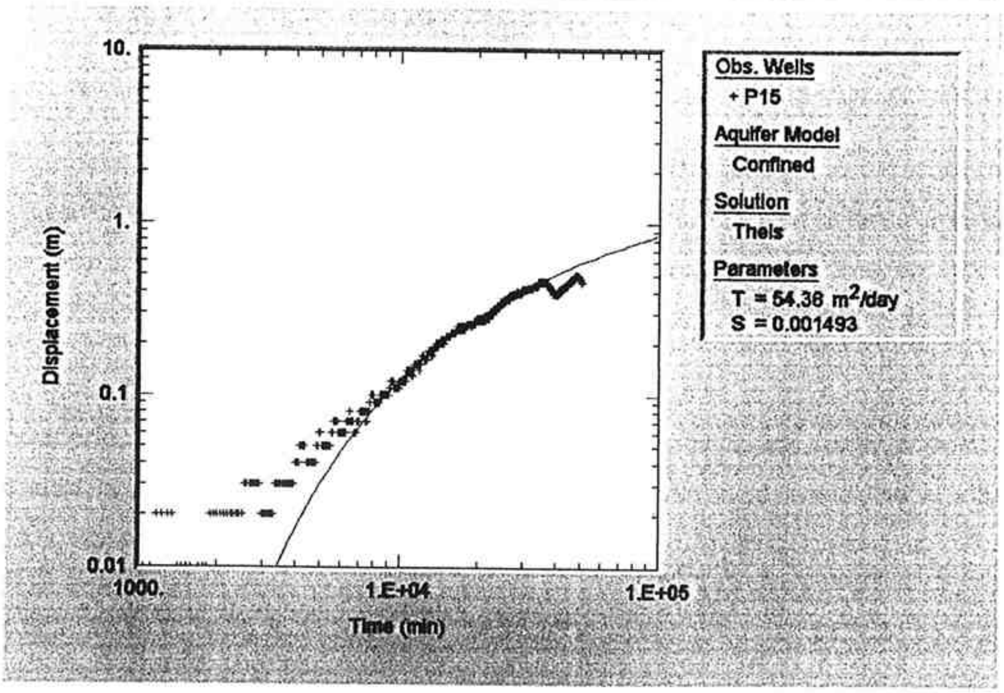


Figure C.5: Type Curve Analysis for TL28

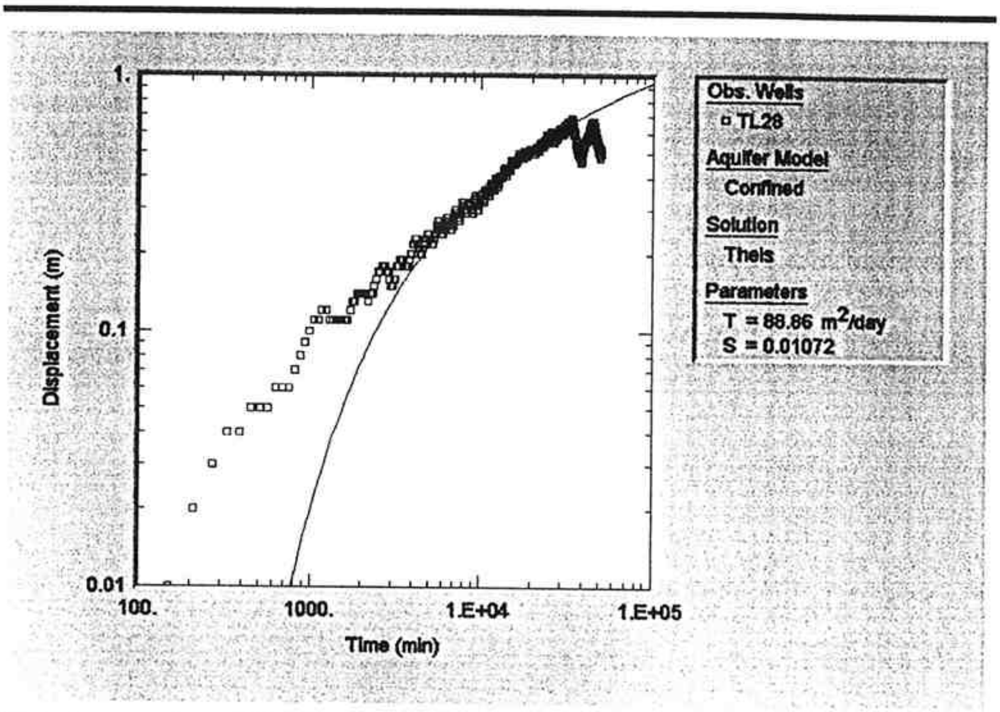


Figure C.6: Type Curve Analysis for TL29

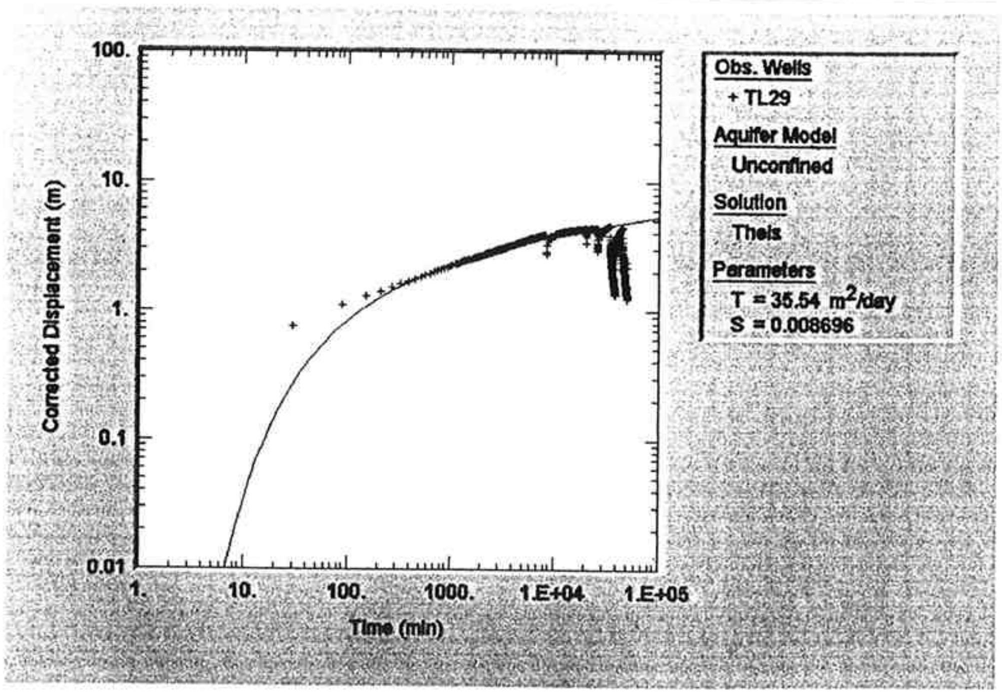
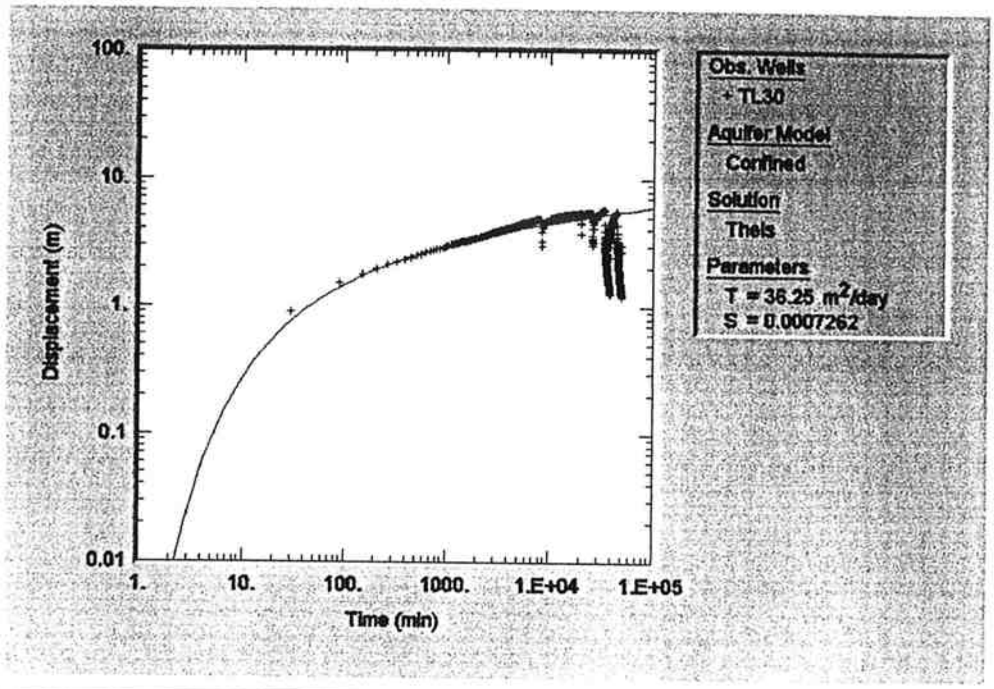


Figure C.7: Type Curve Analysis for TL30



100.
10.
1.
0.1
0.01
Displacement (m)
1.
10.
100.
1000.
1.E+04
1.E+05
Time (min)
Obs. Wells
+ TL30
Aquifer Model
Confined
Solution
Theis
Parameters
T = 36.25 m²/day
S = 0.0007262