SouthmetroConnect

MIKE SHE surface and groundwater modelling

AECOM, May 2011. *Roe Extension Project: Modelling Existing groundwater and surface water movement*. Unpublished report prepared for Main Roads, Perth, WA.

Appendix G

MIKE SHE surface and groundwater modelling

South Metro Connect
Main Roads WA
13 May 2011
Document No. 60100953-412G-EN-REP-0004

Roe Highway Extension

Modelling Existing Groundwater and Surface Water Movement

Roe Highway Extension

Modelling Existing Groundwater and Surface Water Movement using MIKE SHE

Prepared for

Main Roads WA

Prepared by

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In association with

DHI and South Metro Connect

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Prepared by Luke Cummins and Natalie Horsfield

Reviewed by David Westwater, David Western and Mark Pearcey

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Revision	Revision Date	Details	Authorised	
			Name/Position	Signature
A	04-May-2011	Issued for Internal Review	David Westwater Principal Engineer	
B	13-May-2011	Issued for Client Review	Jamie Shaw South Metro Connect Environment Manager	

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Glossary

Acronym	Description
mAHD	Metres above Australian Height Datum
BoM	Bureau of Meteorology
DAFWA	Department of Agriculture Western Australia
DEM	Digital Elevation Model
DoE	Department of Environment
DoW	Department of Water
EPA	Environmental Protection Agency
ERD	Effective Rooting Depth
ET	Evapotranspiration
FAO56	Potential evaporation calculated using the FAO Penman-Monteith formula
LAI	Leaf Area Index
LIDAR	Light Detection and Ranging
MRWA	Main Roads WA
MRS	Metropolitan Region Scheme
PRAMS	Perth Regional Aquifer Modelling System
PER	Public Environmental Review
RHE	Roe Highway Extension
RMSE	Root Mean Square Error
SMC	South Metro Connect
V&CSRG	V&C Semeniuk Research Group
WA	Western Australia
Watercorp	Water Corporation
WRC	Water and Rivers Commission

Executive Summary

The Government of Western Australia (WA) is proposing to extend Roe Highway in order to link the Kwinana Freeway to Stock Road, a project known as Roe Highway Extension (RHE [the proposed project]). The middle portion of the project area passes between North Lake and Bibra Lake, ephemeral wetlands that form part of the eastern chain of the Beeliar Wetlands. A groundwater-surface water model has been developed for the wetlands using MIKE SHE to simulate seasonal and storm event water movement as an aid to the road design process. This report and accompanying MIKE SHE model has been prepared for Main Roads Western Australia and will inform the Public Environmental Review (PER) for the proposed project.

The project area falls within the extent of a number of existing regional hydrological/hydrogeological models, but has not been previously modelled at a local scale in this location. A review of the existing literature informed the development of a conceptual hydrological/hydrogeological understanding of the physical setting and water flows within the project area that formed the basis of the MIKE SHE model.

MIKE SHE simulates the major processes of the land phase of the hydrological cycle. The model that has been developed for the project area is a gridded, lumped 3D model with 2D and 1D linkages that simulate the interactions between surface water and groundwater. They are discretised to allow overland surface water flow and unsaturated and saturated groundwater flows. The structure of the different simulations (base case, long term simulation and short term simulation) is described, including all inputs, and the rationale behind their development.

Model parameters were calibrated using historical time series of observed groundwater and surface water levels provided by the Department of Water (DoW) and validated using recent discrete observed water levels obtained during 2010. The calibrated model recreated well the seasonal and long-term variability in surface water and groundwater levels; however, absolute values are not always accurately simulated. The overall flow direction and groundwater contours generally compare well to observed flow regimes, but the coarse 80m model grid limits the ability to estimate water levels at discrete locations along the road alignment. The model is relatively sensitive to changes in boundary condition water levels, with some sensitivity to effective rooting depth and unsaturated zone water content at field capacity.

Results generally suggest that during ‘dry’ periods the project area generally has parallel groundwater contours with groundwater flow in an east-west direction. During dry periods, the model suggests there is very little surface water within the project area. These flow patterns are consistent with other sources of data. The model exhibits surface water in the lakes, Murdoch Drain and Roe Swamp during ‘wet’ periods. Under extreme scenario conditions it seems Bibra Lake and North Lake are connected and Frog Swamp connects to North Lake. These results suggest that during ‘dry’ periods the model is driven primarily by the groundwater boundary conditions, whereas, during ‘wet’ periods there is significant infiltration of surface water.

Limitations inherent in the use of the model have been identified, relating to the model grid size, boundary conditions, saturated zone geology, land use characteristics and the model calibration. Opportunities for further work to remove or reduce these limitations include refining the grid size, the incorporation of the latest 2 years of data, which is considered a particularly dry period, and also to improve the quality of the surface water monitoring sites by increasing the range at which low lake levels may be monitored.

1.0 Introduction

The current State Government has made a commitment to extend Roe Highway westwards from its current termination at the Kwinana Freeway to Stock Road. The Roe Highway Extension (RHE) is expected to largely utilise the existing Metropolitan Region Scheme (MRS) reservation established in the 1960s for that purpose. In order to deliver this commitment Main Roads Western Australia (MRWA) has implemented an Integrated Project Development (IPD) arrangement for the concept design of the extension. The IPD is being managed and resourced by a project team named South Metro Connect (SMC) which is comprised of both MRWA and AECOM Australia Pty Ltd staff.

The concept design commenced in late 2009 and is anticipated to finish in late 2011. During that time, various concept road designs were prepared and a preferred option was identified. Environmental approval will be sought from the Environmental Protection Authority (EPA) for the preferred design option, through the Public Environmental Review (PER) process.

This report details a water modelling exercise that has been undertaken by DHI on behalf of AECOM for SMC. A PER report will be produced which will be subject to public comment as stipulated by the EPA.

This report should be read in conjunction with the Concept Geometric Road Design Report (60100953-215J-CI-REP-0001) in order to gain an understanding of the proposed road alignment and bridge locations.

1.1 Background Understanding of Existing Environment

Surface water within the study area is understood to be mostly comprised of expressions of groundwater, particularly within North and Bibra Lakes, with other contributions from piped networks discharging to the area from surrounding catchments and direct rainfall to the area. To better understand the water balance and water movement patterns, the interaction of surface water with groundwater needs to be appreciated. In order to meet the objective of this study a coupled groundwater-surface water model was built by DHI, using MIKE SHE software, and was run to simulate seasonal and storm event water movement.

1.2 Water Modelling Study Objectives

The objective of the modelling study was to develop a tool to aid the understanding of the groundwater and surface water movements within the project area and could be used to aid the concept design decision making process and to provide supporting documentation for environmental approvals for the RHE project.

1.3 Development of Final Modelling Scope of Works

Initially, the extent of the modelling exercise was to develop a fully integrated surface and groundwater model of the study area which would represent the existing environment and then could be used for predictive purposes using design scenarios to assess the impact of the RHE Project.

Changes to the project priorities, as well as a delay in collection of validation data meant that it became inappropriate to use the model as a predictive tool for impact assessment, including impacts from climate change and land use. Instead the scope was focussed on understanding the existing interaction of groundwater and surface water movements within the limitations of the model, given the modelling assumptions and calibration data.

Hence, This model is another ‘tool’ that can be used to inform both concept design decisions and impact assessments, in conjunction with other studies to develop an understanding of existing water movement patterns and provide information to support both concept design decisions and impact assessment.

This report and accompanying MIKE SHE model has been prepared for Main Roads Western Australia (MRWA) and will provide part of the supporting documentation for the PER.

2.0 Literature and Data Review

A desktop review of previous studies has revealed a range of relevant investigations that sought to provide a broad scale understanding of the Perth groundwater system.

The report entitled *Hydrology and groundwater resources of the Perth region* by Davidson (1995) is generally accepted as a standard reference for the Perth region including the project area. The regional hydrogeology and wetland systems of the project area have both been discussed by a number of authors (Townley *et al*. 1993, Nield 1999, Smith and Hick 2001, Smith and Nield 2003, Burkett 2005, Davidson and Xu 2006). The hydrogeology of North and Bibra Lakes is also discussed by Megirian (1982) and Davidson (1983).

The project area falls within the extent of the Perth Regional Aquifer Modelling System (PRAMS). PRAMS is a regional coupled recharge and groundwater model on a 500m grid that was developed by the Water Corporation and DoW to aid management of the regional groundwater system around the Perth coastal area (Davidson and Xu 2006, Silberstein *et al*. 2009, Xu *et al*. 2009).

Nield (1999) developed a numerical model of the unconfined aquifer in the Cockburn Groundwater Area to assist with a review of groundwater allocation. The model includes Bibra Lake, but does not extend across the full project area. Smith and Nield (2003) extended this model further north to fully cover the East Beeliar Wetlands to estimate submarine groundwater discharge into Cockburn Sound.

Bibra Lake and North Lake are also discussed within the review of shallow groundwater systems on the Gnangara and Jandakot mounds. This review was undertaken by DoW to identify current management issues facing selected lakes and wetlands within the Perth region (McHugh and Bourke 2008). These wetlands and associated geology are also examined by V & C Semeniuk Research Group (2009).

The following discussion on the physical characteristics of the project area is based upon information contained within the above reports and studies.

2.1 Climate

The climate of the south-western region of Western Australia is characterised as 'Mediterranean', with hot, dry summers and cool to mild, wet winters. The closest meteorological recording station to the project area is the Bureau of Meteorology (BoM) maintained Jandakot Aero Weather Station (station 009172) at Jandakot Airport, which is located approximately five kilometres east of Bibra Lake. The mean annual rainfall recorded at Jandakot Airport is approximately 827mm, with the majority of rainfall occurring between May and September (Bureau of Meteorology 2011). Evaporation peaks in summer and is lower during the winter.

Two DataDrill time series of climatic data were also obtained from *SILO*, which is provided by the State of Queensland (Department of Environment and Resource Management 2009) [http://www.longpaddock.qld.gov.au/silo/]. The two DataDrill dataset locations are the western and eastern sections of the project area presented in Figure 2-1. The DataDrill is a gridded dataset that is interpolated from BoM's station records. The resultant dataset is entirely synthetic. The full available time series were obtained, extending from 1911 to 2009, to include the rainfall and reference potential evapotranspiration daily data. Full sets of time series data can be found in Appendix B.

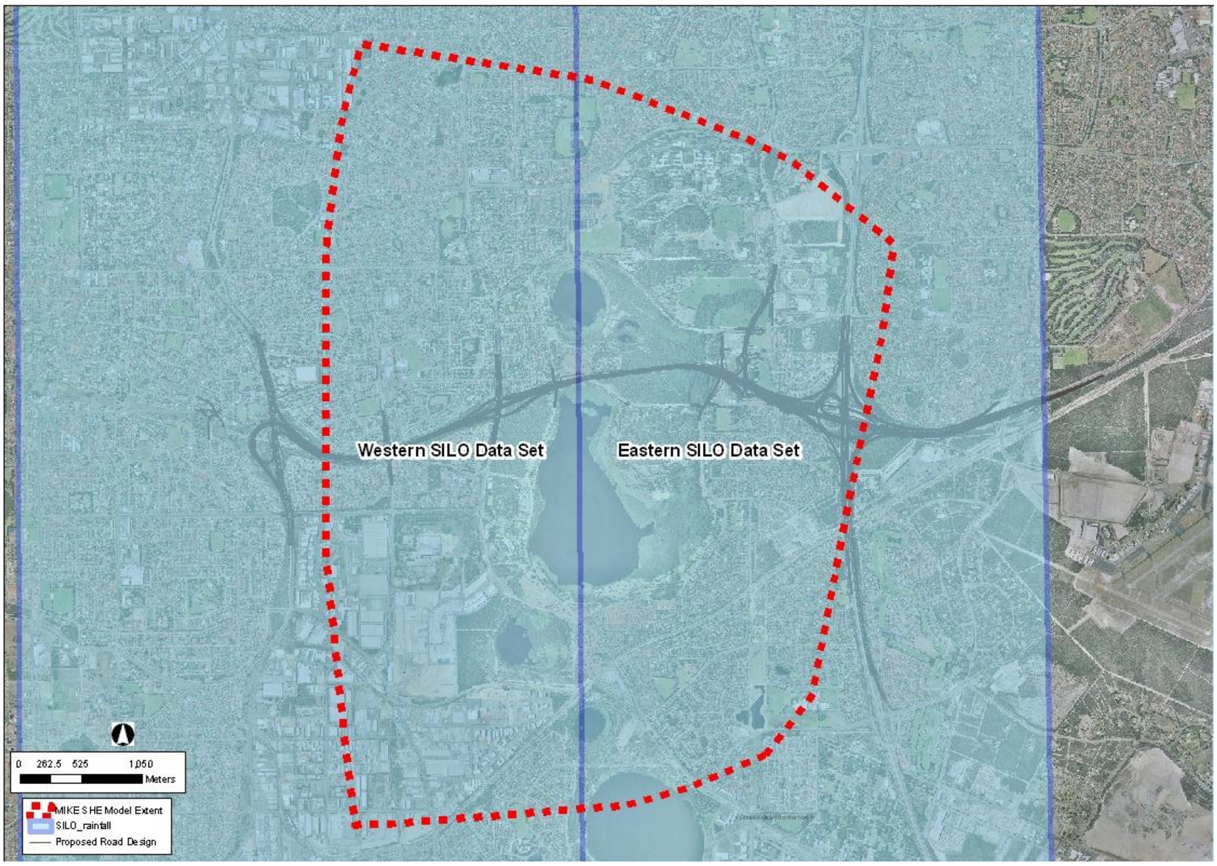


Figure 2-1 Western and eastern SILO dataset locations

A comparison between the SILO rainfall and rainfall recorded at Jandakot Aero Weather Station found that the SILO rainfall values for the project area were generally lower. The SILO rainfall data has been adopted for this study, as it represents an interpolation of observed rainfall values to the project area. Average monthly values of rainfall and evaporation for the western SILO dataset are presented in Table 2-1.

Table 2-1 Average total monthly rainfall and potential evapotranspiration for the Western SILO Dataset

Average Monthly Total (mm)	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Rainfall 1889-2009	9	12	17	41	111	172	165	120	75	48	21	10	802
Potential Evapotranspiration 1889-1969	264	225	192	118	77	58	59	75	98	146	192	241	1744
Potential Evapotranspiration 1970-2009	278	237	204	124	82	60	62	75	97	146	196	252	1814

Annual total rainfall and the long term linear trend, pre and post 1975, for the western SILO dataset are presented in Figure 2-2.

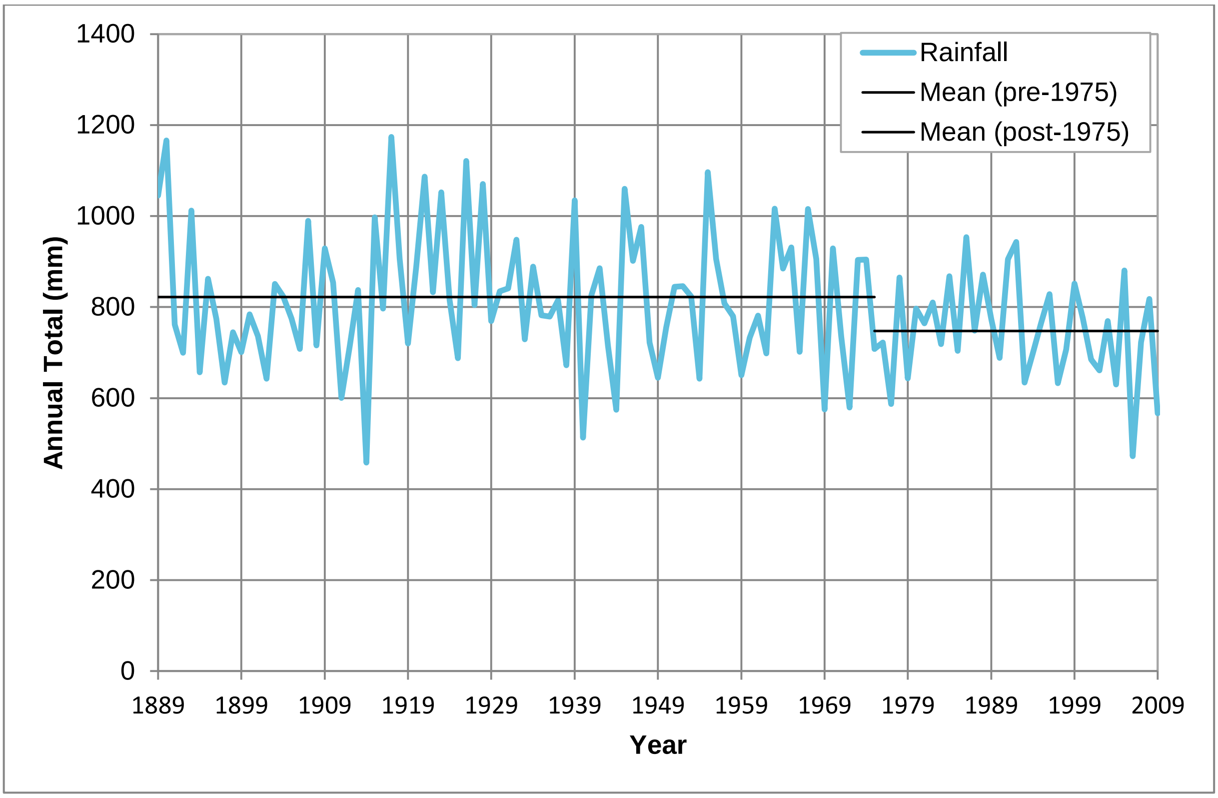


Figure 2-2 Annual total rainfall for the Western SILO Dataset

2.2 Geology and Soils

The geology of the project area is illustrated by Figure 2-3. The project area is located on the Swan Coastal Plain, a low-lying area of sand, limestone and fluvial deposits located between the Darling Scarp and the Indian Ocean. The regional geology is discussed in detail by Davidson and Xu (2006).

The eastern margin of the Swan Coastal Plain is dominated by silts and clays (muds), while the central area is predominantly sand. To the west, the sandy materials pass laterally into limestone, which borders the coastal strip (V&CSRG 2009). Geological formations include Bassendean Sand and Tamala Limestone which are relevant to the project area (V&CSRG 2009). Tamala Limestone forms part of the Spearwood Dunes system.

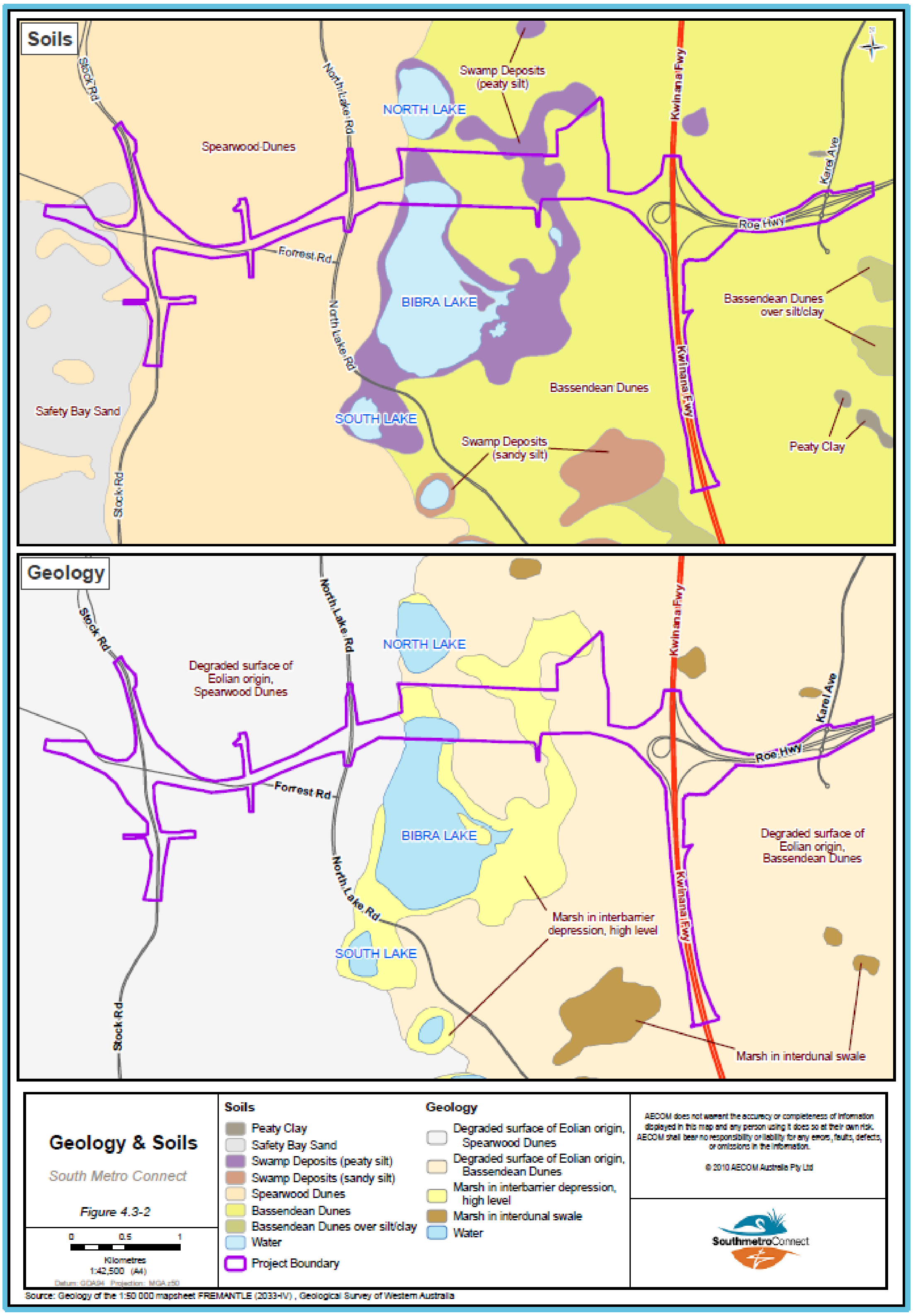
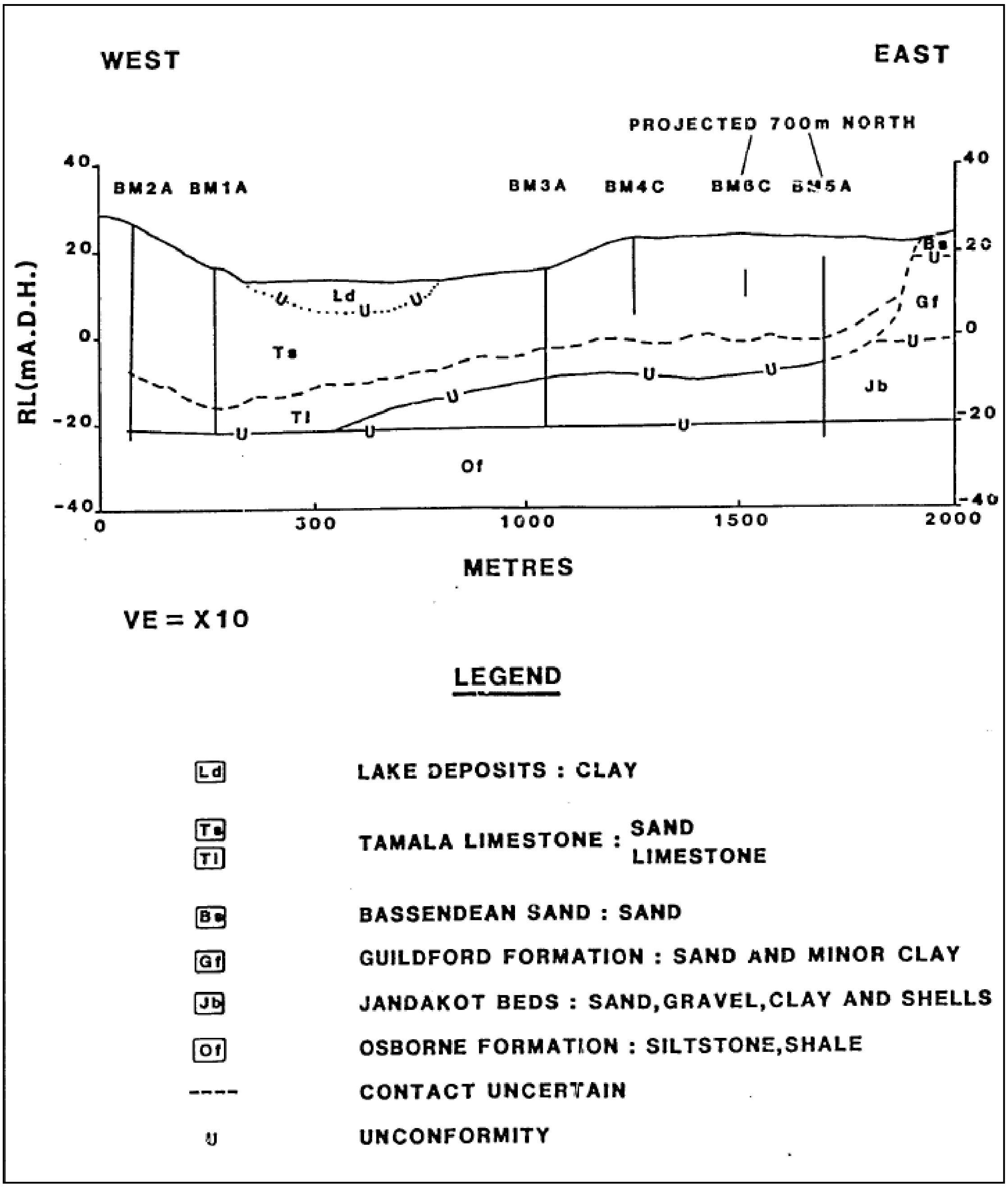


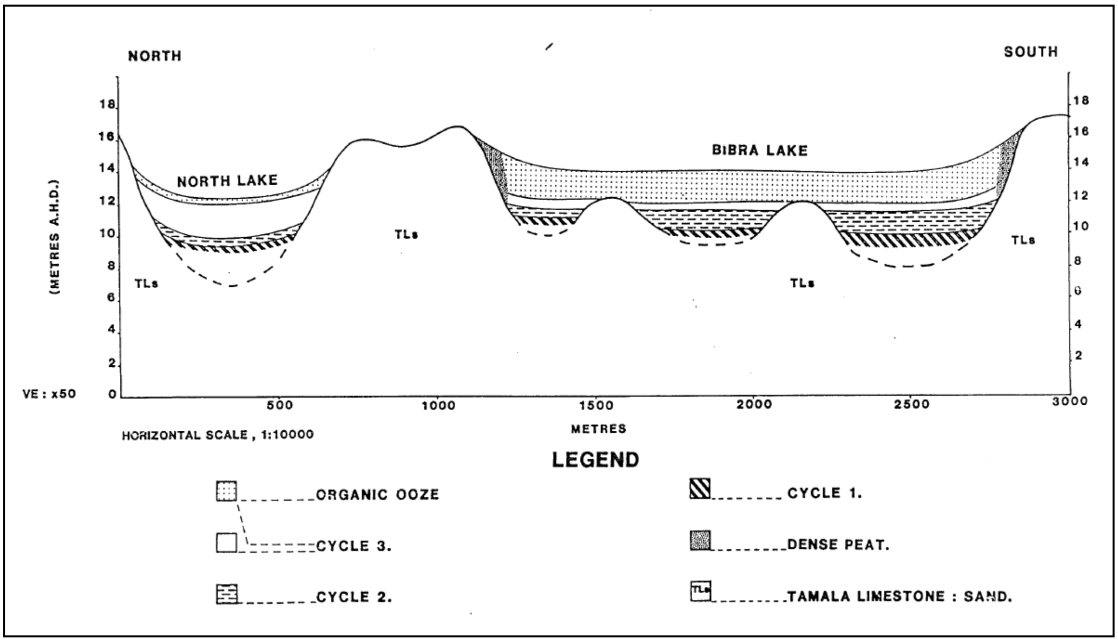
Figure 2-3 Geology and Soils

North and Bibra Lakes form part of a chain of lakes that occupy interdunal depressions in the Spearwood Dune system at the contact with the Bassendean Sands. A low saddle in the Spearwood Dunes separates Bibra Lake from North Lake (Davidson 1983). Geological cross sections through Bibra Lake from Davidson (1983) are presented in Figure 2-4 and Figure 2-5.



Source Davidson (1983)

Figure 2-4 Geological cross-section through Bibra Lake



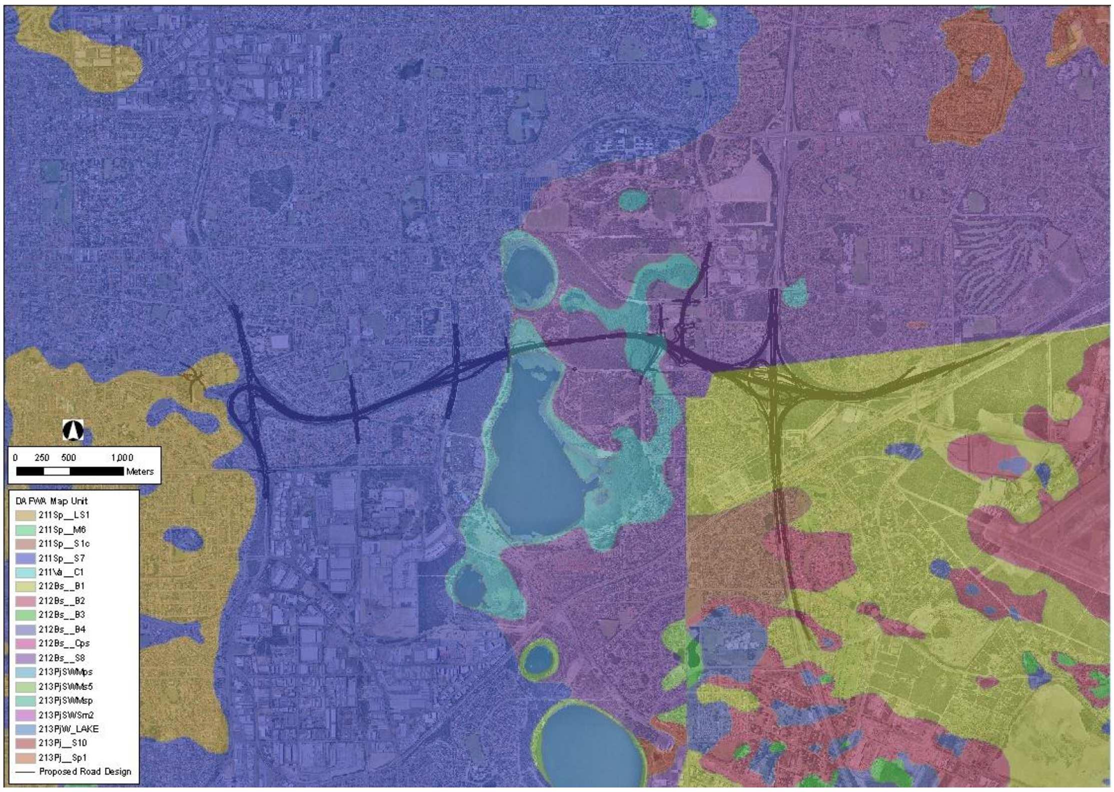
Source: Davidson (1983)

Figure 2-5 Geological cross-section through North Lake and Bibra Lake

It has been suggested that there is a relatively narrow band of lower permeability sediments that run roughly parallel to the coastline along the contact between the Bassendean Sands and Tamala Limestone (Nield 1999, Smith and Hick 2001, Smith and Nield 2003). Smith and Hick (2001) and Smith and Nield (2003) suggest that the East Beeliar wetlands are surface expressions of higher groundwater levels that are 'dammed' on the eastern side of the barrier of lower permeability sediments.

2.2.1 Surface Geology

Department of Agriculture and Food Western Australia (DAFWA) digital soil landscape mapping is available for the southwest (agricultural area) of Western Australia and covers the project area at the scales of 1:20,000 to 1:50,000 (Figure 2-6). The soil landscape mapping was produced using field observations, sampling, interpretation of aerial photography and satellite imagery, with the map unit descriptions compiled from various land resource surveys and published maps and reports.



Source: DAFWA (2009)

Figure 2-6 DAFWA soil landscape mapping of the project area

A summary description of the prevailing map units within the project area is presented in Table 2-2.

Table 2-2 Summary description of relevant DAFWA soil landscape map units

Map Unit	Zone	Summary Description
211Sp_S7	Perth Coastal (Spearwood)	SAND - pale and olive yellow, medium to coarse-grained, sub-angular to sub-rounded quartz, trace of feldspar, moderately sorted, of residual origin
212Bs_S8	Bassendean	SAND - very light grey at surface, yellow at depth, fine to medium-grained, sub-rounded quartz, moderately well sorted of aeolian origin
213PjSWMps	Pinjarra	PEATY SILT - black, friable silt with abundant organic material, variable fine quartz sand content, soft, of lacustrine origin
213PjW_LAKE	Pinjarra	Lake

Source: DAFWA (2009)

2.3 Hydrogeology

2.3.1 Regional Hydrogeology

The Jandakot Groundwater System is present beneath the project area and is comprised of the superficial (unconfined) aquifer and the confined Leederville and Yarragadee Aquifers (Water Corporation 2008).

The saturated thickness of the superficial aquifer formation is approximately 40m at the centre of the Jandakot Groundwater System (Water Corporation 2008). Low permeability materials underlying the superficial formation form a barrier to vertical groundwater flow (Nield 1999).

The thickness of the unconfined aquifer generally decreases towards the coast. It is believed that the Jandakot Mound, a feature of the superficial aquifer that lies slightly to the east of the project area, has developed as a result of the rate of infiltration exceeding the rate of horizontal groundwater flow within the superficial aquifer

(Jandakot Airport Holdings 2009). During dry summer months, the rate of horizontal groundwater flow exceeds vertical infiltration, resulting in a subsidence of the mound as the water table falls.

2.3.2 Hydraulic Properties

Typical regional horizontal hydraulic conductivities for geological units within the superficial aquifer reported by Davidson and Xu (2006) are presented in Table 2-3. Table 2-4 presents soil profile and hydraulic properties adopted within PRAMS (Xu *et al*. 2009) and Figure 2-7 presents hydraulic conductivities adopted by Nield (1999). Playford *et al*. (1976) also measured a mean hydraulic conductivity of 13m/day for Swan Coastal Plain Bassendean Sands.

Table 2-3 Regional values of horizontal hydraulic conductivity within the superficial aquifer

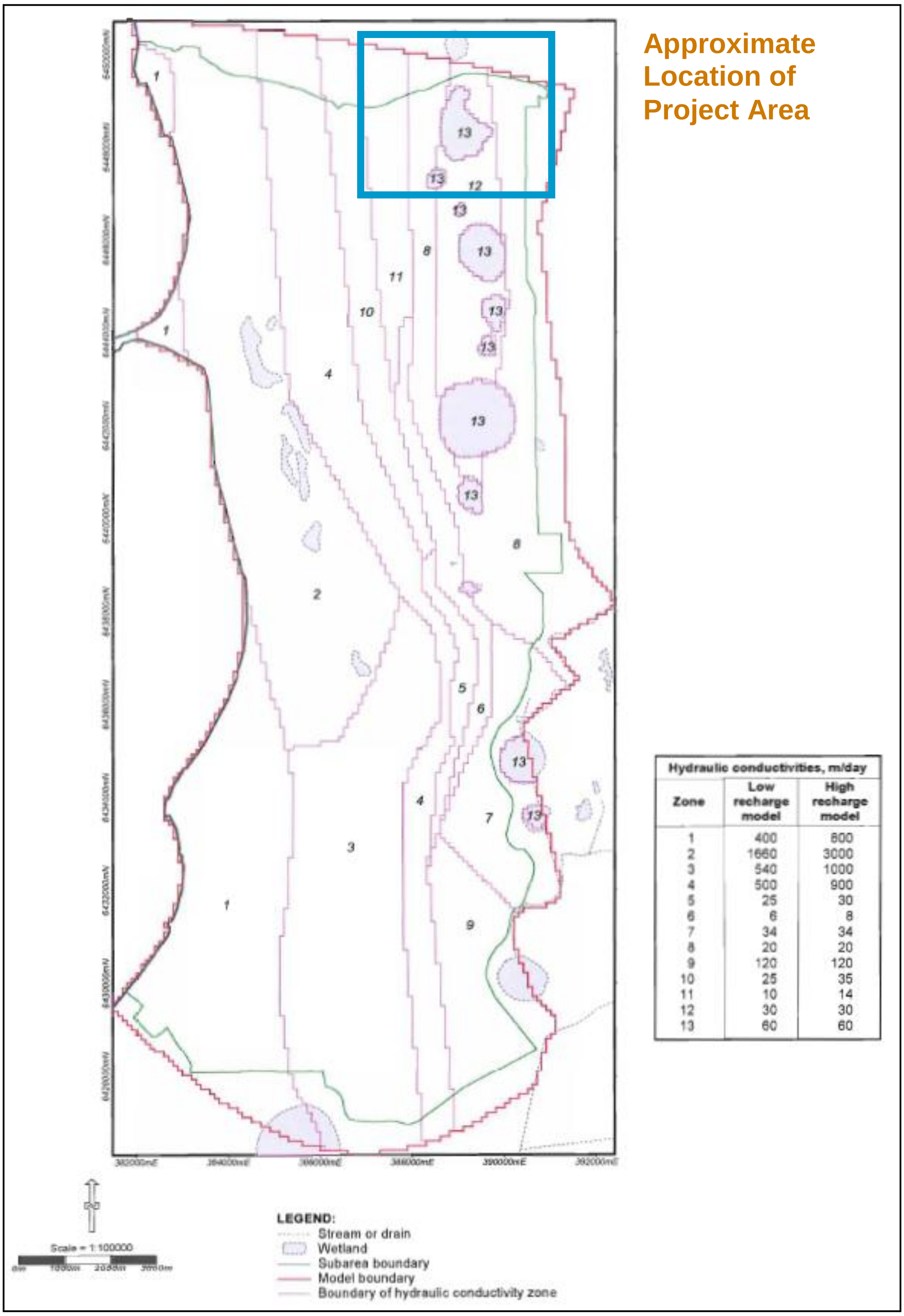
Geological Unit	Hydraulic Conductivity (m/day)	
	Regional Range	Regional Average
Bassendean Sand	10 - 50	15
Tamala Limestone	<1 - 1000	50

Source: Davidson and Xu (2006)

Table 2-4 Soil profile and hydraulic properties adopted within PRAMS

Soil Profile	Soil Layer	Depth (m)	Saturated Hydraulic Conductivity (m/day)	Effective Saturated Water Moisture Content	Estimated Soil Water Holding Capacity (%)
Spearwood Dunes	Topsoil A	0 - 0.15	3.41	0.37	6.0
	Topsoil B	0.15 – 0.5	3.64	0.36	3.5
	Subsoil C	0.5 – 50	5	0.33	4.0
Bassendean Sands	Topsoil A	0 - 0.15	1.63	0.38	3.5
	Topsoil B	0.15 – 0.5	3.59	0.35	3.0
	Subsoil C	0.5 – 50	10	0.33	3.0
Lacustrine Sediments	Topsoil A	0 - 3	0.01	0.32	17.0
	Topsoil B	3 - 30	5.0	0.30	6.0

Source: Xu et al. (2009)

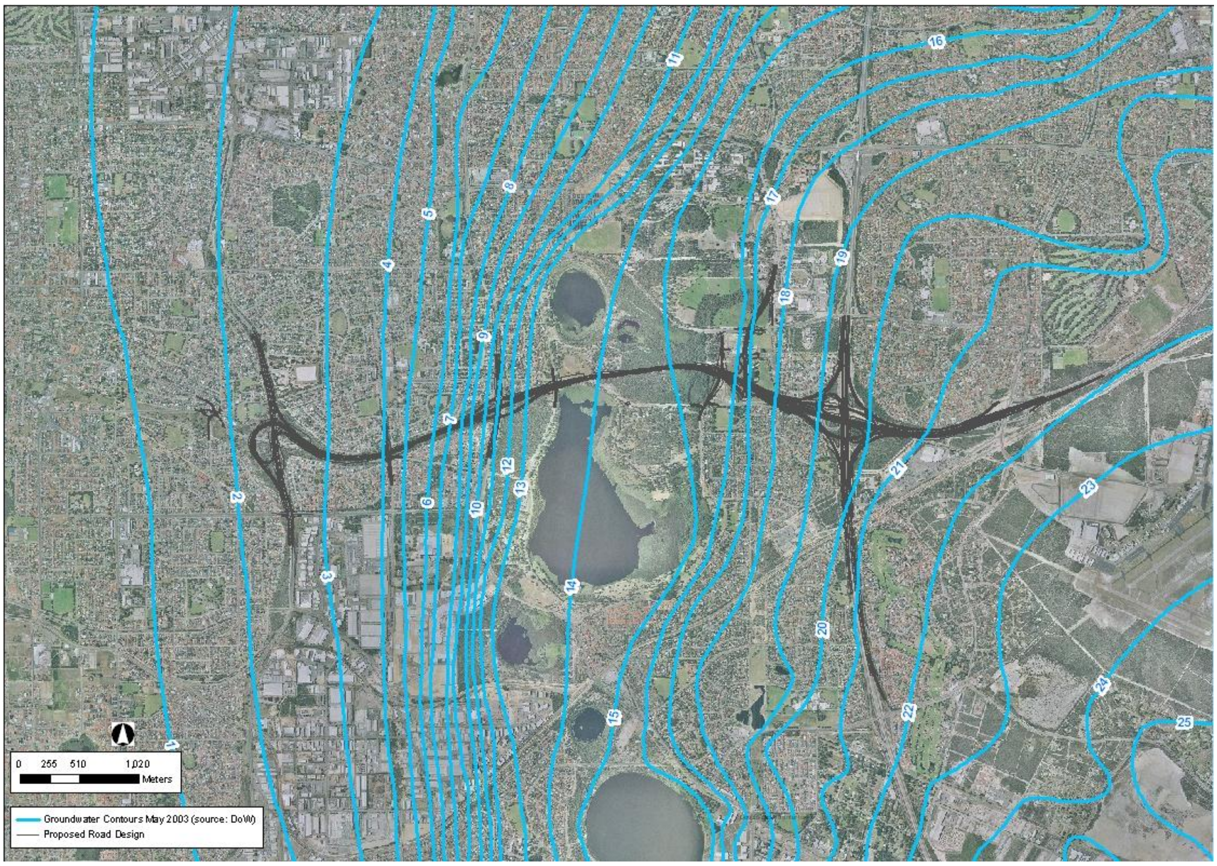


Hydraulic conductivities, m/day		
Zone	Low recharge model	High recharge model
1	400	800
2	1660	3000
3	540	1000
4	500	900
5	25	30
6	6	8
7	34	34
8	20	20
9	120	120
10	25	35
11	10	14
12	30	30
13	60	60

Figure 2-7 Hydraulic conductivities adopted by Nield (1999)

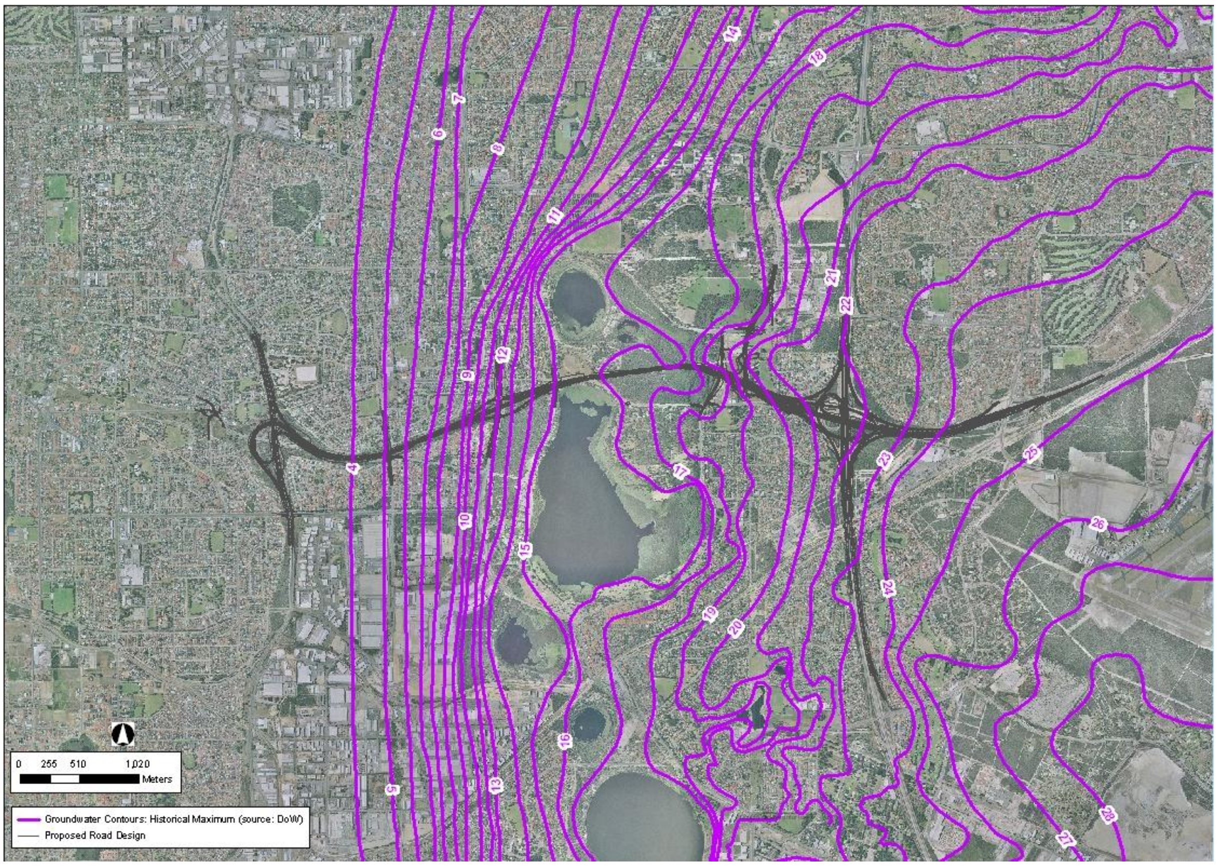
2.3.3 Groundwater flows and levels

Inspection of DoW groundwater contour maps, presented in Figure 2-8 and Figure 2-9, suggests that groundwater generally flows in a westerly direction from the Jandakot Mound to discharge in the near-shore marine environment of Cockburn Sound. Groundwater contours indicate that the wetlands play a role in the flow of groundwater, with flows to and from wetland basins being partly influenced by wetland sediment. Davidson (1983) reported that groundwater flows converge toward the southeast margin of Bibra Lake.



Source: DoW (DoE 2004)

Figure 2-8 Minimum groundwater contours within project area from the Perth Groundwater Atlas

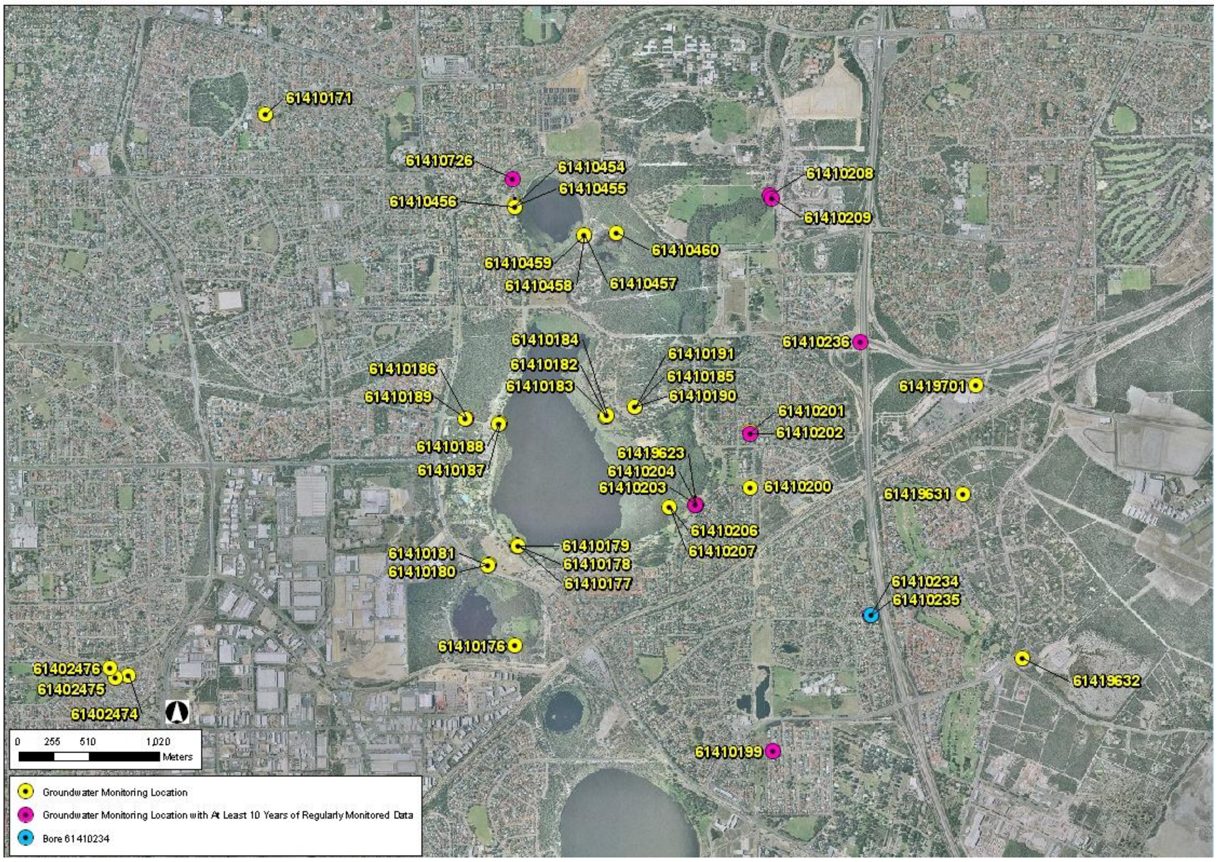


Source: DoW (WRC 1997)

Figure 2-9 Historical maximum groundwater contours

Groundwater gradients across the Swan Coastal Plain are generally small, but steeper gradients are evident along the contact between the Bassendean and Tamala Limestone/Spearwood Dunes (Nield 1999, Smith and Hick 2001, Smith and Nield 2003). Within the project area, hydraulic gradients are fairly constant to the east of Bibra Lake, but steepen towards the lake margin on the eastern side of the lake. Steep hydraulic gradients are also present along the discharge margin on the western side of the lake (Davidson 1983). Nield (1999) suggests that these large gradients are a result of clay within the Tamala Limestone along the transition zone with the Bassendean Sands. From this point forwards, this area will be referred to as 'lower permeability sediments', due to the lack of information on its composition. Davidson (1983) reported that groundwater levels within the project area fluctuate seasonally by approximately one metre and are generally highest during September and October (after winter rainfall recharge) and lowest during April and May (after the summer).

Time series of measured groundwater levels were obtained from DoW for the locations presented on Figure 2-10.



Source: DoW

Figure 2-10 Locations of observed groundwater levels

Figure 2-10 shows a large number of superficial groundwater bores within the study area, but many of these have limited recorded data or incomplete datasets. Monthly results are generally available, but the frequency of reporting is often less. Table 2-5 summarises the data available for bores with a record of 10 years or longer of regular monitoring. The complete bore record may be longer but include periods of infrequent monitoring.

Table 2-5 Summary of Groundwater Datasets with at least 10 years of regularly monitored data

AWRC Reference	Location		Monitoring Start	Monitoring End	Comments	No. Years of Regularly Monitored Data
	Easting	Northing				
61410199	390725	6446470	June 1975	-	Continuous time series. Monthly monitoring June 1975 - present	34
61410234	391437	6447453	July 1975	-	Continuous time series. Monthly monitoring July 1975 - present	34
61410202	390562	6448772	October 1981	-	Continuous time series. Monthly monitoring Oct 1981 - present	28
61410235	391445	6447453	January 1984	-	Continuous time series. Monthly monitoring Jan 1984 - present	25
61410203	390173	6448261	September 1983	-	No data April 1986 – May 1993	19

AWRC Reference	Location		Monitoring Start	Monitoring End	Comments	No. Years of Regularly Monitored Data
	Easting	Northing				
61410209	390723	6450488	June 1973	April 1993	Continuous time series. Quarterly monitoring from January 1989.	16
61419623	390165	6448261	January 1993	-	Continuous time series. Monthly monitoring Jan 1993 - present	16
61410236	391367	6449444	July 1975	July 1989	Continuous time series. Monthly monitoring July 1975 – July 1989	14
61410208	390708	6450512	October 1976	April 1993	Continuous time series. Quarterly monitoring from January 1989.	13
61410726	388839	6450629	February 1997	-	Continuous time series. Monthly monitoring Feb 1997 - present	12
61410186	388502	6448887	November 1982	-	No data April 1986 – May 1993. Quarterly monitoring from July 1999.	10
61410185	389724	6448971	November 1982	June 1999	No data April 1986 – May 1993.	10

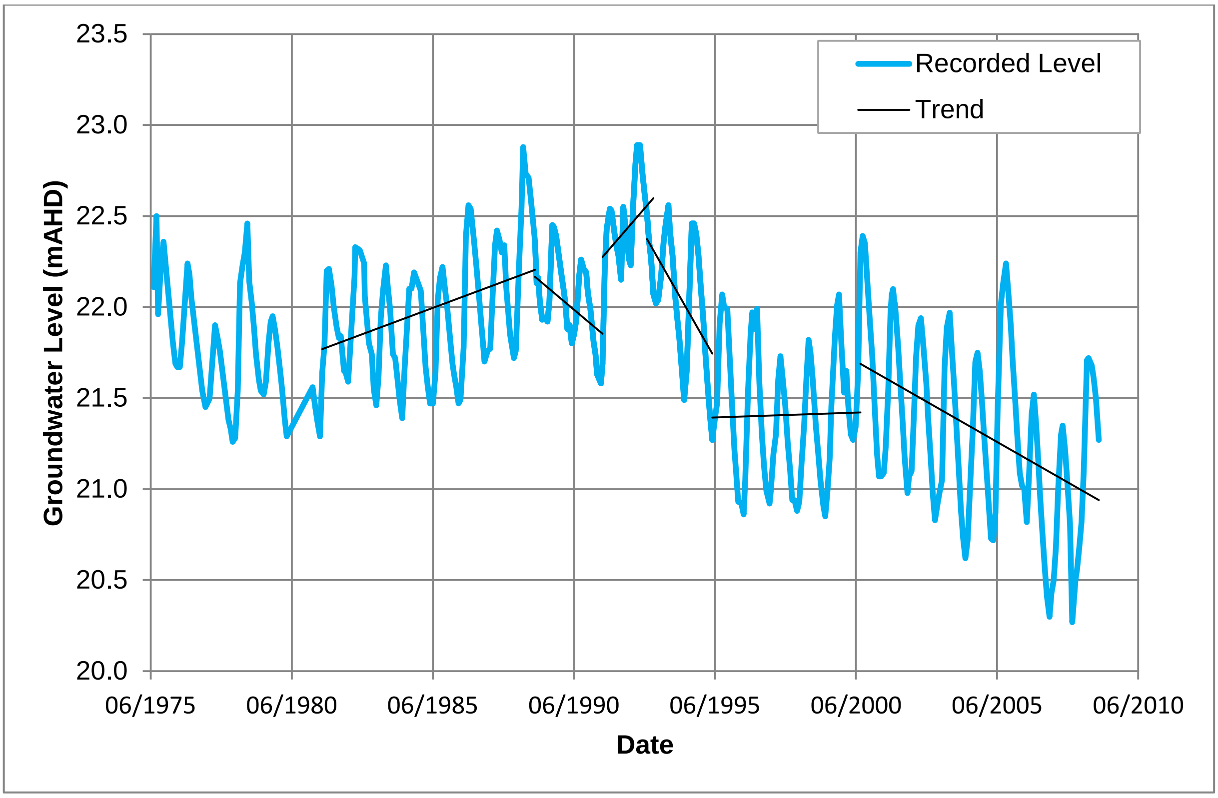
Source: DoW

Bore 61410234, located approximately 2 km to the south-east of Bibra Lake (Figure 2-9), provides one of the longest time series of groundwater levels within the study area, having continuously recorded levels since 1975. The historical levels for Bore 61410234 are presented on Figure 2-11 and demonstrate an annual cycle of peaks in winter and troughs in summer that is typical of the region. Bore 61410199 has an additional month of monitoring but this data contained inconsistencies that DoW could not account for.

The following trends can be observed from Figure 2-11:

- An increase between the early 1980s to1988.
- A period of fluctuation between 1989 to 1995.
- Relatively stable levels between 1995 and 2000.
- A period of decline since 2001.

The overall variation during the period of record was 2.62 m. The same general trends in groundwater levels can be observed in bores throughout the study area, the results for which are presented in Appendix A, although the magnitude of seasonal and inter-annual ranges is variable.

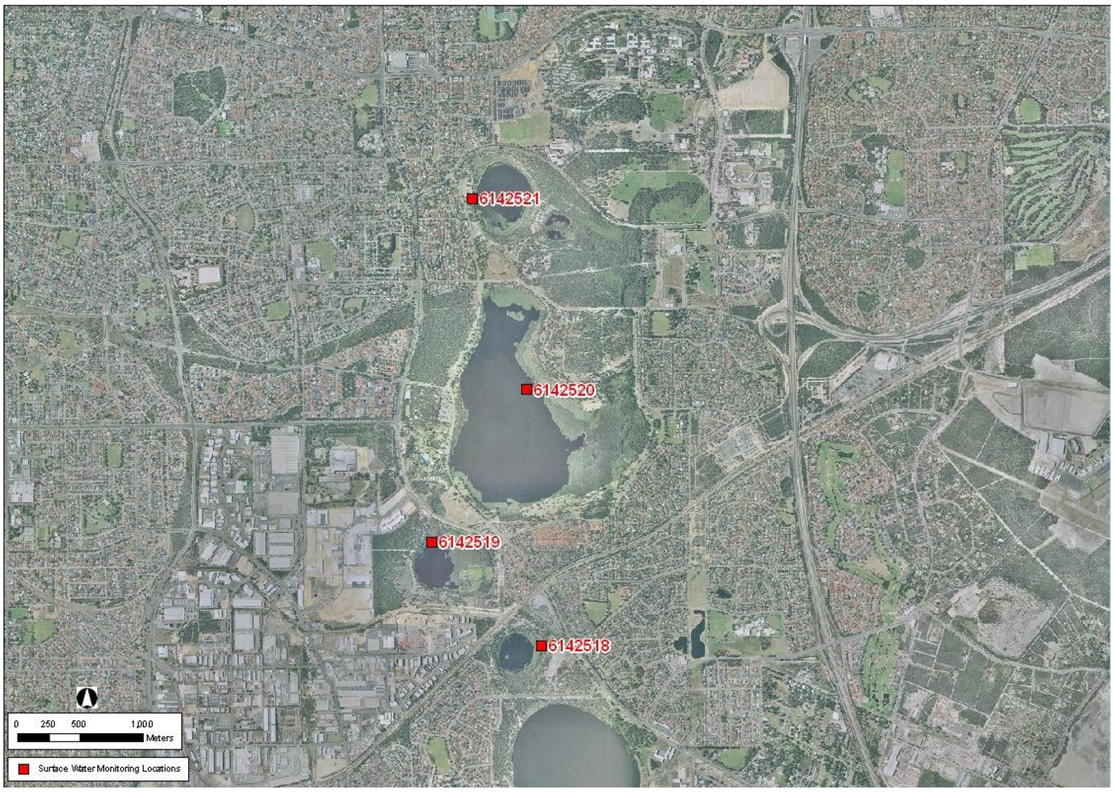


Source: DoW

Figure 2-11 Recorded groundwater levels at Bore 61410234

2.3.4 Surface Water

Time series of measured surface water levels were obtained from DoW for the gauge locations presented in Figure 2-12. The available historical surface water levels are summarised in Table 2-6. The recorded water levels at all four locations provide continuous water levels from the late 1980s.



Source: DoW

Figure 2-12 Locations of observed surface water levels

Table 2-6 Summary of surface water datasets

Australian Wetlands and Rivers Centre Reference	Location			Monitoring Start	Comments	No. Years of Regularly Monitored Data
	Easting	Northing	Lake			
6142518	389409	6446804	Little Rush	July 1974	Occasional water level monitoring between 1952 and 1974. Monthly monitoring from 1974 to present	35
6142519	388539	6447628	South	July 1974	Occasional water level monitoring between 1960 and 1974. Monthly monitoring from 1974 to present	35
6142520	389289	6448839	Bibra	May 1964	Occasional water level monitoring between 1928 and 1964. Monthly monitoring from 1964 to present	45
6142521	388859	6450359	North	June 1971	Occasional water level monitoring between 1928 and 1971. Monthly monitoring from 1971 to present	38

The time series of surface water levels at Bibra Lake is presented in Figure 2-13 and the time series for North Lake is presented in Figure 2-14. The time series of surface water levels for the other locations can be found in Appendix A. The time series demonstrate similar patterns to those observed in the groundwater bores. Seasonal variability produces a peak after winter, dropping off to low levels in late summer, which produces a seasonal variation in the areal extent of the lakes (Davidson 1983). This may suggest a slight lag time between groundwater and surface water expression in the project area.

All of the time series demonstrate periods where the water level is below the reading datum which suggests that new gauge boards were installed at an elevation above the minimum water level. The result is that the lowest water levels are not accurately recorded.

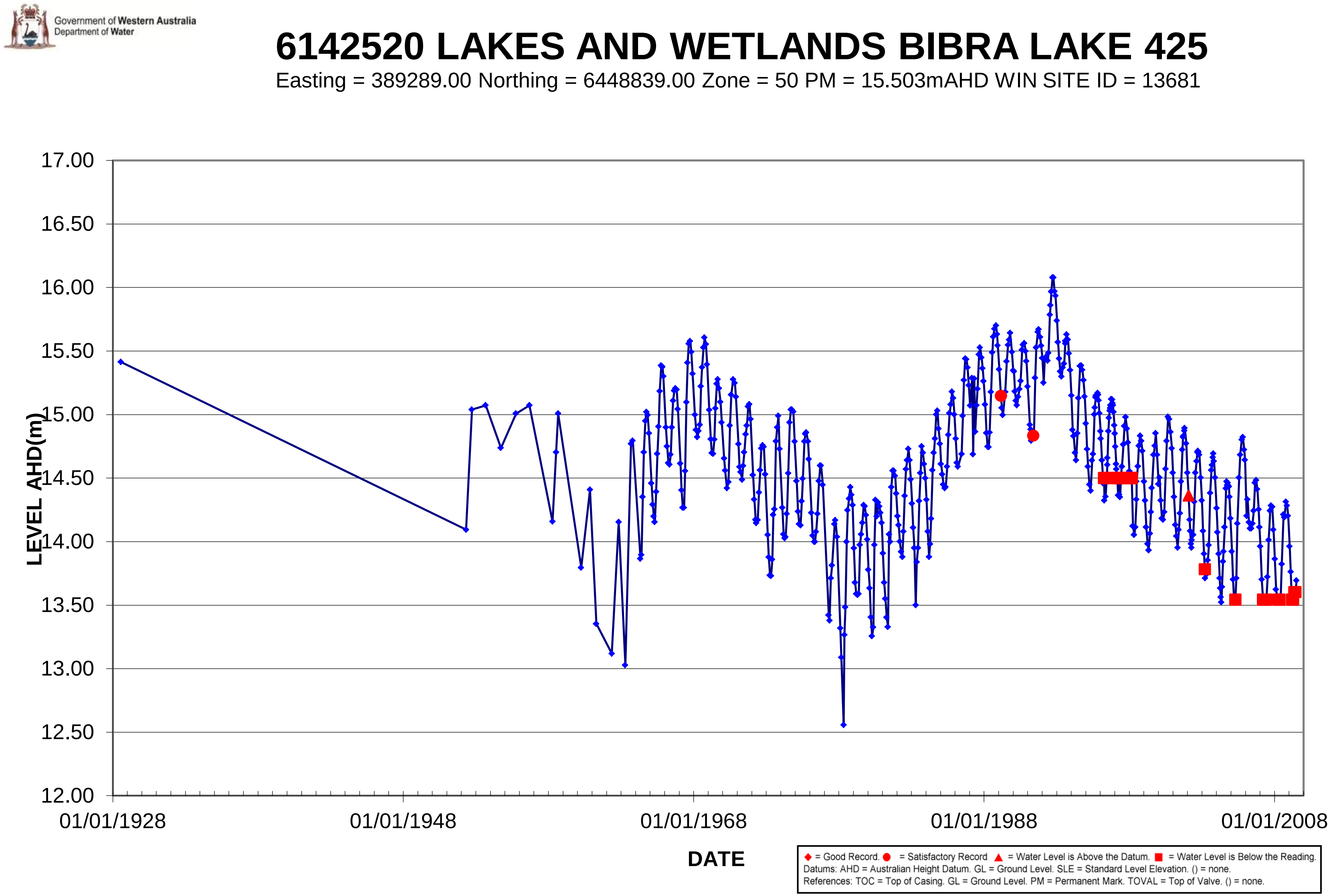


Figure 2-13 Observed Surface Water Levels at Bibra Lake (6142520)

Government of Western Australia
Department of Water

6142521 LAKES AND WETLANDS NORTH LAKE 424

Easting = 388859.04 Northing = 6450358.82 Zone = 50 PM = 17.244mAHD WIN SITE ID = 13682

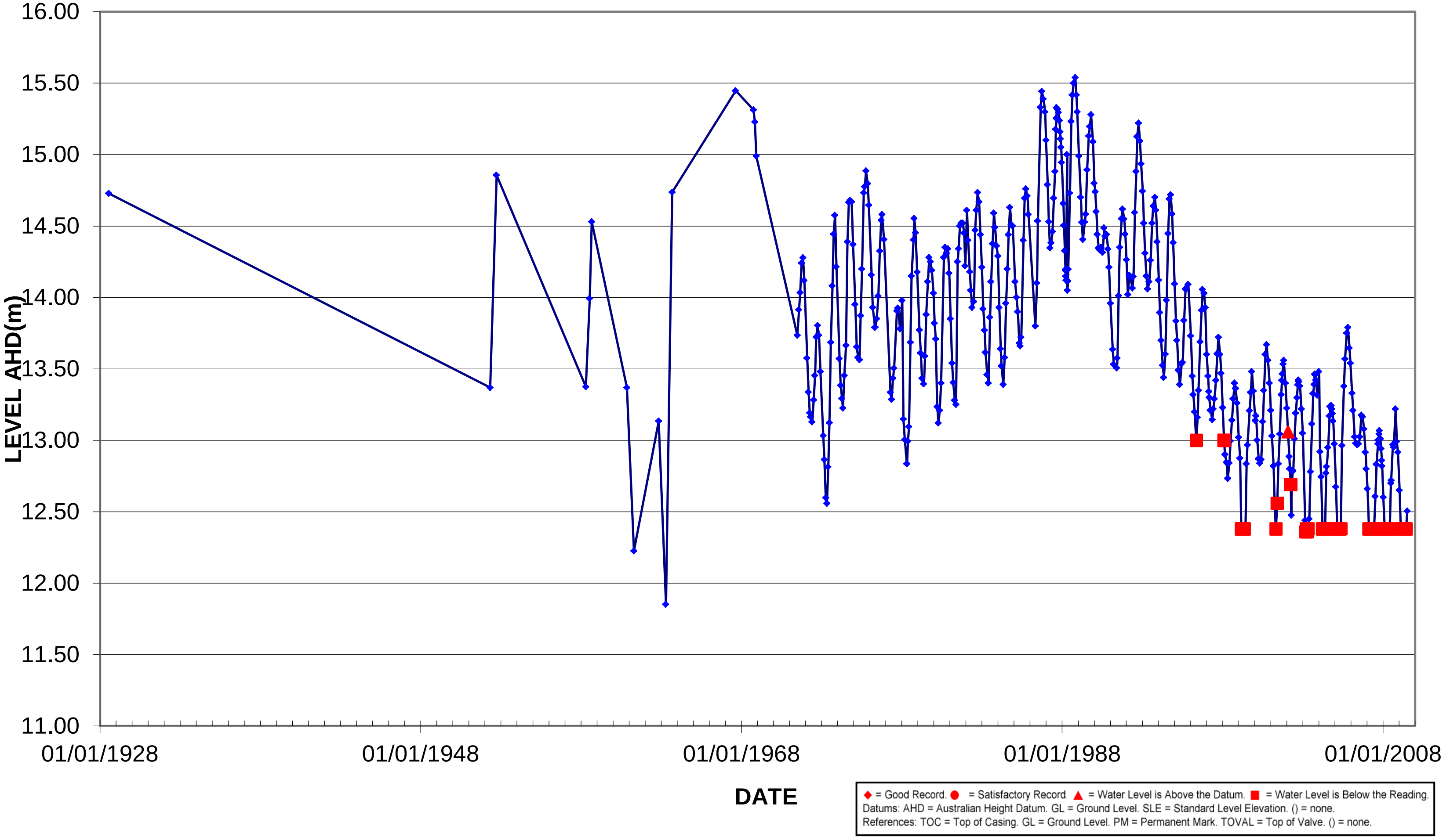


Figure 2-14 Observed Surface Water Levels at North Lake (6142521)

There are a number of geomorphic wetlands in the vicinity of the project area, as shown by Figure 2-15. The project area intersects the catchment that contributes surface water runoff to the following water bodies (the project wetland system):

- Bibra Lake.
- North Lake.
- Horse Paddock Swamp.
- Roe Swamp (Lower, Melaleuca and Roe swamps).
- Murdoch Drain.

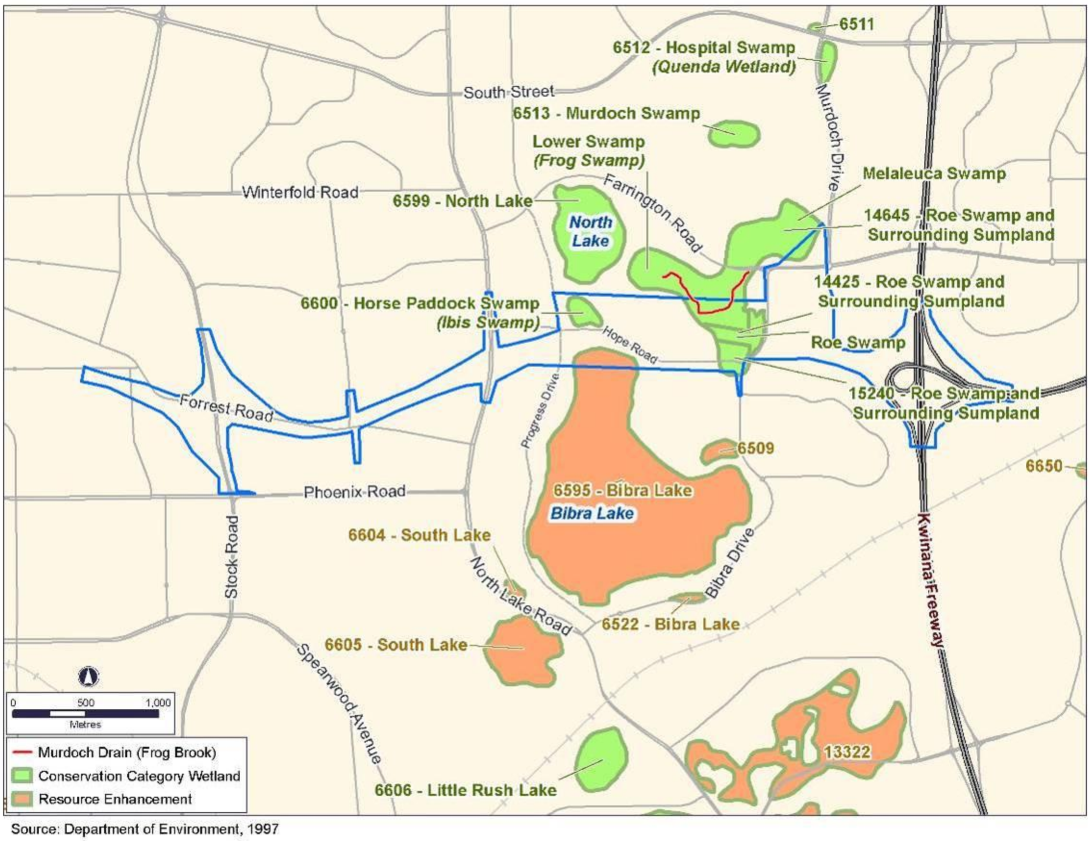


Figure 2-15 Geomorphic wetlands in the vicinity of the project area

Surface water within the project wetland system is a combination of groundwater expression, direct rainfall and surface water runoff from adjacent urban areas (Megirian 1982, Davidson 1983). The surface water catchment is approximately 730 hectares as calculated by a combination of Department of Land Administration topographic contours and City of Cockburn drainage information. North and Bibra Lakes are considered in hydraulic connection with unconfined groundwater in the superficial formations. The elevation of the water table on the eastern side of the lakes is higher than that of the lake bed, resulting in discharge of groundwater into the lakes. The water table on the western side of the lakes is lower than the lake level, indicating some outflow from the lakes to groundwater (Davidson 1983). Davidson (1983) also reports that seasonal fluctuations in lake water levels are in phase with variations in water table levels, but that a greater response is observed during periods of high rainfall or evaporation. This may indicate that North and Bibra Lakes are acting as 'through-flow' wetlands that are primarily influenced by groundwater. There are no surface water outflows from North and Bibra Lake (Megirian 1982).

2.4 Topography

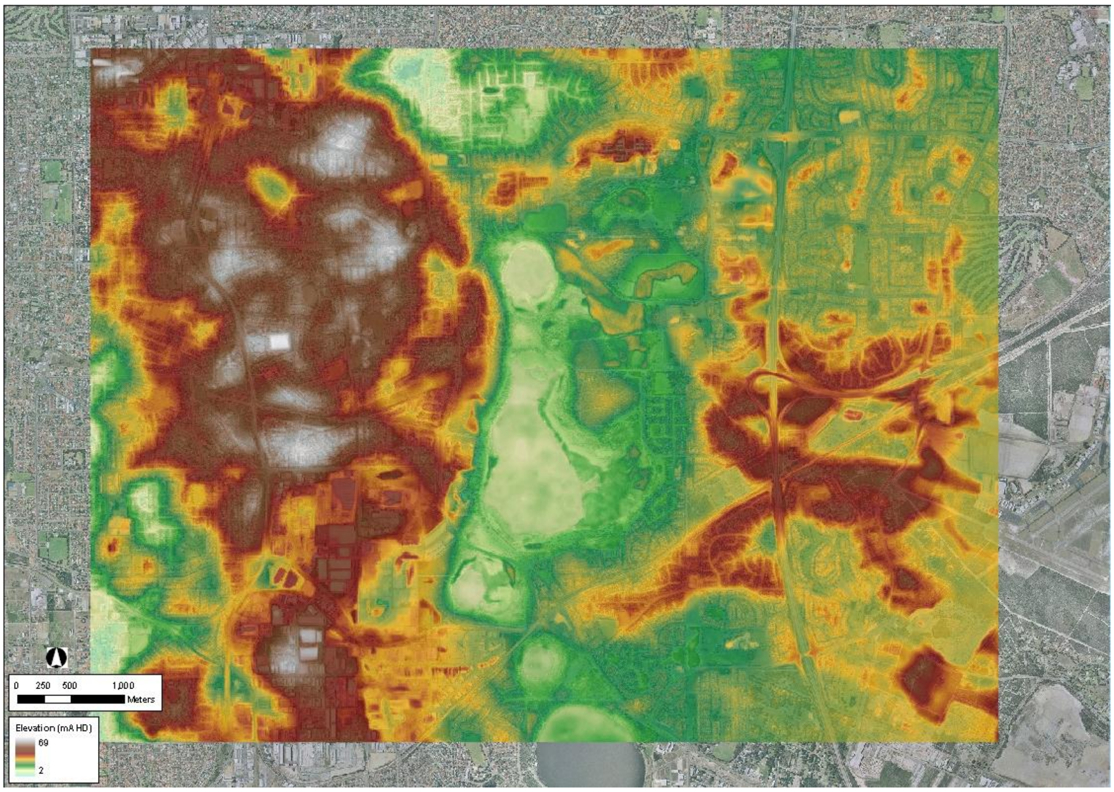
Two sets of topographical data covering the project area have been obtained:

- A Digital Elevation Model (DEM) generated from photogrammetry and
- 25cm contours obtained using LIDAR (Light Detection and Ranging).

Localised bathymetry of Bibra and North Lakes was also reported by Megirian (1982).

2.4.1 Photogrammetry Digital Elevation Model

The photogrammetry dataset consists of a DEM and derived 1m contours generated by Landgate from digital photogrammetry of aerial photography flown in 2008. This DEM is presented in Figure 2-16. Gross errors may exist in areas covered by dense vegetation and there may be some gaps in the data. A 10m DEM grid is available, with the expected vertical accuracy being for 90% of points to be within ±1.5m.



Source: Landgate

Figure 2-16 Landgate Photogrammetry Digital Elevation Model

2.4.2 250mm LIDAR Contours

250mm contours obtained through LIDAR imaging were provided by the City of Cockburn. It is believed that the dataset has been filtered correctly, however, there are some areas lacking data, for example the wetlands. The vertical accuracy of LIDAR data is typically ±0.1m.

2.4.3 Lake Bathymetry

Megirian (1982) presented bathymetric contours for Bibra and North Lakes in hard copy format, but the data accuracy is unknown and elevations around the perimeters of the wetlands were found to be higher than those recorded by the LIDAR.

2.5 Leaf Area Index

Leaf Area Index (LAI) is a measure of leaf density; a value of two means that there are two square metres of leaf surface for each square metre of ground surface (units are m^2/m^2, or dimensionless). In areas with a higher LAI, water is retained longer on vegetation, making this water available for evapotranspiration (ET) before it is necessary to draw moistures from the soil.

Values of LAI used with PRAMS for banksia woodlands (Xu *et al*. 2009) are presented in Table 2-7. The ranges given in the middle column are used to classify banksia woodlands based on LAIs derived from Landsat images and data received from the Landsat series of satellites and processed by Geoscience Australia.

Table 2-7 LAI values adopted within PRAMS

Land Use Class	LAI Range based on Landsat Classification	Adopted LAI within PRAMS
Banksia – low density	0.5 – 0.75	0.66
Banksia – medium density	0.75 – 0.85	1.08
Banksia – high density	> 0.85	1.26

Source: Xu et al. (2009)

3.0 Water Movement Modelling

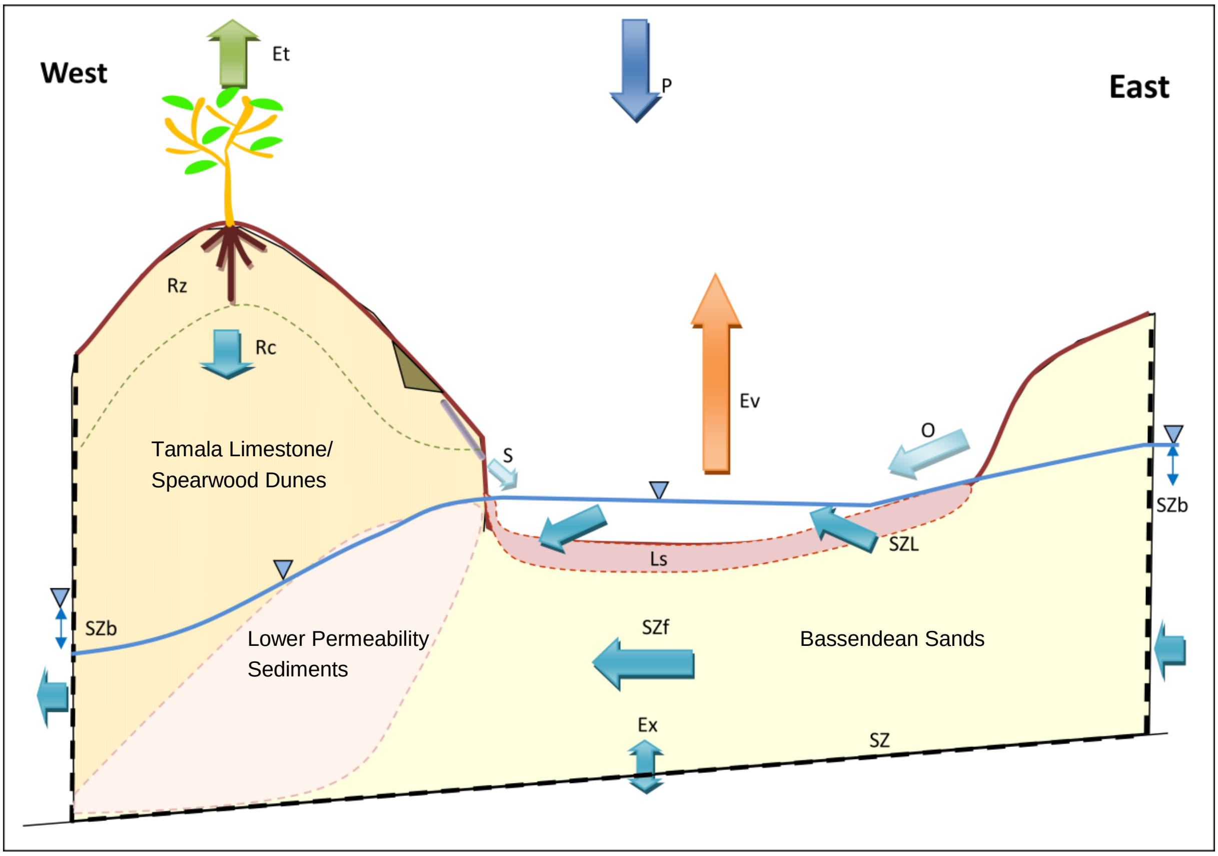
Water movement modelling was undertaken by DHI, specifically:

- System conceptualise.
- Numerical model development, calibration and sensitivity analysis.
- Model simulation.

The following is a summary of the work undertaken by DHI.

3.1 Conceptualisation

The schematic diagram shown in Figure 3-1 is considered to be a generalised conceptualisation of the system based on the literature review.



Legend	
P	Precipitation
Et	Evapotransipiration
Ev	Evaporation
O	Overland flow
S	Stormwater runoff piped from impervious urban areas to the lakes
Rc	Recharge
Rz	Root zone
Ls	Lacustrine sediments
SZ	Saturated zone
SZL	Saturated zone flow
SZb	Saturated zone boundary condition
SZf	Saturated zone flow driven by groundwater levels
Ex	Exchange with groundwater

Figure 3-1 Sketch of the system provided by DHI

3.2 Model Build

3.2.1 Model Domain

The extent of the model domain is shown in Figure 3-2. The model does not cover the full extent of the project area, but is roughly centred on the area containing the sensitive wetlands. The western section of the project area has not been included in the model. The proposed road level is well above (>10 m) the groundwater table and there are no significant surface water drainage lines that will be affected in this area.

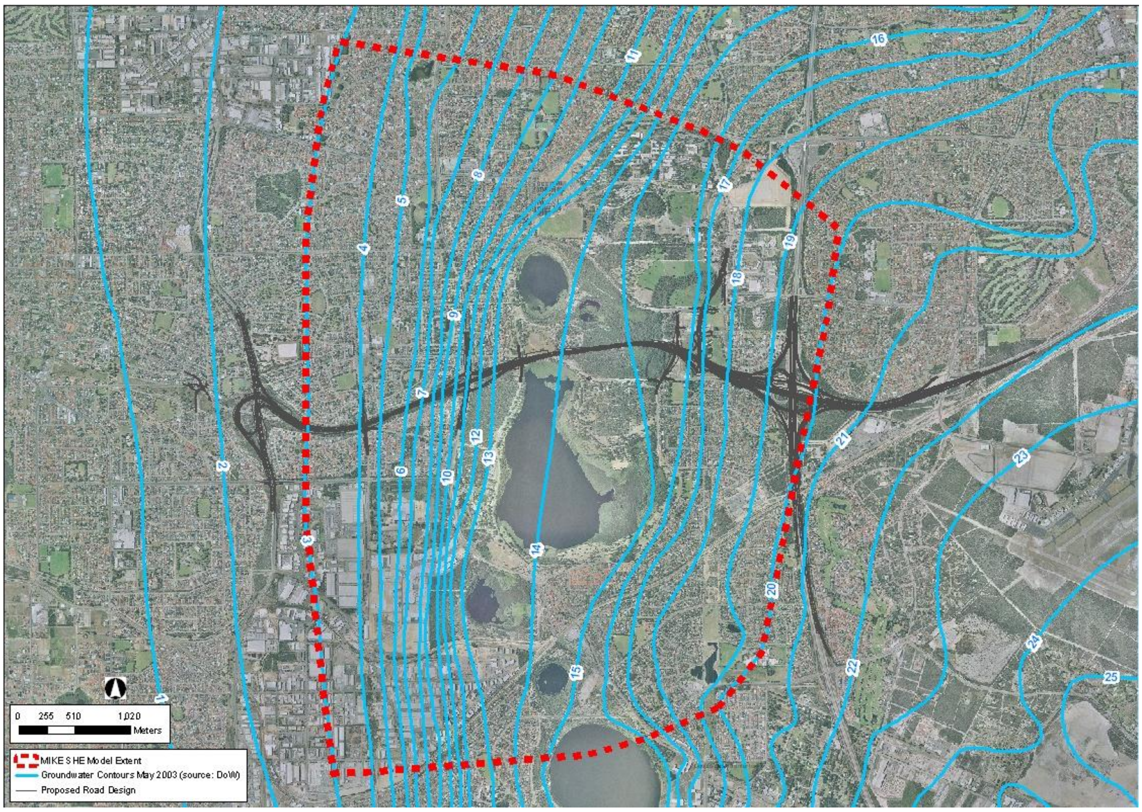


Figure 3-2 MIKE SHE Model Domain

3.2.2 Model Boundaries

The boundaries were defined with regard for the orientation of Perth Groundwater Atlas (Department of Environment 2004) groundwater contours, which are based upon May 2003 (end of Summer) measurements of superficial aquifer groundwater levels from DoW monitoring bores. The eastern and western boundaries lie approximately parallel to the groundwater contours. The northern and southern boundaries lie approximately perpendicular to the groundwater contours to allow the use of zero flow boundary conditions.

The eastern and western boundaries of the model area were selected at a sufficient distance away from the wetlands so that any numerical instabilities at the boundaries are unlikely to influence water levels within the area of interest.

3.2.3 Model Grid

A model grid cell size of 80×80m has been used in order to achieve a balance between spatial resolution and reasonable model run times. At this scale the model's ability to simulate roads, drains and small bodies of water will be limited.

Model inputs and results are also averaged across these 80m cells which limits the ability of the model to represent the system, or produce results, at discrete locations.

3.2.4 Model Geometry

3.2.4.1 Base Elevation

The base elevation of the model was defined by interpolating the base contours of the superficial formation presented in the Perth Groundwater Atlas (Water and Rivers Commission 1997), as shown in Figure 3-3. These contours are higher than those reported in the 2004 Atlas (Department of Environment 2004), which results in a more conservative model configuration.

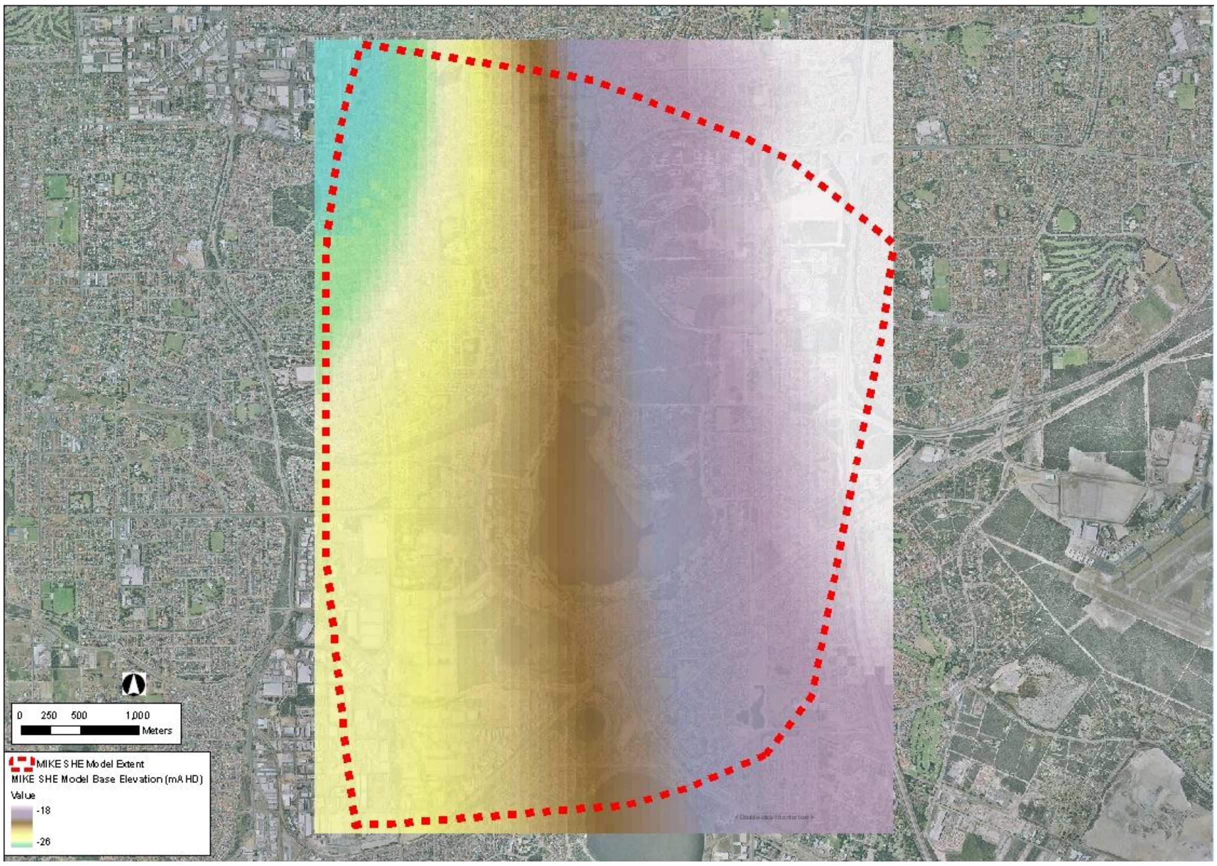


Figure 3-3 MIKE SHE Model Base Elevation

3.2.4.2 Surface Topography

The surface topography was defined using the LiDAR dataset, with the Landgate DEM being used for areas outside the extent of the LIDAR data. The following manual adjustments were made to the LIDAR elevations for areas that are assumed to be inaccurately represented, or where data are missing:

- Bed elevations for Little Rush Lake were lowered using the Landgate DEM.
- Areas within Bibra Lake that were not defined by the LiDAR data were defined using the bathymetry reported by Megirian (1982) and manual interpolation for unreported areas.
- The elevations of North Lake Road between Bibra Lake and South Lake and Hope Road between Horse Paddock Swamp and Bibra Lake were manually raised to 16.25mAHD.
- The level of the path around Bibra Lake was raised through Roe Swamp.

The resultant surface topography is shown in Figure 3-4.

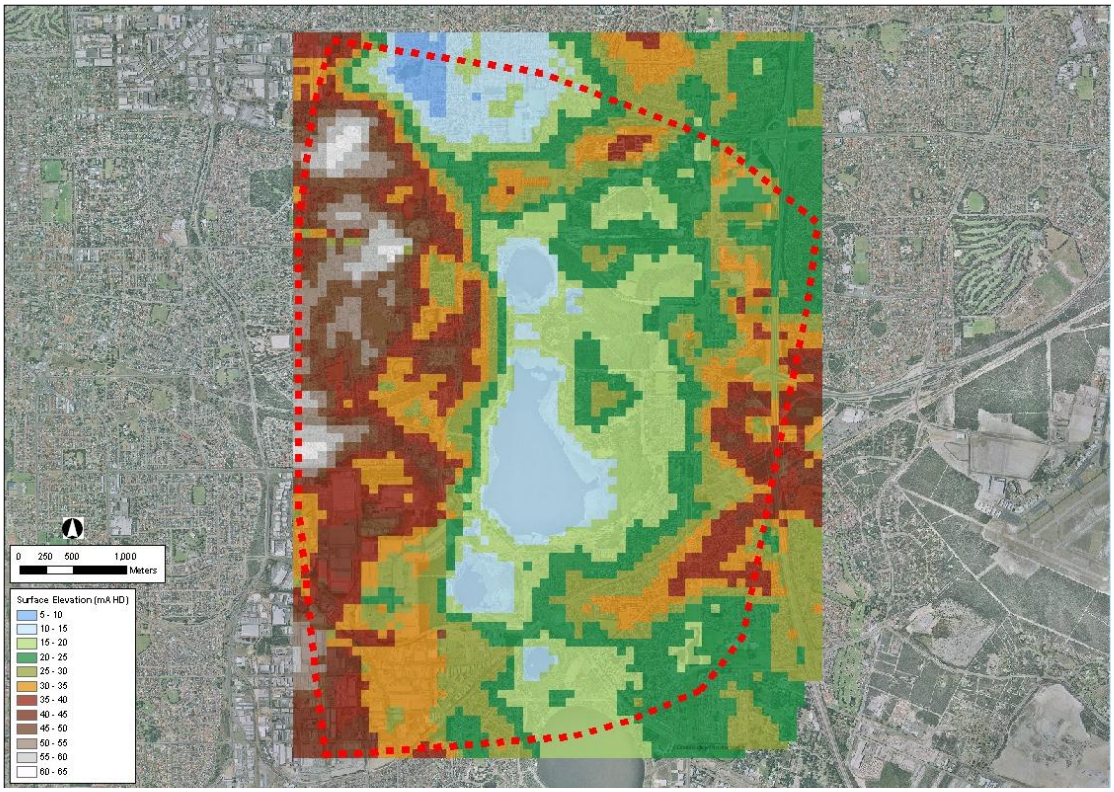


Figure 3-4 MIKE SHE surface topography

3.2.4.3 Unsaturated Zone

The upper unsaturated zone extends from the surface down as far as the Effective Rooting Depth (ERD) or to the water table, whichever is higher at that point in time. ERD values represent the depth to which roots are able to draw on groundwater.

3.2.4.4 Saturated Zone

The saturated soil zone extends from the base of the unsaturated zone to the base of the model, the depth is therefore varying with the movement of the water table.

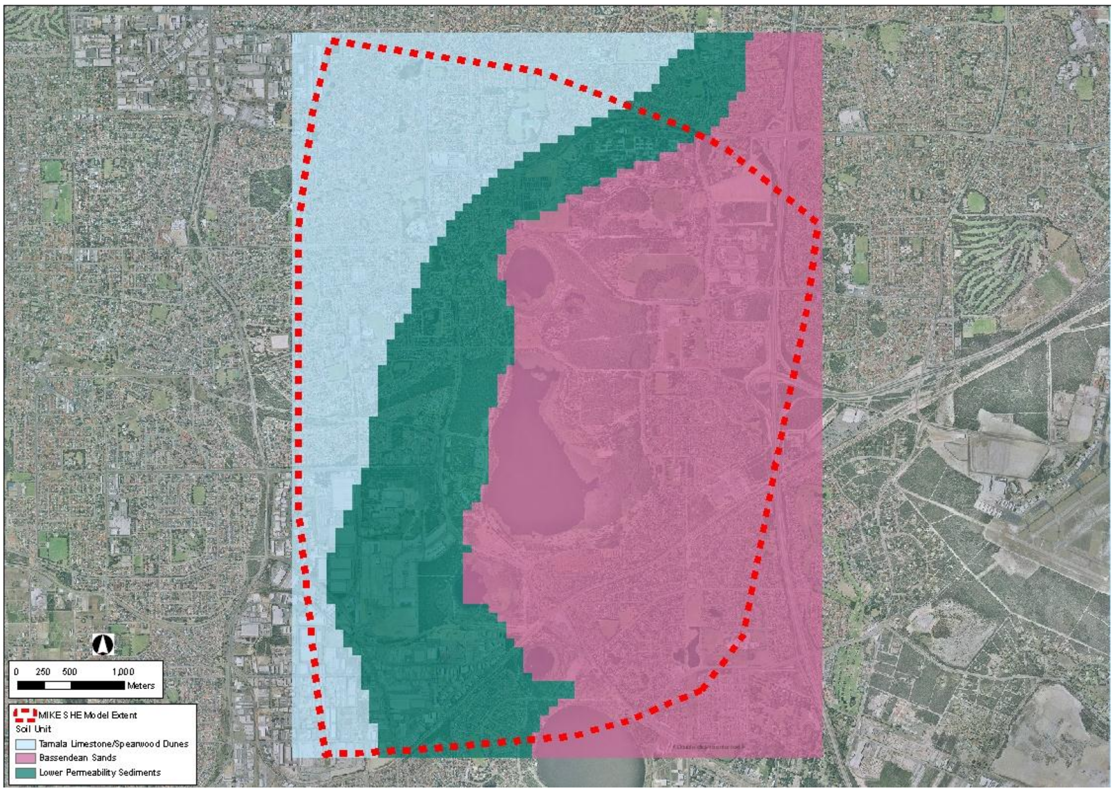


Figure 3-5 Model soil units of the saturated zone

The depth of the top layer of the saturated zone varies laterally by soil units. Soil unit distributions are presented on Figure 3-5. The Bassendean Sands covering the eastern half of the model domain have been assigned a nominal depth of 3m, as the unit extends through the full vertical extent of the model. The lacustrine sediments below the wetlands extend for 5m and are underlain by Bassendean Sands. The base of the upper layer of the Tamala Limestone/Spearwood Dunes grades towards the west, producing a sloping interface with the lower permeability sediments located below (Figure 3-5). Along the western boundary of the model, the Tamala Limestone/Spearwood Dunes extend to the base of the model. A vertical profile of the saturated zone through Bibra Lake is shown in Figure 3-7.

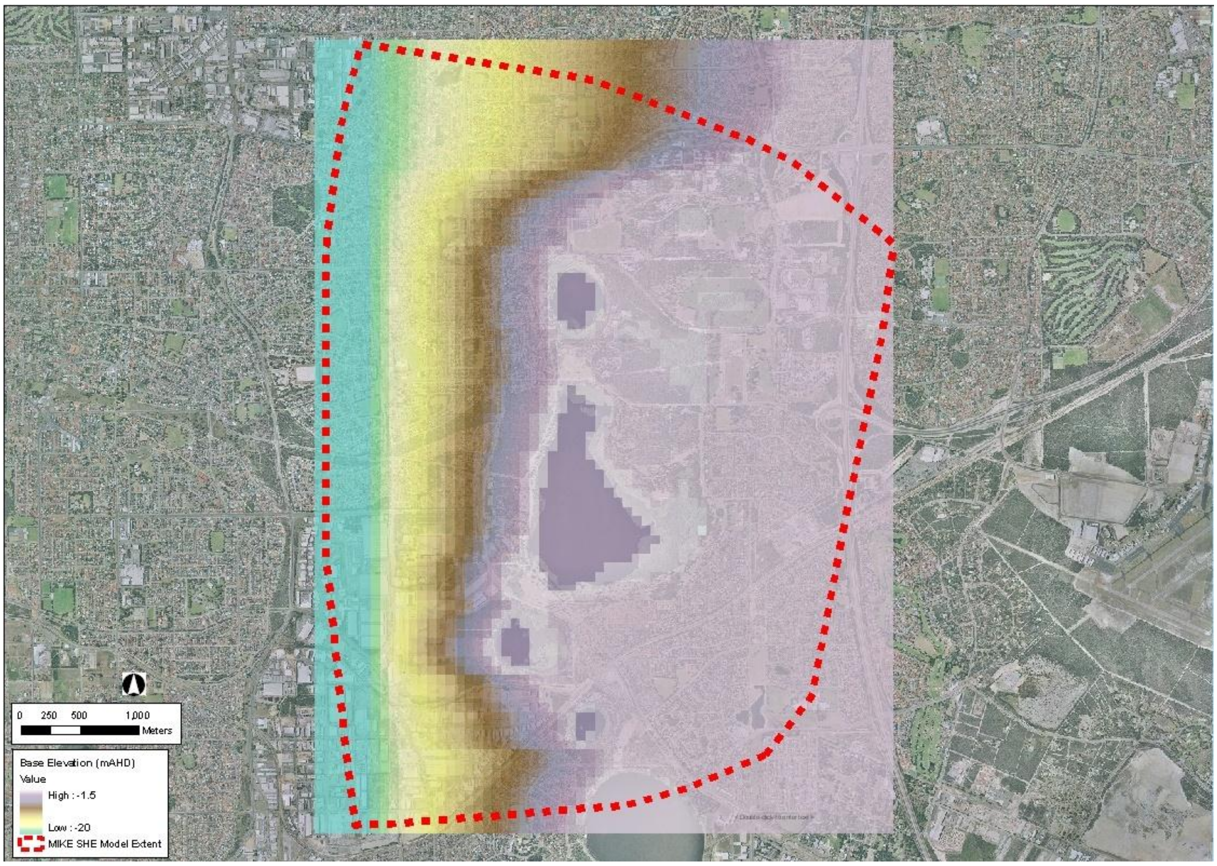


Figure 3-6 MIKE SHE model base elevation of the upper layer of the saturated zone

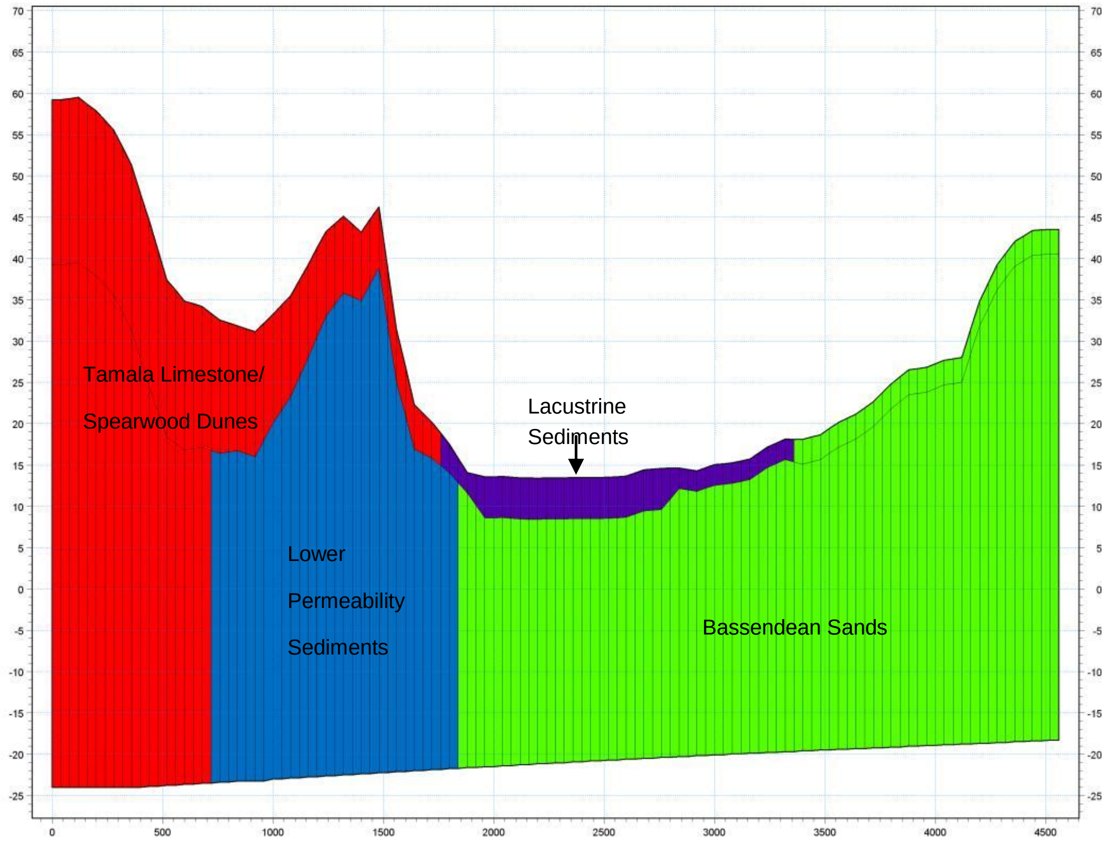


Figure 3-7 Section of the MIKE SHE model saturated zone through Bibra Lake

3.2.4.5 Channel Flow

There is a constructed drainage channel known as Murdoch Drain, which is located to the South East of North Lake, to the north of Row Swamp. Murdoch Drain has been modelled using the MIKE 11 one-dimensional flow linkage, as presented on Figure 3-8, with channel cross-sections extracted from the LiDAR data. Overland flow will discharge into a MIKE 11 river link if the water elevation in the MIKE SHE grid cell is higher than the bank elevation. Water in the model cannot flow from the MIKE 11 channel directly to overland flow but instead will recharge to the saturated zone.

There is a raised cross section in this channel between Frog Swamp and North Lake that represents a walking path, which acts as weir in this area.

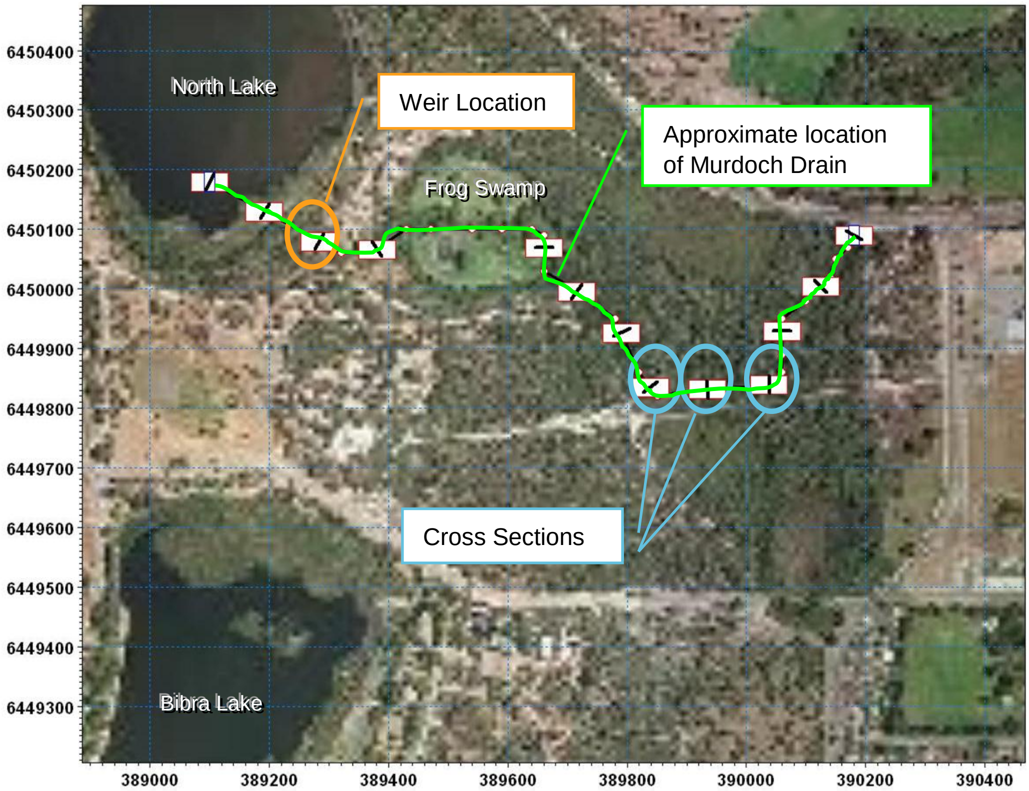


Figure 3-8 MIKE 11 Channel Representation

3.2.5 Model Parameters

3.2.5.1 Land Use Classification

The land use classification used within the model is presented in Figure 3-9, which is based on an assessment of recent aerial photographs, field work and the land use categories used within PRAMS (Xu *et al.* 2009). A constant land use time series has been assumed for all simulations, based on an assessment of historical aerial photographs and the temporal land use patterns used within PRAMS (Xu *et al*. 2009), which indicated that land use has remained relatively unchanged since around 1990. Values of LAI and ERD have been assigned to each of the land use classes.

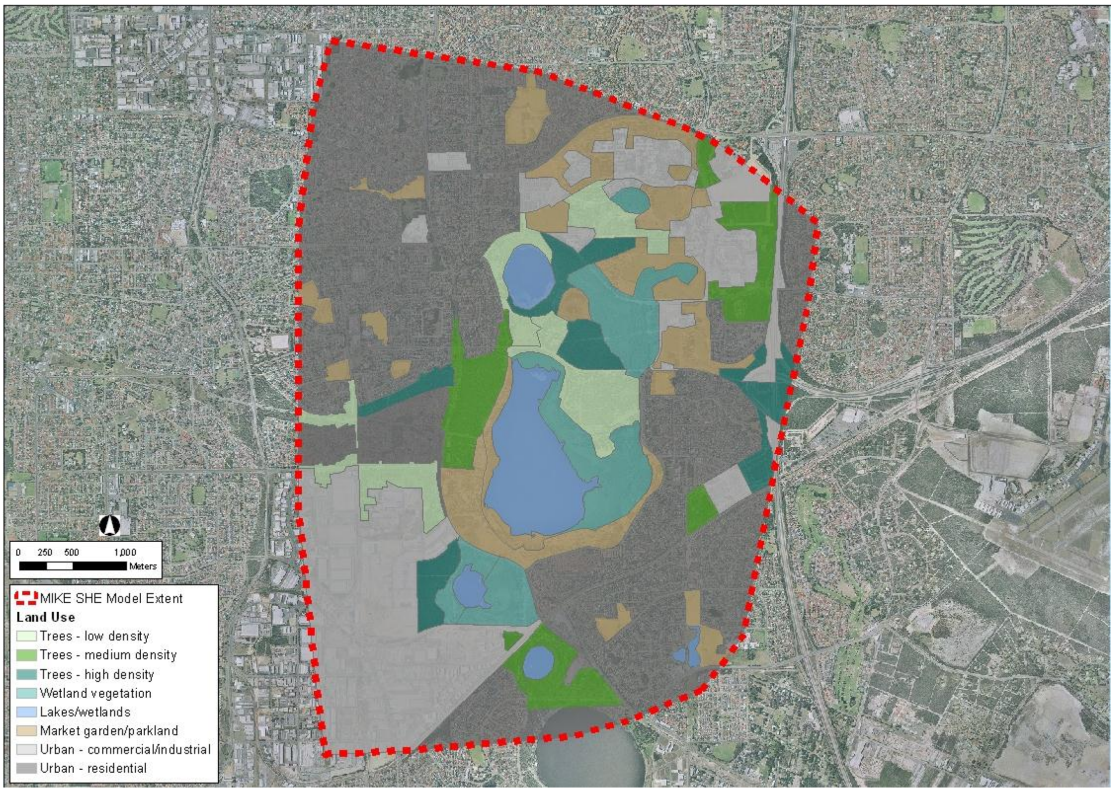


Figure 3-9 MIKE SHE land use classification

3.2.5.2 Leaf Area Index

The LAI of each land use classification used within the model is presented in Table 3-1. The LAI for trees is based on PRAMS (Xu *et al.* 2009).

Table 3-1 LAI values

Land Use	LAI
Trees – high density	1.3*
Trees – medium density	1.1*
Trees – low density	0.7*
Lakes/wetlands	1
Market garden/parkland	3
Wetland vegetation	3
Urban residential	1
Urban commercial/industrial	1

* Taken from Xu *et al*. (2009)

3.2.5.3 Hydraulic Conductivity

The adopted unsaturated zone soil parameters for the model were distributed as shown in Figure 3-10. These parameters are distributed in a similar manner to the map available from DAFWA.

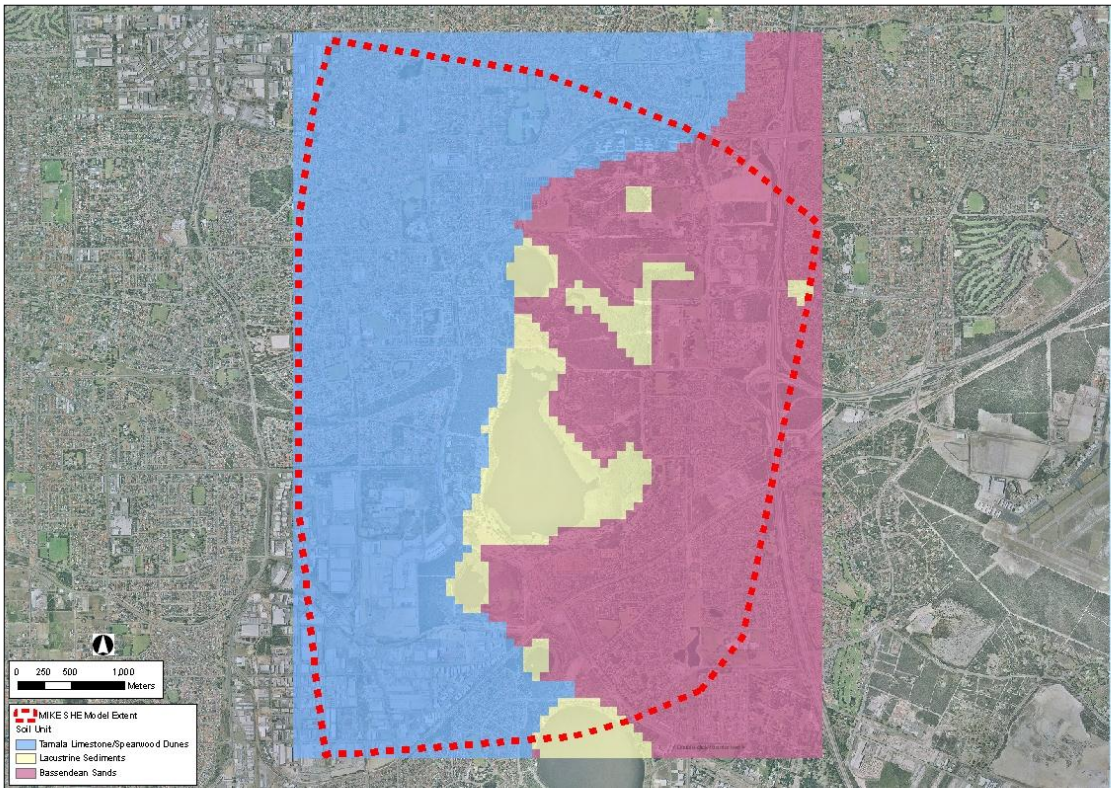


Figure 3-10 Model soil units defined for the unsaturated zone

The unsaturated zone hydraulic conductivities are taken directly from the Topsoil A layer within PRAMS (Table 2-4) and are presented in Table 3-2.

Table 3-2 Saturated hydraulic conductivity for the unsaturated zone

Soil Category	Saturated Hydraulic Conductivity	
	m/s	m/day
Tamala/ Spearwood Dunes	3.9×10^{-5}	3.4*
Lacustrine sediments	1.2×10^{-7}	0.01*
Bassendean Sand	1.8×10^{-5}	1.6*

* Taken from Xu *et al*. (2009)

The soil units defined for the unsaturated zone (Figure 3-10) have been used to define the geology for the top layer of the saturated zone, as the boundary between the two zones fluctuates with the movement of the water table. The horizontal distribution of these units was manually modified to define the geology of the lower layer of the saturated zone (Figure 3-5). This was done by introducing the band of lower permeability sediments described in Section 2.2 and extending the Bassendean Sands beneath the wetland areas.

3.2.5.4 Surface Roughness

A Manning's n of 0.1 has been applied across the whole model domain.

3.2.6 Initial Conditions

Initial values for surface water levels and the potential head across the top and bottom of the saturated zone were generated by running the model for five years from 1984 and extracting water levels at the end of the simulation. The initial water levels are presented on Figure 3-11 and the initial potential heads in the saturated zone are presented on Figure 3-12.

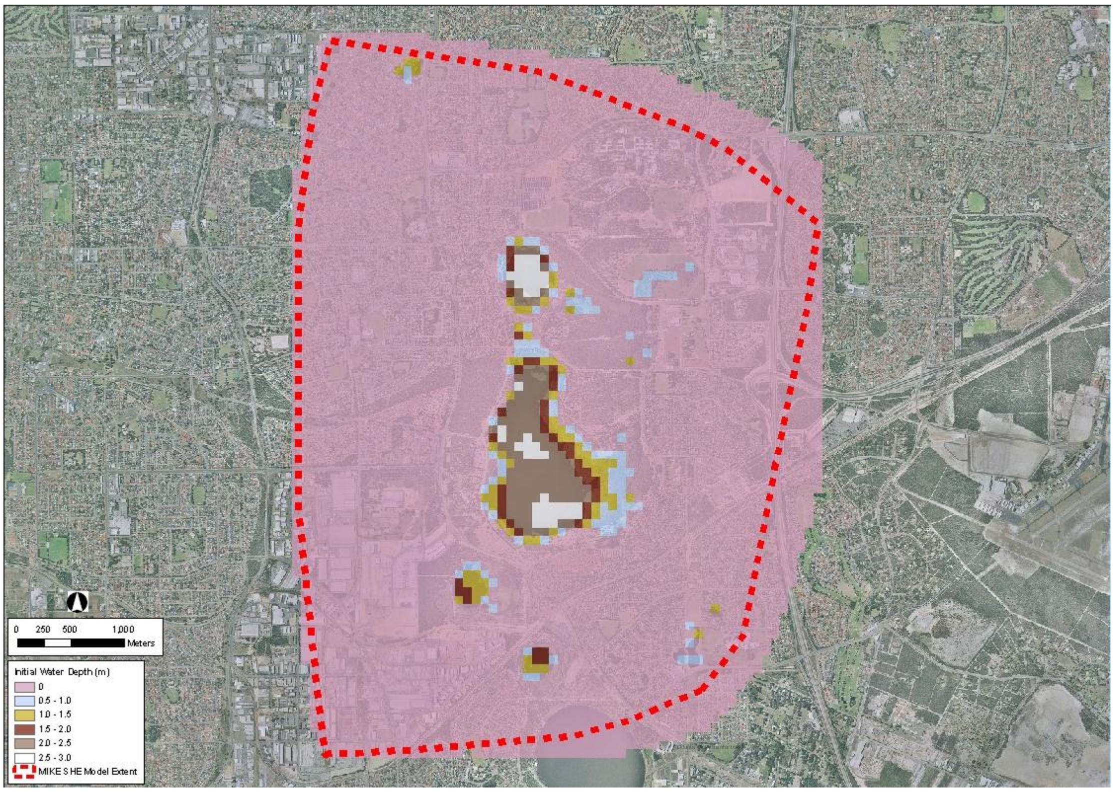


Figure 3-11 MIKE SHE initial water levels

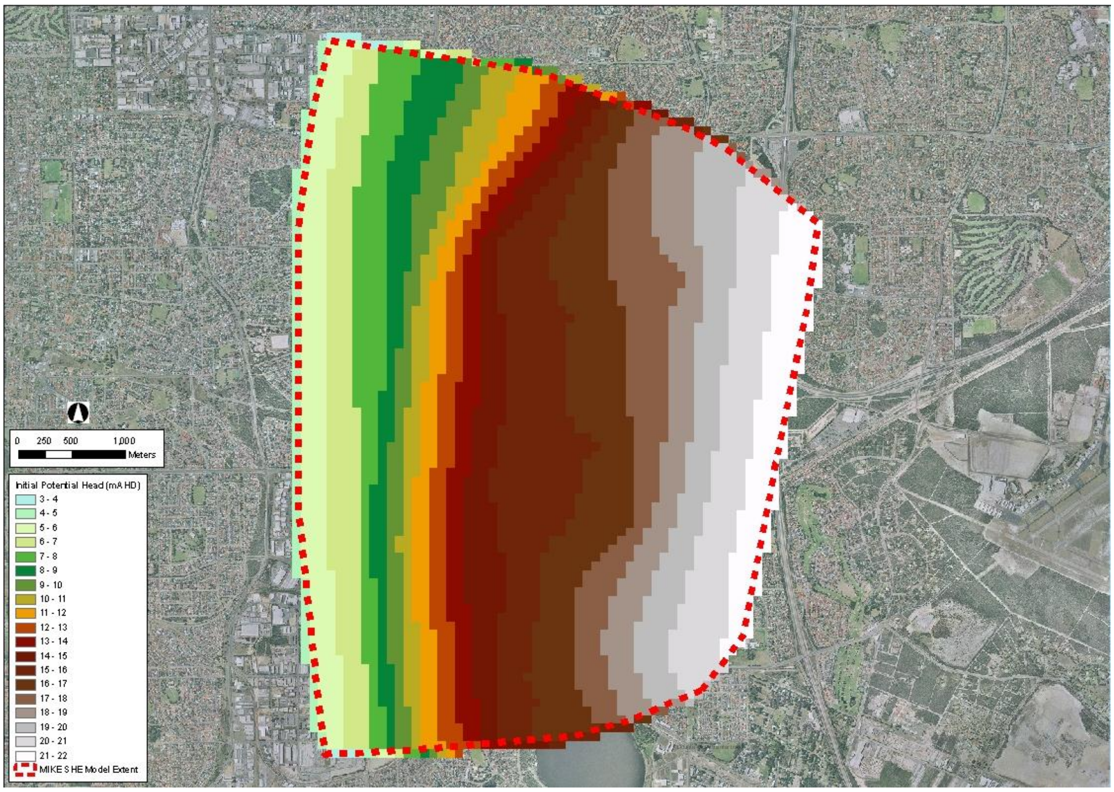


Figure 3-12 MIKE SHE initial potential head in the saturated zone

4.0 Model Simulations

Five simulations were identified as follows:

- Base case simulation.
- Long term simulation that was run with:
  - Maximum groundwater time series.
  - Minimum groundwater time series.
  - Average groundwater time series.
- Short term simulation.

The short term simulation runs for 1 year to simulate the complete response to a 100 year ARI 72 hour rainfall event occurring at the start of the run. A hyetograph was created using data from BoM and AR & R (Pilgrim 2001) and applied across the whole model domain. This was likely undertaken to assess the influence of large, infrequent, storm events on the groundwater and surface water within the project area. The single rainfall event simulated by the short term simulation was found to have minimal impact on surface water and groundwater levels. It was therefore concluded that water levels in the project area are more dependent on long term variability than the response to individual rainfall events. The short term simulation set up and results are therefore not discussed further in this report.

4.1 Period of Simulation

4.1.1 Base Case

The base case model runs for 20 years from 1 January 1989 to 1 January 2009. This is based on the assumption that land use across the project area has remained relatively unchanged since 1990, following a review of the historical land use data presented for PRAMS (DoW, 2009). Measured water levels are only available from 1975, and there is sufficient data available for a number of surface water and groundwater sites during the chosen time period to allow model parameters to be calibrated.

4.1.2 Long Term Simulation

The long term simulation runs for 98 years, due to the availability of historical rainfall from *SILO*. Historical rainfall was used as a projection of future rainfall. This rainfall was applied to current land use and is assumed to simulate potential future conditions under a variety of boundary conditions.

4.2 Fixed Head Time Series

4.2.1 Base Case

The time series applied to the fixed head boundary conditions for the base case model were defined using modified groundwater levels from Bore 61410234. The measured groundwater levels have been modified by a fixed amount, based on an assessment of local groundwater levels and data within DoW's estimated maximum historical groundwater contours (DoW, 2001). The eastern boundary condition has been reduced by 0.75m and the western boundary condition has been reduced by 17.5m.

4.2.2 Long Term Simulation

The time series used for the long term simulation boundary conditions were defined by repeating cycles of monthly average groundwater levels, calculated from the historical record for measured bores. The model was run separately using minimum, mean and maximum average values to determine the potential range of responses that may result from long term variability in groundwater levels. The levels presented on Figure 4-1 and Figure 4-2 are repeated throughout the model duration in order to simulate the seasonal variation in levels.

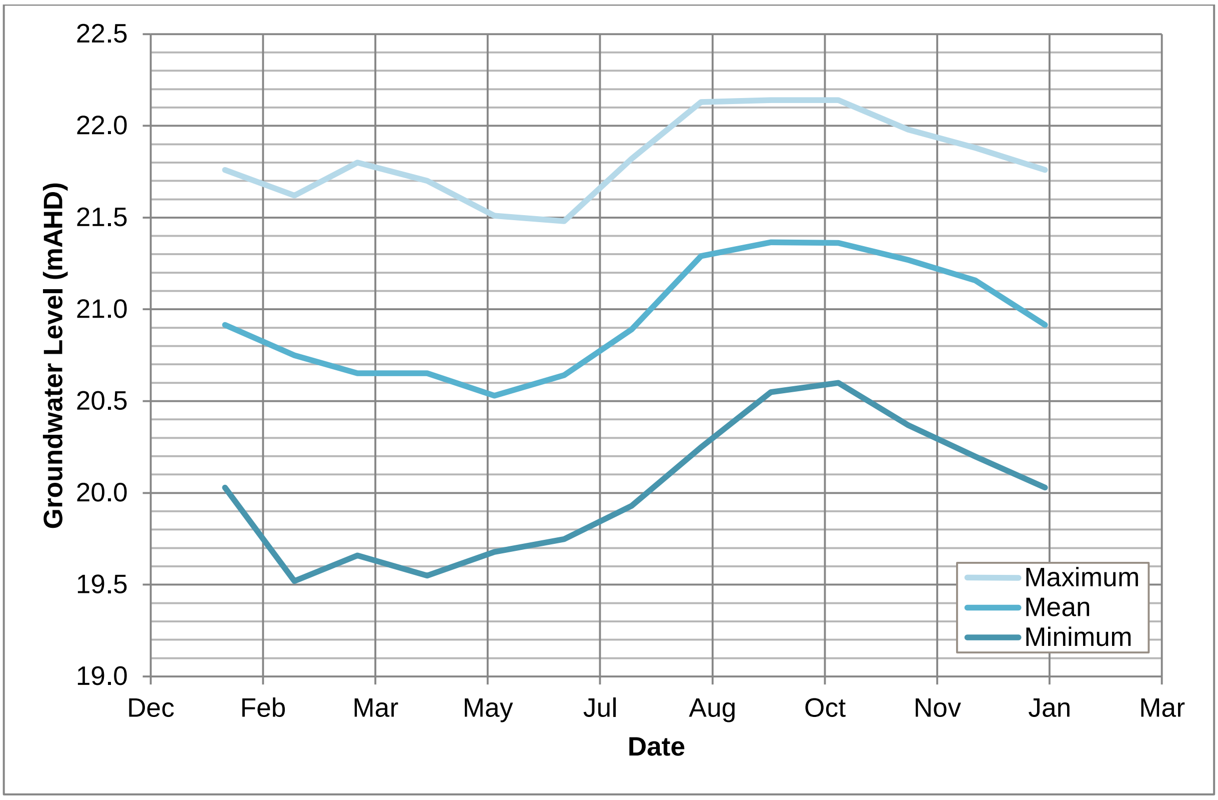


Figure 4-1 Long Term Simulation Eastern Boundary Conditions

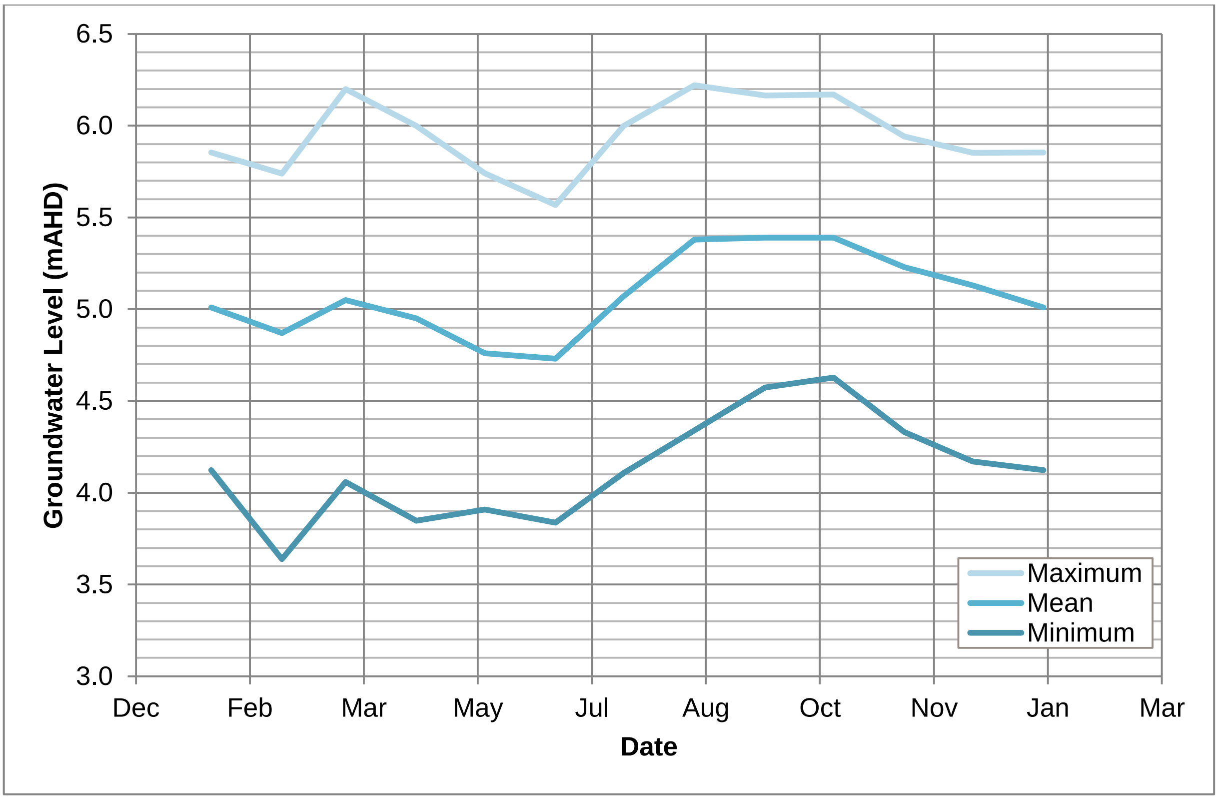


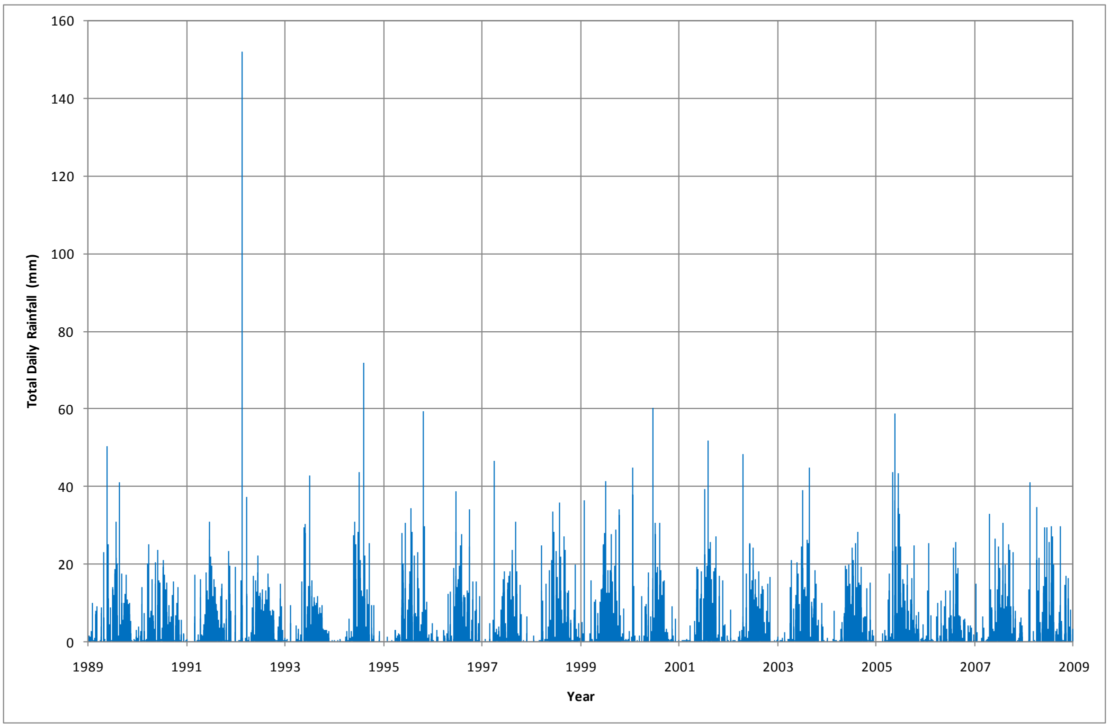
Figure 4-2 Long Term Simulation Western Boundary Conditions

4.3 Rainfall Time Series

Complete sets of the SILO data collected for both the eastern and western areas of the model domain can be found in Appendix B.

4.3.1 Base Case

The SILO DataDrill rainfall time series have been used for daily rainfall totals in the base case simulation. The rainfall hyetograph for the western side of the model area is presented on Figure 4-3. There is very little difference between the eastern and western datasets.

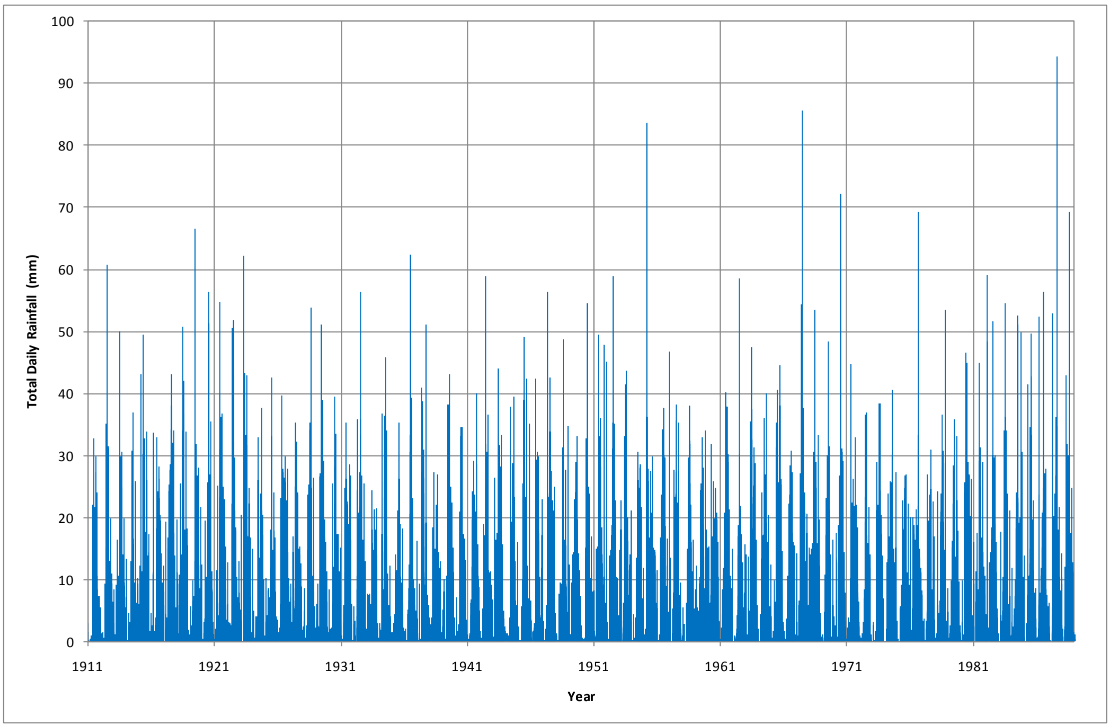


Source: SILO

Figure 4-3 Base case simulation western rainfall time series

4.3.2 Long Term Simulation

The historical time series obtained from SILO were used to represent rainfall for the long term simulation as a substitute for predicted future rainfall. Application of this longer term data set allows for the assessment of the response of the wetland area under different hydrological regimes. The additional rainfall data prior to 1989 are shown in Figure 4-4 for the western dataset.



Source: SILO

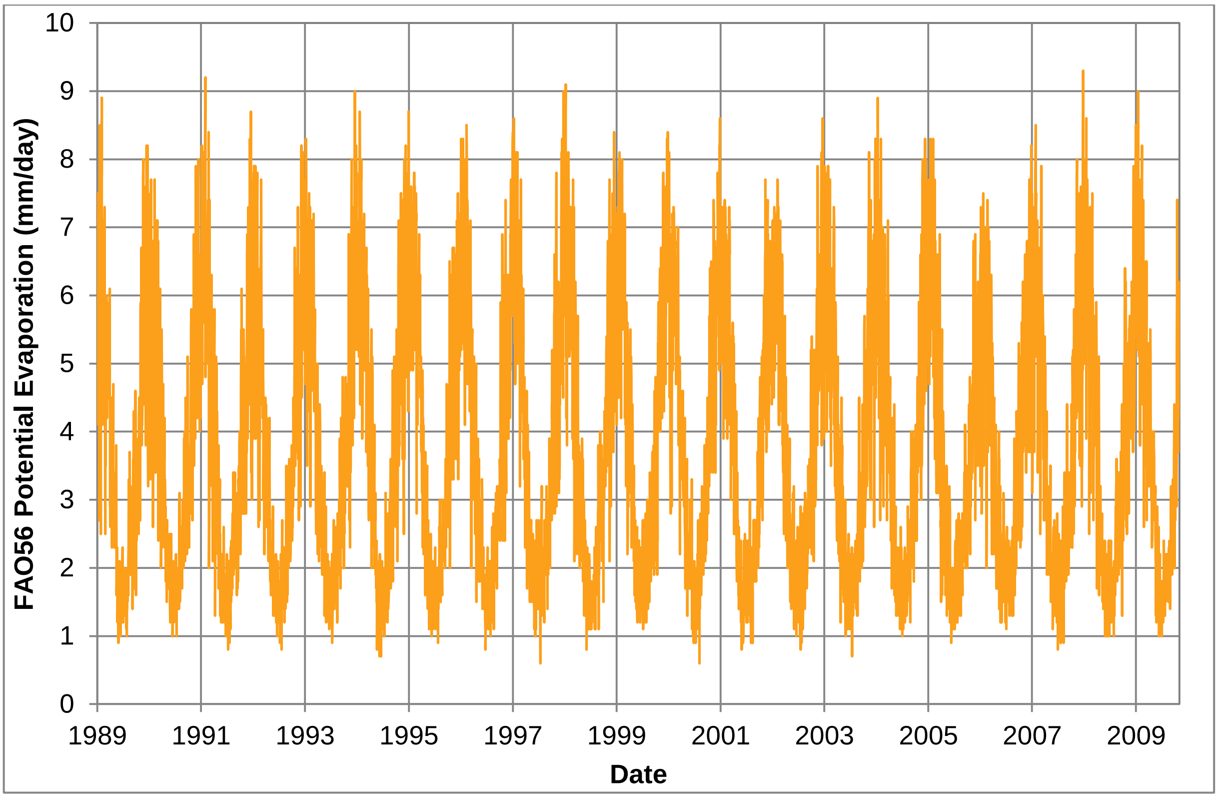
Figure 4-4 Long term simulation western rainfall time series

4.4 Evaporation Time Series

Complete sets of the SILO data collected for both the eastern and western areas of the model domain can be found in Appendix B.

4.4.1 Base Case

Daily evaporation totals for input into the base case simulation were defined using the FAO56 reference crop evapotranspiration data contained in the SILO datasets. The two time series (western and eastern) contain very similar values. The western time series used within the base case simulation is shown in Figure 4-5.

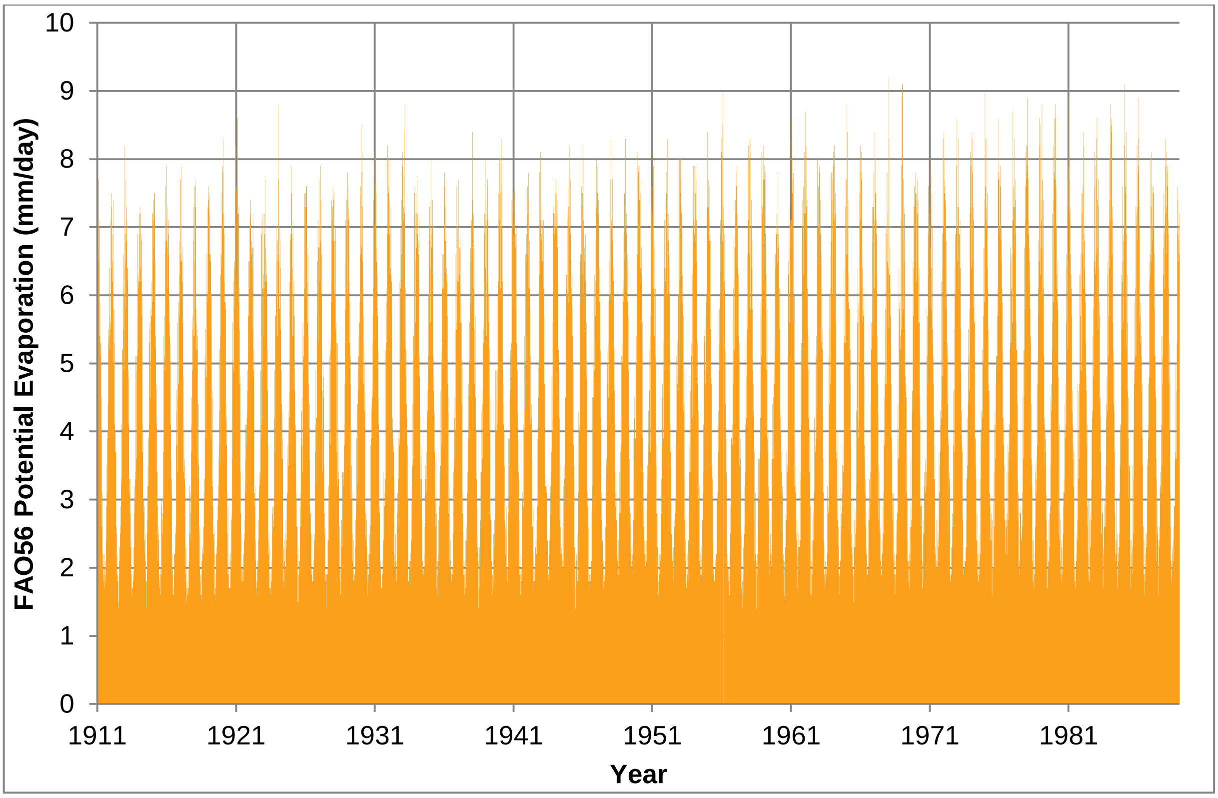


Source: SILO

Figure 4-5 Base case simulation western potential reference crop evapotranspiration time series

4.4.2 Long Term Simulation

The FAO56 time series data obtained from SILO were used to represent evapotranspiration for the long term simulation. The data for the western half of the catchment from 1911 to 1989 are presented in Figure 4-6.



Source: SILO

Figure 4-6 Long term simulation western reference crop evapotranspiration time series 1911 to 1989

5.0 Calibration

Historical time series of observed groundwater and surface water levels for locations shown in Figure 2-10 and Figure 2-12 were used to calibrate model parameters through comparison with simulated water levels at the monitoring locations. These calibration time series data can be found in Appendix A. This section presents the calibrated parameter values and compares simulated and observed water levels to demonstrate the performance of the calibrated model.

For an integrated groundwater-surface water model, the ERD and saturated zone hydraulic conductivity parameters can be some of the more important controlling factors. Calibration of ERD and saturated zone hydraulic conductivities is discussed below, together with relatively less significant parameters.

5.1 Land Use Characteristics

The calibrated values of ERD that were adopted for use within the model are presented in Table 5-1. The values for urban areas were calibrated using bore water level responses and annual rises.

Table 5-1 Calibrated ERD values

Land Use	ERD (m)
Trees – high density	8
Trees – medium density	6
Trees – low density	3
Lakes/wetlands	0.3
Market garden/parkland	0.7
Wetland vegetation	0.95
Urban residential	0.5
Urban commercial/industrial	0.3

5.2 Unsaturated Zone

Calibrated values for unsaturated zone soil properties are presented in Table 5-2. The "water content at saturation" and "water content at field capacity" parameter values are similar to the values adopted within PRAMS (Xu *et al*. 2009), if averaged across all layers within the soil unit. The "water content at saturation" is slightly higher than that used in PRAMS for lacustrine sediments and all water contents at field capacity are four to five percent higher than those used in PRAMS.

Table 5-2 Calibrated values for the unsaturated zone soil properties

Soil Category	Water Content at Saturation	Water Content at Field Capacity	Water Content at Wilting Point
Tamala/ Spearwood Dunes	0.36	0.07	0.03
Lacustrine sediments	0.37	0.22	0.05
Bassendean Sand	0.36	0.07	0.03

5.3 Saturated Zone

Calibrated values for the saturated zone geological properties are presented in Table 5-3. The horizontal hydraulic conductivity adopted for the Tamala Limestone/Spearwood Dunes is within the range of values adopted by Nield (1999) for geological units to the east of the lakes (Figure 2-7), but the value for lacustrine sediments is much lower than that presented by Neild (1999). The value adopted for Bassendean Sand is similar to the 13m/day measured by Playford *et al*. (1976) and the regional average of 15m/day reported by Davidson and Xu (2006). It is however, lower than the values presented by Nield (1999) for this area, which range from 10 to 35 m/day, with a tendency towards the higher values.

Table 5-3 Calibrated values for saturated zone geological properties

Geological Unit	Horizontal Hydraulic Conductivity		Vertical Hydraulic Conductivity		Specific Yield	Specific Storage (m^{-1})
	m/s	m/day	m/s	m/day		
Tamala Limestone/ Spearwood Dunes	2.89×10^{-4}	25	9.65×10^{-5}	8	0.29	1.0×10^{-4}
Lacustrine sediments	1.20×10^{-6}	10	2.00×10^{-7}	0.002	0.13	1.0×10^{-4}
Bassendean Sand	1.85×10^{-4}	16	6.17×10^{-5}	5	0.29	1.0×10^{-4}
Lower Permeability Sediments	1.00×10^{-4}	8.6	3.33×10^{-5}	3	0.29	1.0×10^{-4}

5.4 Comparison of Surface Water Levels

Simulated surface water levels were compared to observed levels to assess the performance of the model. A statistical analysis of the results produced by MIKE SHE is presented in Table 5-4.

Table 5-4 Surface water correlation statistics

Location	Type	Gauge ID	RMSE	r^2
Little Rush Lake	Surface water	6142518	0.21	0.73
South Lake	Surface water	6142519	0.27	0.60
Bibra Lake	Surface water	6142520	0.16	0.92
North Lake	Surface water	6142521	0.23	0.89

The statistical analysis produced values of root mean square error (RMSE) less than 0.30 for the 4 surface water analysed, with r^2 values ranging from 0.60 to 0.92.

The RMSE is an indication of ability of the model the simulate water levels. The lower the RMSE, the closer the simulated water levels to the observed values. The coefficient of determination or r^2 provides an indication of the 'goodness of fit' of the model. r^2 ranges between 0 and 1 with the value of 1 indicating that simulated values are the same as observed values. The lowest RMSE and highest r^2 values were produced for Bibra Lake while the highest RMSE and lowest r^2 values were produced for South Lake.

Figure 5-1, which presents simulated and observed surface water levels in Bibra Lake, shows that the simulated time series correlates to the seasonal variability in levels, with an r^2 value of 0.92. The simulated results for all of the lakes however exhibit periods where the simulated surface water levels are above, or below, the observed water levels, which are summarised in Table 5-5.

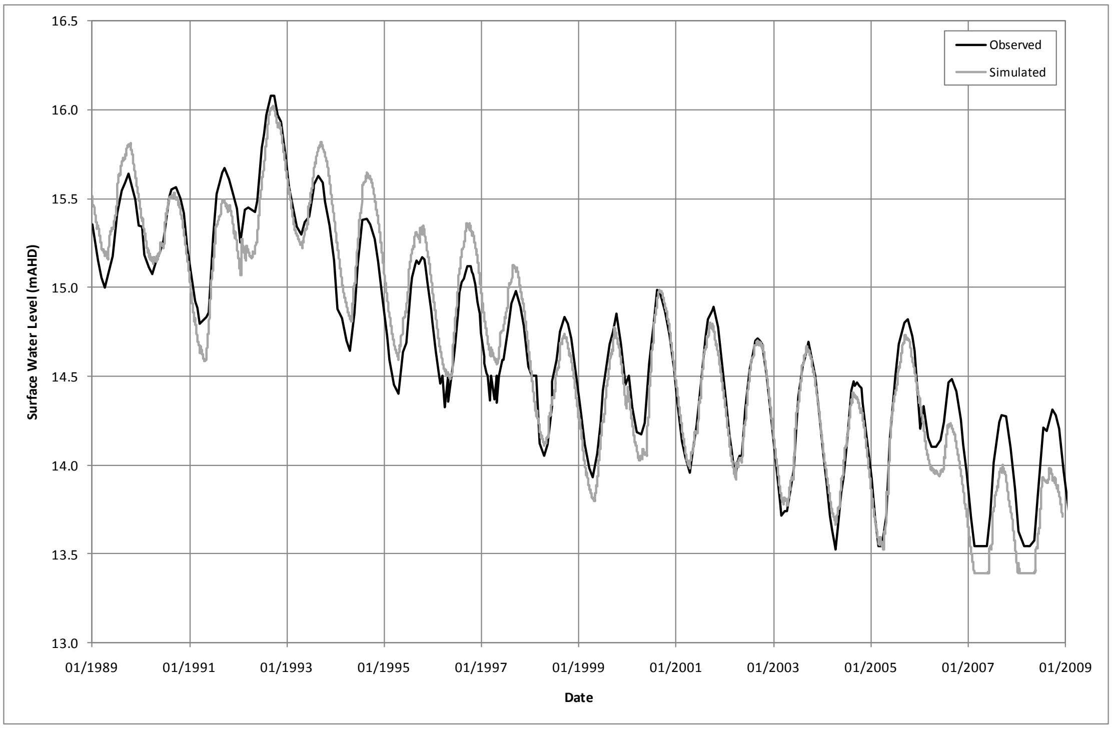


Figure 5-1 Comparison of simulated and observed surface water levels in Bibra Lake (6142520)

Table 5-5 Table of comparison of simulated and observed surface water levels

Location	ID	Simulated Water Levels Above Observed Water Levels	Simulated Water Levels Below Observed Water Levels
Little Rush Lake	6142518	- Winter maximum 1994 to 2006	- Summer minimum 1990 to 1994 - 2006 to 2008
South Lake	6142519	- 1989 to 2002	- 2000 - 2006 to 2008
Bibra Lake	6142520	- 1989 - 1993 to 1997	- 1990 to1992 - 1999 to 2000 - 2006 to 2008
North Lake	6142521	- 1996 to 2008	- 1989 to 1995

Simulated levels for Bibra Lake (Figure 5-1) , Little Rush Lake (Figure 5-2), South Lake (Figure 5-3) and North Lake (Figure 5-4) all demonstrate periods when the simulated surface water levels differ from observed surface water levels. Bibra Lake, Little Rush Lake and South Lake tend to demonstrate simulated levels that are below observed levels towards the end of the simulation. North Lake, post-1996, experiences simulated surface water levels that are consistently above observed surface water levels, as presented on Figure 5-4.

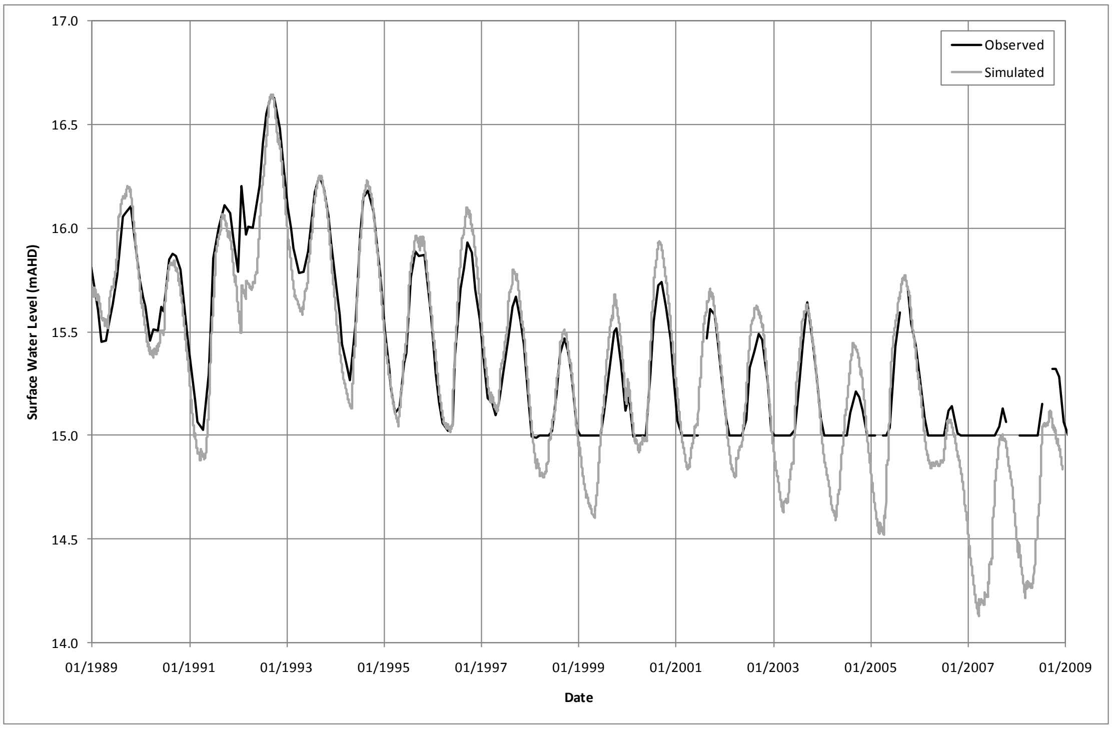


Figure 5-2 Comparison of simulated and observed surface water levels in Little Rush Lake (6142518)

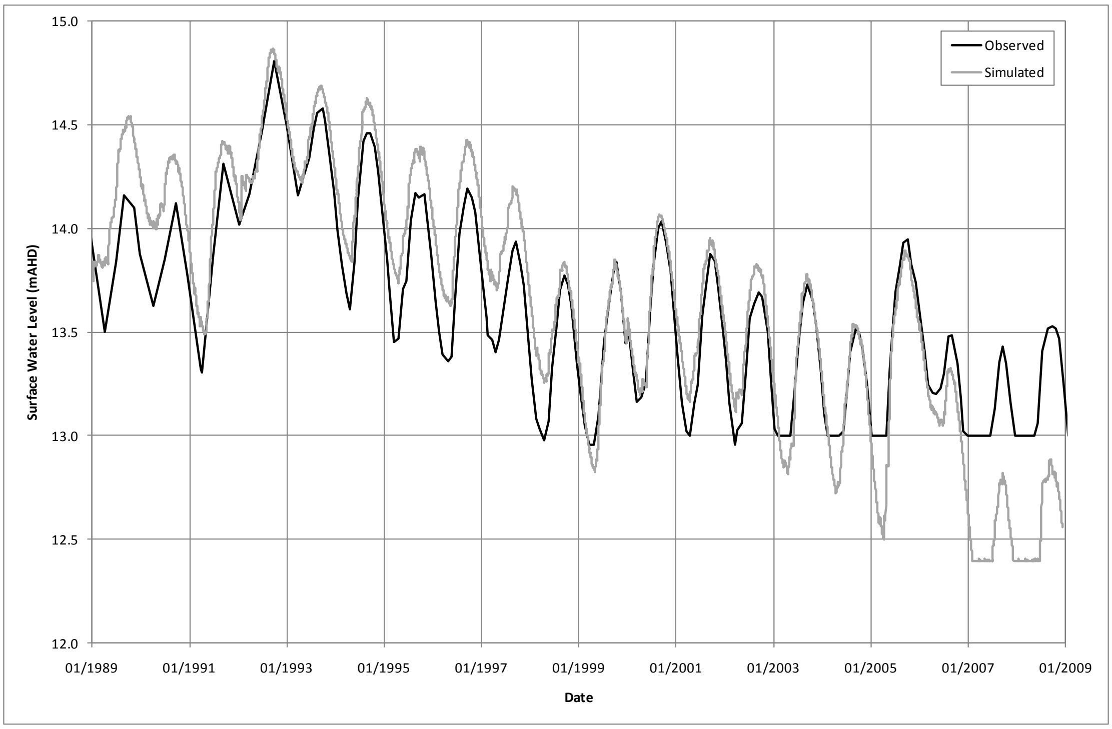


Figure 5-3 Comparison of simulated and observed surface water levels in South Lake (6142519)

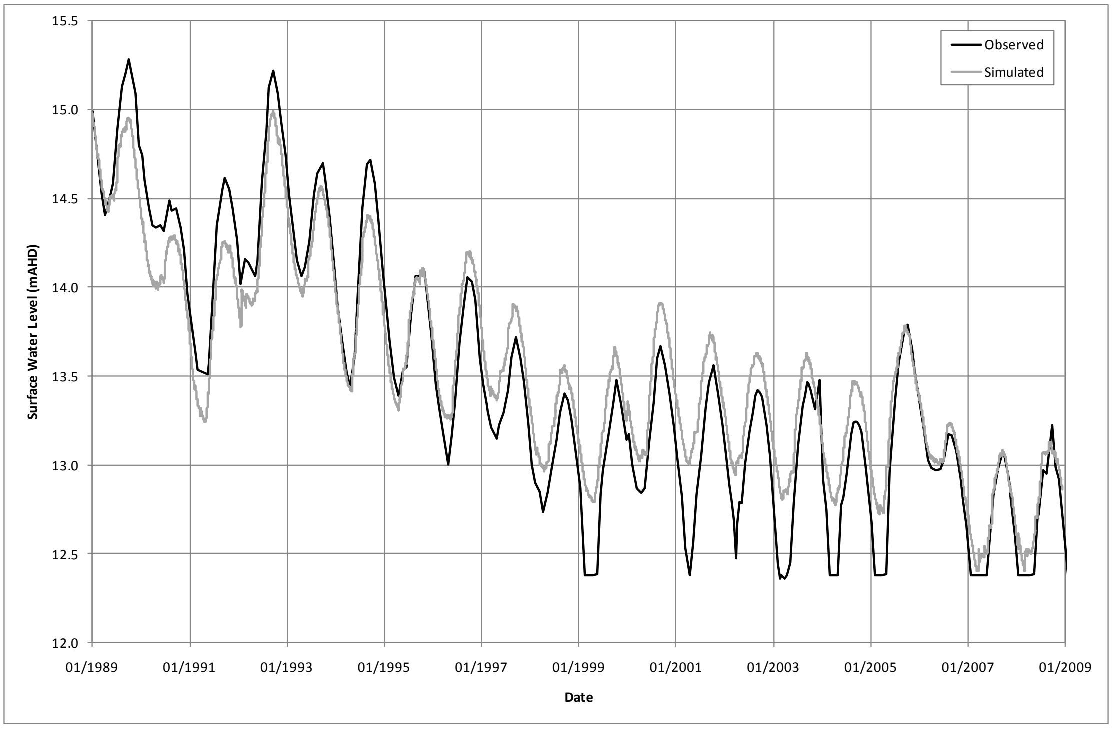


Figure 5-4 Comparison of simulated and observed surface water levels in North Lake (6142521)

Simulated water levels in North Lake also remain above the minimum observed water level, whereas the simulated levels for Little Rush Lake, South Lake and Bibra Lake fall below the minimum observed water levels. This is most apparent for Little Rush Lake, as presented in Figure 5-2, where the simulated levels regularly drop below the observed base level of 15mAHD. It should be noted that as the monitoring stations cannot record water levels during dry periods, calibration of the model and the resultant calibration statistics will be affected. DoW has provided time-series plots, presenting the observed water levels and indicating periods where the water level drops below the monitoring gauge level. These can be found in Appendix A.

5.5 Comparison of Groundwater Levels

Simulated groundwater levels were compared to observed levels to assess the performance of the model. A statistical analysis of the results produced by MIKE SHE is presented in Table 5-6.

Table 5-6 Groundwater correlation statistics

Location	Type	ID	RMSE	r2
Southwest of Bibra Lake	Groundwater	61410177	0.20	0.76
East of Bibra Lake	Groundwater	61410202	0.12	0.85
West of North Lake	Groundwater	61410726	0.30	0.60

The statistical analysis produced values of root mean square error (RMSE) less than or equal to 0.30 for all of the locations analysed, with r^2 values ranging from 0.60 to 0.85. The highest RMSE and lowest r^2 values were produced for Bore 61410726, located to the west of North Lake. The simulated results for all of the bores exhibit periods where the simulated groundwater water levels are above or below the observed water levels. A summary is presented in Table 5-5.

The time series of simulated and observed groundwater levels for bores 61410177 (Figure 5-5), 61410202 (Figure 5-6) and 61410726 (Figure 5-7) show that the model recreates both the seasonal and longer term variation in water levels.

Table 5-7 Table of comparison of simulated and observed groundwater levels

Location	ID	Simulated Water Levels Above Observed Water Levels	Simulated Water Levels Below Observed Water Levels
Southwest of Bibra Lake	61410177		- 1993 to 1999*
East of Bibra Lake	61410202	- 1994 to 2005	- 2006 to 2008
West of North Lake	61410726		- 1997 to 2000 - 2003 to 2008

* Complete time period of observed data

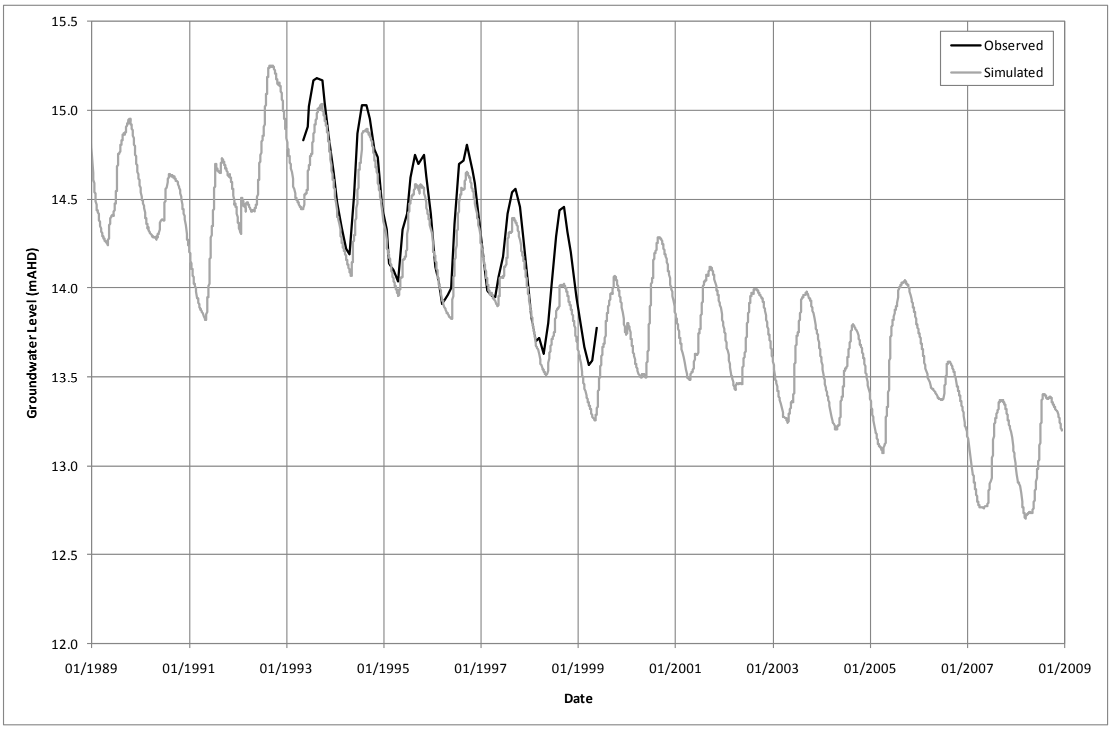


Figure 5-5 Comparison of simulated and observed groundwater levels in Bore 61410177 (south west of Bibra Lake)

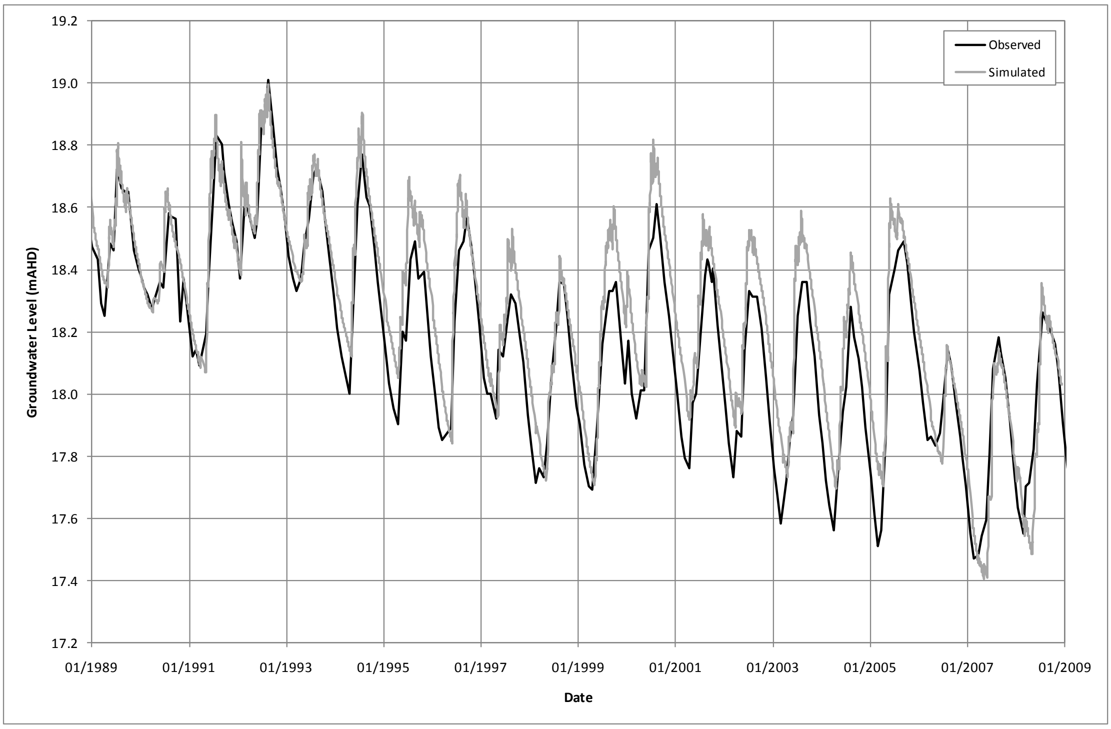


Figure 5-6 Comparison of simulated and observed groundwater levels in Bore 61410202 (east of Bibra Lake)

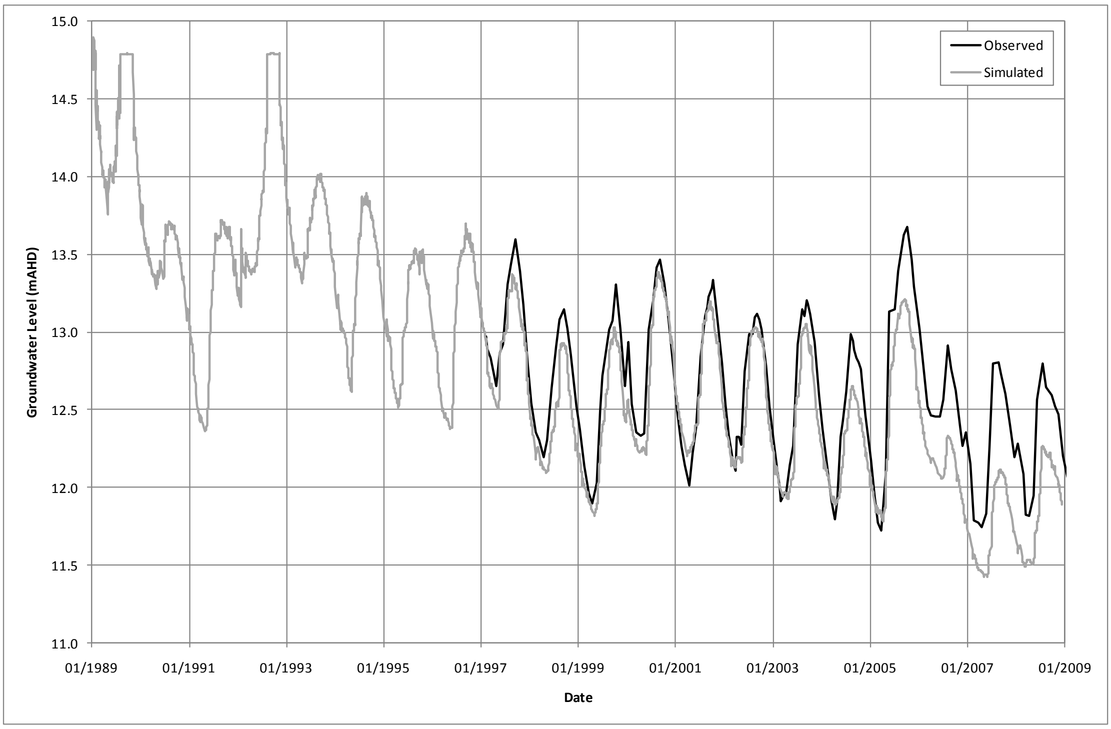


Figure 5-7 Comparison of simulated and observed groundwater levels in Bore 61410726 (west of North Lake)

5.6 Discussion

The calibration results show that the model is generally well calibrated well against observed water levels, but that the accuracy of simulated water levels declines during the increasingly dry years towards the end of the simulation. The simulated surface water levels are typically below the observed water levels between the years of 2006 to 2008. The highest r^2 value and lowest RMSE were obtained for simulated levels in Bibra Lake, North Lake and Bore 61410202 which is east of Bibra Lake. The calibration may be improved by extending the model to include data for 2009 and 2010, particularly because 2010 was a significantly dry year, and by installing the surface water monitoring gauges so that the gauge may read lower water levels that have been experienced during Perth's recent drying climate.

6.0 Base Case Simulation Results

This section presents a summary of the results of the base case simulation. The complete results are presented in Appendix C. Relevant information from this simulation are:

- Groundwater levels.
- Groundwater flow directions.
- Surface water depths.
- Surface water flows.

For the purpose of examining the range of conditions experienced within the project area, 'wet' and 'dry' months were selected by identifying the highest and lowest simulated water levels from the full period of the base case simulation. Simulated water levels vary across the model domain, however, it has been noted that generally September 1992 was the month of highest groundwater and surface water levels during the model simulation. April 2007 was the month of lowest groundwater and surface water levels.

These two periods also coincided with periods of high rainfall and surface water expression for September, and low rainfall and surface water expression for April. Therefore, September 1992 is assumed to be representative of a period of high groundwater and surface water, while April 2007 is assumed to be representative of a period of low groundwater and surface water.

6.1 'Wet' Period

Simulated groundwater contours for September 1992, presented in Figure 6-1, fall gradually from the eastern boundary to the eastern margin of the wetlands with the gradient declining across the wetlands before increasing to the west. This pattern is generally consistent with the Perth Groundwater Atlas (DoW) (Figure 2-8 and Figure 2-9) and the hydraulic gradient increasing as water flows through the band of "lower permeability" sediments to the west of the wetlands and then decreasing once the water reaches the Tamala Limestone/Spearwood Dunes with their higher hydraulic conductivity.

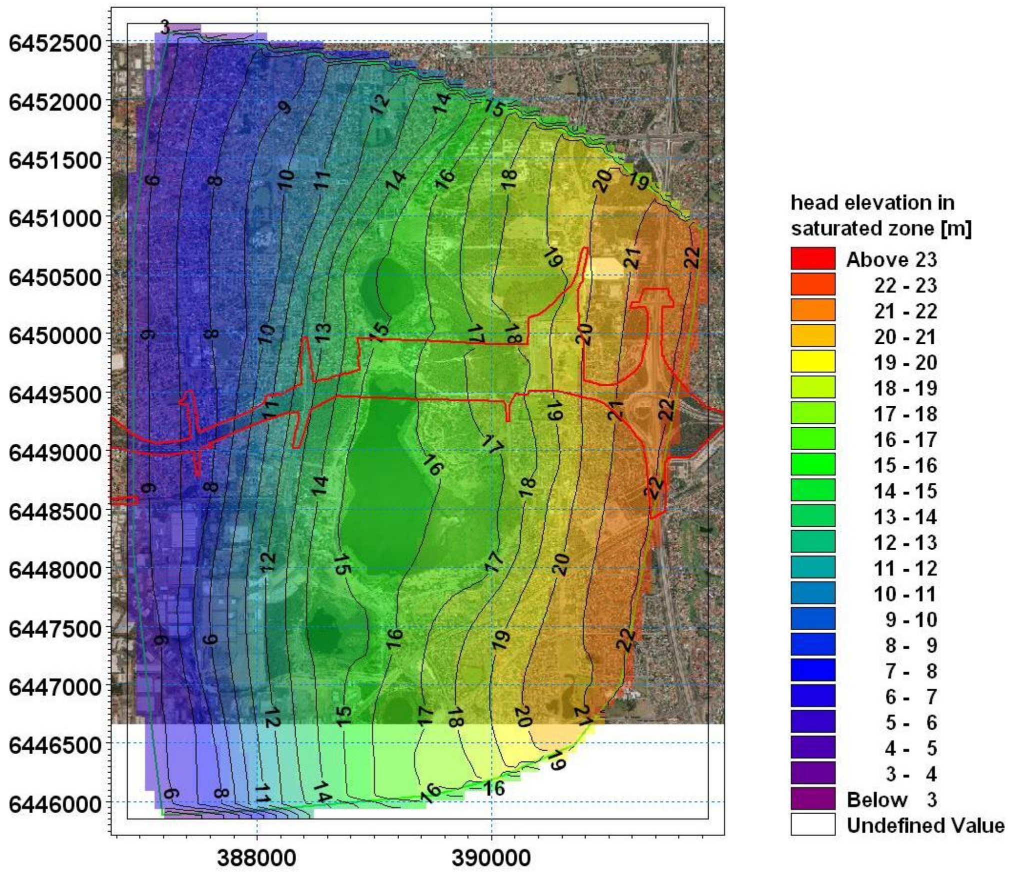


Figure 6-1 Simulated Groundwater Contours for September 1992 – Base Case

The results indicate a general east-west flow of groundwater for this period, with a marginal change in direction to the north-north east in the area between Bibra Lake and North Lake and complex flow patterns in the vicinity of Murdoch Drain. Groundwater flows converge to the east of Roe Swamp, which can be explained by the presence of the wetland itself and is typical of a groundwater discharge. A convergence of groundwater flows in the south east corner of Bibra Lake is also visible. This was anticipated due to the change in hydraulic properties in this area and is in agreement with the observations of Davidson (1983). This is characteristic of groundwater discharge to surface water.

Figure 6-2 shows that, during September 1992 the model simulates surface water in Murdoch Drain and a connection between Roe Swamp and Frog Swamp. Frog Swamp appears to flow to North Lake, but closer inspection of the model results reveals this is not the case due to the weir in this area. Surface water flows into Bibra Lake are clearly visible in its south-eastern corner.

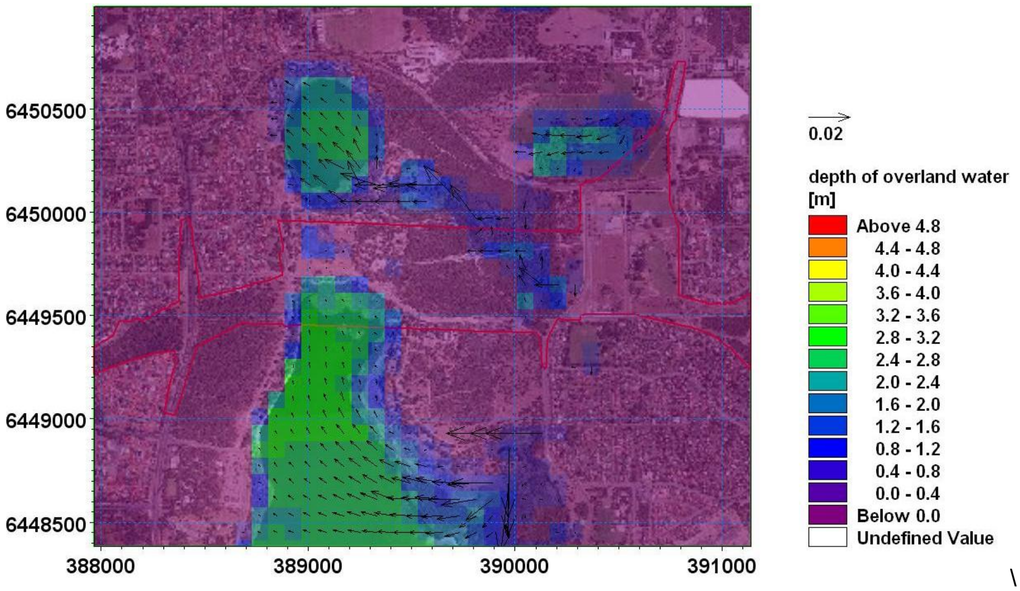


Figure 6-2 Simulated surface water depth and flows for September 1992 – Base Case

6.2 'Dry' Period

Simulated groundwater contours for April 2007, shown in Figure 6-3 are approximately 2-3m lower than during September 1992 and remain relatively parallel to each other and evenly spaced across the lakes. Groundwater flows from east to west, as expected, but retains a more constant flow direction through the lakes than observed for the wet period Figure 6-1. This may suggest that groundwater flows are not being discharged into the lakes during the dry period. Groundwater levels are lower in the 'dry' year as compared to the 'wet' year and flows are less affected by the more variable superficial soils, which have lower hydraulic conductivities.

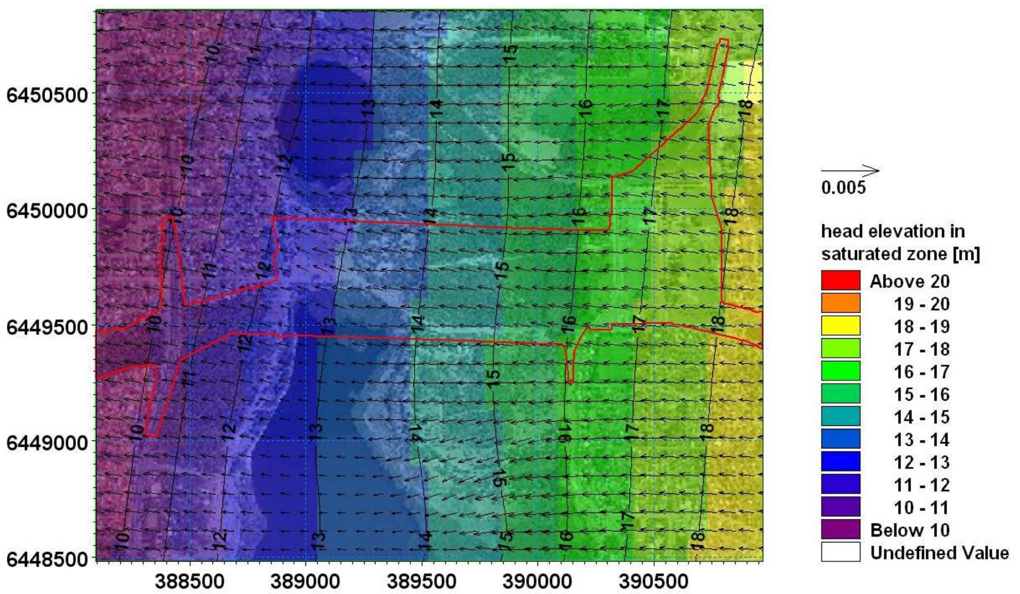


Figure 6-3 Simulated groundwater flow for April 2007 – Base Case

Simulated water levels from the extracted 'dry' month of April 2007 indicate that very little surface water was evident. The observed lake levels in Little Rush Lake, South Lake, Bibra Lake and North Lake all reached their lowest points and dropped below the gauge during this period, making it difficult to determine the accuracy of the simulated water levels at this time.

6.3 Water Balance

A water balance is '*an account of all the water in some specified system*' (Ladson 2008). It accounts for all inflows and outflows of water, plus changes in the volume of water held in storage. Over time, the mass of water flowing into a system minus the mass of water flowing out of the system is equal to the change in storage within the system.

Annual total water balances have been created for both the whole model domain and for Bibra Lake using the model outputs from the base case simulation. The area included in the water balance for Bibra Lake was defined based upon the extent of surface water runoff generated during the 'wet' year of 1992. The water balance results are summarised below.

A comparison of the water balance for Bibra Lake with the whole model domain is presented in Table 6-1. This highlights the following key differences:

- ET over Bibra Lake is virtually double that simulated over the model domain as a whole.
- ET is also higher than precipitation.
- Overland storage increases by a considerably higher amount in Bibra Lake.
- Boundary inflows are greater than boundary outflows for Bibra Lake.
- The saturated zone storage change is less than for the model domain.

The water balance for Bibra Lake indicates that the change in storage within the lake is driven by groundwater flows through the saturated and unsaturated zones.

Table 6-1 Comparison of key water balance components for wet period

Water Balance Component	Storage Depth (mm)	
	Total Model Domain	Bibra Lake
Precipitation	1 031	1 044
ET	662	1212
Surface Water Storage Change	55	419
Unsaturated to saturated infiltration	548	438
Saturated to unsaturated infiltration	274	748
Unsaturated zone boundary inflow	0	276
Unsaturated zone boundary outflow	30	4
Saturated zone boundary inflow	98	992
Saturated zone boundary outflow	282	617
Saturated zone storage change	96	27

Table 6-2 presents a comparison of Bibra Lake and the model domain during the 'dry' year.

Table 6-2 Comparison of key water balance components for dry period

Water Balance Component	Storage Depth (mm)	
	Total Model Domain	Bibra Lake
Precipitation	735	740
ET	563	1174
Surface Water Storage Change	-7	-74
Unsaturated to saturated infiltration	256	107
Saturated to unsaturated infiltration	81	471
Unsaturated zone boundary inflow	0	7
Unsaturated zone boundary outflow	1	2
Saturated zone boundary inflow	72	886
Saturated zone boundary outflow	262	533
Saturated zone storage change	-13	-10

A comparison of the model domain water balances for the 'wet' and 'dry' years of 1992 and 2007 respectively, presented in Table 6-3. These results indicate that although higher rainfall is experienced during the wet simulation, the total evaporation for the two simulations is comparable (Table 6-4).

There is a greater boundary inflow of water to the saturated zone during the 'dry' year of 2007. Conversely, the wet year experiences much higher infiltration to the saturated zone, a resultant increase in saturated zone storage, and greater outflows from the saturated zone.

Table 6-3 Comparison of key water balance components for wet and dry years for the whole model domain

Water Balance Component	Storage Depth (mm)	
	Wet Year	Dry Year
Precipitation	1 031	735
ET	662	563
Surface Water Storage Change	55	-7
Unsaturated to saturated infiltration	548	256
Saturated to unsaturated infiltration	274	81
Unsaturated zone boundary inflow	0	0
Unsaturated zone boundary outflow	30	1
Saturated zone boundary inflow	98	72
Saturated zone boundary outflow	282	262
Saturated zone storage change	96	-13

The differences between the wet and dry years are even more pronounced for Bibra Lake, as shown by the comparison presented in Table 6-4.

Table 6-4 Comparison of key water balance components for wet and dry years for Bibra Lake

Water Balance Component	Storage Depth (mm)	
	Wet Year	Dry Year
Precipitation	1 044	740
ET	1212	1174
Surface Water Storage Change	419	-74
Unsaturated to saturated infiltration	438	107
Saturated to unsaturated infiltration	748	471
Unsaturated zone boundary inflow	276	7
Unsaturated zone boundary outflow	4	2
Saturated zone boundary inflow	992	886
Saturated zone boundary outflow	617	533
Saturated zone storage change	27	-10

The model water balance comparisons strongly suggest that the lakes are being fed by groundwater. ET is considerably higher over Bibra Lake than over the model domain, with water being drawn from the lake and from the saturated zone. During wet years, the saturated zone is recharged and overland storage increases, but during dry years these stores are depleted.

7.0 Simulation Results

As discussed previously, there are several different simulations that have been run under a variety of conditions;

- Base case simulation.
- Long term simulation that was run with:
  - Maximum groundwater time series.
  - Minimum groundwater time series.
  - Average groundwater time series.
- Short term simulation.

These simulations were undertaken to gauge the response of the system under various hydrological conditions. A short term simulation was developed to assess the response of the system to a large, infrequent, storm event. This event did not yield any significant results and thus it was concluded that the system is more dependent on long term conditions. A summary of the long term results is presented below and the complete set of results are presented in Appendix F to H. Further sensitivity and validation discussion of the long term and short term simulation results are not provided because calibration was not undertaken on these simulations.

7.1 Long Term Simulation

To present the range of conditions experienced within the project area, 'wet' and 'dry' months were again selected by identifying the highest and lowest simulated water levels from the complete period of the model simulation. Simulated water levels vary across the model domain during the period of simulation but generally, September 1928 was the month of highest groundwater and surface water levels. April 2007 was the month of lowest groundwater and surface water levels. These two time periods also coincided with periods of high rainfall and surface water expression for September, low rainfall and surface water expression for April. Thus, September 1928 is assumed to be representative of a period of high groundwater and surface water, while April 2007 is assumed to be representative of a period of low groundwater and surface water.

Results for these 'wet' and 'dry' months were extracted from the complete long term simulation for the various model runs. It should be noted that the long term model has been run using historical rainfall and current land use to simulate potential future scenarios.

These results do not represent the actual historical conditions experienced at those times, as current land use conditions have been used throughout the simulation. However, they may be considered to be representative of 'wet' and 'dry' climatic conditions, where 'wet' conditions are defined as the period of highest water elevations and 'dry' conditions are defined as the period of lowest water elevations. The most extreme 'wet' and 'dry' conditions are produced using the maximum boundary conditions during the wet year and the minimum boundary conditions during the dry year, respectively. These results are discussed in the following sections, with results for all boundary conditions presented in Appendix F to H.

7.1.1 Maximum Groundwater Boundaries

Groundwater contours simulated for the 'wet' period using the synthetic maximum boundary conditions are, shown in Figure 7-1 and range from above 22mAHD in the east of the model domain to 4mAHD in the west. They demonstrate the same general pattern as observed for the base case simulation 'wet' period, but with a shallower gradient across the wetlands. It should be noted that the contours on this 'wet' simulation are slightly higher than the maximum groundwater contours reported within the Perth Groundwater Atlas (Water and Rivers Commission 1997), particularly across Bibra Lake.

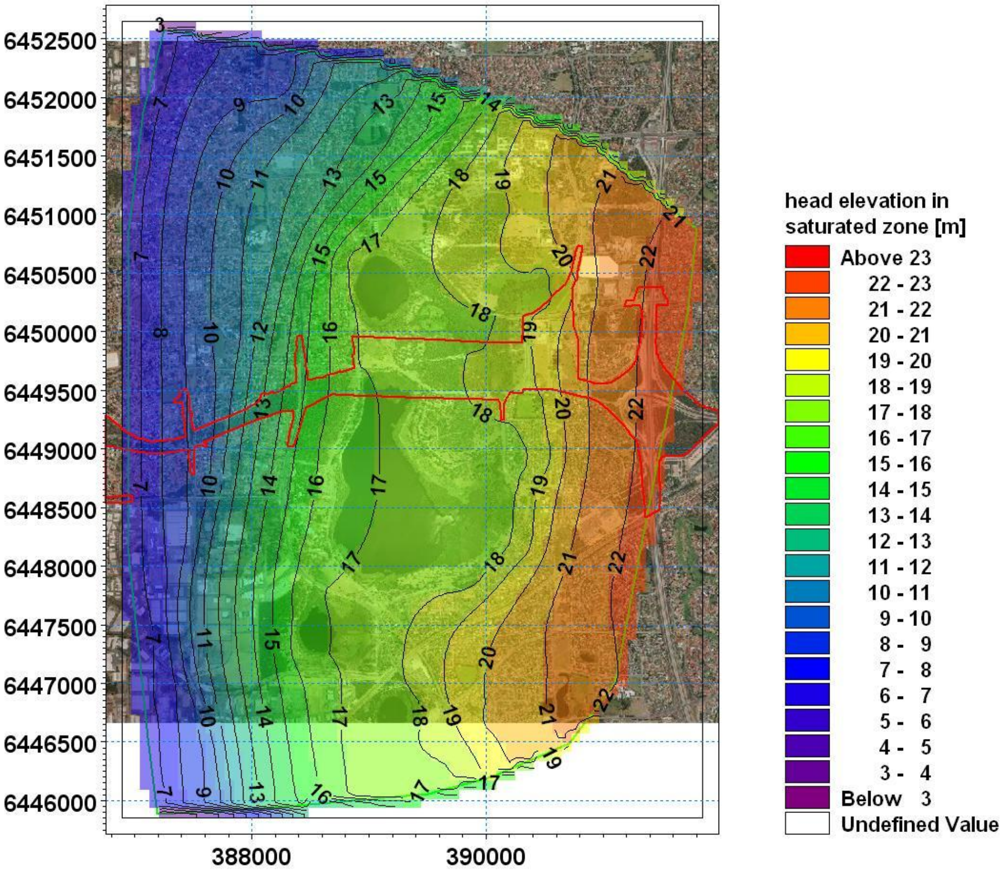


Figure 7-1 Simulated groundwater contours for 'wet' period - Long Term Simulation Maximum Boundary Conditions

Surface water depths and flows, shown in Figure 7-2, exhibit complex flow patterns with a connection apparent between Bibra Lake and North Lake. The crest of Hope Road is modelled at 16.25mAHD in the model, with simulated water levels in Bibra Lake and North Lake peaking at approximately 17.3mAHD. This creates a water depth of just over 1m across Hope Road within the model under this extreme wet simulation. In reality the crest of Hope Road is approximately 16.8 mAHD and thus only a small amount of weir flow will occur. It is believed that the crest of Hope Road has been set at 16.25 mAHD in the model as a result of the grid size and the inability of the model to represent roads at a fine scale. It should also be noted that this maximum water elevation is created only with the application of the synthetic maximum groundwater boundary conditions that have been used. Therefore, connection between these two lakes is to be expected under only extreme infrequent circumstances. Also clearly visible is the connection between Murdoch Drain, Roe Swamp and Frog Swamp. This is consistent with the wetland mapping provided by the DoE (1997) presented in Figure 2-15.

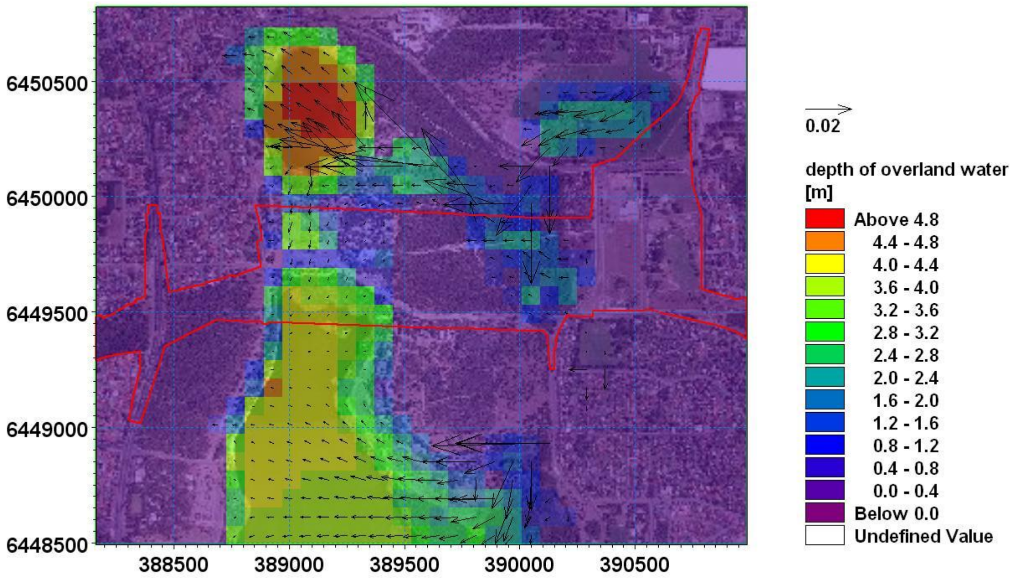


Figure 7-2 Simulated surface water depth and flows for 'wet' period- Long Term Simulation Maximum Boundary Conditions

7.1.2 Minimum Groundwater Boundaries

The simulated groundwater contours from the 'dry' period, generated using the synthetic minimum boundary conditions, estimate that groundwater levels range from over 19mAHD in the east to below 4mAHD in the west and remain almost parallel throughout the model domain. These results are presented in Figure 7-3. It should be noted that these groundwater contours are lower than those reported in the Perth Groundwater Atlas for May 2003 (after summer) (DoW 2004). During the simulation in the 'dry' period, the lakes dry out.

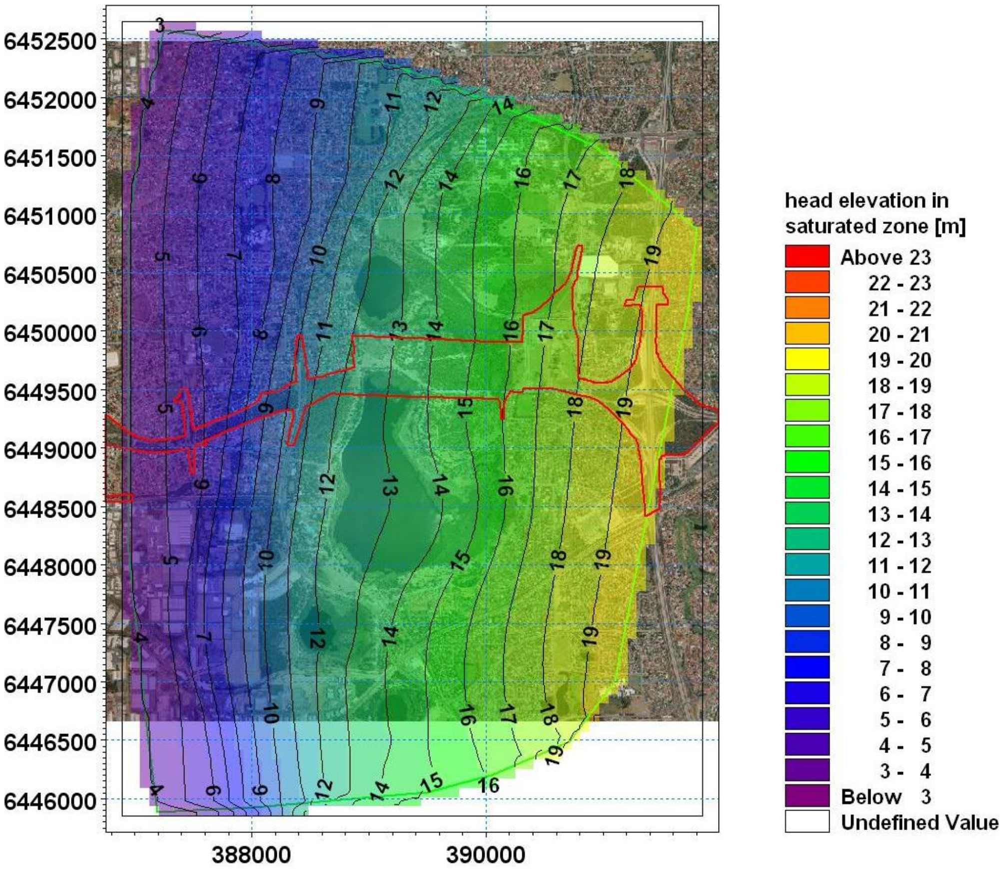


Figure 7-3 Simulated groundwater contours for 'dry' period - Long Term Simulation Minimum Boundary Condition

7.1.3 Average Groundwater Boundaries

The simulated groundwater contours for the 'wet' period, generated using the average boundary conditions (Figure 7-4) simulate groundwater levels that range from over 21mAHD in the east to 5mAHD in the west. The groundwater contours can be observed to develop complex flow patterns around Bibra Lake and Murdoch Drain. Surface water flows (Appendix H) again suggest that Roe Swamp and Murdoch Drain are connected in 'wet' years, but surface water does not overtop Hope Road in this simulation.

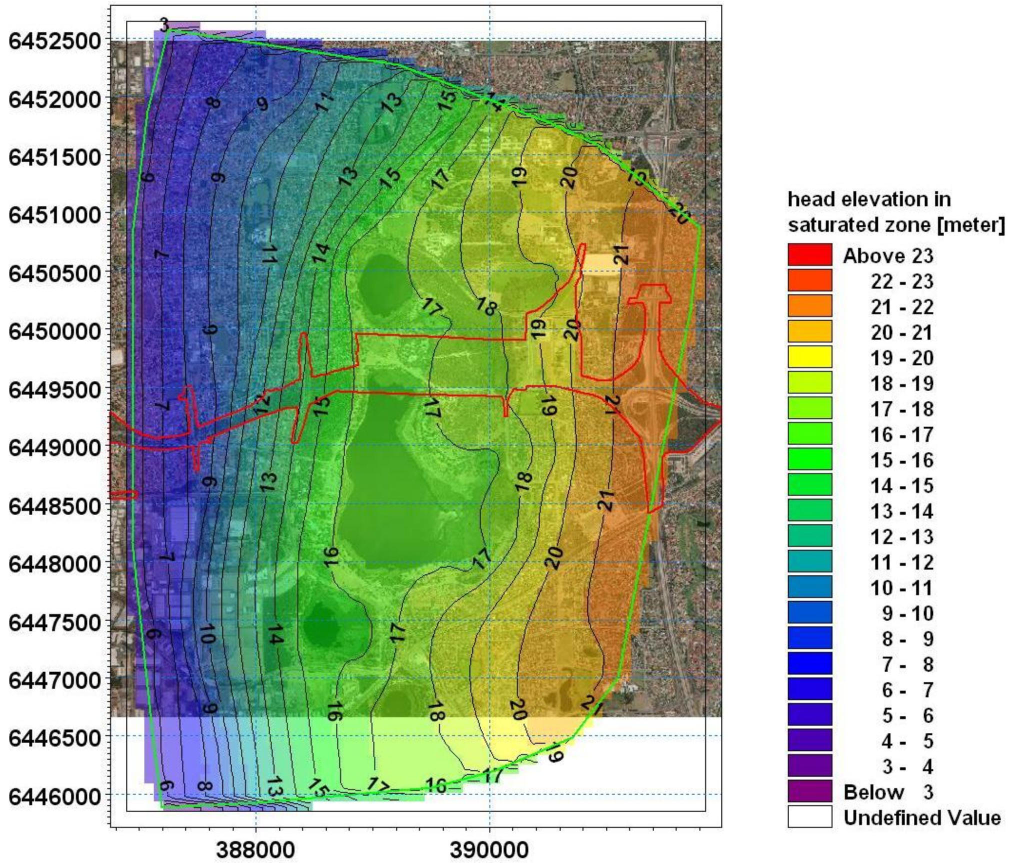


Figure 7-4 Simulated groundwater contours for ‘wet’ period - Long Term Simulation Average Boundary Conditions

The simulated groundwater contours for the ‘dry’ period (Figure 7-5), generated using the average boundary conditions demonstrate that modelled groundwater levels range from over 20mAHD in the east to 5mAHD in the west. Surface water is also visible in North Lake, Bibra Lake, Roe Swamp and Murdoch Drain.

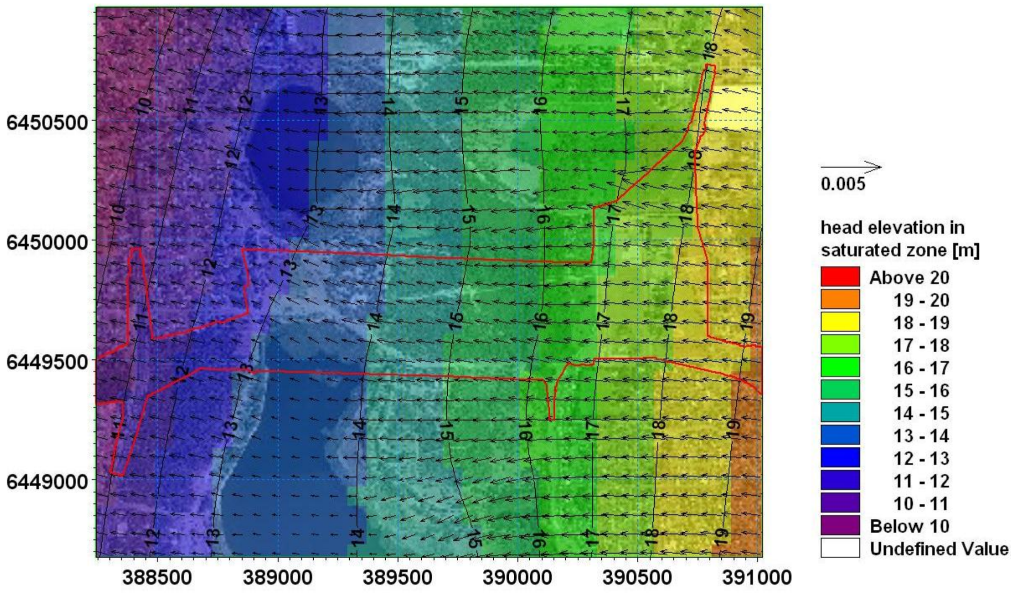


Figure 7-5 Simulated groundwater flow for ‘dry’ period - Long Term Simulation Average Boundary Conditions

7.1.4 Discussion of Simulations

The different simulations have provided a range of results. The two extremes are:

- maximum ('wet' period and maximum boundary conditions).
- minimum ('dry' period and minimum boundary conditions).

These maximum and minimum groundwater and surface water results do not represent actual events, but provide an estimate of the conditions that may be experienced under extreme hydrological conditions.

The difference in groundwater levels between the extreme 'wet' and 'dry' simulations is approximately 3m throughout the model domain, increasing to 4m through the centre of the Bibra Lake. The hydraulic gradient also decreases more significantly through the wetlands under the 'wet' simulation. Distinctive groundwater flow patterns emerge in the 'wet' simulation, which significantly deviate from the general east-west flows experienced during the 'dry' simulation. Convergent flows are visible in the upper section of Murdoch Drain, Roe Swamp and the southeast corner of Bibra Lake. These are likely to be caused by the groundwater entering the wetland sediments that possess different hydraulic properties and discharging to surface water. During the 'wet' simulation there are also surface water flows connecting Murdoch Drain, Roe Swamp and North Lake, whereas, during the 'dry' simulation very little surface water is simulated.

These results suggest that, during the 'wet' simulation, surface water flows and rainfall contribute to water levels within the wetlands and a that there is a connection between surface water and groundwater. During the 'dry' simulation, however, Bibra Lake dries and groundwater flows are driven by the model boundary conditions.

8.0 Sensitivity Analysis

The sensitivity of the base case simulation was tested by comparing simulated and observed water levels, to determine its sensitivity to changes of the following key parameters:

- Boundary condition water levels (±1m);
- LAI (±25%);
- ERD (±25%);
- Soil saturated hydraulic conductivity within the unsaturated zone (±25%);
- Water content at saturation, at field capacity and at wilting point within the unsaturated zone;
- Vertical and horizontal hydraulic conductivity within the saturated zone;
- Specific yield within the saturated zone (±25%); and
- Surface roughness (Manning's n) for overland flow (n=0.02 and n=0.011).

The complete set of results for the sensitivity analysis, with comparisons of simulated and observed water levels at Bibra Lake and Bore 61410202, are presented in Appendix D. Water levels in both Bibra Lake and Bore 61410202 were found to be most sensitive to changes in the boundary condition water levels, particularly at the eastern boundary, as shown by the results presented in Table 8-1 and in Figure 8-1and Figure 8-2.

Table 8-1 Results of sensitivity testing of boundary condition water levels

Sensitivity Test	Change in Mean Simulated Water Level (m)	
	Bore 61410202	Bibra Lake
Boundary condition water levels plus 1m	0.33	0.74
Boundary condition water levels minus 1m	-0.36	-0.46
Eastern boundary condition water levels plus 1m	0.33	0.72
Western boundary condition water levels plus 1m	0.08	0.35

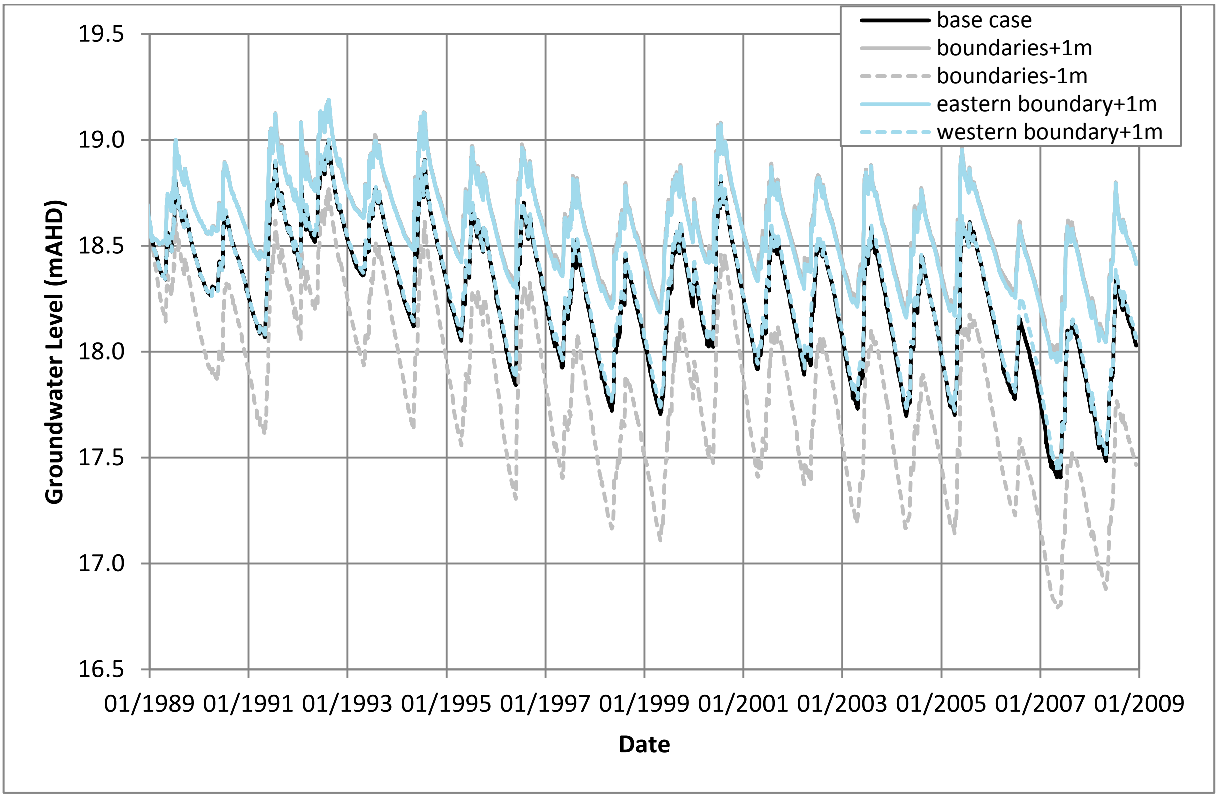


Figure 8-1 Water levels in Bore 6140202 during sensitivity testing of the boundary conditions

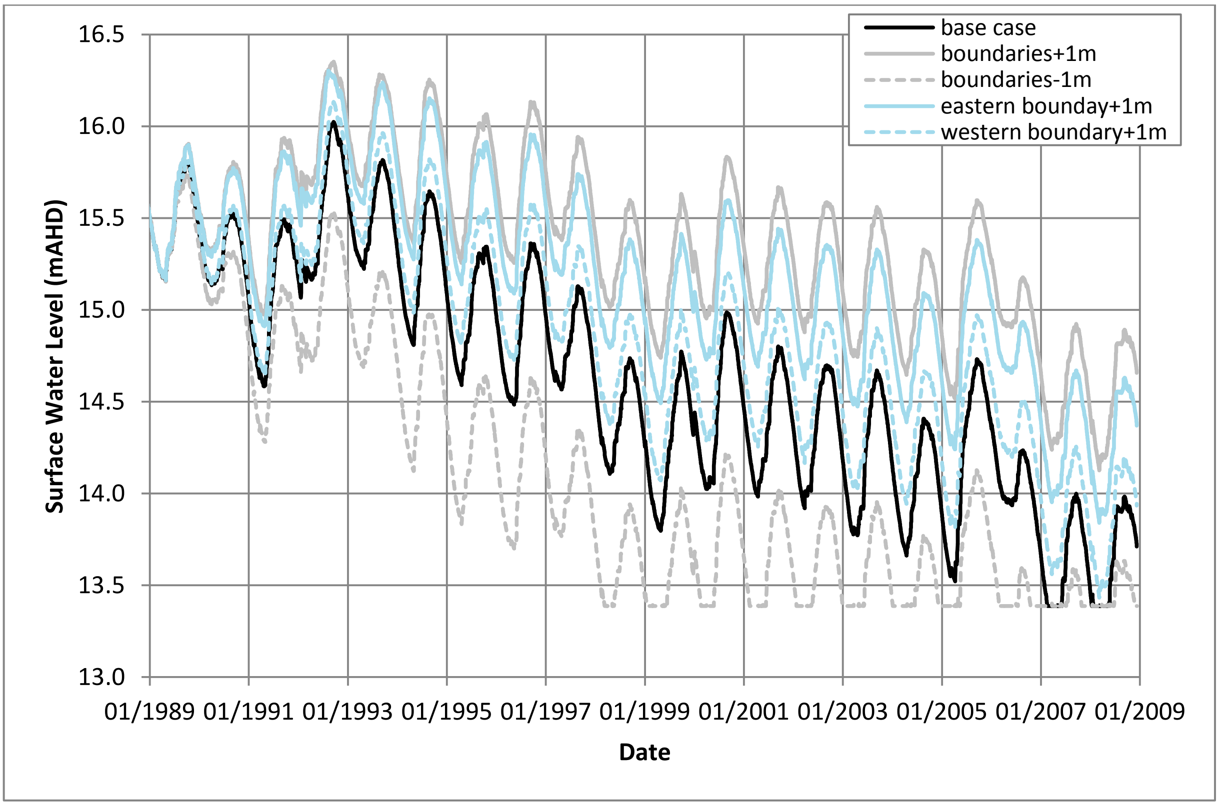


Figure 8-2 Water levels in Bibra Lake during sensitivity testing of boundary conditions

Groundwater levels in Bore 61410202 were relatively insensitive to changes in the other parameters that were tested. Surface water levels in Bibra Lake, however, showed some sensitivity to the ERD and unsaturated zone water content at field capacity, as presented in Table 8-2 and shown in Figure 8-3 and Figure 8-4, respectively.

Table 8-2 Results of sensitivity testing on ERD and unsaturated zone water content at field capacity

Sensitivity Test	Change in Mean Simulated Water Level (m)	
	Bore 61410202	Bibra Lake
ERD +25%	-0.07	-0.16
ERD -25%	0.04	0.20
Unsaturated zone water content at field capacity +25%	0.00	-0.07
Unsaturated zone water content at field capacity -25%	0.01	0.19

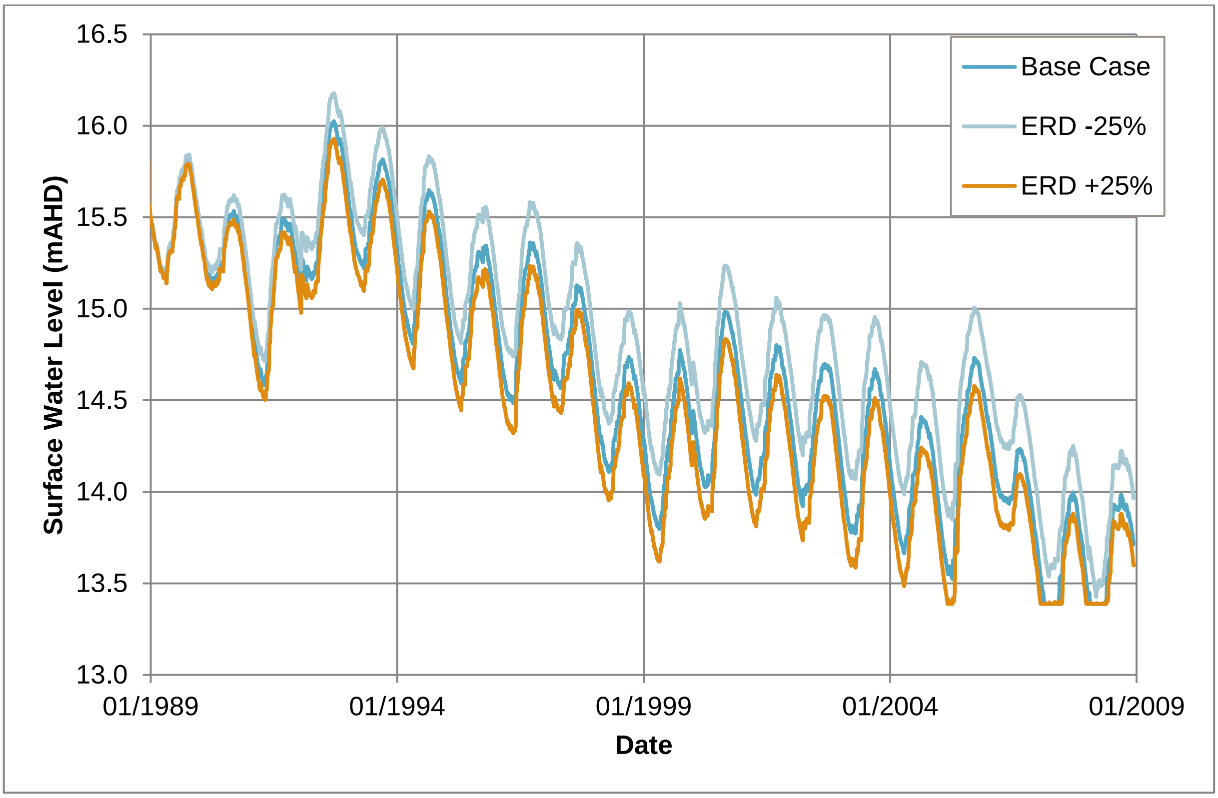


Figure 8-3 Water levels in Bibra Lake during sensitivity testing of ERD

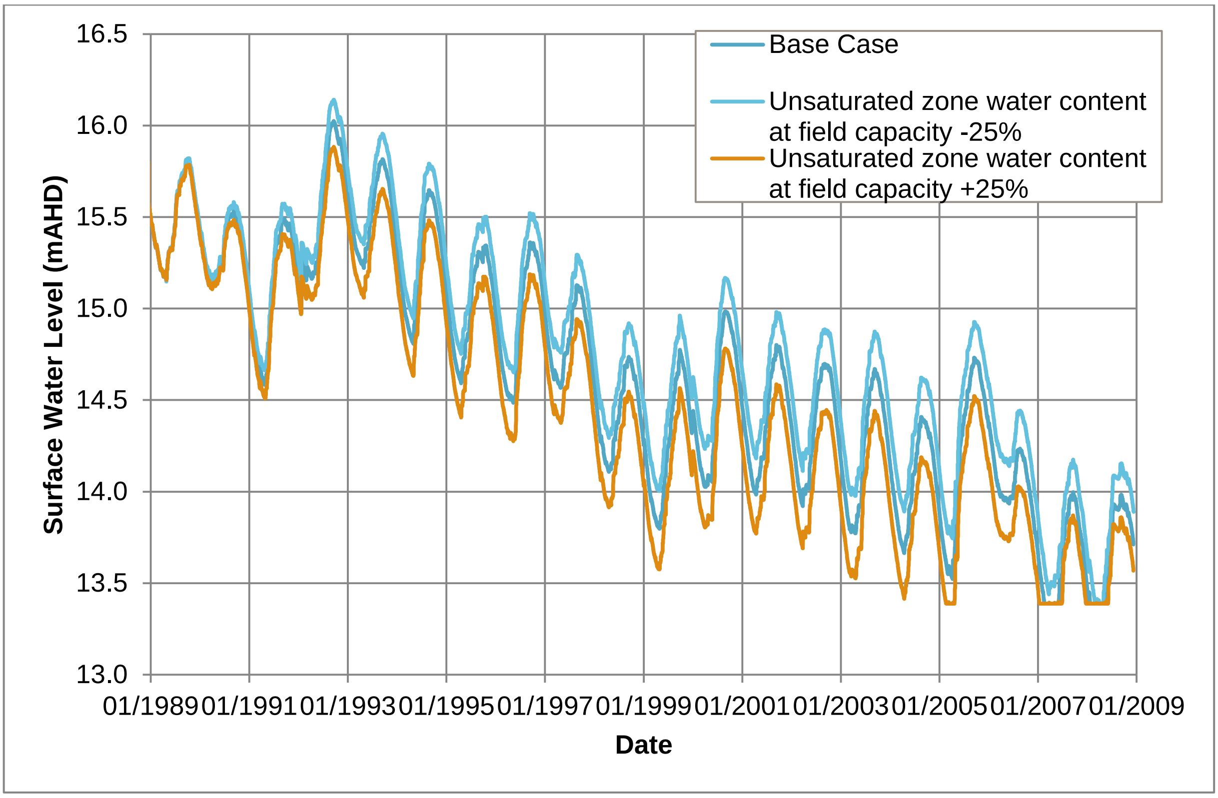


Figure 8-4 Water levels in Bibra Lake during sensitivity testing of unsaturated zone water content at field capacity

The model was found to be relatively insensitive to changes in Manning's n and LAI, as demonstrated by the results presented in Table 8-3.

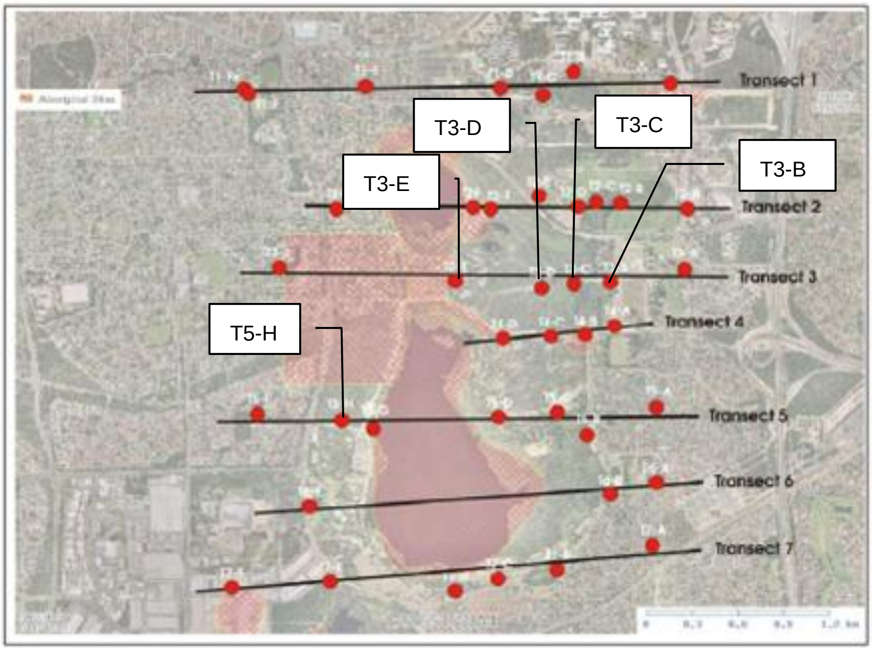
Table 8-3 Results of sensitivity testing on Manning's M and LAI

Sensitivity Test	Change in Mean Simulated Water Level (m)	
	Bore 61410202	Bibra Lake
Manning's n = 0.020	-0.01	0.09
Manning's n= 0.011	-0.03	0.09
LAI +25%	-0.03	0.03
LAI -25%	-0.03	0

9.0 Validation

The late provision of groundwater level data for 2009 and 2010 provided the opportunity to use this data for validation in conjunction with additional precipitation and evaporation data. Following calibration and sensitivity analysis, the model duration was extended to include this additional data. Simulated water levels were compared to discrete observations reported by Syrinx and V&CGRS (2011) to provide an assessment of the model performance. Syrinx and V&CGRS (2011) chose the months March, April and August. This is based on the assumption that March has the lowest groundwater water levels, April has recharged groundwater levels and August has the highest groundwater levels. These months have therefore been used for comparison with simulated results.

Simulated and observed groundwater contours for March, April and August 2010 are presented in Appendix E. The monitoring bores, located along Transect 3 shown in Figure 9-1, are located within the yellow rectangle drawn on the maps in Appendix E and roughly coincide with the proposed road alignment. The simulated groundwater contours demonstrate a generally westerly groundwater flow, with a slight orientation west by north west. The general shape and spacing of the contours is comparable to those determined from the observed data. It should be noted that, due to the delay in obtaining the necessary approvals for monitoring in heritage areas, it was not possible for groundwater levels to be observed in certain sections of the project area (shaded in red on Figure 9-1) and assumptions have been made by Syrinx and V&CGRS (2011) regarding the shape of contours in these areas.



Source: Syrinx and V&CGRS (2011)

Figure 9-1 Location of Syrinx and V&CGRS monitoring bores for 2010

Table 9-1 presents a comparison of simulated and observed levels at individual bore locations.

Table 9-1 Comparison of observed and simulated groundwater levels for 2010

Bore Details	Site Name		T3B	T3C	T3D	T3E	Average
	Easting		390280.6	390003	389832.6	389242	
	Northing		6449816	6449795	6449786	6449817	
Groundwater Level (mAHD)	Mar-10	Observed	15.51	14.58	15.4	12.65	
		Simulated	16.56	15.36	14.93	13.13	
		Difference	1.05	0.78	-0.47	0.48	0.695
	Apr-10	Observed	15.78	14.94	14.99	13.18	
		Simulated	16.51	15.35	14.85	13.12	
		Difference	0.73	0.41	-0.14	-0.06	0.335
	Aug-10	Observed	16.44	15.72	14.3	13.59	
		Simulated	16.82	15.76	15.24	13.5	
		Difference	0.38	0.04	0.94	-0.09	0.365

The results presented in Table 9-1 show that, for bore T3E, which is located near the centre of the model domain, the simulated results match quite well to the observed data for April and August, however for March, results do not match very well. Closer to the model boundaries however (bore T3B), the simulated levels deviate further from the observed data.

The large model grid size may have some impact on the accuracy of the results comparison, because the observed data is collected from discrete locations, whereas the modelling results are limited to an average value across an 80m cell. The spatial variation in groundwater contours over this distance is significant, and it is likely that a more accurate comparison may be obtained by refining this grid and decreasing the cell size.

Simulated water levels are also only output at monthly intervals, which may not coincide exactly with the discrete timing of the observed data. The exact dates of the Syrinx and V&CGRS (2011) data are unknown so some allowance for temporal variability in levels should be made in the comparison. These differences are illustrated (Table 9-2) by the difference in monitoring data between DoW bore 61410186 and Syrinx and V&CGRS (2011) bore T5-H. The two bore locations are only 39m apart, yet a difference in the recorded data of over 400mm can be seen for October 2010.

Water levels are simulated within the model at much smaller timestep intervals but these results are only stored at monthly intervals due to computer data storage limitations. In order to remove these inaccuracies, an exact date should be obtained from the monitoring agents and compared to a set of modelled data that has been output at a time interval appropriate to enable comparison.

Table 9-2 Comparison of DoW and Syrinx and V&CGRS monitoring data

Bore Details	Site Name	T5-H	61410186	Difference
	Easting	388538.2	388502	<40m
	Northing	6448902	6448887	
Groundwater Level (mAHD)	Apr-10	11.88	11.795	0.085
	Jul-10	11.93	11.895	0.035
	Oct-10	11.88	11.465	0.415

It is acknowledged that 2010 was a very dry year and thus, in sequence with 2009, it may be considered an outlying period in relation to the historical rainfall dataset. The exclusion of these years from the model calibration may have resulted in the reduced ability of the model to simulate groundwater levels for very dry years.

Following consideration of the results presented in Table 9-1 it was determined that the ability of the model to estimate water levels at discrete locations along the road alignment is limited. The overall flow direction and groundwater contours, however, are generally comparable with the Syrinx and V&CGRS monitoring results.

10.0 Model Limitations

There are a number of limitations inherent in the use of the model. These are discussed within the following sections. These limitations may reduce the ability of this model to be used in future for predictive purposes.

10.1 Model Grid Size

The MIKE SHE model has been developed with an 80m grid, which is relatively coarse. The nature of this grid resolution results in a broad representation of flow processes and can result in poor correlation with discrete recorded data in some locations, but allows for acceptable model run times and manageable sizes of output data.

10.2 Boundary Conditions

The model is driven by the eastern and western model fixed head boundary condition time series.

The time series adopted for the eastern boundary condition within the base case model and short term simulation are based on local observed bore levels. The western boundary condition for these models is the same time series with a vertical adjustment applied, which may be considered acceptable in the absence of local observed groundwater levels, but it is unlikely to reflect 'real' groundwater levels at this location. This vertical adjustment is assumed to represent the decline in groundwater levels across the model domain, from east to west, and is based upon the Perth Groundwater Atlas (DoE 2004).

The boundary conditions applied to the long term simulation are repeated cycles of monthly average groundwater levels calculated from the historical record for measured bores. The maximum and minimum values have also been used to simulate 'wet' and 'dry' conditions, but the model does not directly incorporate long term variability in groundwater levels. The model simply uses repeated seasonally adjusted cycles of groundwater and historical rainfall to gauge the response of the system under various conditions.

Zero flow boundaries are applied along the northern and southern boundaries for all of the simulations. The result of this is that water cannot flow across these boundaries. The velocity changes in the vicinity of these zero flow boundaries could potentially impose a change in groundwater levels, although surface water flows are unlikely to be significantly affected. This effect will become less prominent away from these zero flow boundaries. The zero flow boundaries are considered to be selected at a distance far enough away from the project area such that the results closer to the road alignment will not be impacted by this assumption.

10.3 Saturated Zone Geology

The conceptual model of the project area assumes the presence of a unit of lower permeability sediments to the west of the wetlands. There is limited evidence for the presence of this unit, but it is noted that groundwater contours produced by the Department of Environment (2004) and Syrinx and V&DSRG (2011) demonstrate a similar profile. This may indicate the presence of a lower permeability geological feature. Confirmation of this assumed geological layer should be sought for further validation or application of this model.

10.4 Land Use Characteristics

Land use across the model domain were defined using aerial imagery and local knowledge, but they have not been directly compared to current vegetation conditions on the ground. The parameter values for land use characteristics were also derived based on literature values and model calibration, but have not been verified by a vegetation specialist.

10.5 Overland Flow

A constant Manning's *n* value is applied across the model domain, which is a broad simplification. This is considered acceptable due to the lack of overland flow and the results of the sensitivity analysis demonstrate that the model is has limited response to changes in the overland roughness coefficient.

11.0 Conclusions and Recommendations for Further Work

A coupled surface water-groundwater model has been developed by DHI, using MIKE SHE, to simulate existing water movement under a variety of conditions. The model is centred between Bibra and North Lakes and extends across the adjacent wetlands. Model parameters were calibrated using observed groundwater and surface water levels provided by DoW and validated using recent discrete observed water levels obtained by Syrinx and V&CSRG (2011).

A comparison of simulated and observed DoW groundwater and surface water levels for the calibration model produced values of RMSE less than 0.30 for all locations analysed, with r^2 values ranging from 0.41 to 0.92. The model recreated seasonal and long-term variation in levels, although it is noted that absolute values were not always accurately simulated. Validation of model simulation results against discretely sampled groundwater levels for 2010 suggested that the overall flow direction and groundwater contours are generally comparable, but the coarse 80m model grid limited the accuracy of the modelled water levels at discrete locations along the road alignment.

Sensitivity testing of key model parameters demonstrated that simulated water levels are most sensitive to changes in boundary condition water levels, with surface water levels in Bibra Lake demonstrating some sensitivity to values of ERD and unsaturated zone water content at field capacity.

A long term model was used to simulate the behaviour of surface water and groundwater under ‘wet’ and ‘dry’ conditions. Groundwater contours generated from the two simulations indicated a difference of approximately 3m throughout the model domain, increasing to 4m through the centre of Bibra Lake. This represents the extreme variation in water levels that occur under the simulated wet and dry simulations and is not the predicted variability. These extreme model simulations do, however, allow a qualitative analysis of the response for the wetland area to wet and dry periods.

The wet simulation indicated that groundwater flow converges in Murdoch Drain, Roe Swamp and Bibra Lake. This may indicate the discharge of groundwater into the surface water systems and is in agreement with Davidson (1983). The wet simulation also revealed a surface water connection between Roe Swamp and Murdoch Drain. Surface water connections between Bibra Lake and North Lake and Frog Swamp and North Lake also seemed to occur during the extreme events. The dry simulation indicated that the system has consistent east to west groundwater flow and that very little surface water is evident. These observations are confirmed by the corresponding water balance analysis, the wet year demonstrating surface water recharge to the groundwater, and the dry year is driven by the groundwater boundary conditions.

Limitations inherent in the use of the model have been identified, relating to the model grid size, boundary conditions, saturated zone geology, land use characteristics, urban drainage, overland flow and the model calibration. The following discussion presents opportunities for further work to address these limitations.

Future work may require modelling of predicted impacts due to the road embankment. There is some concern that the weight of the proposed road embankment may compact the underlying soils. This compression may then result in altered hydraulic conductivities, which may potentially alter the groundwater flow regime in these areas. The further adaptation of this MIKE SHE model is possible as a tool for the development of such a model. Examination of other possible means to quantify these issues would be required first, but if MIKE SHE is determined to be the most appropriate means to quantify these changes there are several areas for improvement before this will be achievable.

The model will require refinement to a smaller grid size in order to capture the effect of the road at an appropriate scale. A compromise between model run times and cell size is required therefore it is recommended that a cell size of 20m is first considered. The increase in model run times that are to be expected with a decreased cell size can partially be addressed by alteration of several areas in which model run time may be improved. These include:

- Adjustment of the model layer geometry so that it is appropriate for use with the two-layer water balance solver and simplifying its variability.
- Removal of overland flow within the lakes by adding detention storage areas.
- Simplification of the ET and precipitation data.
- Refinement of the existing MIKE 11 open channel representation.

Several elements within the unsaturated zone and the vegetation characteristics may also be improved. These are summarised as follows:

- The inclusion of macropore bypass flow to allow greater recharge.
- The revision of the ET surface depth.
- The revision of the use of the Green and Ampt infiltration solution.
- The revision and verification of the adopted LAI and ERD for the model.
- Incorporation of urban drainage elements.

It is possible to develop a coarse regional scale model to capture regional groundwater behaviour, with a refined local model nested within. Allowing the regional boundaries to be set at the Jandakot Mound to the east, the coastline to the west and having the north and south boundaries extended may enable the nested model to achieve an improved representation of the boundary conditions.

Sensitivity analysis was undertaken for LAI, ERD and Manning's roughness. This testing confirmed that the model is relatively insensitive to these parameters. Sensitivity testing of parameters for individual land uses may develop an understanding of the model sensitivity to specific land use changes.

Large extents of the project area were unable to be accessed for sampling of water levels and geological features due to heritage issues. Future work for the area should include water level sampling in these areas, to allow for improved calibration, testing and validation of parameters used for the lake bed sediments. Geological investigations should also confirm the existence of lower permeability sediments, their location, extent and properties.

The model does not simulate water levels well during the dry years, toward the end of the simulation period. Using the latest data a better calibration may be achieved by incorporating 2009 and 2010 as these years have been particularly dry. The lake surface monitoring stations also reach the lowest recordable level on the water gauges and so future work may include rectifying this problem by fixing the gauges and calibrating against this improved data. Climate change scenarios and the addition of some water quality elements to the model are also areas for consideration for future work.

Information presented by Syrinx and V&CSRG (2010) and Syrinx and V&CSRG (2011) was not available during the development of the model. This information includes vegetation classification, mapping and characteristics and bore logs, including stratigraphic soil profiles, It is recommended that this information be used to comprehensively review and validate future development of the model.

While there are various elements of the model that may be improved, the flow regime is generally consistent with previous work and overall is confirmed by DoW information and Syrinx and V&CSRG (2011) monitoring data. The best correlations have been obtained at Bibra Lake and east of Roe Swamp, for surface water and groundwater, respectively. These are important areas of the RHE project and confidence in the model flow regime is greatest within these areas. The development of this model has been useful to allow a qualitative analysis of the wetlands within the RHE project area in the absence of other information during the design process.

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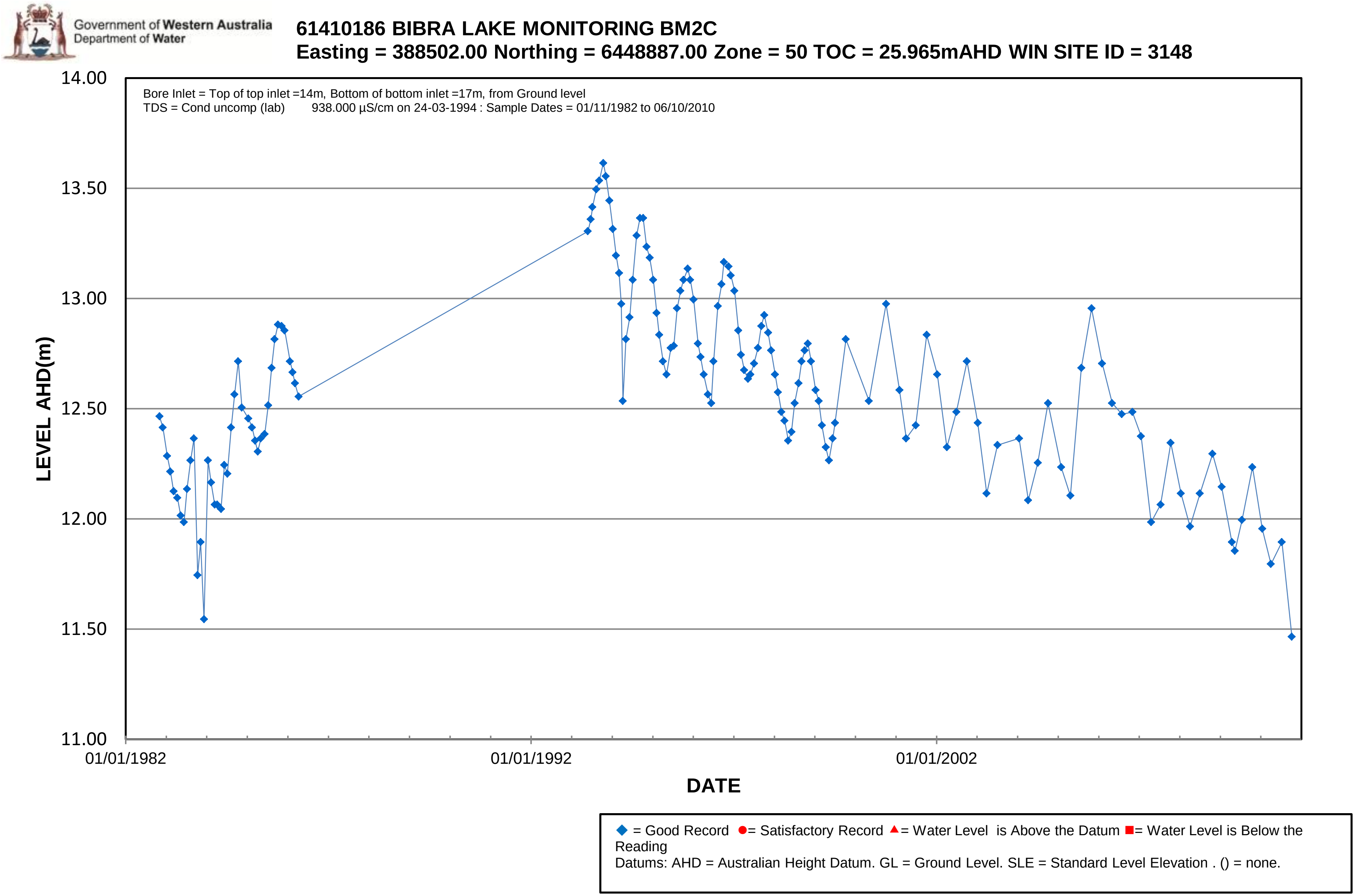
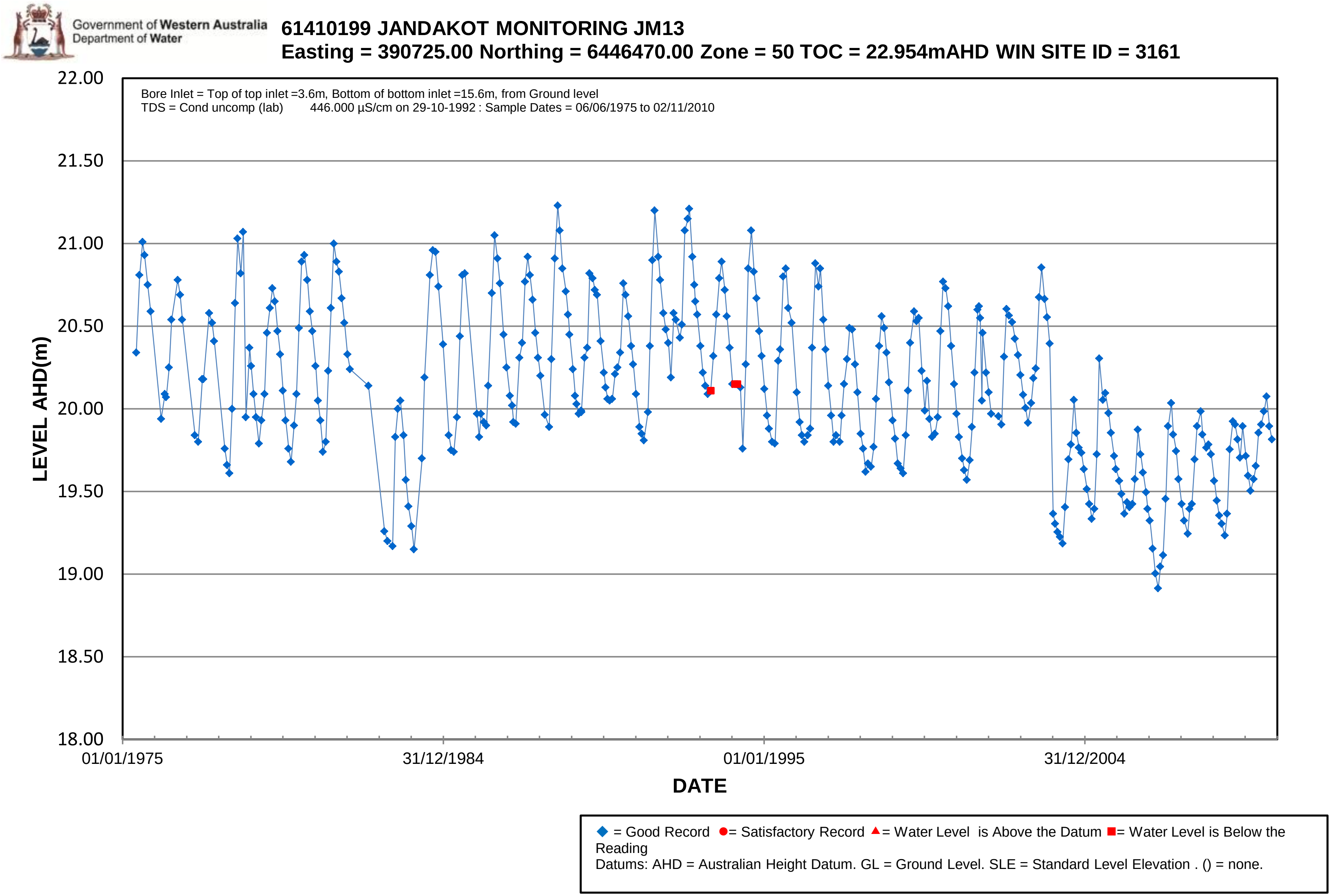
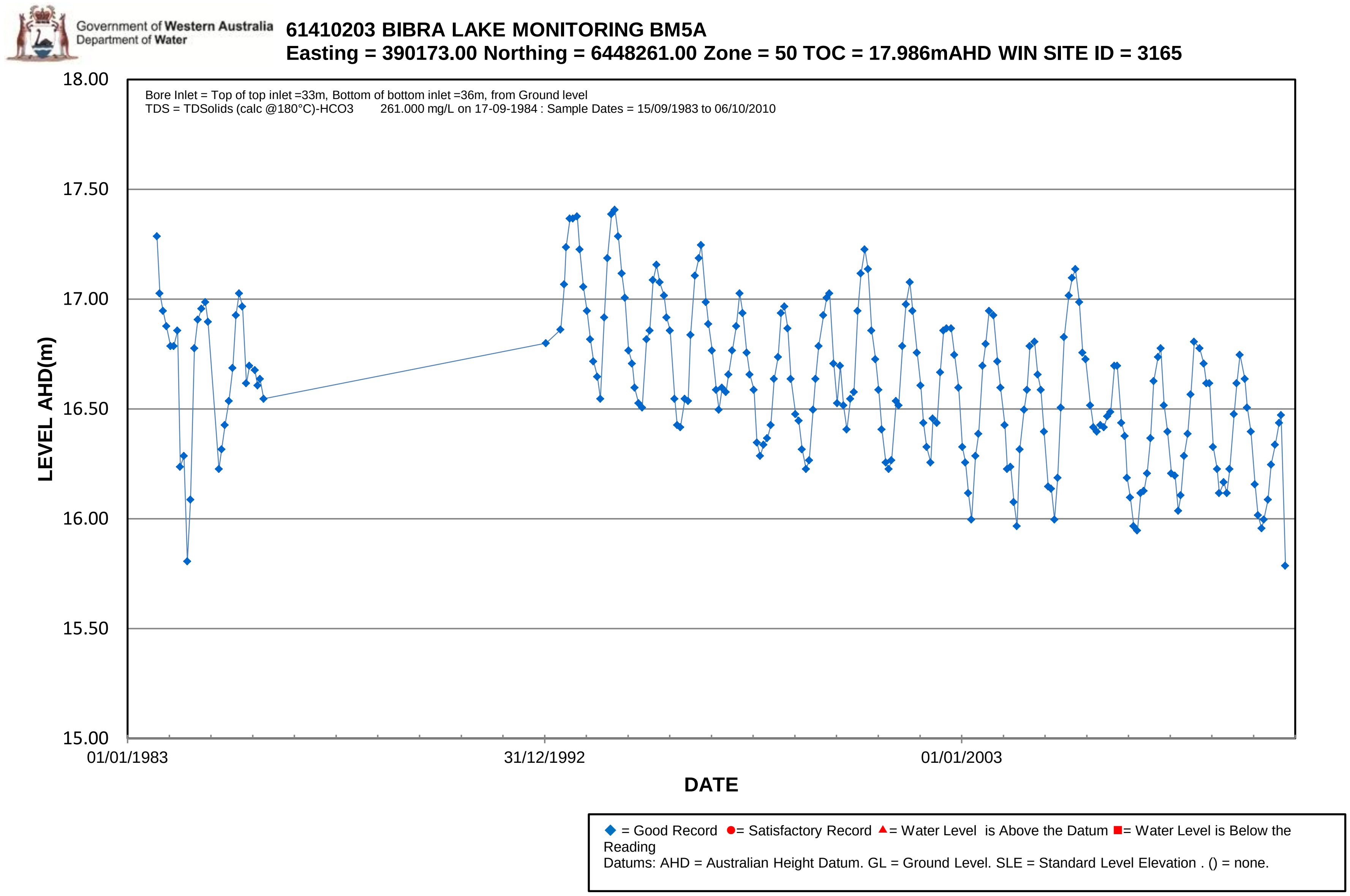
Appendix A

DoW Observed Groundwater and Surface Water Levels

Appendix A DoW Observed Groundwater and Surface Water Levels


Government of Western Australia
Department of Water
61410186 BIBRA LAKE MONITORING BM2C
Easting = 388502.00 Northing = 6448887.00 Zone = 50 TOC = 25.965mAHD WIN SITE ID = 3148
Bore Inlet = Top of top inlet =14m, Bottom of bottom inlet =17m, from Ground level
TDS = Cond uncomp (lab) 938.000 µS/cm on 24-03-1994 : Sample Dates = 01/11/1982 to 06/10/2010
LEVEL AHD(m)
14.00
13.50
13.00
12.50
12.00
11.50
11.00
01/01/1982
01/01/1992
01/01/2002
DATE
= Good Record = Satisfactory Record = Water Level is Above the Datum = Water Level is Below the Reading
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation . () = none.


Government of Western Australia
Department of Water
61410199 JANDAKOT MONITORING JM13
Easting = 390725.00 Northing = 6446470.00 Zone = 50 TOC = 22.954mAHD WIN SITE ID = 3161
Bore Inlet = Top of top inlet =3.6m, Bottom of bottom inlet =15.6m, from Ground level
TDS = Cond uncomp (lab) 446.000 µS/cm on 29-10-1992 : Sample Dates = 06/06/1975 to 02/11/2010
LEVEL AHD(m)
22.00
21.50
21.00
20.50
20.00
19.50
19.00
18.50
18.00
01/01/1975
31/12/1984
01/01/1995
31/12/2004
DATE
= Good Record = Satisfactory Record = Water Level is Above the Datum = Water Level is Below the Reading
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation . () = none.


Government of Western Australia
Department of Water
61410203 BIBRA LAKE MONITORING BM5A
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Bore Inlet = Top of top inlet =33m, Bottom of bottom inlet =36m, from Ground level
TDS = TDSolids (calc @180°C)-HCO3 261.000 mg/L on 17-09-1984 : Sample Dates = 15/09/1983 to 06/10/2010
18.00
17.50
17.00
16.50
16.00
15.50
15.00
LEVEL AHD(m)
01/01/1983
31/12/1992
01/01/2003
DATE
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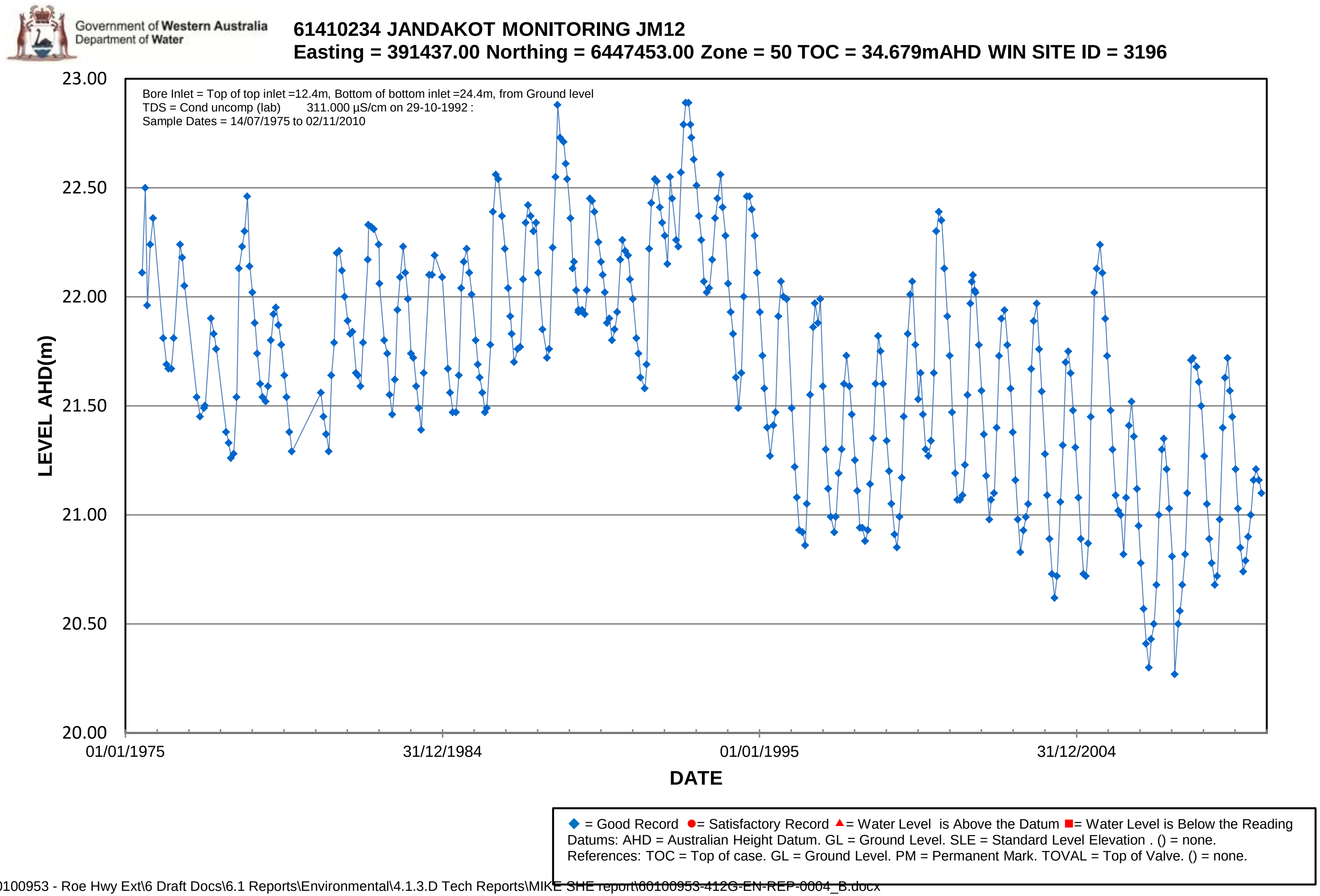
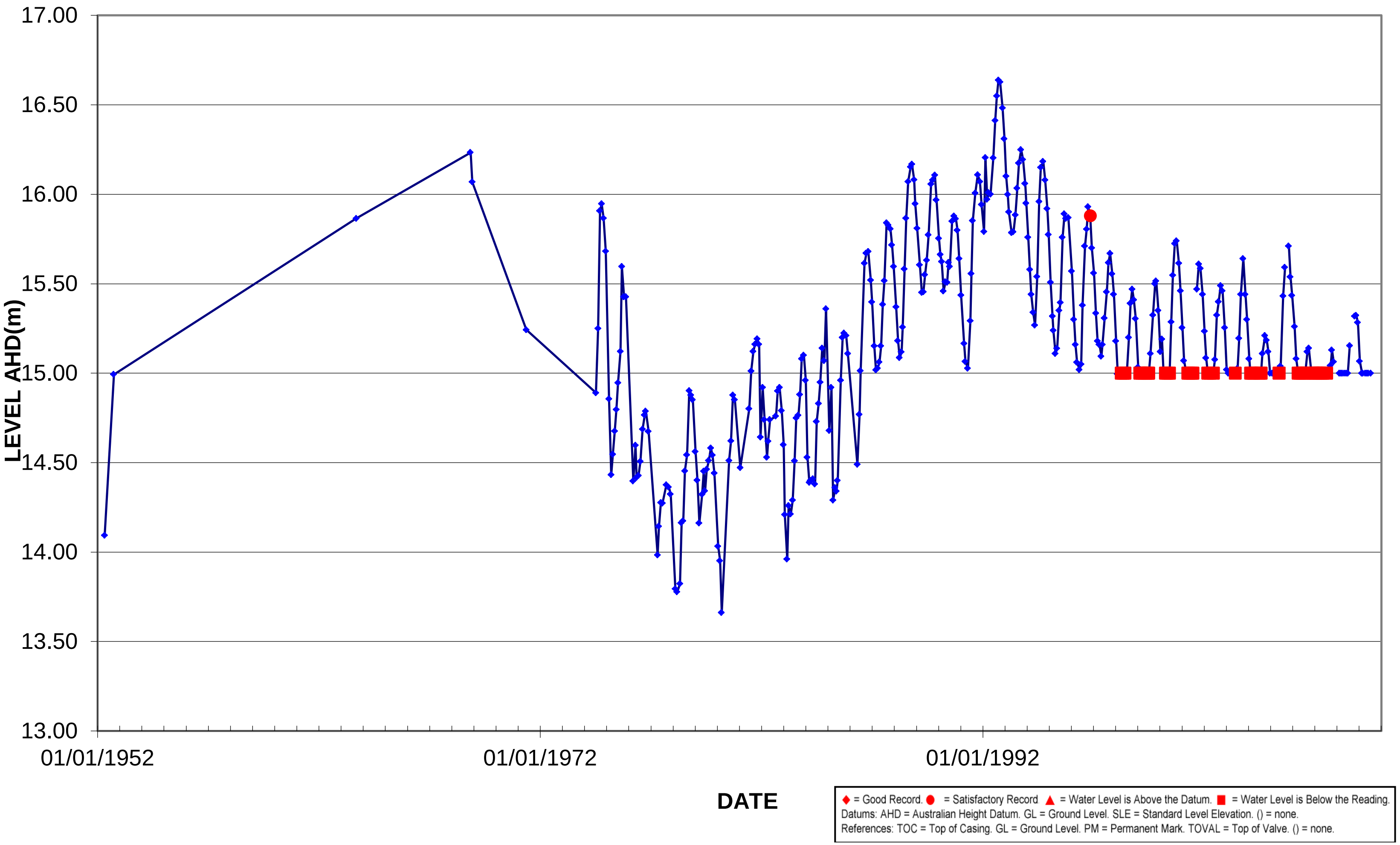
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation . () = none.

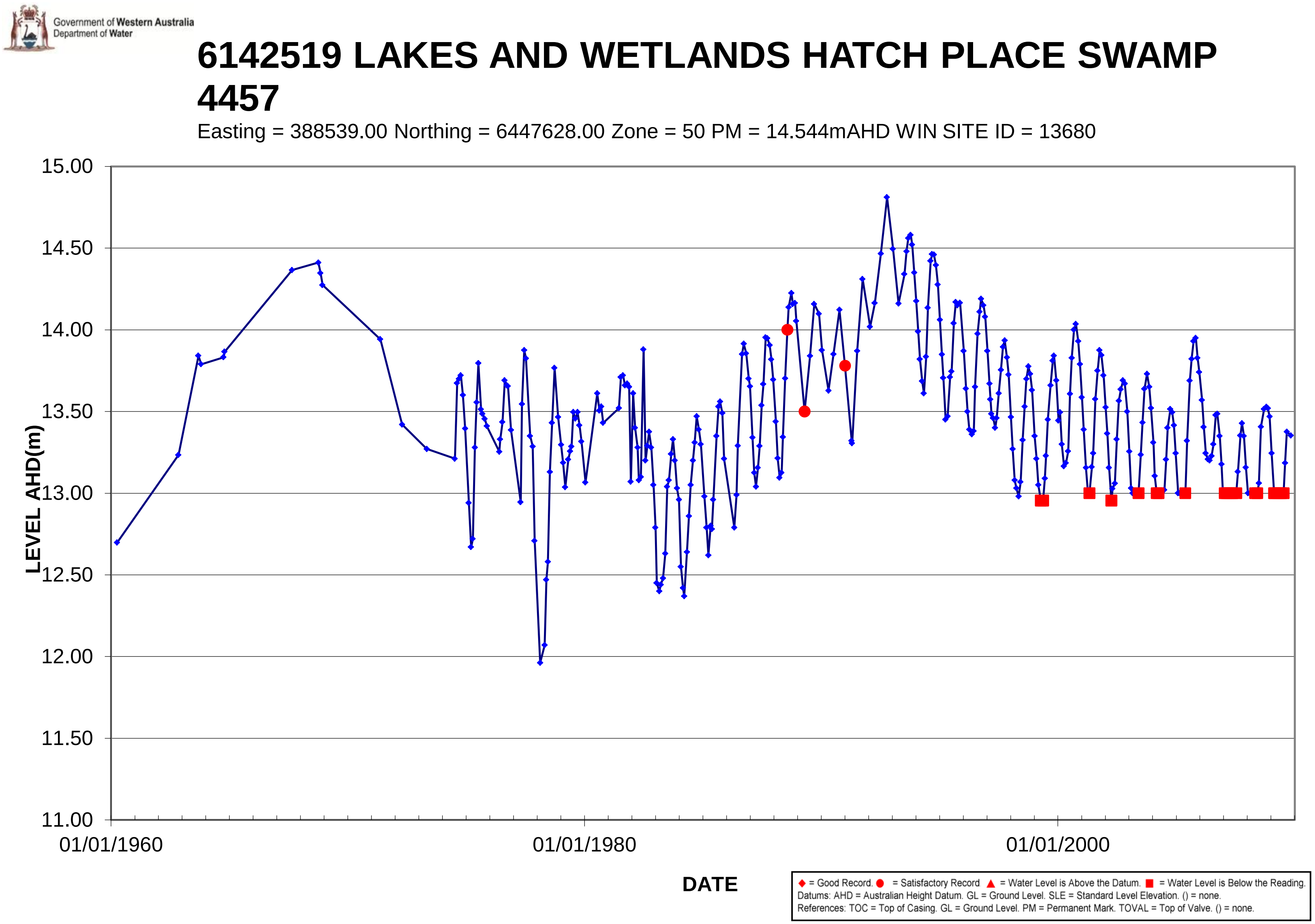

Government of Western Australia
Department of Water
61410234 JANDAKOT MONITORING JM12
Easting = 391437.00 Northing = 6447453.00 Zone = 50 TOC = 34.679mAHD WIN SITE ID = 3196
Bore Inlet = Top of top inlet =12.4m, Bottom of bottom inlet =24.4m, from Ground level
TDS = Cond uncomp (lab) 311.000 µS/cm on 29-10-1992 :
Sample Dates = 14/07/1975 to 02/11/2010
LEVEL AHD(m)
23.00
22.50
22.00
21.50
21.00
20.50
20.00
01/01/1975
31/12/1984
01/01/1995
31/12/2004
DATE
= Good Record = Satisfactory Record = Water Level is Above the Datum = Water Level is Below the Reading
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation . () = none.
References: TOC = Top of case. GL = Ground Level. PM = Permanent Mark. TOVAL = Top of Valve. () = none.

Government of Western Australia
Department of Water

6142518 LAKES AND WETLANDS PARKES SWAMP 606

Easting = 389409.00 Northing = 6446804.00 Zone = 50 PM = 17.965mAHD WIN SITE ID = 13679




Government of Western Australia
Department of Water
6142519 LAKES AND WETLANDS HATCH PLACE SWAMP 4457
Easting = 388539.00 Northing = 6447628.00 Zone = 50 PM = 14.544mAHD WIN SITE ID = 13680
15.00
14.50
14.00
13.50
13.00
12.50
12.00
11.50
11.00
LEVEL AHD(m)
01/01/1960
01/01/1980
01/01/2000
DATE
= Good Record. = Satisfactory Record = Water Level is Above the Datum. = Water Level is Below the Reading.
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation. () = none.
References: TOC = Top of Casing. GL = Ground Level. PM = Permanent Mark. TOVAL = Top of Valve. () = none.

Government of Western Australia
Department of Water

6142520 LAKES AND WETLANDS BIBRA LAKE 425

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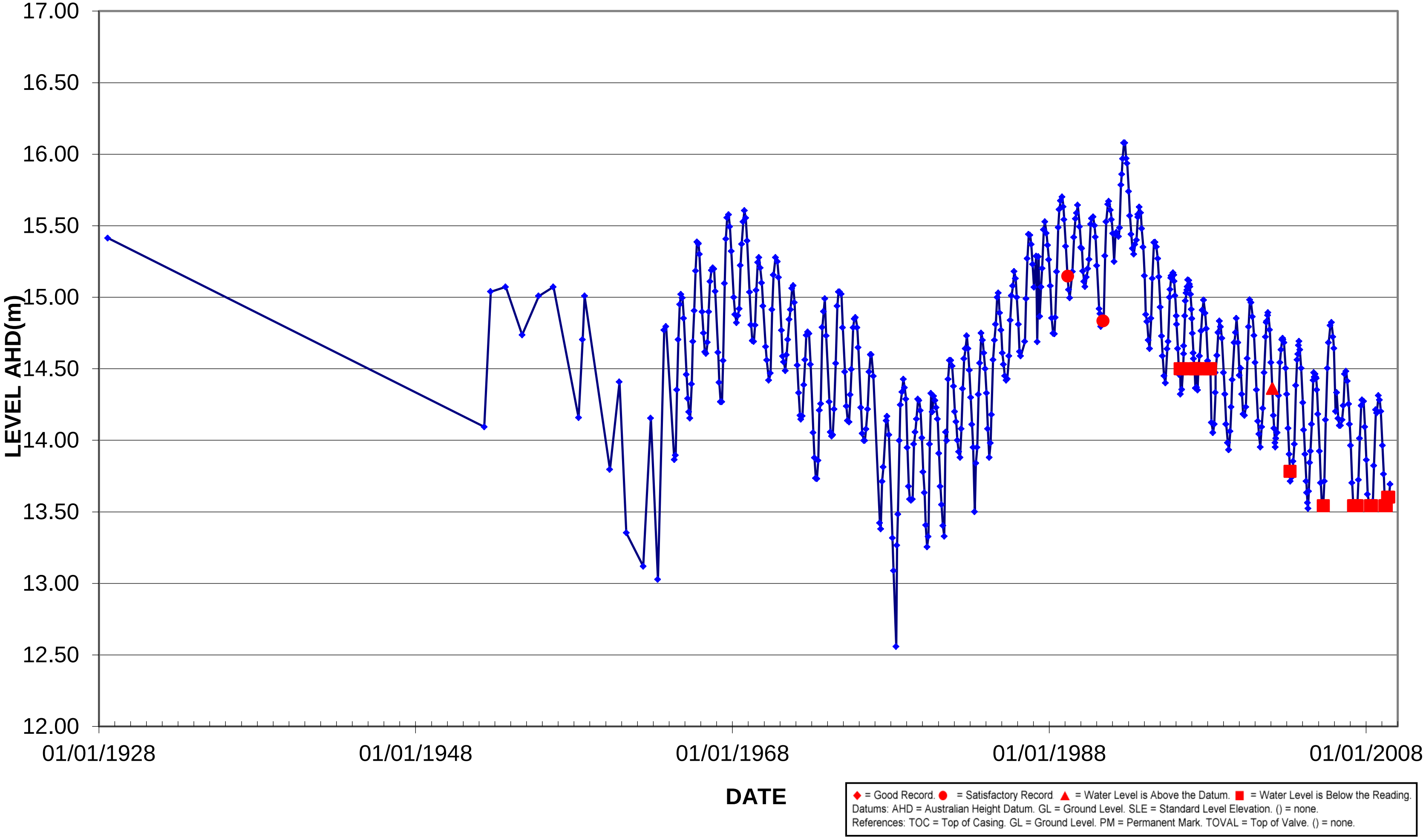
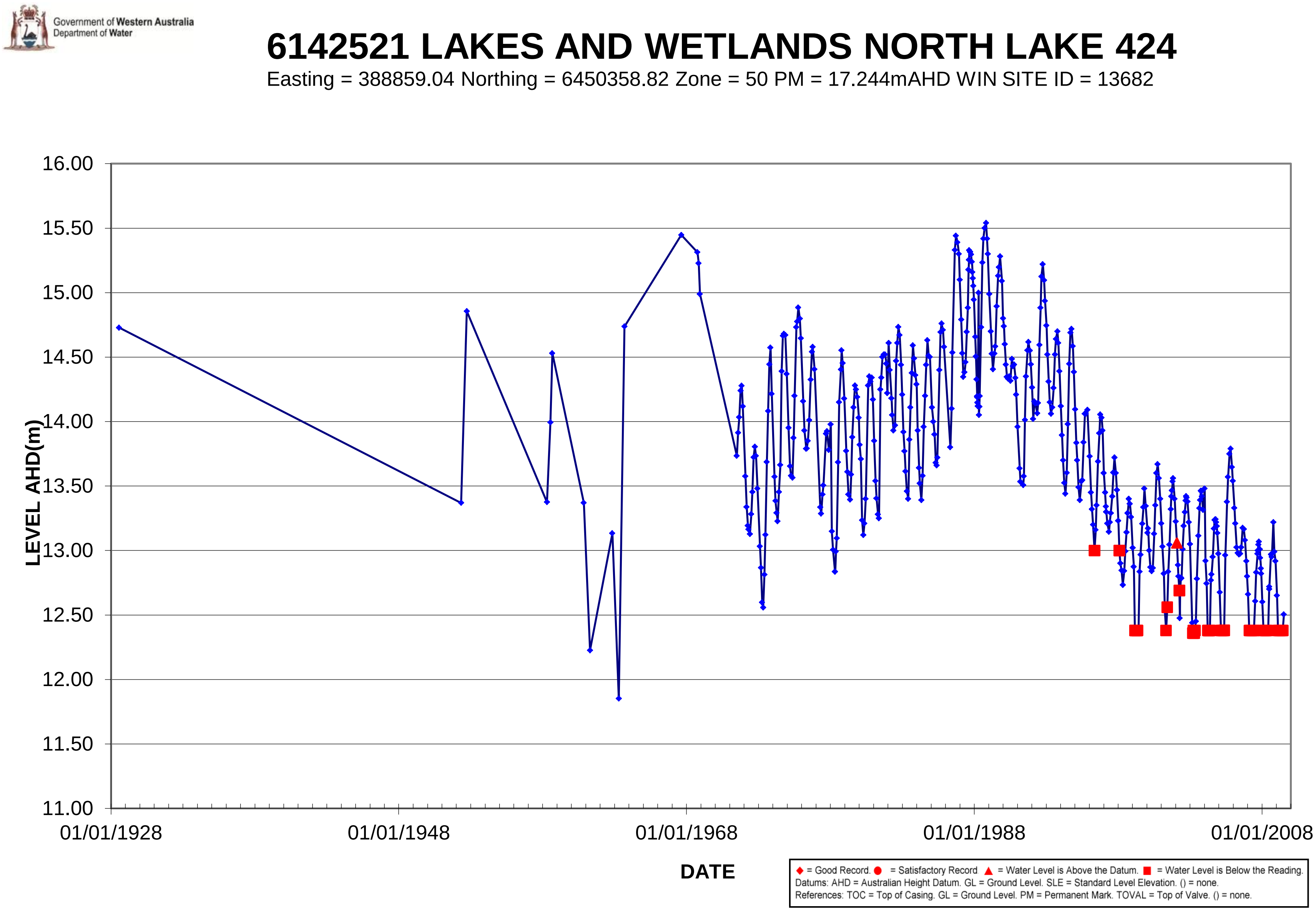
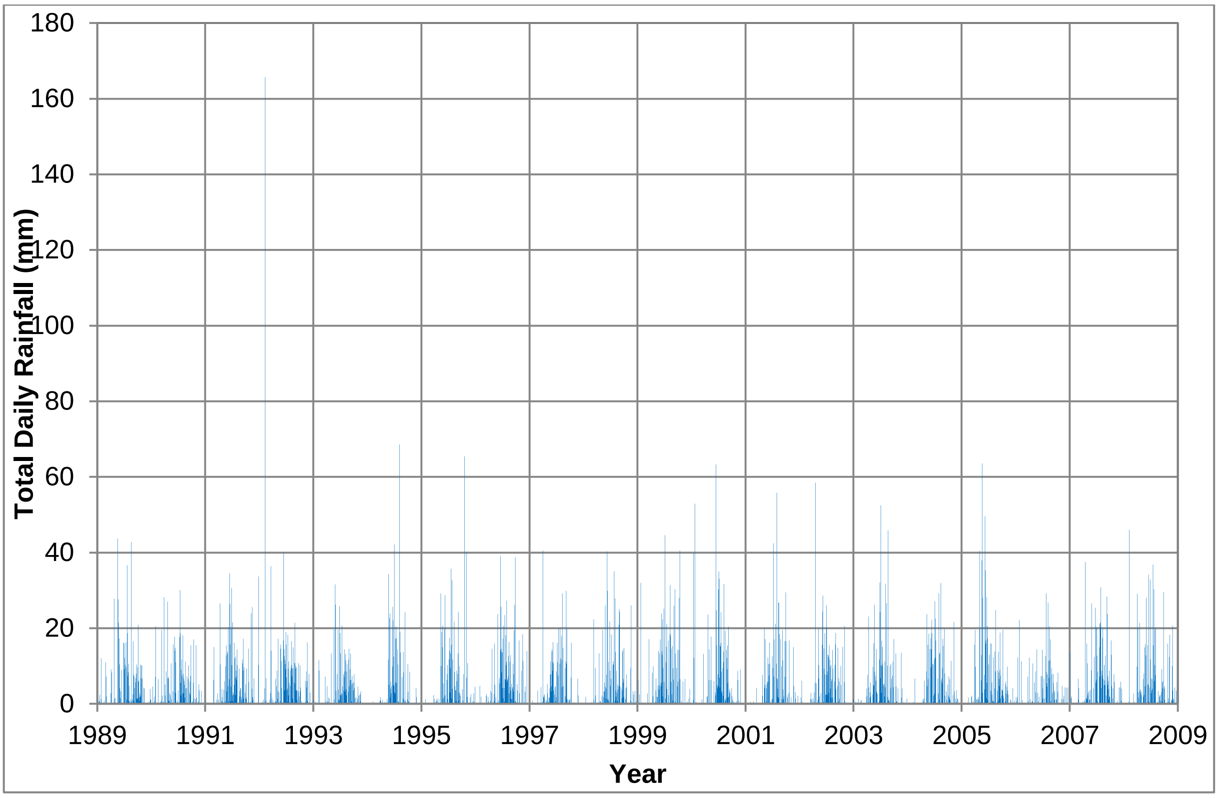



Government of Western Australia
Department of Water
6142521 LAKES AND WETLANDS NORTH LAKE 424
Easting = 388859.04 Northing = 6450358.82 Zone = 50 PM = 17.244mAHD WIN SITE ID = 13682
LEVEL AHD(m)
16.00
15.50
15.00
14.50
14.00
13.50
13.00
12.50
12.00
11.50
11.00
01/01/1928
01/01/1948
01/01/1968
01/01/1988
01/01/2008
DATE
= Good Record. = Satisfactory Record = Water Level is Above the Datum. = Water Level is Below the Reading.
Datums: AHD = Australian Height Datum. GL = Ground Level. SLE = Standard Level Elevation. () = none.
References: TOC = Top of Casing. GL = Ground Level. PM = Permanent Mark. TOVAL = Top of Valve. () = none.

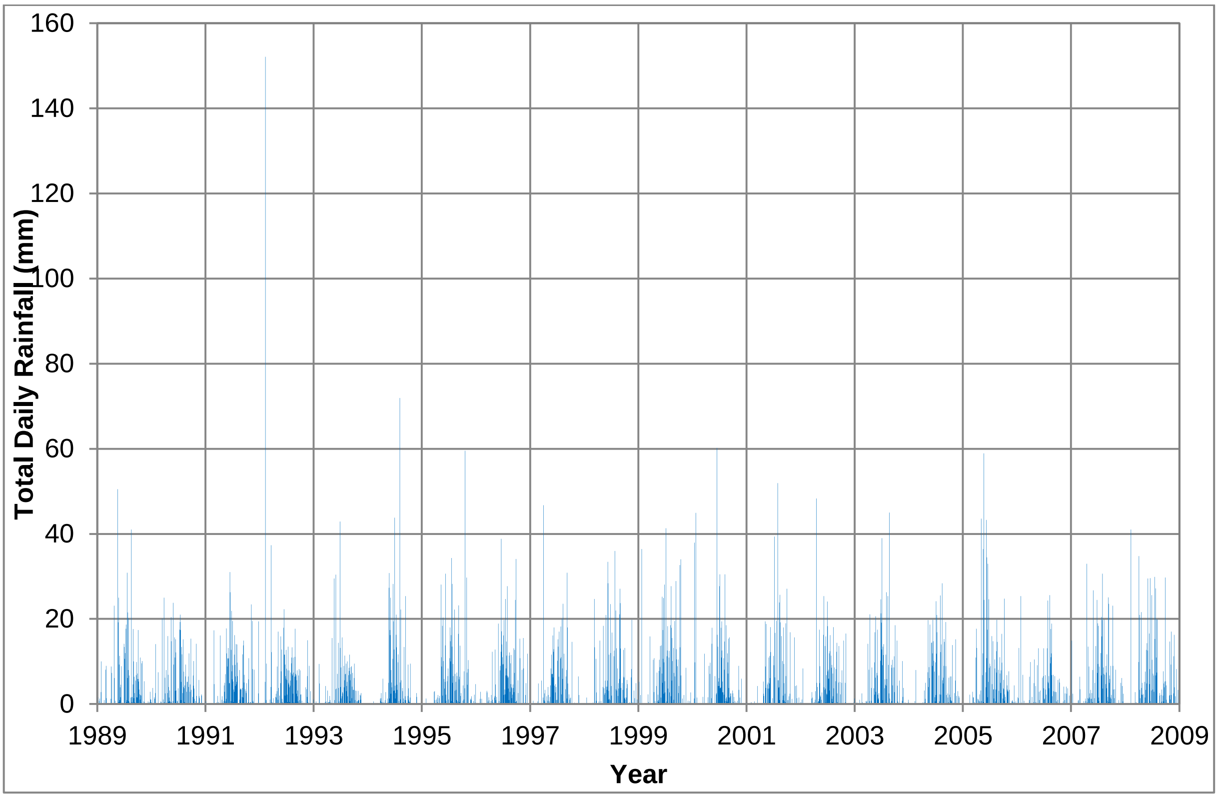
Appendix B

SILO Data

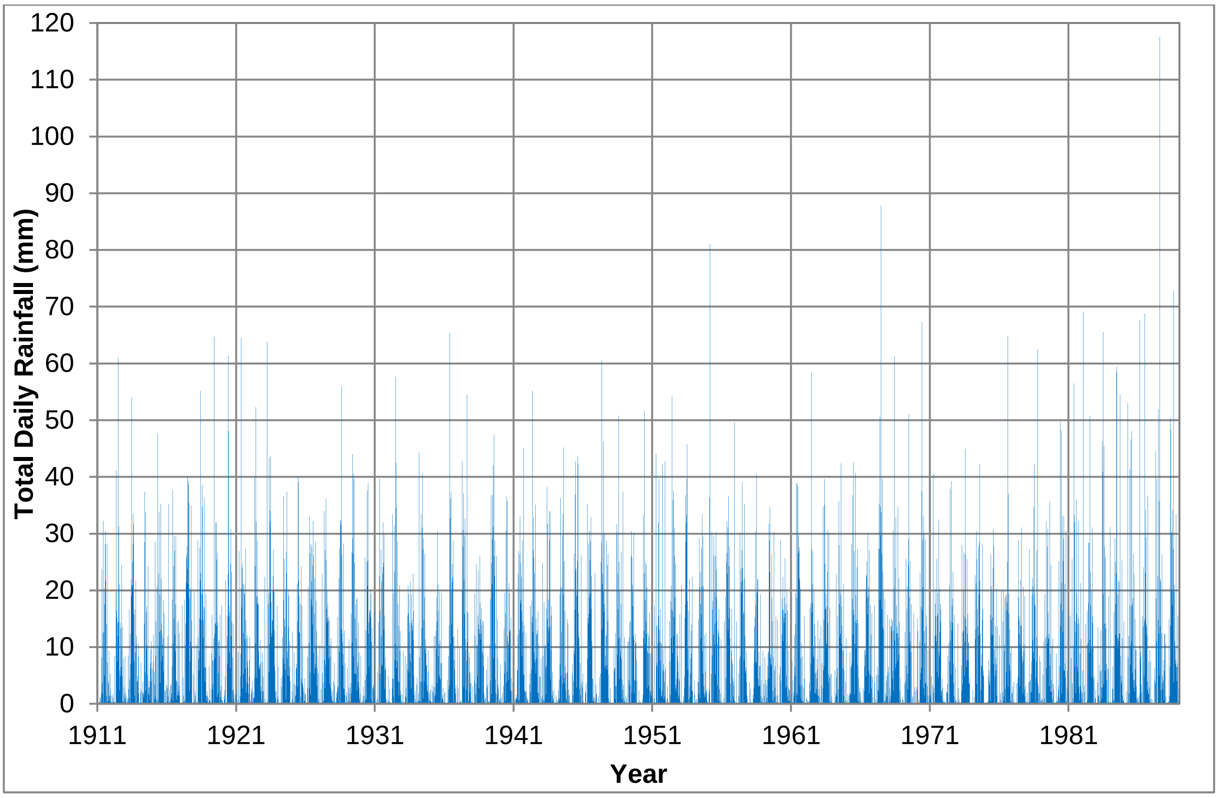
Appendix B SILO Data



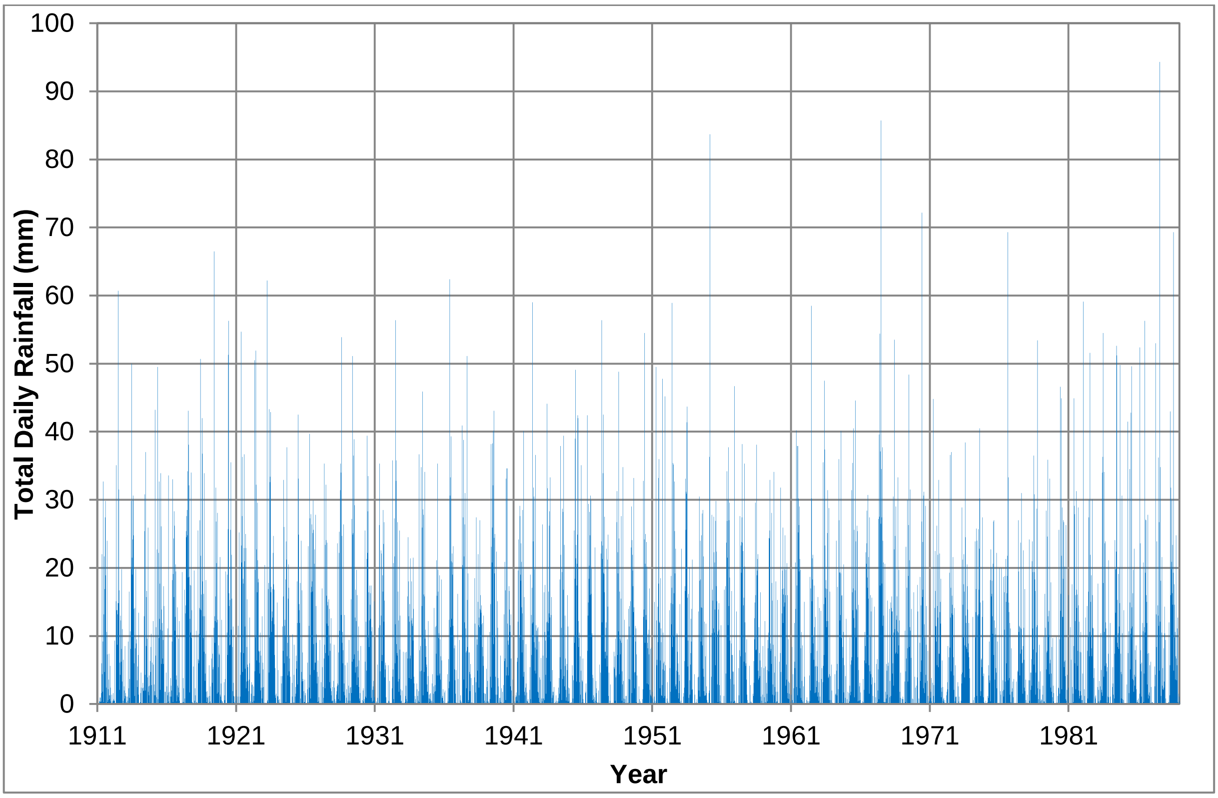
SILO rainfall data - Base Case - Eastern Time Series



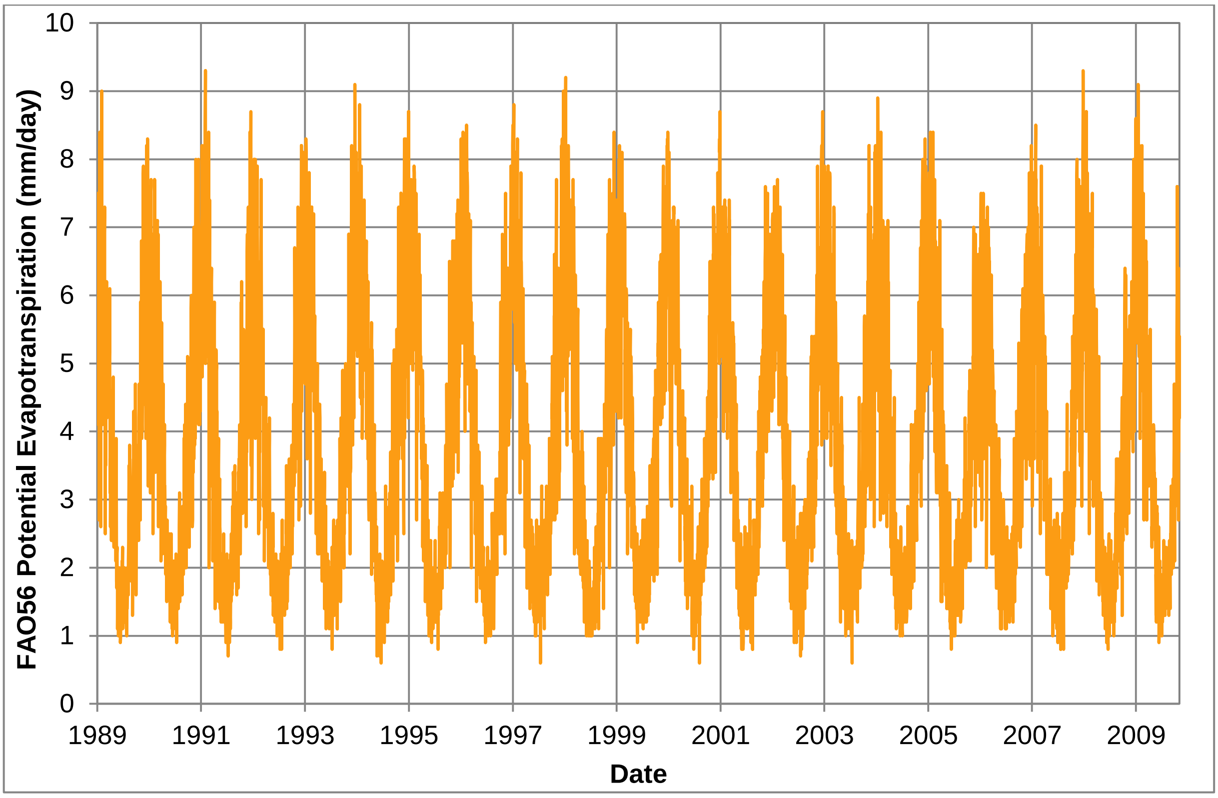
SILO rainfall data – Base Case – Western Time Series



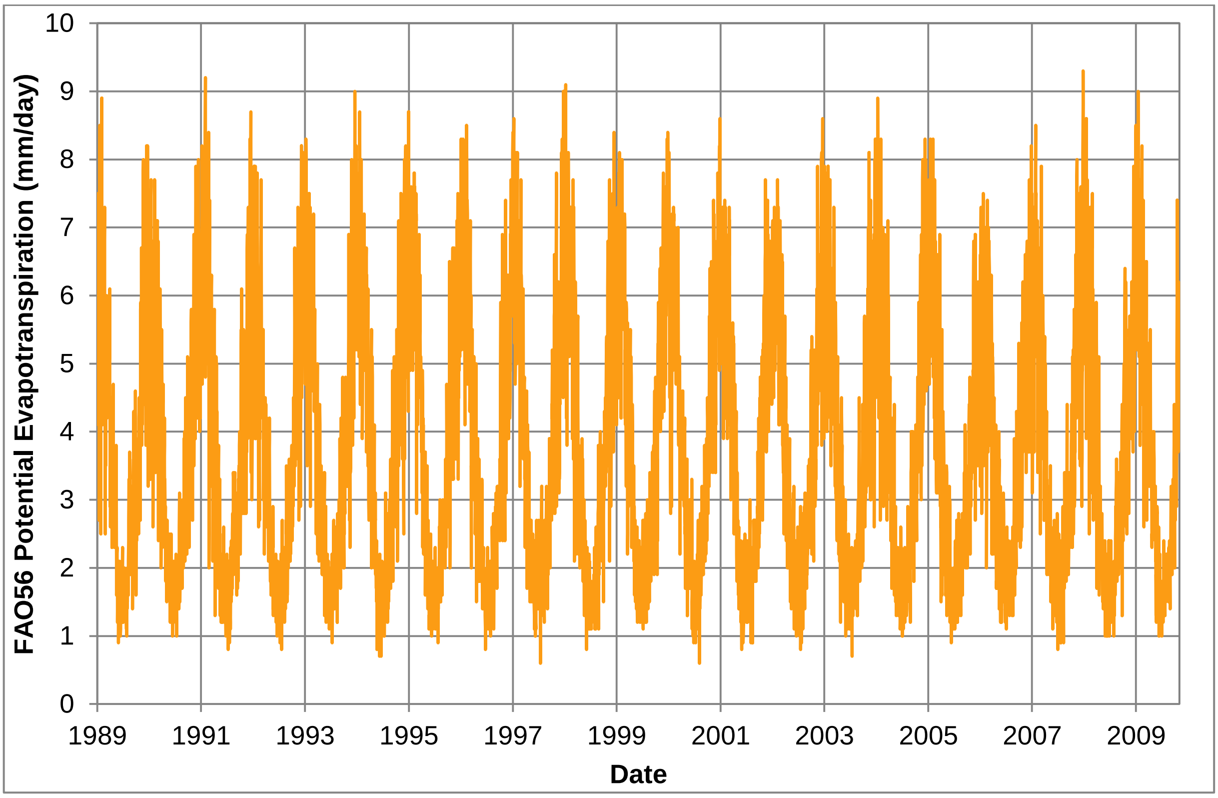
SILO rainfall additional data - Long Term Simulation - Eastern Time Series



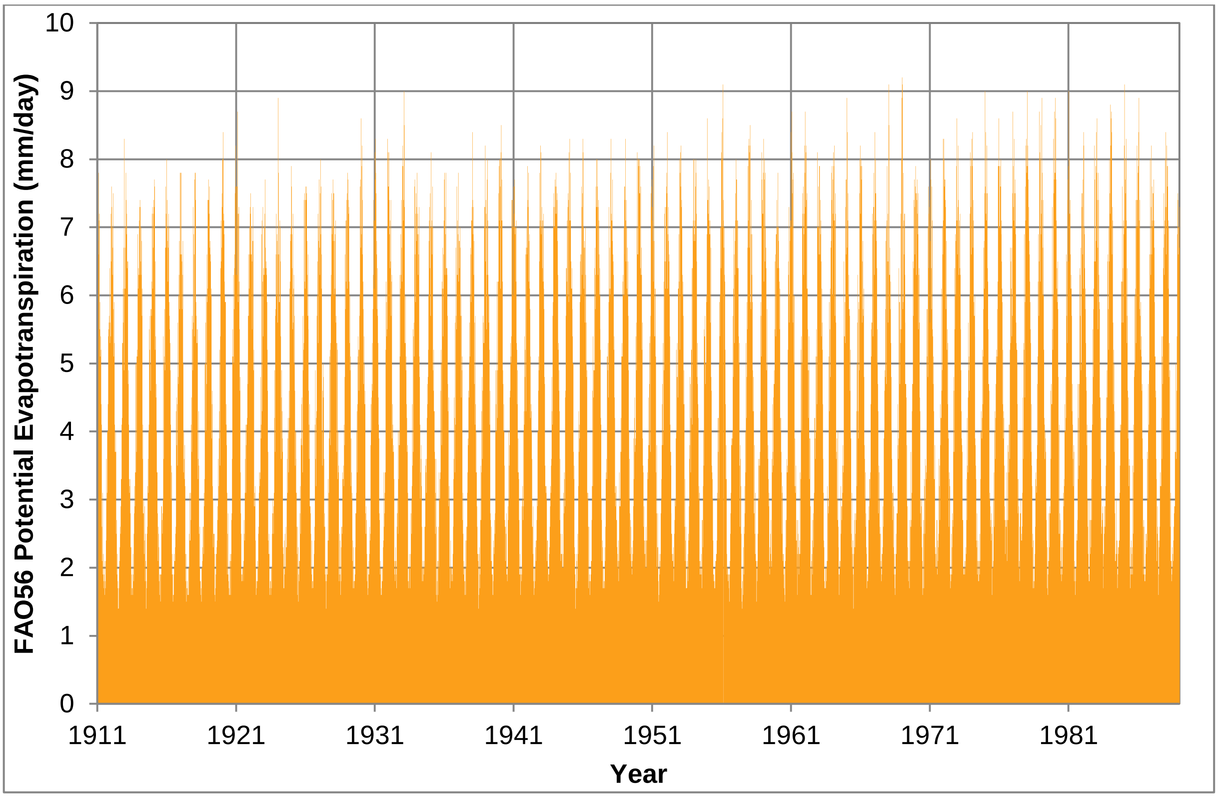
SILO rainfall additional data - Long Term Simulation - Western Time Series



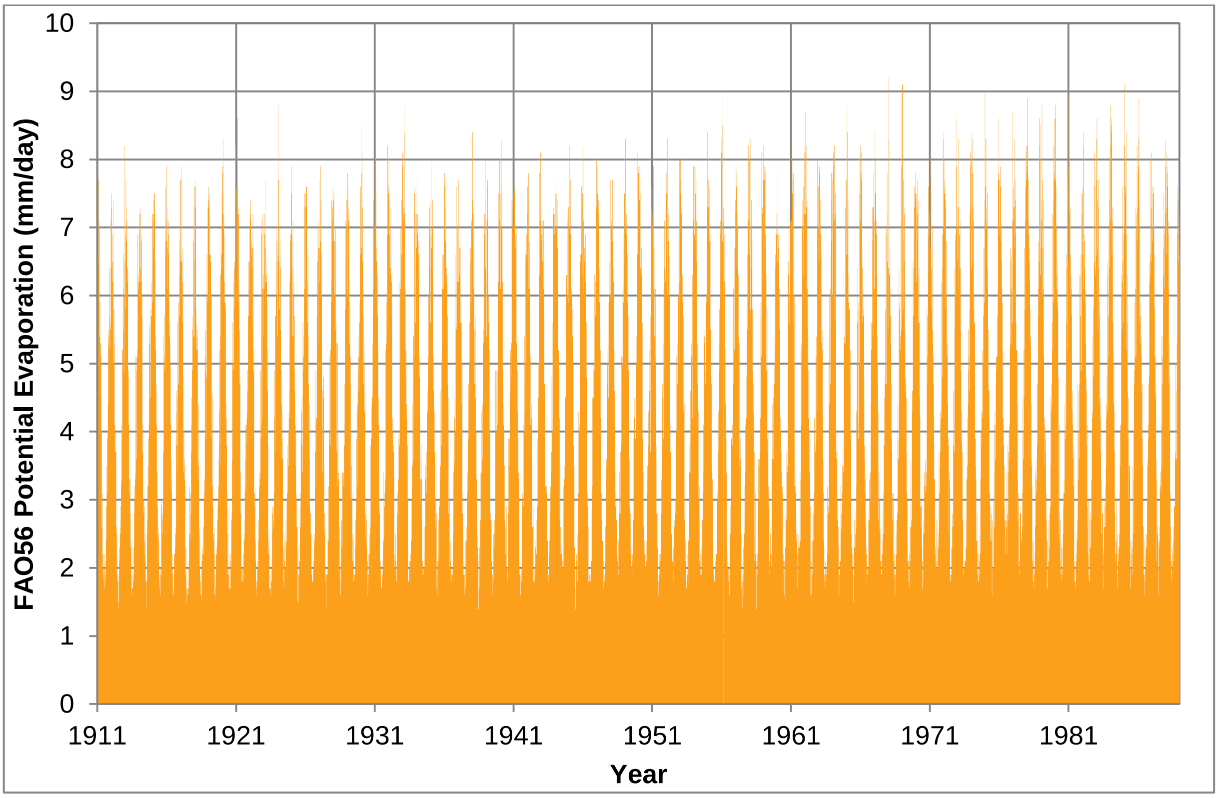
SILO potential reference crop evapotranspiration - Base Case - Eastern Time Series



SILO potential reference crop evapotranspiration - Base Case - Western Time Series



SILO potential reference crop evapotranspiration additional data - Long Term Simulation - Eastern Time Series



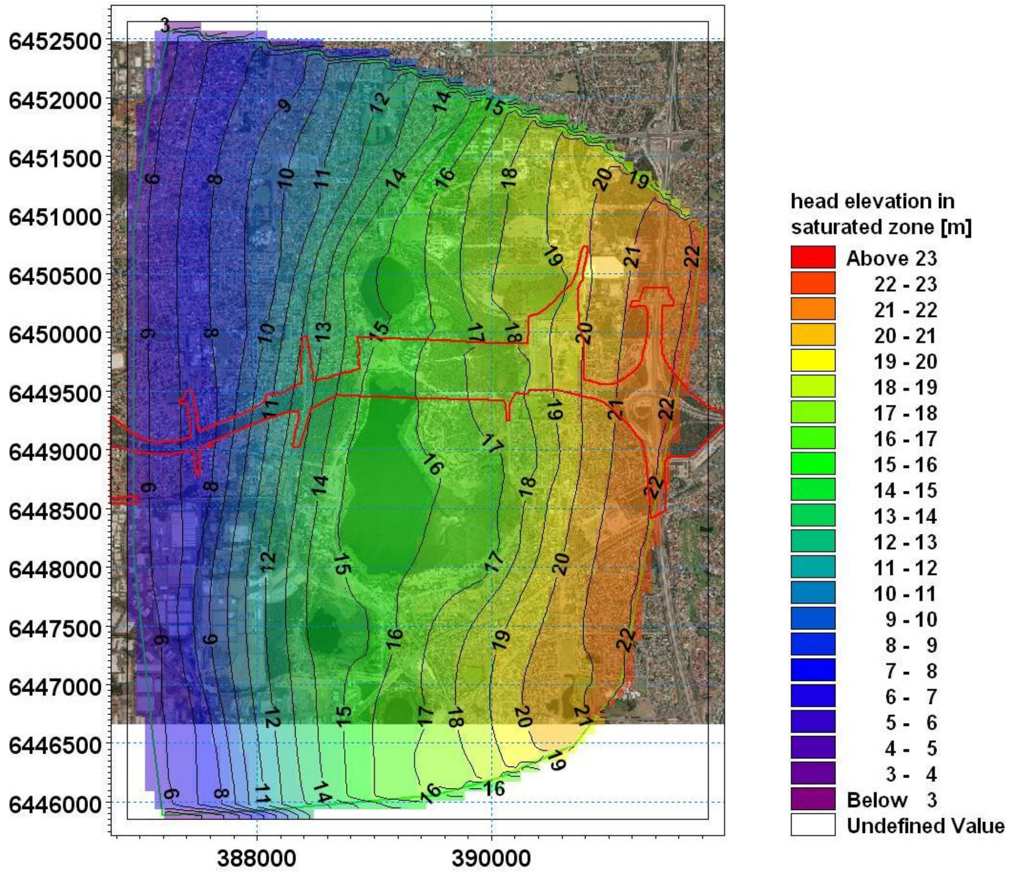
SILO potential reference crop evapotranspiration additional data - Long Term Simulation - Western Time Series

Appendix C

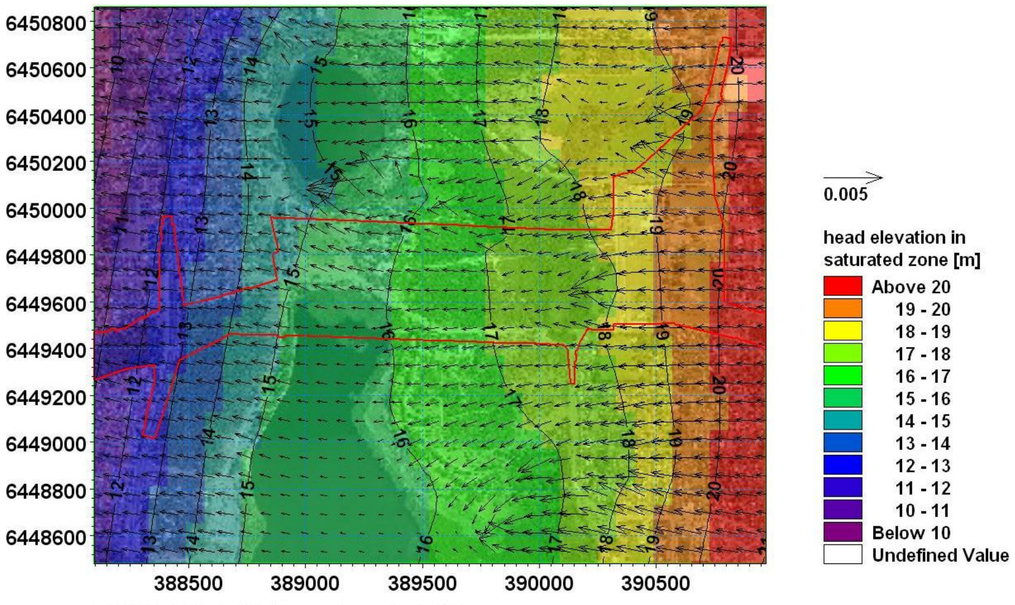
Base Case Model Results

Appendix C Base Case Model Results

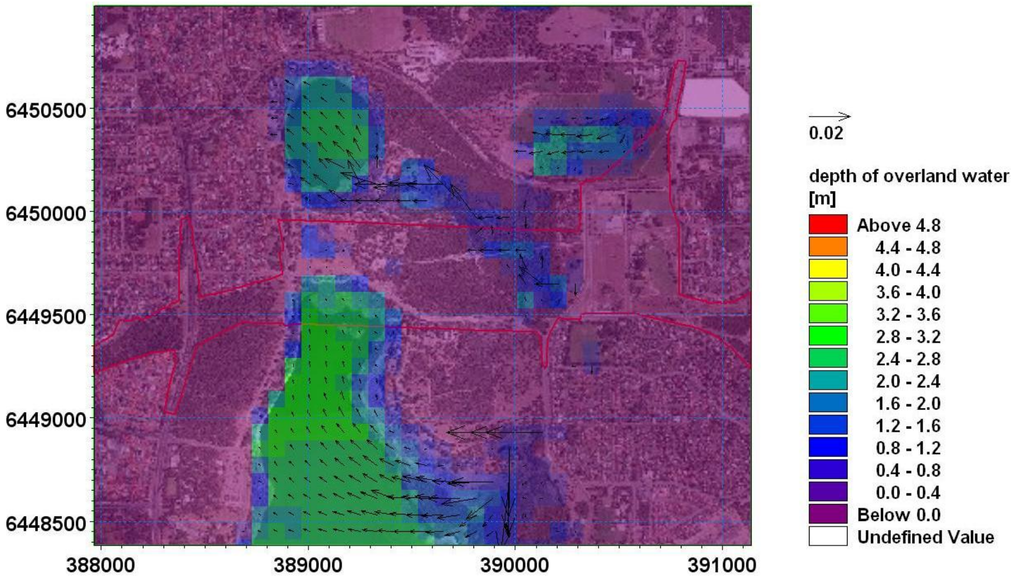
September 1992 ('wet' period)



Simulated Groundwater Contours for September 1992 - Base Case Model

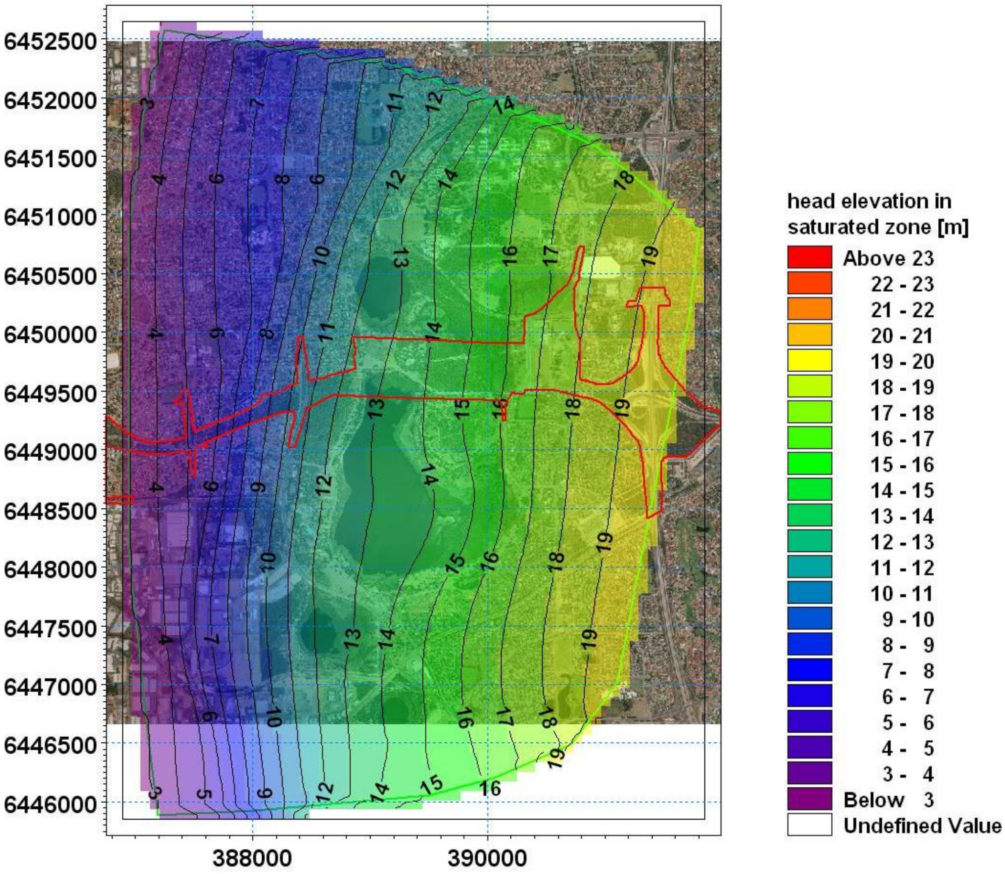


Simulated Groundwater Flow for September 1992 - Base Case Model

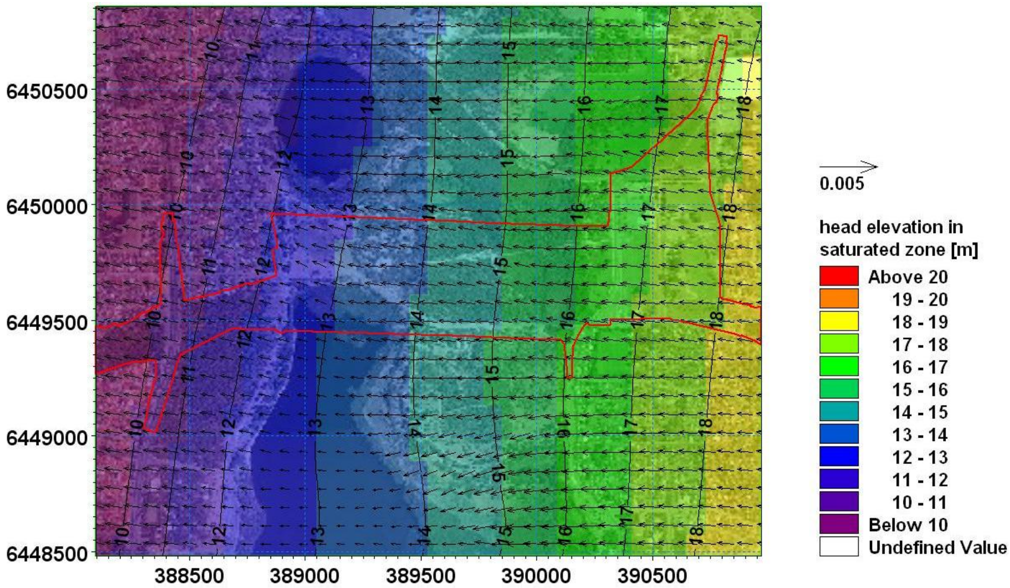


Simulated Surface Water depth and flows for September 1992 - Base Case Model

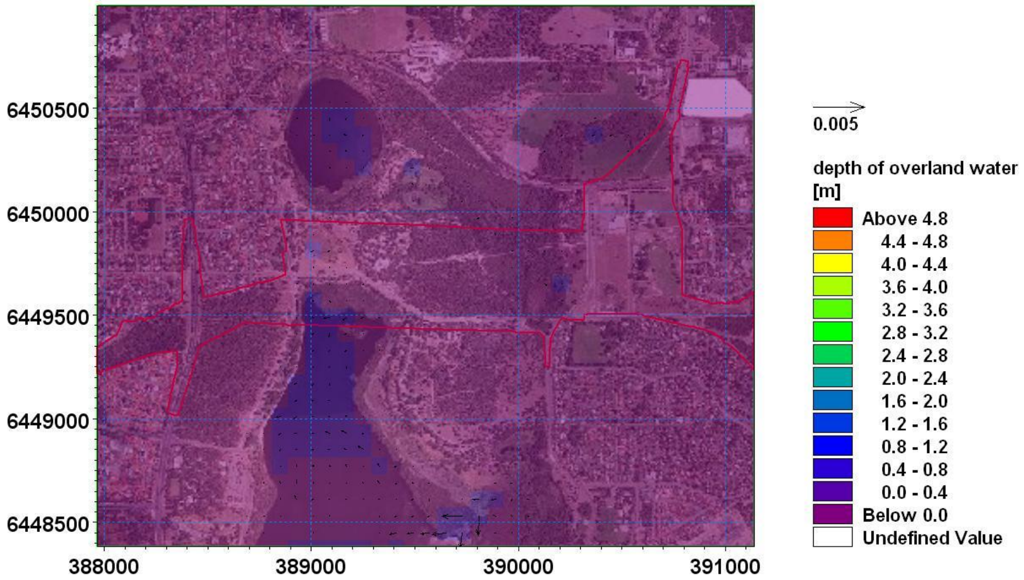
April 2007 ('dry' period)



Simulated Groundwater Contours for April 2007 - Base Case Model



Simulated Groundwater Flow for April 2007 - Base Case Model



Simulated Surface Water depth and flows for April 2007 - Base Case Model

Appendix D

Sensitivity Analysis Results

Appendix D Sensitivity Analysis Results

Model Set-up		Bore 61410202			Bibra Lake	
		Mean	Max	Min	Mean	Max
Calibration	Actual (mAHD)	18.31	19.00	17.40	14.68	16.02
Boundary condition water levels +1m	Actual (mAHD)	18.64	19.19	17.99	15.43	16.35
	Difference (m)	0.33	0.19	0.59	0.74	0.33
	Difference (%)	1.78	1.02	3.37	5.05	2.04
Boundary condition water levels -1m	Actual (mAHD)	17.95	18.78	17.99	14.22	15.80
	Difference (m)	-0.36	-0.22	0.59	-0.46	-0.23
	Difference (%)	-1.96	-1.15	3.09	-3.14	-1.41
Eastern boundary condition water levels +1m	Actual (mAHD)	18.64	19.19	17.95	15.40	16.30
	Difference (m)	0.33	0.19	0.55	0.72	0.28
	Difference (%)	1.82	1.01	3.16	4.89	1.74
Western boundary condition water levels +1m	Actual (mAHD)	18.39	19.00	17.43	15.04	16.13
	Difference (m)	0.08	0.01	0.03	0.35	0.11
	Difference (%)	0.43	0.03	0.19	2.42	0.67
LAI -25%	Actual (mAHD)	18.282	19.00	17.40	14.72	16.02
	Difference (m)	-0.03	0.00	0.00	0.03	-0.01
	Difference (%)	-0.16	0.00	0.00	0.24	-0.04
LAI +25%	Actual (mAHD)	18.28	19.00	17.40	14.69	16.02
	Difference (m)	-0.03	0.00	0.00	0.00	-0.01
	Difference (%)	-0.16	0.00	0.00	0.01	-0.04
ERD -25%	Actual (mAHD)	18.35	19.01	17.51	14.88	16.18
	Difference (m)	0.04	0.01	0.11	0.20	0.15
	Difference (%)	0.21	0.05	0.61	1.35	0.96
ERD +25%	Actual (mAHD)	18.24	18.99	17.33	14.52	15.93
	Difference (m)	-0.07	-0.01	-0.07	-0.16	-0.10
	Difference (%)	-0.39	-0.04	-0.39	-1.09	-0.60
Soil saturated hydraulic conductivity -25%	Actual (mAHD)	18.28	19.00	17.40	14.66	3
	Difference (m)	-0.03	0.00	0.00	-0.02	0.00
	Difference (%)	-0.18	0.01	0.00	-0.16	0.02

Model Set-up		Bore 61410202			Bibra Lake	
		Mean	Max	Min	Mean	Max
Soil saturated hydraulic conductivity +25%	Actual (mAHD)	18.35	19.00	17.69	14.85	16.02
	Difference (m)	0.04	0.00	0.29	0.17	-0.01
	Difference (%)	0.20	0.02	1.67	1.13	-0.04
Unsaturated zone water contents -25%	Actual (mAHD)	18.35	19.03	17.42	14.94	16.15
	Difference (m)	0.03	0.03	0.02	0.25	0.13
	Difference (%)	0.18	0.16	0.09	1.71	0.82
Unsaturated zone water contents +25%	Actual (mAHD)	18.25	18.97	17.37	14.65	15.91
	Difference (m)	-0.06	-0.03	-0.03	-0.04	-0.11
	Difference (%)	-0.34	-0.14	-0.17	-0.25	-0.70
Unsaturated zone water content at field capacity -25%	Actual (mAHD)	18.32	19.01	4	14.87	16.14
	Difference (m)	0.01	0.01	0.04	0.19	0.12
	Difference (%)	0.05	0.07	0.22	1.26	0.73
Unsaturated zone water content at field capacity +25%	Actual (mAHD)	18.31	18.98	17.32	14.62	15.88
	Difference (m)	0.00	-0.01	-0.08	-0.07	-0.14
	Difference (%)	-0.01	-0.08	-0.48	-0.46	-0.88
Unsaturated zone water content at saturation -25%	Actual (mAHD)	18.32	19.02	17.37	14.83	16.06
	Difference (m)	0.00	0.02	-0.03	0.14	0.03
	Difference (%)	0.03	0.11	-0.15	0.98	0.19
Unsaturated zone water content at saturation +25%	Actual (mAHD)	18.32	18.98	17.44	14.68	16.00
	Difference (m)	0.01	-0.02	0.04	0.00	-0.03
	Difference (%)	0.04	-0.09	0.22	-0.02	-0.16
Unsaturated zone water content at wilting point -25%	Actual (mAHD)	18.26	18.99	17.36	14.65	15.96
	Difference (m)	-0.05	-0.01	-0.04	-0.03	-0.07
	Difference (%)	-0.27	-0.04	-0.21	-0.23	-0.42
Unsaturated zone water content at wilting point +25%	Actual (mAHD)	18.33	19.01	17.44	14.84	16.10
	Difference (m)	0.02	0.01	0.04	0.15	0.08
	Difference (%)	0.10	0.07	0.23	1.05	0.49
Saturated zone horizontal hydraulic	Actual (mAHD)	18.30	18.97	17.33	14.70	16.04
	Difference (m)	-0.01	-0.03	-0.07	0.02	0.02

Model Set-up		Bore 61410202			Bibra Lake	
		Mean	Max	Min	Mean	Max
conductivity +25%	Difference (%)	-0.07	-0.15	-0.39	0.11	0.11
Saturated zone horizontal hydraulic conductivity -25%	Actual (mAHD)	18.42	19.04	17.53	14.83	15.96
	Difference (m)	0.10	0.05	0.13	0.14	-0.07
	Difference (%)	0.57	0.24	0.75	0.98	-0.42
Saturated zone vertical hydraulic conductivity +25%	Actual (mAHD)	18.28	18.99	17.39	14.67	15.99
	Difference (m)	-0.03	-0.01	-0.01	-0.01	-0.03
	Difference (%)	-0.16	-0.05	-0.05	-0.07	-0.20
Saturated zone vertical hydraulic conductivity -25%	Actual (mAHD)	18.30	19.02	17.41	14.67	16.05
	Difference (m)	-0.01	0.02	0.01	-0.01	0.02
	Difference (%)	-0.06	0.10	0.06	-0.07	0.14
Mannings M = 50	Actual (mAHD)	18.30	19.00	17.40	14.78	16.01
	Difference (m)	-0.01	0.00	0.00	0.09	-0.01
	Difference (%)	-0.08	0.00	-0.02	0.62	-0.09
Mannings M = 90	Actual (mAHD)	18.29	19.00	17.40	14.77	16.00
	Difference (m)	-0.03	0.00	0.00	0.09	-0.02
	Difference (%)	-0.14	0.01	-0.01	0.58	-0.15

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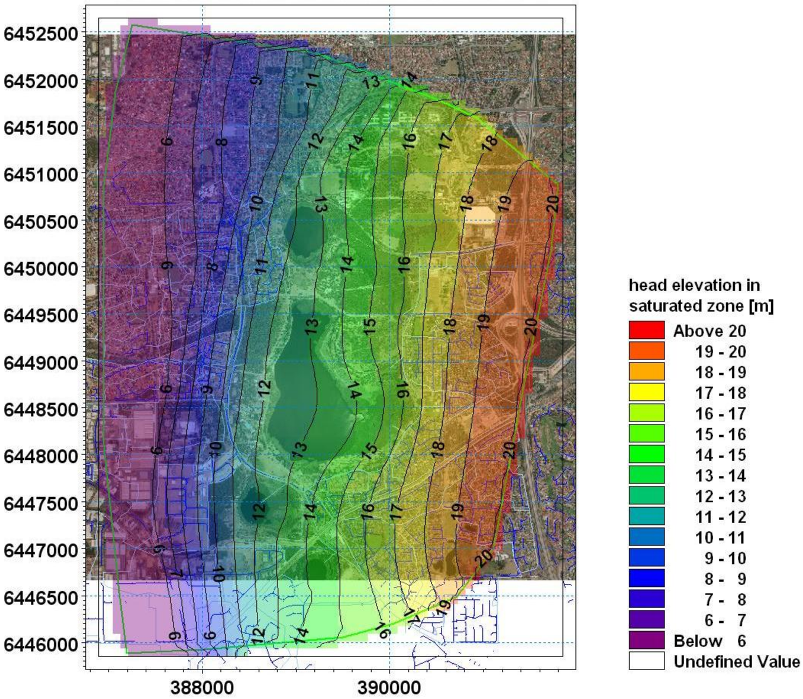
Appendix E

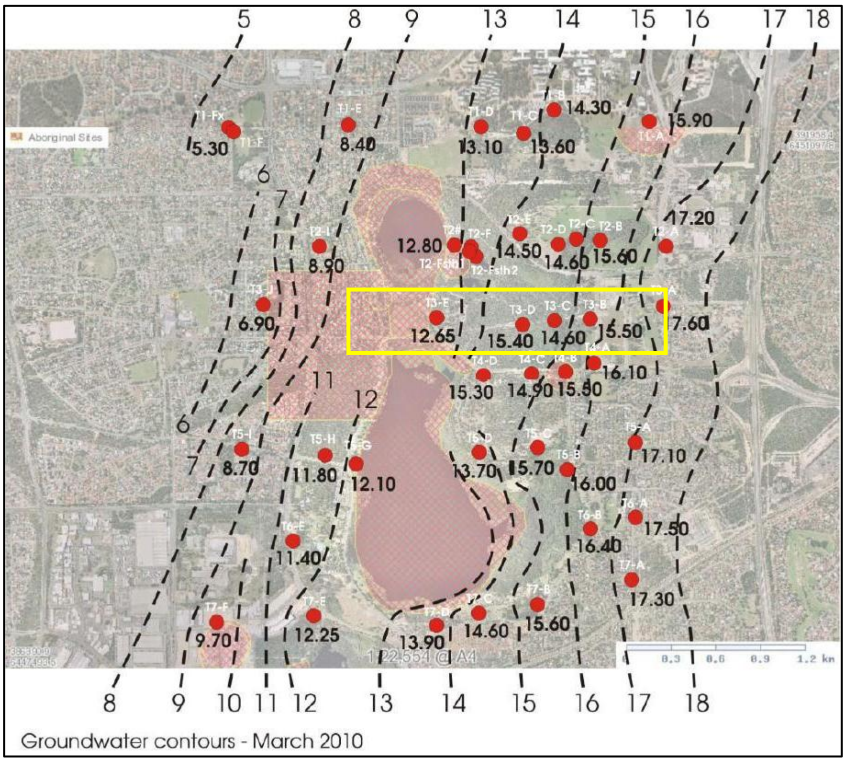
Validation Results

Appendix E Validation Results

March 2010



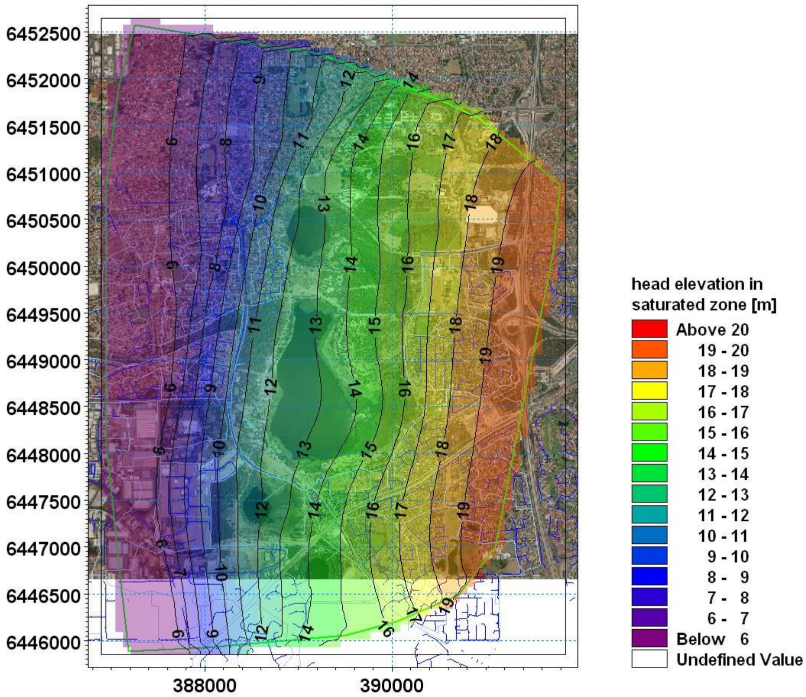
Simulated Groundwater Contours for March 2010



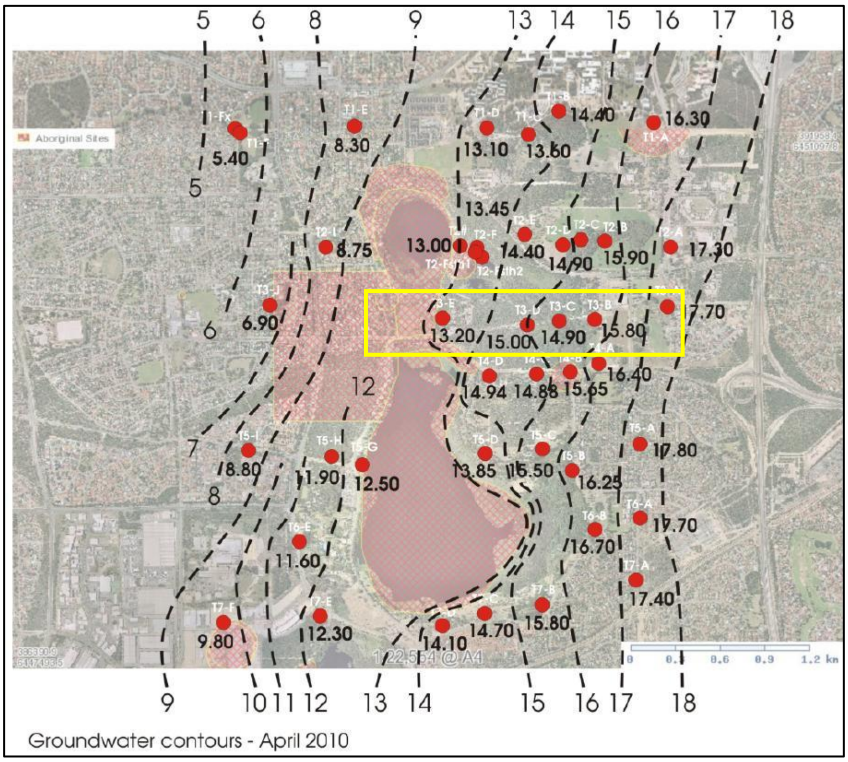
Source: Syrinx and V&CGRS (2011)

Observed Groundwater Contours for March 2010

April 2010



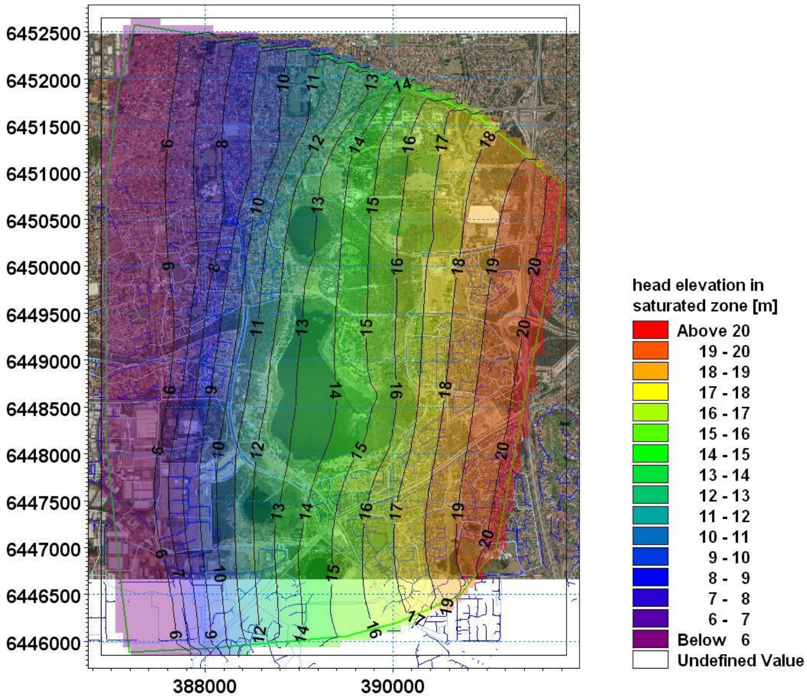
Simulated Groundwater Contours for April 2010



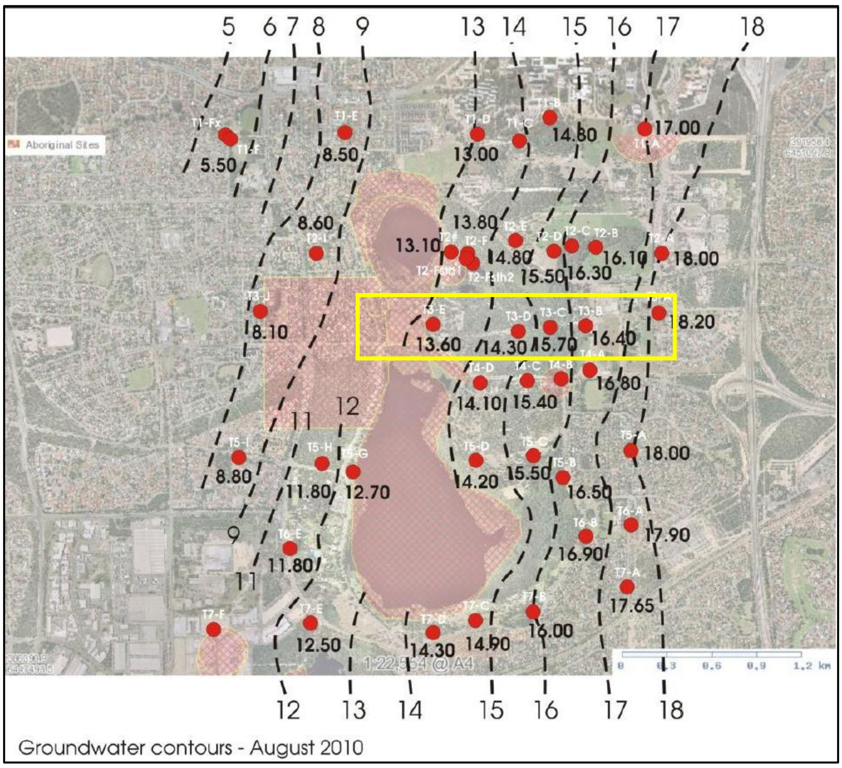
Source: Syrinx and V&CGRS (2011)

Observed Groundwater Contours for April 2010

August 2010



Simulated Groundwater Contours for August 2010



Source: Syrinx and V&CGRS (2011)

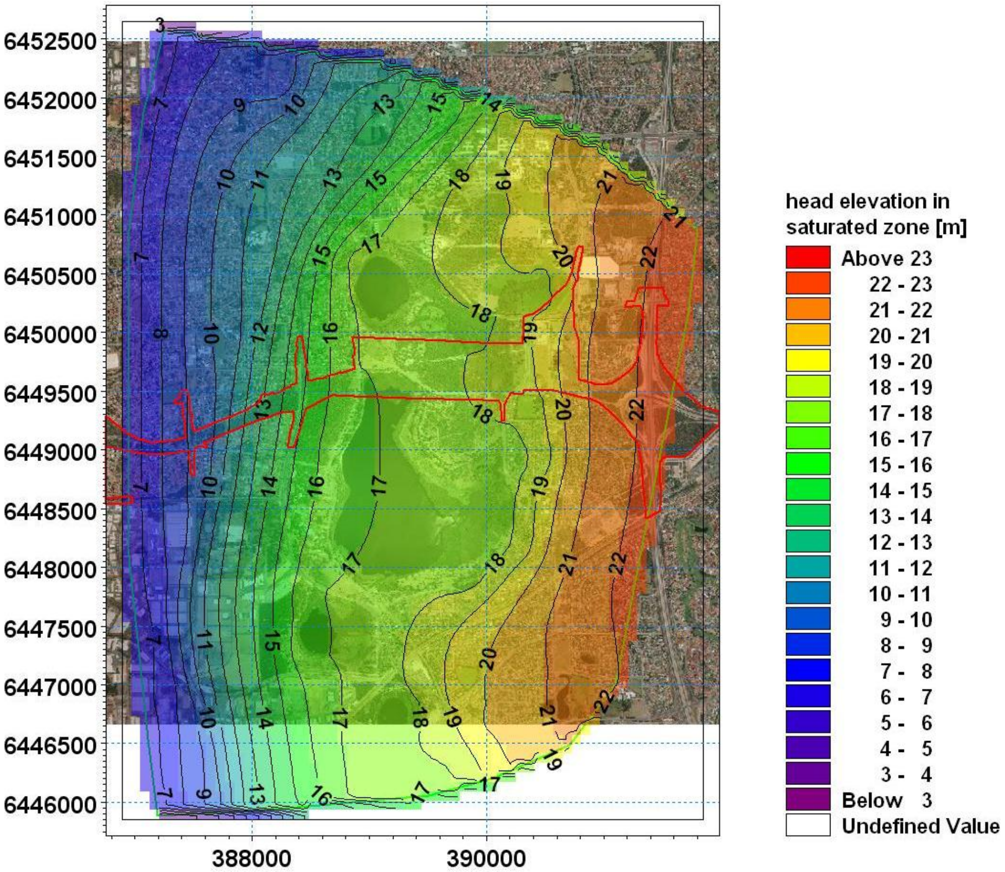
Observed Groundwater Contours for August 2010

Appendix F

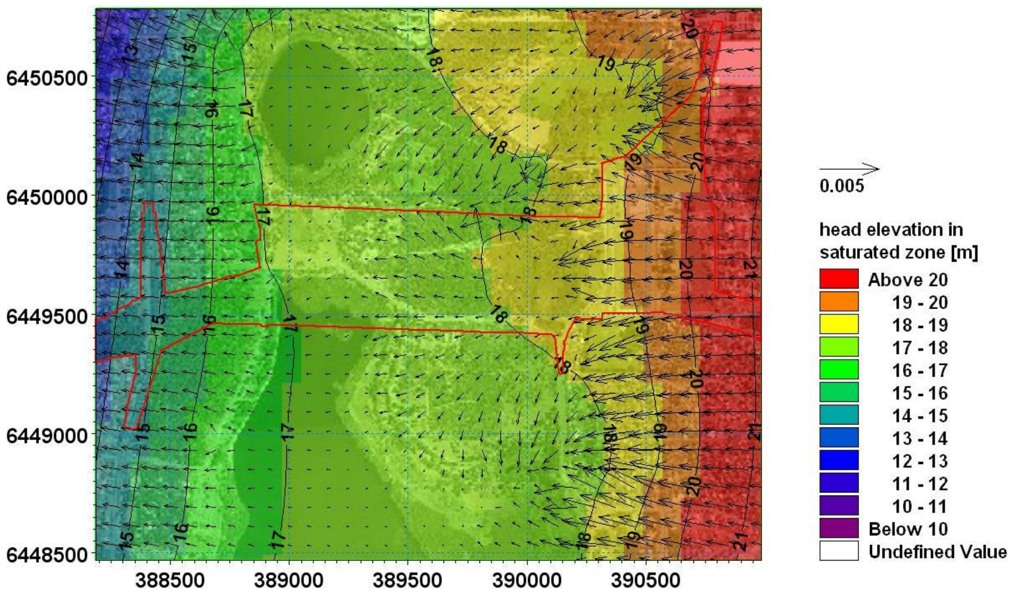
Long Term Maximum Groundwater Boundary Condition Results

Appendix F Long Term Maximum Groundwater Boundary Condition Results

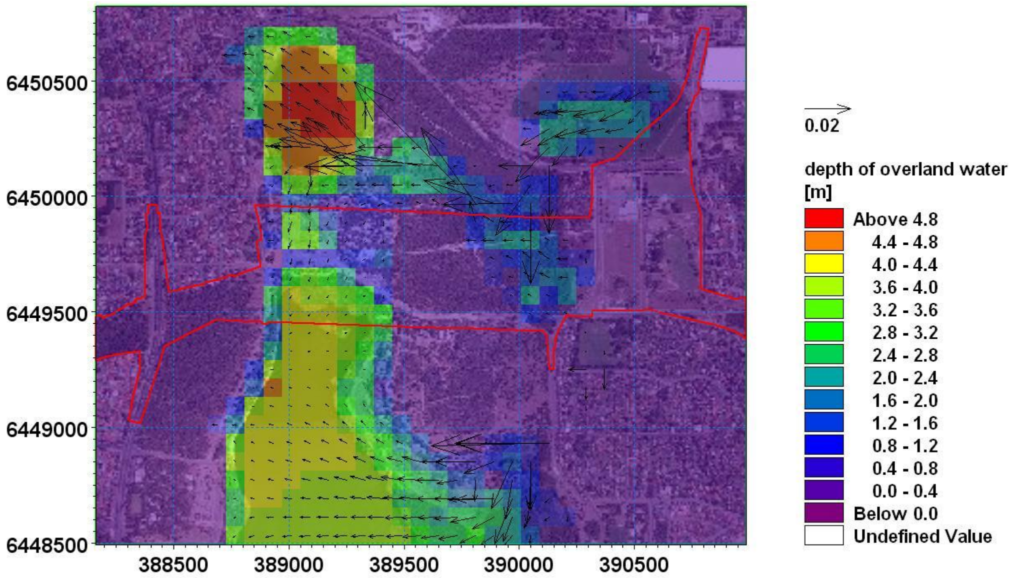
Long-Term Simulation – Maximum Groundwater Boundary Condition – 'Wet' Period September 1928



Simulated Groundwater Contours for September 1928- Long Term Simulation Maximum Boundary Conditions

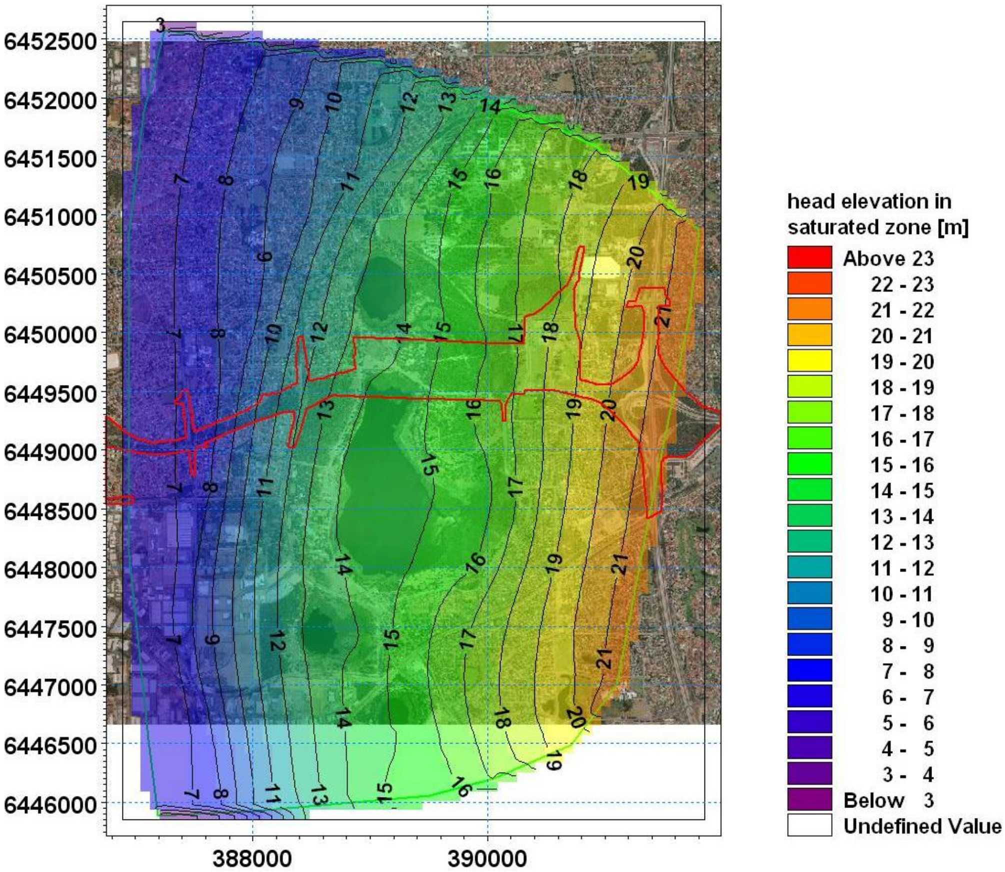


Simulated Groundwater Flow for September 1928- Long Term Simulation Maximum Boundary Conditions

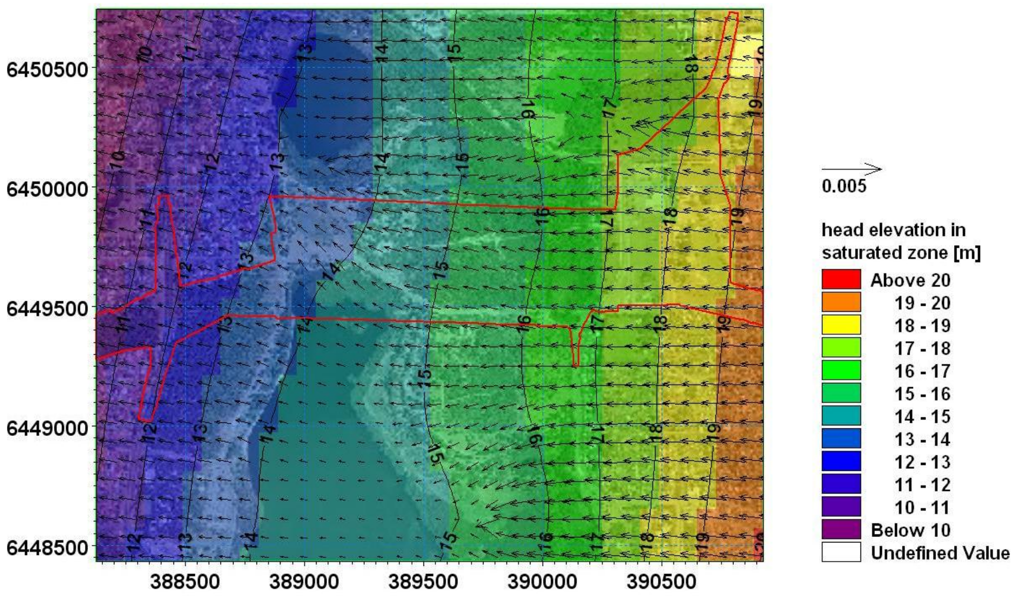


Simulated Surface Water depth and flows for September 1928- Long Term Simulation Maximum Boundary Conditions

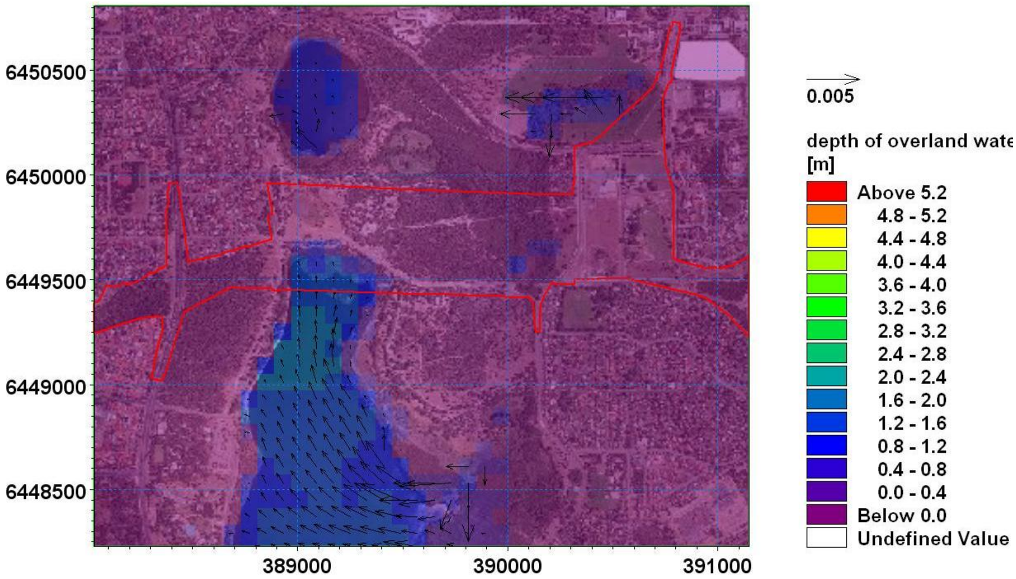
Long-Term Simulation – Maximum Groundwater Boundary Condition – 'Dry' Period April 2007



Simulated Groundwater Contours for April 2007- Long Term Simulation Maximum Boundary Conditions



Simulated Groundwater Flow for April 2007- Long Term Simulation Maximum Boundary Conditions



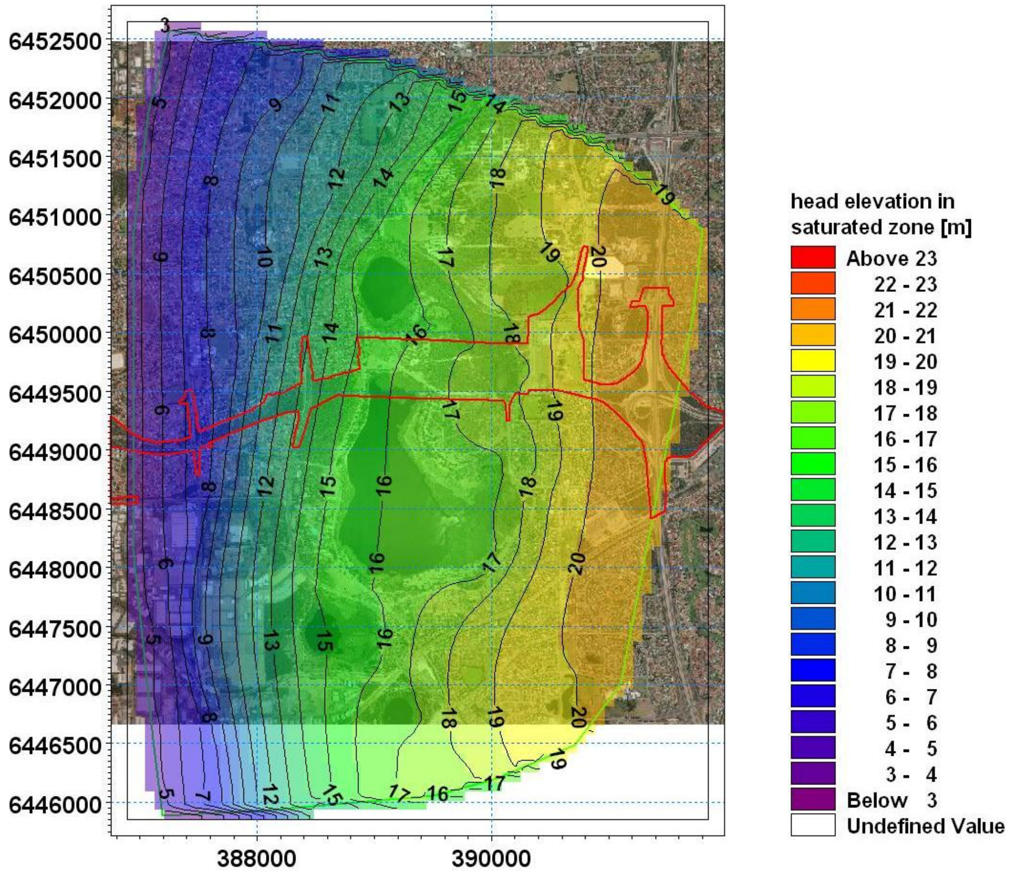
Simulated Surface Water depth and flows for April 2007- Long Term Simulation Maximum Boundary Conditions

Appendix G

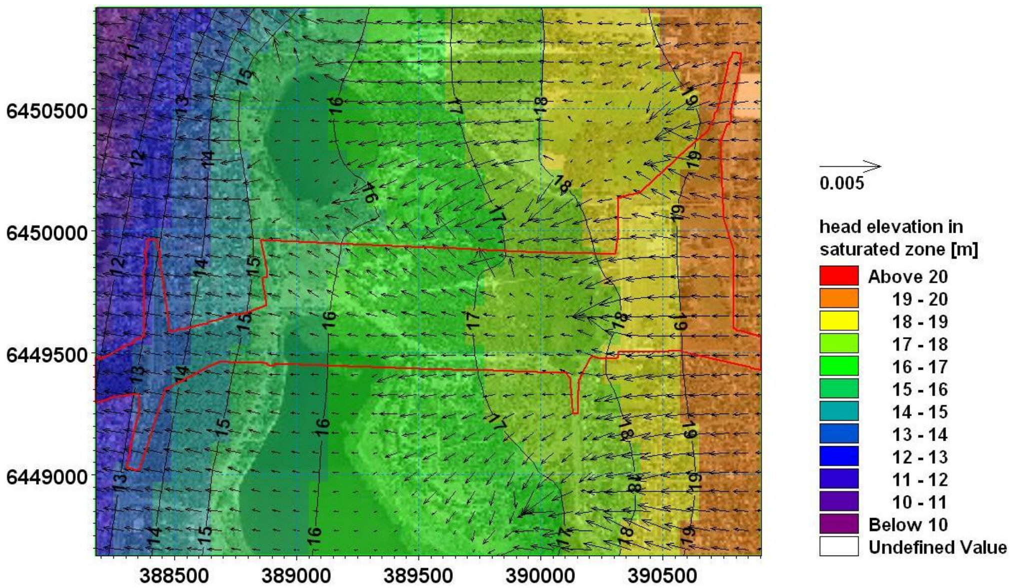
Long Term Minimum Groundwater Boundary Condition Results

Appendix G Long Term Minimum Groundwater Boundary Condition Results

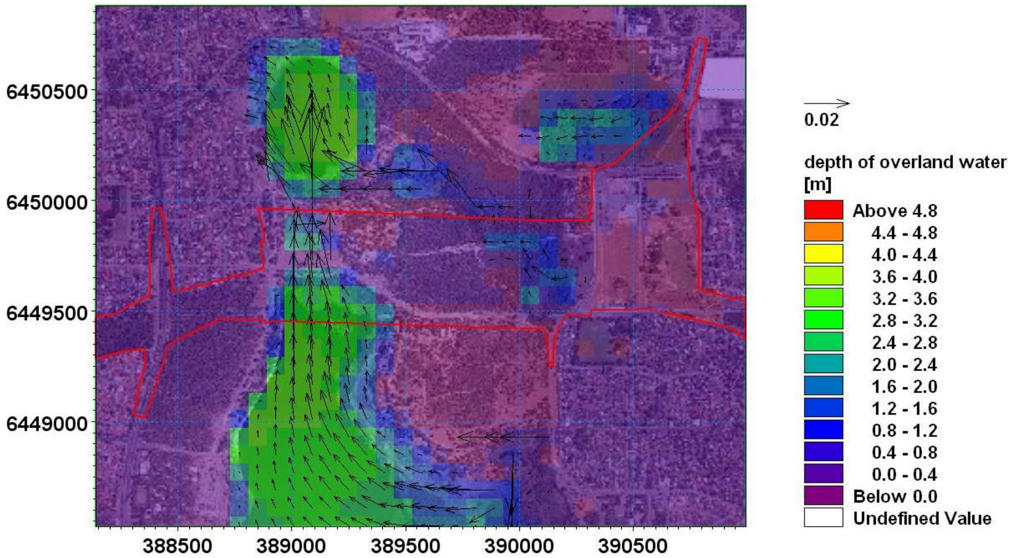
Long-Term Simulation – Minimum Groundwater Boundary Condition – 'Wet' Period September 1928



Simulated Groundwater Contours for September 1928- Long Term Simulation Minimum Boundary Conditions

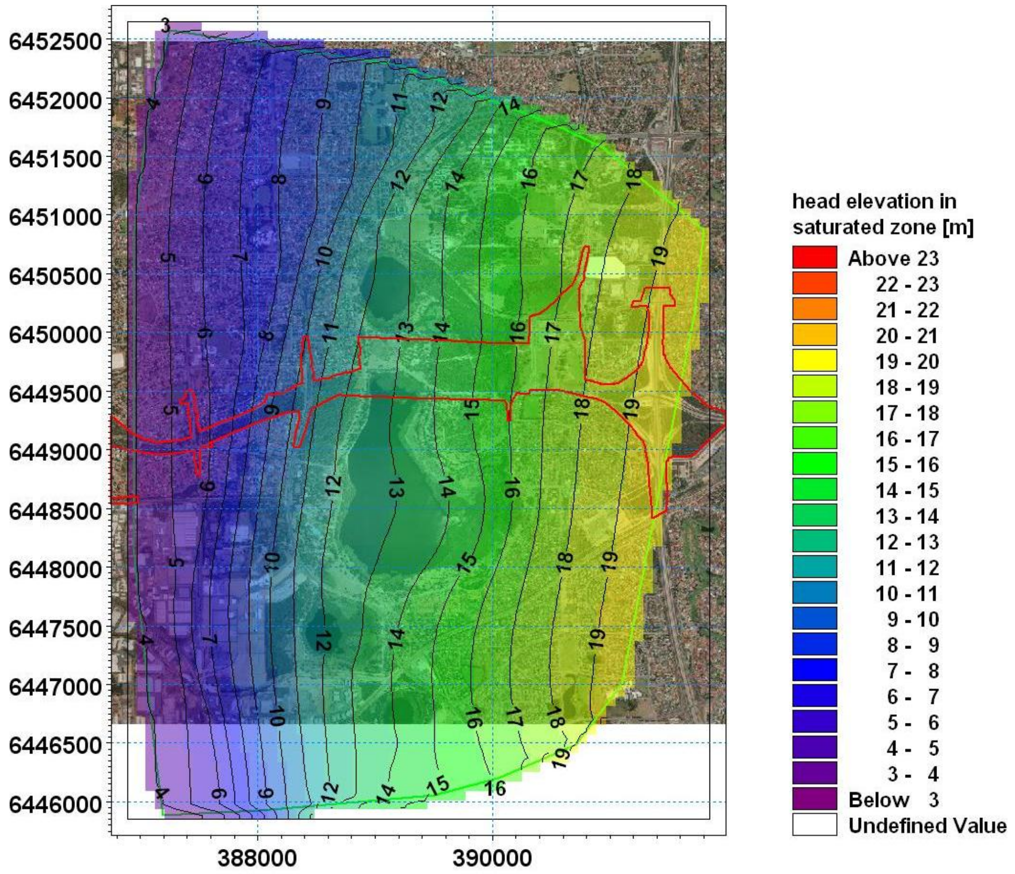


Simulated Groundwater Flow for September 1928- Long Term Simulation Minimum Boundary Conditions

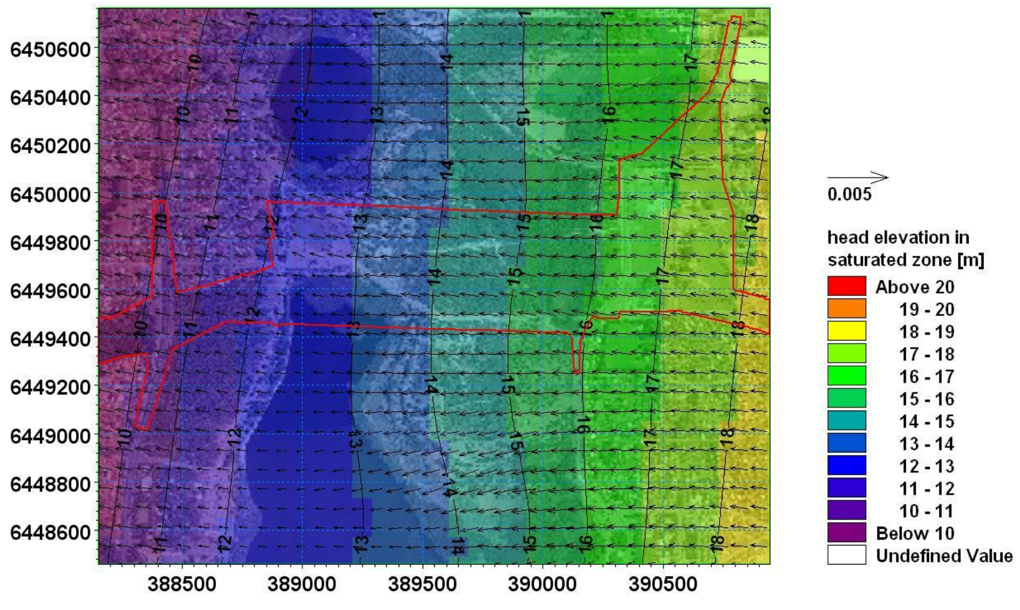


Simulated Surface Water depth and flows for September 1928- Long Term Simulation Minimum Boundary Conditions

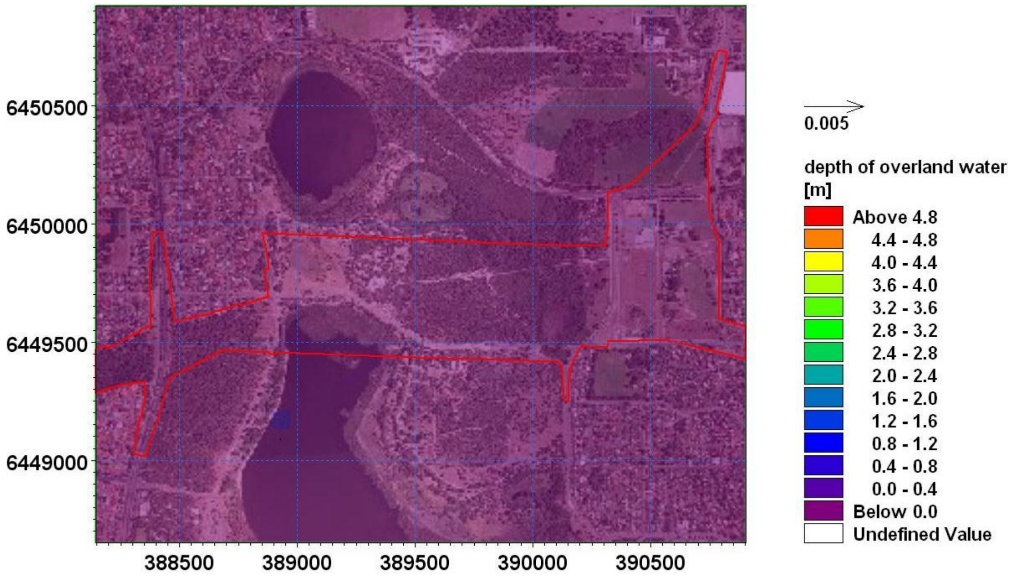
Long-Term Simulation –Minimum Groundwater Boundary Condition – 'Dry' Period April 2007



Simulated Groundwater Contours for April 2007- Long Term Simulation Minimum Boundary Conditions



Simulated Groundwater Flow for April 2007- Long Term Simulation Minimum Boundary Conditions



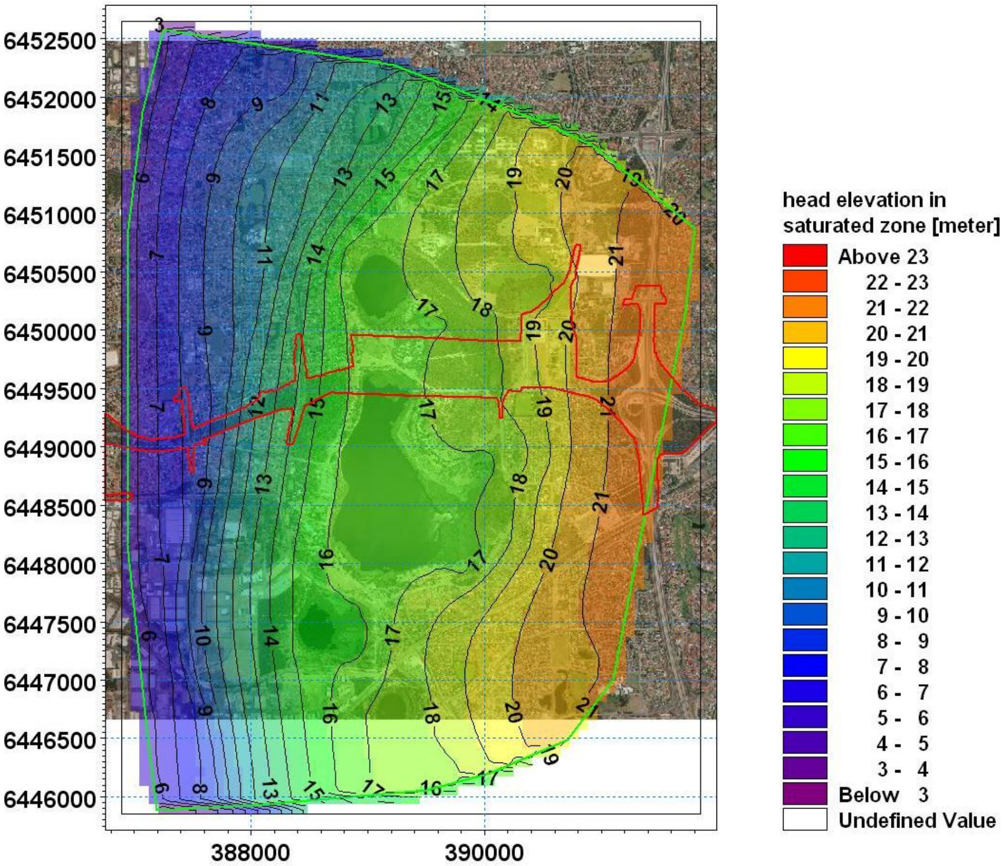
Simulated Surface Water depth and flows for April 2007- Long Term Simulation Minimum Boundary Conditions

Appendix H

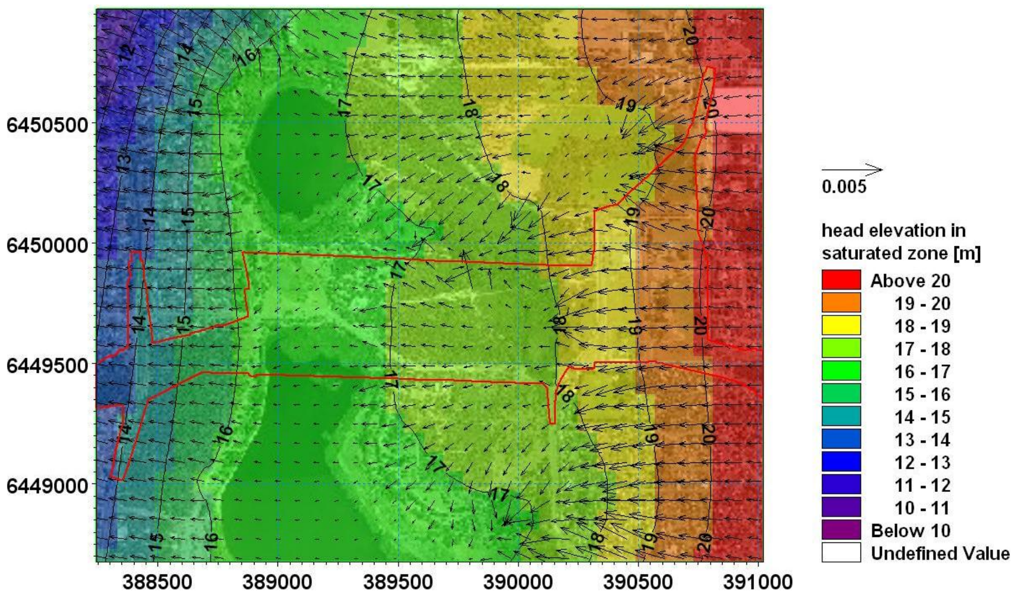
Long Term Average Groundwater Boundary Condition Results

Appendix H Long Term Average Groundwater Boundary Condition Results

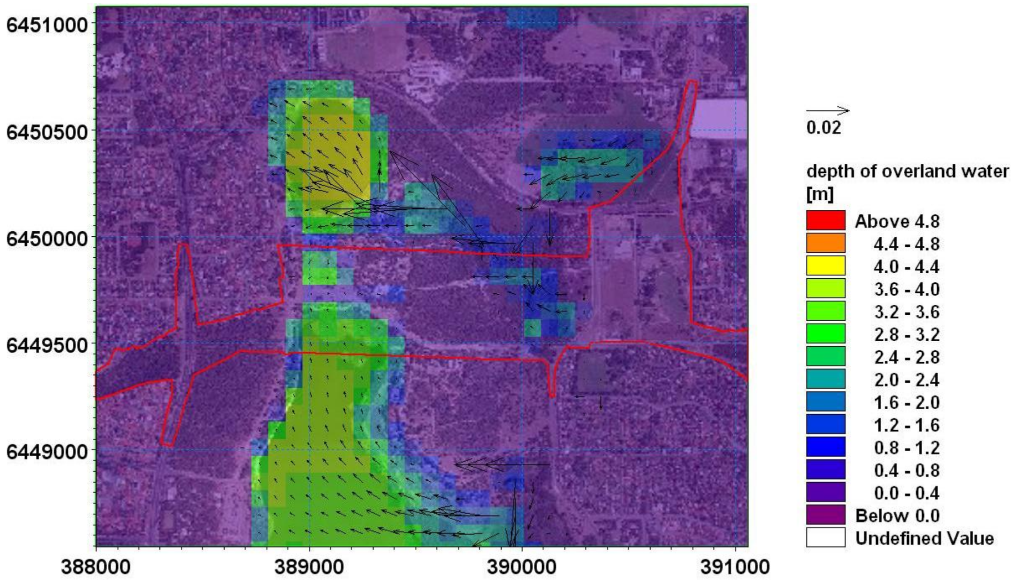
Long-Term Scenario – Average Groundwater Boundary Condition – 'Wet' Period September 1928



Simulated Groundwater Contours for September 1928- Long Term Scenario Average Boundary Conditions

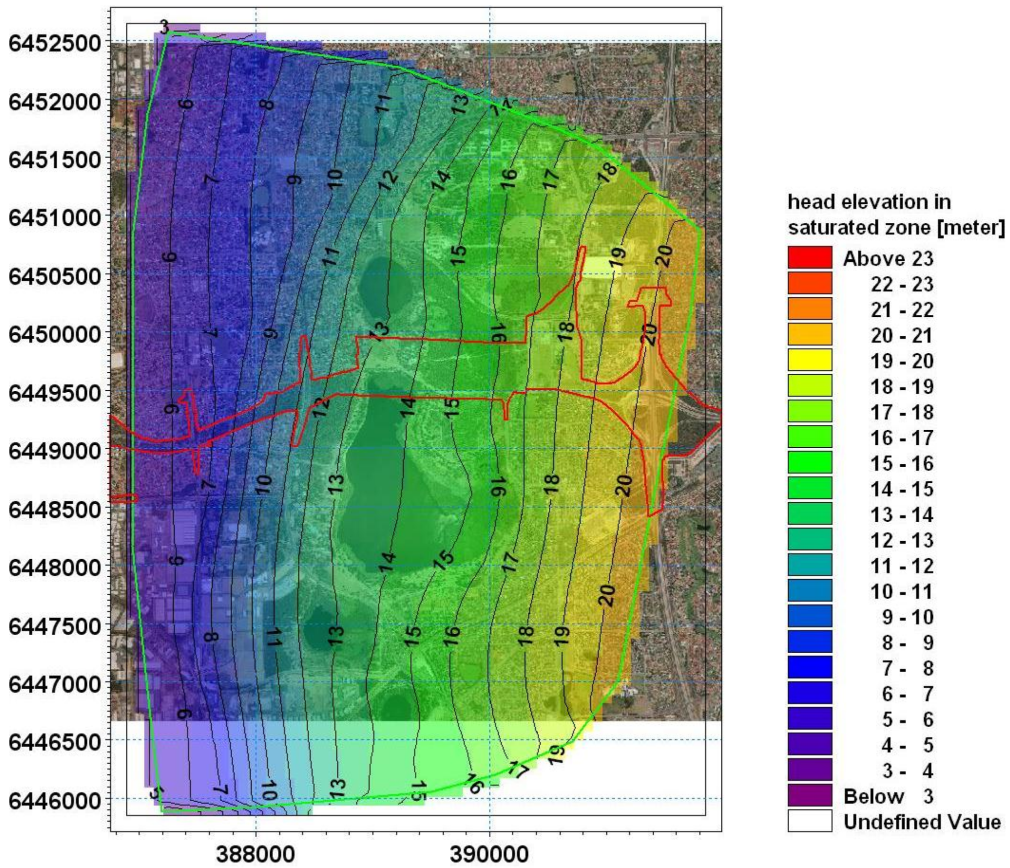


Simulated Groundwater Flow for September 1928- Long Term Scenario Average Boundary Conditions

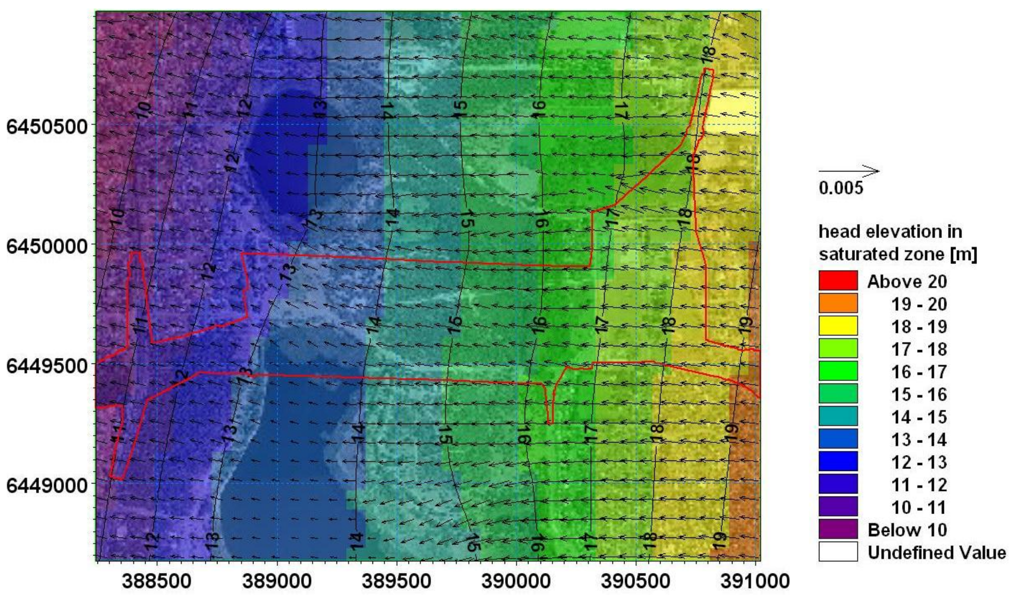


Simulated Surface Water depth and flows for September 1928- Long Term Scenario Average Boundary Conditions

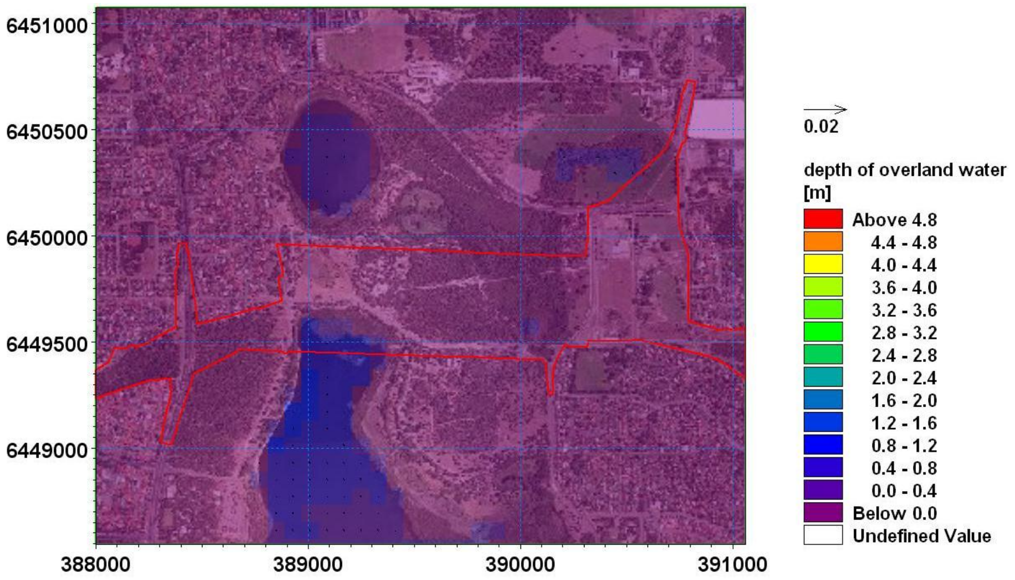
Long-Term Scenario –Average Groundwater Boundary Condition – 'Dry' Period April 2007



Simulated Groundwater Contours for April 2007- Long Term Scenario Average Boundary Conditions



Simulated Groundwater Flow for April 2007- Long Term Scenario Average Boundary Conditions



Simulated Surface Water depth and flows for April 2007- Long Term Scenario Average Boundary Conditions