Woy Woy Integrated Water Modelling

Upgrade of the Groundwater model and Everglades Catchment Case Study

Final

Central Coast Council

Report

July 2021

The expert in **WATER ENVIRONMENTS**

This report has been prepared under the DHI Business Management System certified by Bureau Veritas to comply with ISO 9001 (Quality Management)

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Upgrade of the Groundwater model and Everglades Catchment Case Study

Final Report

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Executive Summary

The Woy Woy Peninsula is a residential area located 82 km north of Sydney, bounded by Brisbane Water to the north and east, Broken Bay to the south, and Brisbane Water National Park to the west.

The Peninsula (18.5 km2) including the Kahibah Creek Catchment is generally a flat sand-plain, where ground levels typically vary between 4 to 6m (AHD). The remaining study area backs onto the National Park and Blackwell Mountain and is typically of higher elevation with rocky outcrops.

Catchments contributing to rainfall-runoff processes are not well-defined at Woy Woy (except for the Kahibah Creek catchment), due to the peninsula's flat topography and alteration of natural flow paths by urban development. While the remnant sand dunes dictate the overland flow patterns, residential development has contributed to flooding at localised low points. The Everglades Catchment, in particular, lying in the north-western section of the peninsula is prone to nuisance flooding.

Literature review of stormwater infiltration and flood studies on the Woy Woy peninsula since 1990 was undertaken. Groundwater bore data on the peninsula collected since the previous study (DHI, 2010) were also reviewed and compiled as well as other data such as climate, topographic and drainage data.The Peninsula groundwater model developed in a previous study (DHI, 2010) was upgraded to include the Kahibah catchment and incorporates new LiDAR data. Review of the literature and data provided understanding of necessary inputs and assumptions to be incorporated in the model. Recalibration of the upgraded groundwater model was undertaken using a new set of groundwater level data derived from gauged pressure data collected at the monitoring bores. This data required manual adjustments. In the absence of the surface water records such as flow or water level data at the open drain or the Kahibah Creek system, the model was calibrated against the long-term groundwater level records at the monitoring bores. The model reproduced well the known groundwater pattern of a groundwater mound at the Everglades Catchment.

The Peninsula groundwater model was run with a long-term rainfall timeseries, and the average sea level, for more than 100 years to estimate the groundwater trend in the catchment.

The model was used to simulate a scenario with a constant 4ML/d pumping at the existing production bores to assess the sustainability of the groundwater extraction for portable water. The groundwater level drops by 0.5 to 1m at the centre of the peninsula under the 4ML/d extraction scenario, compared to the Baseline.

A flood model for the Everglades Catchment was derived by refining the Peninsula groundwater model and coupling to an urban drainage model. The model was calibrated against a series of nuisance flooding events in 2017. Actual flood depth or discharge records were not available but the reported occurrence of flooding at streets were able to be reproduced.

The Everglades model was used to simulate a series of nuisance flooding events in 2017 as well as a larger event in February 1990 which is the equivalent of the 1%AEP to 0.5%AEP rainfall event. This revealed the following flooding characteristics at the Everglades Catchment:

- Surface runoff flows down streets and ponds at the low points. This is particularly evident at the intersection of MacKenzie Avenue and Onslow Avenue, the middle sections of Connex Road, Lovell Road, Glenn Street, Shepard Street and Carpenter Street.
- Lack of drainage assets (for example, the intersection between MacKenzie Avenue prior to the 2020 drainage work) or limited drainage capacity (around Veron Road) causes ponding of water at local sag points.
- The shallow sandy aquifer level is responsive to runoff from both local residential blocks and the escarpment.
- The groundwater level reaches the ground surface after a series of minor rainfall events (April 2017) or a large rainfall event (February 1990 event) at several low-lying locations. This can occur quickly (within hours), first around Shepard Street, Connex Road, Glenn Street and Carpenter Street where the groundwater mound is located, but and then followed by the surrounding areas such as MacKenzie Avenue and Watkin Avenue.
- The high groundwater table coincides with the surface water peak in locations along Shepard Street, Connex Road, Glenn Street and Carpenter Street.

- The high groundwater table potentially causes prolonged ponding at these locations.

Conceptual models of the integrated management options for the case study catchment Everglades were developed together with key stakeholders. A selection of five management options were modelled and further assessed to examine the ability to alleviate flooding issues in the Everglades Catchment.

Option 1 modelled the inclusion of additional stormwater drainage inlets, sumps and the ability to redirect a portion of the Everglades Catchment to east which reduces pressure on the Main Drain system to the west of the catchment. The simulations of these options indicated a flood reduction. Further consideration of the practicality of diverting flows to the east, based on the topography would need to be given, once surveyed levels of drainage infrastructure is gathered. The collection of this survey and consideration of detailed feasibility of this option was outside the scope of this work but the survey and would need to be gathered prior to any further consideration of this option.

Option 2 investigated the inclusion of additional storage. Connex Park was identified as a potential location where implementation of addition storage would help alleviate flooding impacts. The influence of groundwater at this location during larger rainfall events would limit the ability of this option to mitigate flooding to only during minor rainfall events. Topographic constraints indicate that utilisation of other existing open areas would have only a limited impact to flood alleviation across the site. The inclusion of swales within road reserves was also modelled which simulated some alleviation of flooding impacts across the site. It is recommended that this option (Option 2 – Swales) is progressed as a potentially viable option for flood mitigation. To further consider this option, site specific and design constraints, in specifically identified locations for swales, would need to be examined in more detail. This more detailed and localised consideration of the viability of the swales option was outside the scope of this study.

Option 3 incorporated the addition of allotment level storage in the model (residential rainwater tanks and infiltration pads). Minor reductions in flooding impacts were observed in several locations. This was particularly evident during longer duration events and secondary peak water levels, when allotment scale runoff may dominate flood contributions. The mitigation of peak flood levels was limited. While this option was not considered effective in reducing flood risk it could potentially be useful when considering demonstration of a 'satisfactory solution' in the context of Development in Areas Identified as Drainage "Black Spots" on the Woy Woy Peninsula (GCC 2017). Any amendments to the current Black Spot policy would need to carefully consider any site specific black spot in the context of the flooding mechanics (e.g. groundwater driven flooding) and should utilise the groundwater information from this study and information in the on-going Woy Woy Floodplain Risk Management Study and Plans. Considerations of the latest flood risk management study and plans were outside the scope of this integrated water study.

Option 4 considered the groundwater abstraction to lower the groundwater table and help alleviate the impact of the groundwater to flooding in the catchment. Long-term strategic lowering of groundwater levels was simulated to improve flooding impacts in areas where the water table to close to the surface. Short-term pumping was not found to have significant impact on flood alleviation.

Option 5 considered rezoning and redevelopment of a sub-area in the Everglades Catchment to be more flood resilient. Modelling of the February 1990 event and nuisance flooding in 2017 revealed that it is hard to eliminate flooding of low points on streets which sit right above the groundwater mound, as flooding is caused by the raised groundwater table fed both by runoff from both the escarpment and the local residential blocks. These are typically Carpenter St, Glenn St, Connex Rd, Shepard St and Lovell Rd. An exact design of the redevelopment such as types of green structures to be implemented and the number of dwellings is not discussed in this study. It is recommended that the redevelopment design should allow natural rise of the groundwater table and ponding of water at the low points.

Outcomes of this study were informed to the current Flood Risk Management Study and Plan.

Other recommendations are:

- To review the options above in the future Flood Risk Management Study and Plan.

- To maintain the groundwater monitoring and to introduce regular processing/compilation of raw data. While a large number of monitoring bores have been installed in the Woy Woy peninsula, a regular compilation of the collected data has not been undertaken for long time. These monitoring bores collect water quality and pressure data of the shallow groundwater which are paramount important for further investigation of some management options and sustainable groundwater extraction.
- To disseminate the updated groundwater model and the outcome of the sustainable groundwater extraction rates to relevant Directorates of Council for evaluation of future water supply strategies and potential synergies for managing groundwater resource.
- To obtain more information about the surface flow as well as the storm drainage. The developed Everglades flood model can be further improved by incorporating by surveyed drainage levels or the water level/discharge records of the surface flow.
- To review the relevance of the Woy Woy Black Spot Policy in the current Development Control Plans taking into account the revised groundwater model and the outcome of this study as a part of the future Floodplain Risk Management Plan.

1 Background and Objectives

The Woy Woy Peninsula is a residential area located 82 km north of Sydney, bounded by Brisbane Water to the north and east, Broken Bay to the south, and Brisbane Water National Park to the west as shown in Figure 1.1.

It is a commuter town of Sydney and a popular holiday destination. The Peninsula has been a key area of interest for the Central Coast Council for decades. One of the reasons is the Peninsula's growing population.

The Peninsula is historically prone to nuisance flooding, especially from long duration rainfall events.

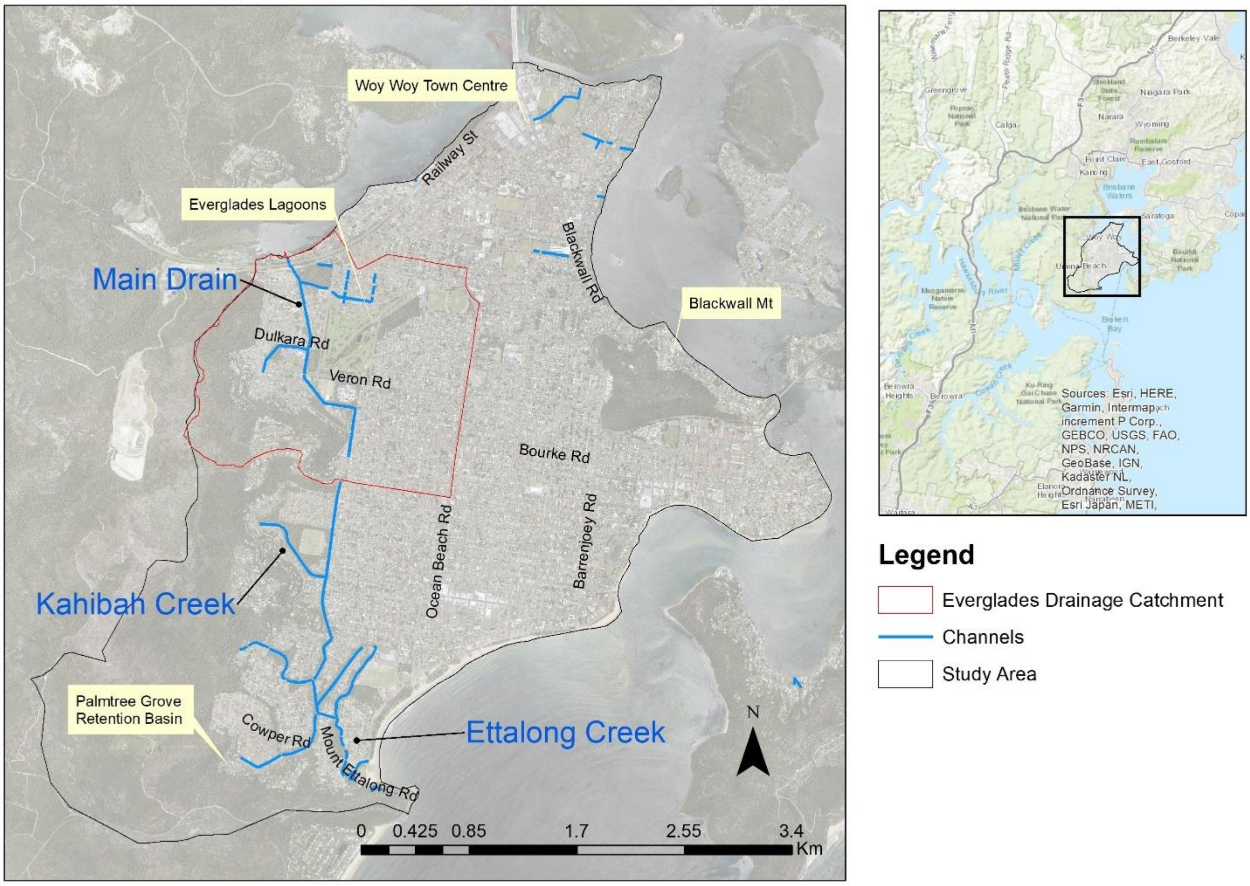


Figure 1.1 Study Area

The tender brief summarises the aims of the project as following.

1. Prepare a groundwater modelling tool that will allow Council to investigate and assess integrated ground water management options across the whole of the Woy Woy Peninsula groundwater system.

2. Prepare a case study for the Everglades Catchment that will investigate the effectiveness of an integrated water management approach that will minimise peak stormwater runoff without causing any detrimental effect to the environment, risk to life or damage to public or private assets.

The objectives of this project are:

- Undertaking a literature review of stormwater infiltration and flood studies completed on the Woy Woy Peninsula since 1990.

- Understanding the hydraulic boundary, groundwater discharges and infiltration rates in order to predict a response from direct rainfall using long term historical data in order to inform future studies.
- Reviewing, updating and calibrating Council's numerical MIKE SHE groundwater model (DHI, 2010) that is representative of the present-day water balance for the entire Woy Woy Peninsula using best practice Australian Guidelines.
- Completing the groundwater modelling above in a timely manner as its completion is critical to the commencement of another project on the Woy Woy Peninsula.
- Develop schematic conceptual models (8) in collaboration with key stakeholders. Construct five (5) approved 1d/2d coupled numerical models from objective 3.4 with the capability of integrating the results of the groundwater model constructed in objective 3.3.
- Providing a final report including recommendations or further investigation, including both the spatially and quantifiable results, including the potential for overall ecological risk from groundwater extraction on Groundwater Dependant Ecosystems (GDE). Inform current floodplain risk management studies and future groundwater supply yield analysis.
- Provide recommendations that could be included in the current Development Control Plan that may address Council's Woy Woy Black Spot Policy.

Council has a policy called "Black Spot Policy" which restricts development in areas identified as drainage "Black spots" on the Woy Woy peninsula. This policy specifies areas having drainage problems which cannot be readily overcome as "Black spots" and prevents further development from deteriorate the drainage problem in identified "black spot" areas. This policy was developed prior to that detailed topographic data or numerical modelling became available. "Black spots" were identified, simply based on examining contours and the vicinity of reported flood locations.

1.1 Overview of tasks

The tasks were divided into the following components.

- Literature review
- Update the existing groundwater model (2010, DHI) with the updated groundwater observations and the new LiDAR data
- Recalibrate the updated groundwater model
- Assessment of sustainable groundwater extraction rate using the updated groundwater model
- Assessment of the integrated management options for the case study catchment Everglades
- Reporting

The existing Woy Woy peninsula model was developed as part of a flood risk management study carried out by DHI (DHI, 2010). The model was developed and calibrated in two stages, using DHI's commercial package MIKE SHE:

- Long-term model: the model without drainage focused on groundwater to understand the long-term fluctuations of the groundwater table. This model was run for 100 years and calibrated against groundwater levels.
- Event model: the long-term model was modified and coupled with the MIKE Urban drainage model to focus on surface water flooding. The model was calibrated against the 1988 flood event and used for design events.

For the current study, the model was updated to incorporate newly obtained LiDAR topographic data, groundwater records and to include the Kahibah Creek catchment. The long-term model was used as the base model for the update, as the focus of the current project is groundwater. The updated model was re-calibrated against the newly obtained groundwater bore records. Re-conceptualisation of the catchment is not part of the current project scope and the model structure has not been updated.

DHI released several updates of MIKE software packages since the previous study. Updates and recalibration of the peninsula model were carried out using MIKE 2017. During calibration, MIKE 2019 was released. Although no major changes have been introduced in the 2019 Release of MIKE SHE compared to Release 2017, the model was updated to Release 2019 .

The updated model was used as a base model for further model developments for the integrated water management study in the Everglades Catchment and for the flood risk management study in the peninsula.

2 Data

2.1 Topographic Data

LiDAR topographic data was provided by Central Coast Council (Council). shows LiDAR ground levels processed to a 1m grid. Despite the urban development, the old beach ridges and swales can be seen in Figure 2.1. The maximum elevation of the colour palette is set to 20 mAHD in order to illustrate low-lying beach ridges with intervening swales between 4 and 6 mAHD. The escarpment (in blue) extends to a height of approximately 180 mAHD in the west.

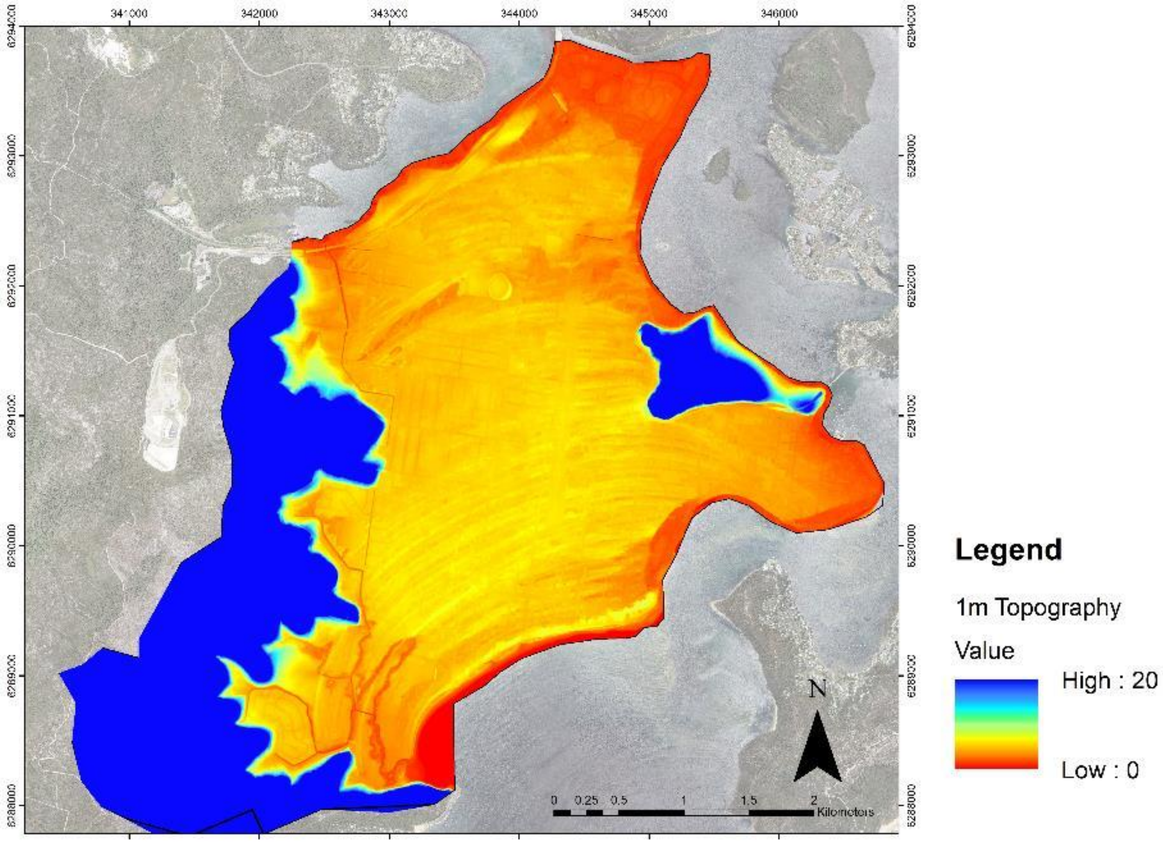


Figure 2.1 1m grid topography processed from LiDAR

2.2 Groundwater Bore Data

The Council provided DHI the following data;

- The locations of bores and its types in shapefile format
- The locations of bores as pdf files
- A list of manually measured monitoring bores in Excel spreadsheet format
- Data logger files for monitoring bores with the data logger
- Maps of bore locations as pdf files
- Production Bores information as Excel spreadsheets

The Council provided DHI a shapefile of bore locations, as shown in Figure 2.2.

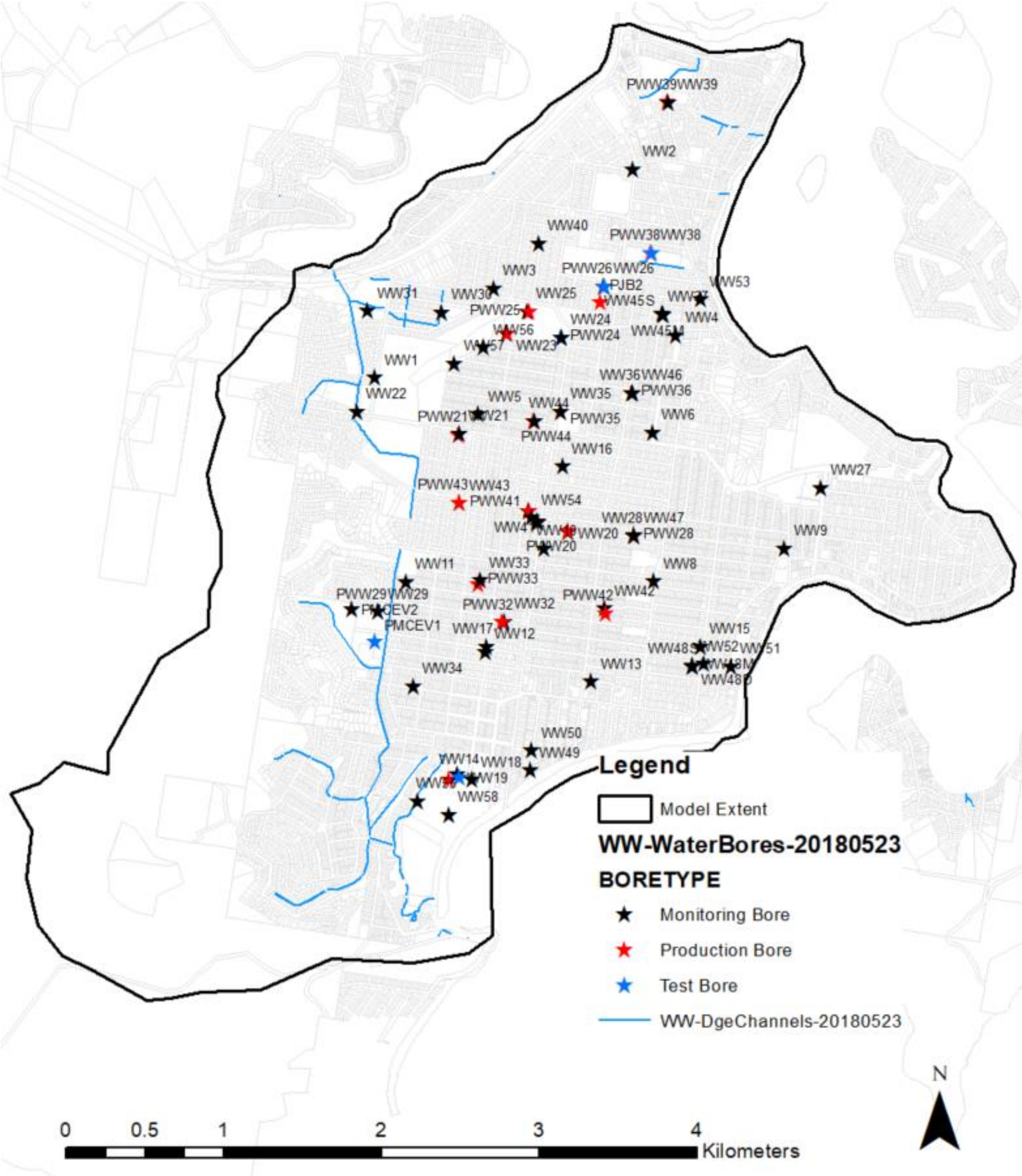


Figure 2.2 Locations of production, monitoring and test bores

2.2.1 Production and test bores

Production bores were installed in the Woy Woy peninsula, primarily for water supply purposes during drought conditions. The bores were only tested occasionally and have not been used for actual water supply. Council possesses information about these production bores in various formats such as Excel spreadsheets, a shapefile of production/monitoring/test bores and reports of pumping tests (Hydroilex, 2005). DHI consulted with Council regarding this data and compiled information into a summary table (Table 2.1). Twelve (12) production bores are designed to be used for water supply.

Production Bores for the water supply scheme are managed using a SCADA (Supervisory Control And Data Acquisition) system and are often referred as SCADA bores. It should be noted that the bore IDs used in SCADA differ from the bore IDs used in this study.

Table 2.1 Production and Test Bores in the Woy Woy peninsula

ID	Common Name	SCADA ID	Type of Bore	Use	Annual licensed allocation (ML)	Address	Pump Duty (m3/hr)
PWW41	Ryans and Crown (P)	WW11	Test	Monitoring	-	-	12.6
PWW20	Paul Street (P)	WW2	Test	Monitoring	-	-	14.9
PMCEV1	McEvoy Oval 2 (T)		Test	Monitoring	-	-	34.8
PWW29	McEvoy Oval 1 (T)		Test	Monitoring	-	-	-
PWW26	James Browne 1 (P)		Test	Monitoring	-	-	-
PWW24	Rogers Park 1 (T)		Test	Monitoring	-	-	-
PWW33	Pozieres Avenue (P)	WW8	Production	Potable	100	44 Poziers Av, Umina Beach	18.8
PWW44	MacKenzie Avenue (P)	WW14	Production	Potable	100	9-11 Mackenzie Av, Woy Woy	18.9
PWW42	Albion Street (P)	WW12	Production	Potable	60	40 Albion St, Umina Beach	10.8
PWW36	Trafalgar and Alma (P)	WW10	Production	Potable	150	58 Trafalgar Av, Umina Beach (Cnr Alma Av)	29.1
PWW21	Veron and Connex (P)	WW3	Production	Potable	80	40 Connex Road (Cnr Vernon Rd), Umina Beach	12.7
PWW43	Ryans and Haynes (P)	WW13	Production	Potable	60	35 Haynes Av (Cnr Ryans Rd), Umina Beach	10.7
PWW28	King and Karingi (P)	WW6	Production	Potable	200	19 King Street (Cnr Karingi St), Umina Beach	37.1
PWW32	Australia Avenue (P)	WW7	Production	Potable	150	16 Australia Av, Umina Beach	27.8

PWW23	Rogers Park 3 (P) ERINA AVE	WW4	Production	Potable	100	Erina Av, Woy Woy	18
PWW25	Rogers Park 2 (P) DUNBAN ROAD	WW5	Production	Potable	100	Dunban Road, Woy Woy	18.8
PWW35	Wow Woy Depot	WW9	Production	Potable	30	236A Ocean Beach Rd, Umina Beach	14.4
PJB2	James Browne Oval (via Ross Street)	WW1	Production	Potable/Recreation	185	16 Ross St, Woy Woy	34.8
PWW38	James Browne Oval (via Alpha Road) (P)		Production	Recreation	13	62 Alpha Road, Woy Woy	-
	Rogers Park		Production	Recreation	25	45 Erina Ave, Woy Woy	-
PWW19	Umina Oval 1 (Parks&Rec)		Production	Recreation	60	Sydney Ave, Umina Beach	-
	James Browne Oval No2		Production	Recreation	20	243B Blackwall Road Woy Woy	-
PWW29	McEvoy Oval		Production	Recreation	14	109 McEvoy Av, Umina Beach	-
	Ettalong Oval		Production	Recreation	11	7 Picnic Pde, Ettalong Beach	-
PWW39	Austin Butler 1 (TR)		Production	Recreation	25	11 Iris Place, Woy Woy	-
	Woy Woy Oval		Production	Recreation	15	51 Chambers Place, Woy Woy	-

2.2.2 Monitoring bores

Many monitoring bores are located on the Woy Woy peninsula, which were installed as part of previous studies in the area (Cook, 1998). Matching the groundwater level timeseries is the main calibration target of the groundwater model.

Figure 2.3 shows the monitoring bore locations where data has been provided. Some of the monitoring bores are manually monitored by Council staff with records stored in an Excel spreadsheet (Black triangles in Figure 2.3). Other bores are equipped with pressure data loggers (Red triangles in Figure 2.3). Bores shown as green dots were used in the previous study.

Figure 2.13 shows the data coverage of each monitoring bore. Some bores such as WW 31 and WW32 have very short record. As it can be seen, some stations do not have updated records after 2007.

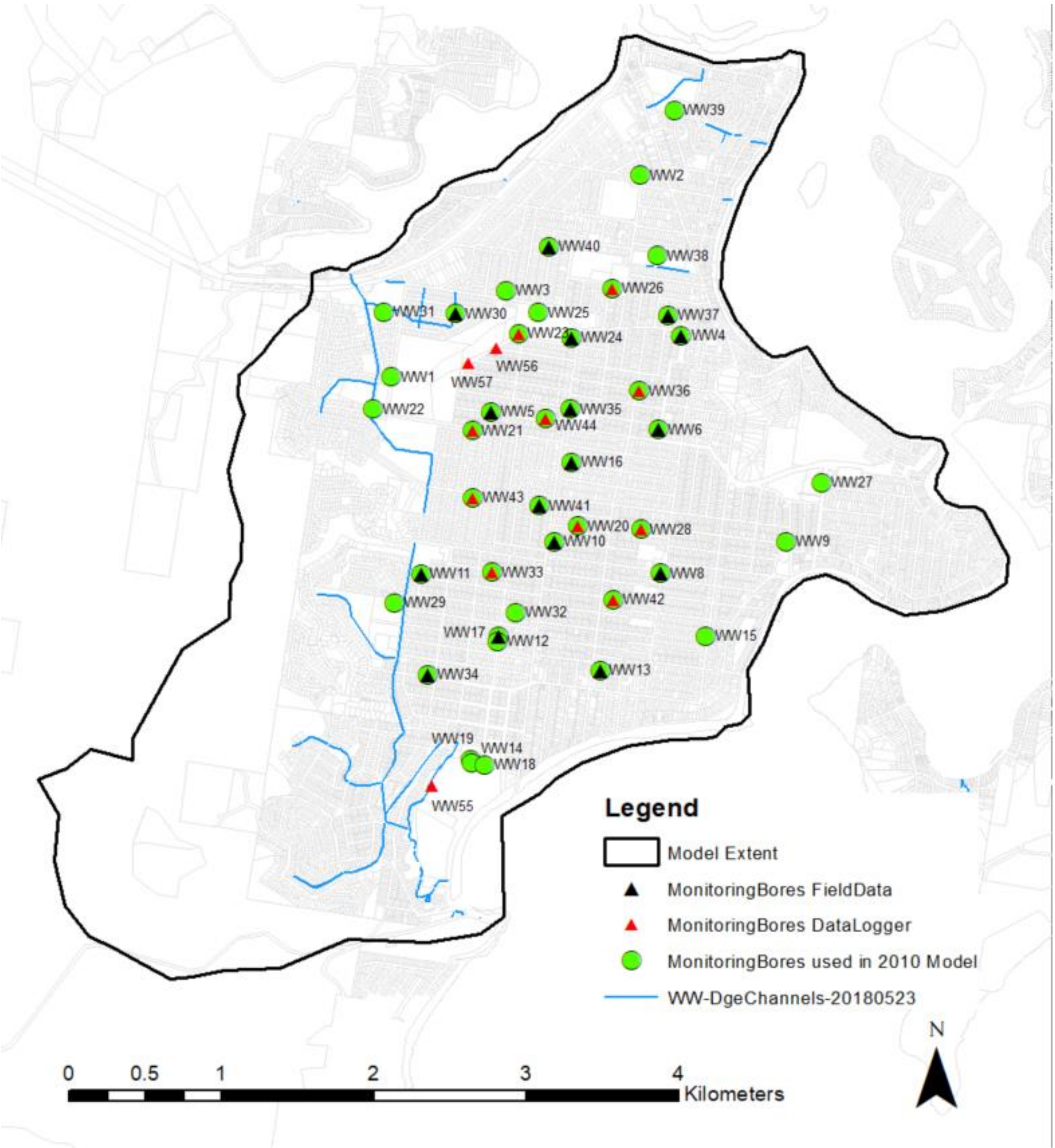


Figure 2.3 Locations of monitoring bores with data

2.2.3 Conversion of pressure to water level at the data loggers

The downloaded logger data had not been compiled since the last flood study in 2008. To use the data for calibration, it was essential to compile the timeseries and convert pressure data to water levels in mAHD. Larry Cook Consulting Pty (LCC) was engaged to undertake compilation of the raw data and conversion of pressures to water levels in mAHD. LCC was involved in the installation of the data loggers and numerous previous groundwater studies in the study area.

During the data review of the converted groundwater levels (at bores with data loggers and manually measured groundwater levels at other stations), DHI identified several data issues associated with the data loggers. These issues were summarised and sent to Council. LCC produced a summary report of the undertaken tasks with comments on the reliability of the data and recommendations for computer modelling. (Appendix A)

The report from LCC recommended the following for use of the produced hydrographs:

- Data anomalies and data shifts were identified. LCC recommends these data blocks to be adjusted or deleted from the analysis.
- LCC recommends not to use bores near the Everglades golf course for the model calibration, as they are likely to have captured artificial activities at the golf course.
- Generally, manually measured groundwater levels seem to be reliable.

DHI and LCC discussed data issues with the converted water levels and assessed the reliability of the data for use in the numerical modelling. Considering the quantity of small to large data shifts identified and the absence of sufficient information to track down when and how these shifts were introduced, it was not considered appropriate to adjust every data shift in the converted water levels. Therefore, only apparent data errors and significant data shifts were removed. LCC's report (Appendix A) lists the data blocks to be deleted for each monitoring bore. It should be noted that data shifts considered minor and data shifts where the start and end dates are difficult to identify, remain in the data.

Figure 2.4 to Figure 2.12 show the original groundwater timeseries that LCC produced from the pressures recorded by the data logger (in green), the timeseries after editing by DHI following removal obvious anomalies as indicated by LCC's advice (in black), and the manually measured standing water levels (in red). Figure 2.13 shows data coverage of each monitoring bore.

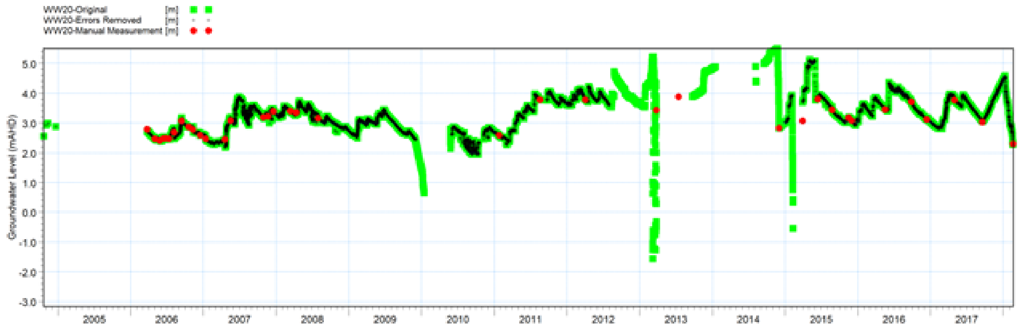


Figure 2.4 WW20 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

Figure 2.5 WW21 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

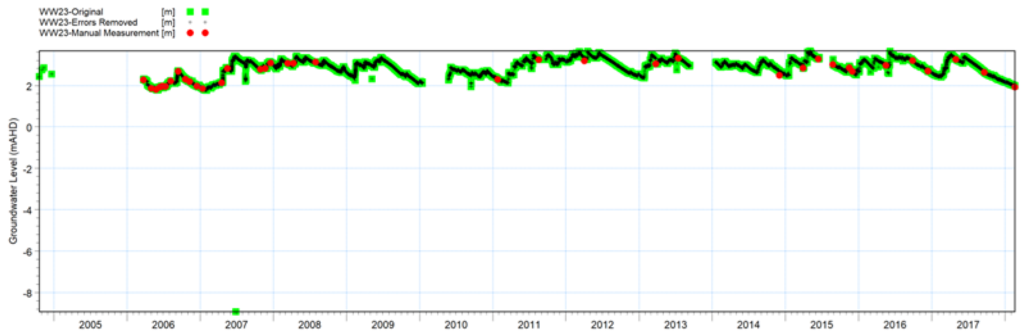


Figure 2.6 WW23 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

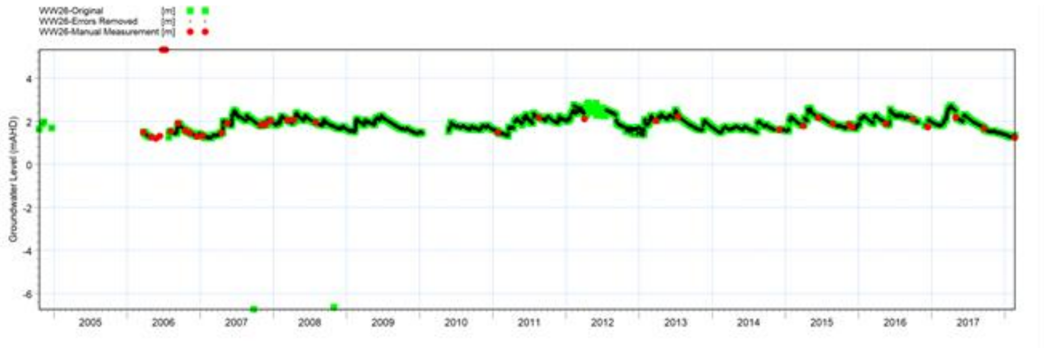


Figure 2.7 WW26 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

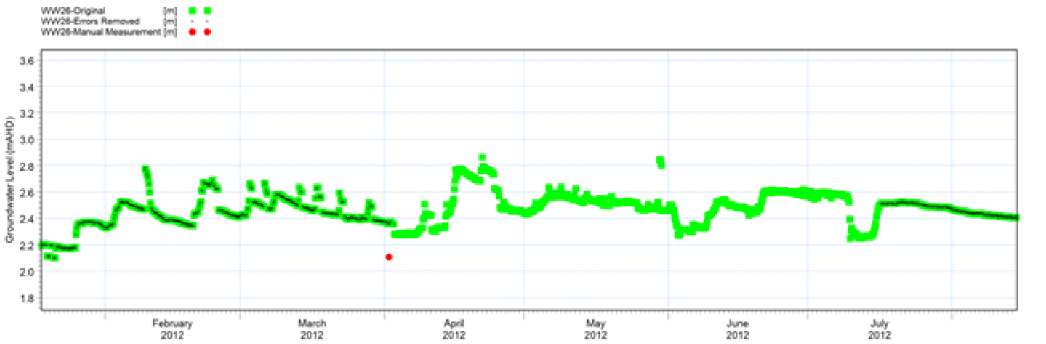


Figure 2.8 WW26 - Converted groundwater levels from pressures (zoomed in to 2012), Before (Green) and After (Black) obvious anomalies are removed

Figure 2.9 WW33 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

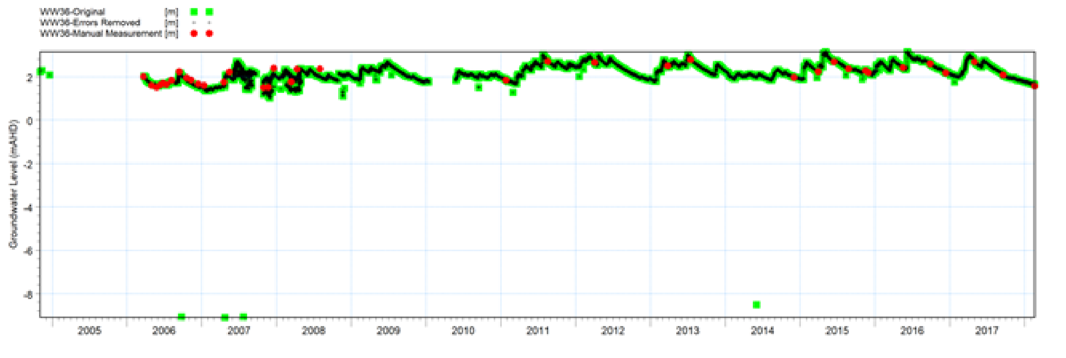


Figure 2.10 WW36 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

Figure 2.11 WW43 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

Figure 2.12 WW46 - Converted groundwater levels from pressures, Before (Green) and After (Black) obvious anomalies are removed

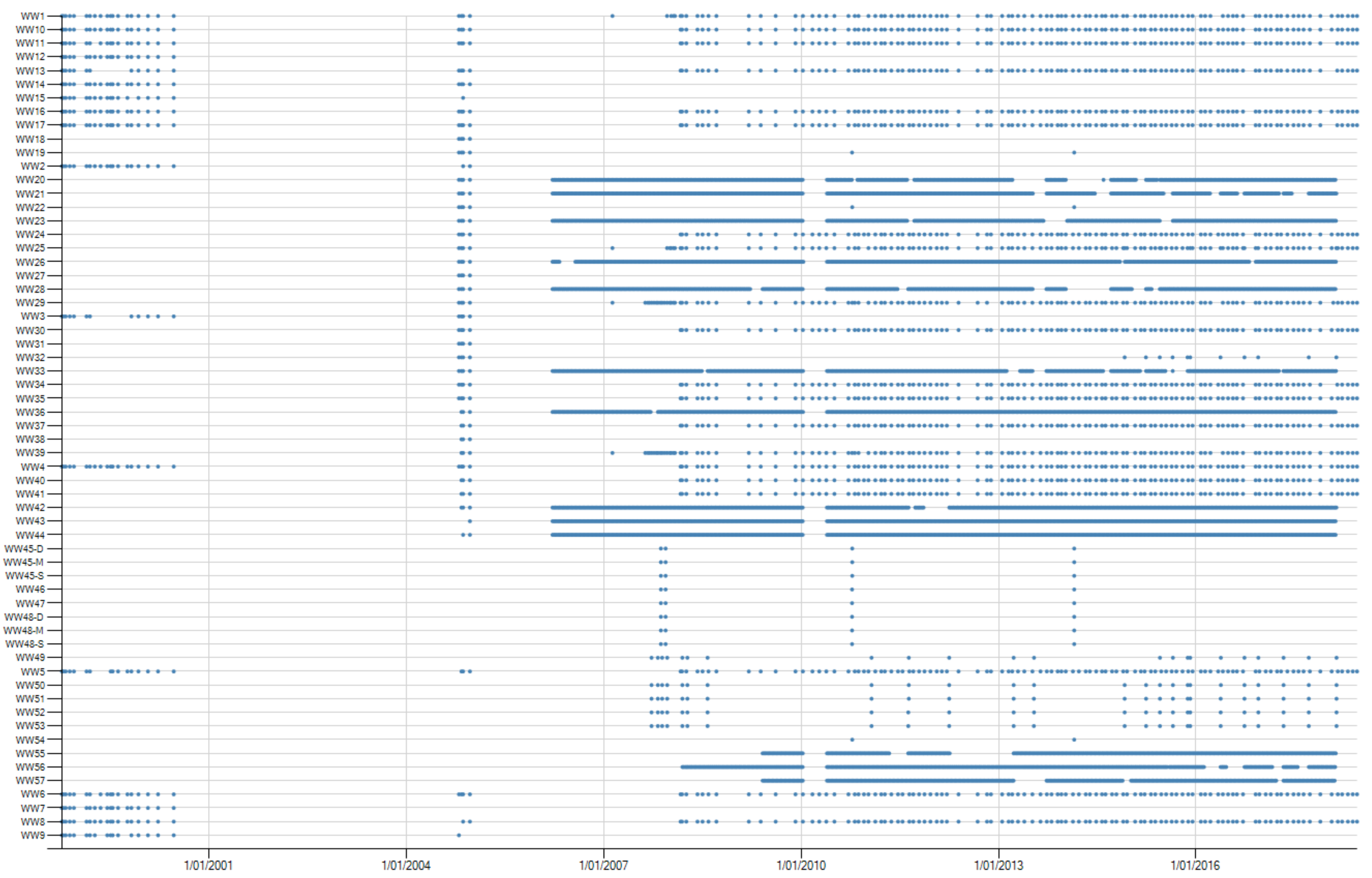


Figure 2.13 Data coverage of the monitoring bores

2.3 Climate Data

2.3.1 Rainfall Data

Several sources of rainfall are available in the study area.

Station	Source	Frequency	Period	Note
061318 Woy Woy Everglades Country Club	BoM	Daily	Dec 1964 - Sep 2010	• Closed in 2010 • There are missing data
Everglades Golf Club Rainfall	CCC*	Daily	Jan 2005 to Feb 2018	No data Sep-Dec 2010
Umina Bowling Club Rainfall	CCC*	Daily	Jan 2006 to Feb 2018	
Ettalong Public School (561140)	MHL	Hourly	May 2006 to May 2018	Long missing data in 2012 and 2018
Woy Woy Tip Rain (561141)	MHL		Nov 2005 to Jun 2018	
Pearl Beach Rain (561151)	MHL	Hourly	May 2005 to Jun 2018	
Koolewong (212422)	MHL		May 2006 to Nov 2016	Outside of the catchment
Gridded rainfall at (-33.50, 151.30) (-33.50, 151.35)	SILO	Daily	Jan 1900 to Today	

*Woy Woy Field Results_14June2018.xlsx

For long-term simulation of groundwater a long rainfall timeseries (over 100 years) was required. SILO gridded dataset derived by splining or kriging interpolation of the observational data is the only source which provided 100 years of rainfall.

2.3.1.1 Composite rainfall

The previous modelling study (DHI, 2010) used a composite rainfall; The daily BoM rainfall at Woy Woy Everglades Country Club was complemented with SILO gridded data at (Latitude -33.50 degrees, Longitude 151.30 degrees). To be consistent with the previous study, the same approach was applied to extend the rainfall timeseries.

The BoM station (061318 Woy Woy Everglades Country Club) was operational between December 1964 and September 2010. SILO gridded rainfall at (-33.50, 151.30) was used to compliment the period outside of the operational period of the BoM station.

The raw data of BoM often contains missing values or rainfall observed over multiple days. An example is shown in Table 2.2. 31.8 mm of rain was observed over two days and the value at 26 Dec 2016 was left blank. In the previous study, it was automatically filled with 0. In this study, instead of filling these timesteps with zero rainfall, the accumulated rainfall was redistributed over multiple days using the temporal pattern of the SILO gridded data at (-33.50, 151.30).

Table 2.2 Example of generation of composite rainfall

Date	BoM Raw Rainfall (mm)	Period over which BoM rainfall was measured (days)	SILO gridded Rainfall (mm)	COMPOSITE Rainfall (mm)
26/12/1971			3.5	7.09
27/12/1971	31.8	2	12.2	24.71

The BoM rainfall data is missing in the period between November and December 2004. SILO rainfall was also used to compliment this period.

Figure 2.14 shows annual rainfall of the composite timeseries. The average of annual rainfall from 1900 to 2017 is 1258mm.

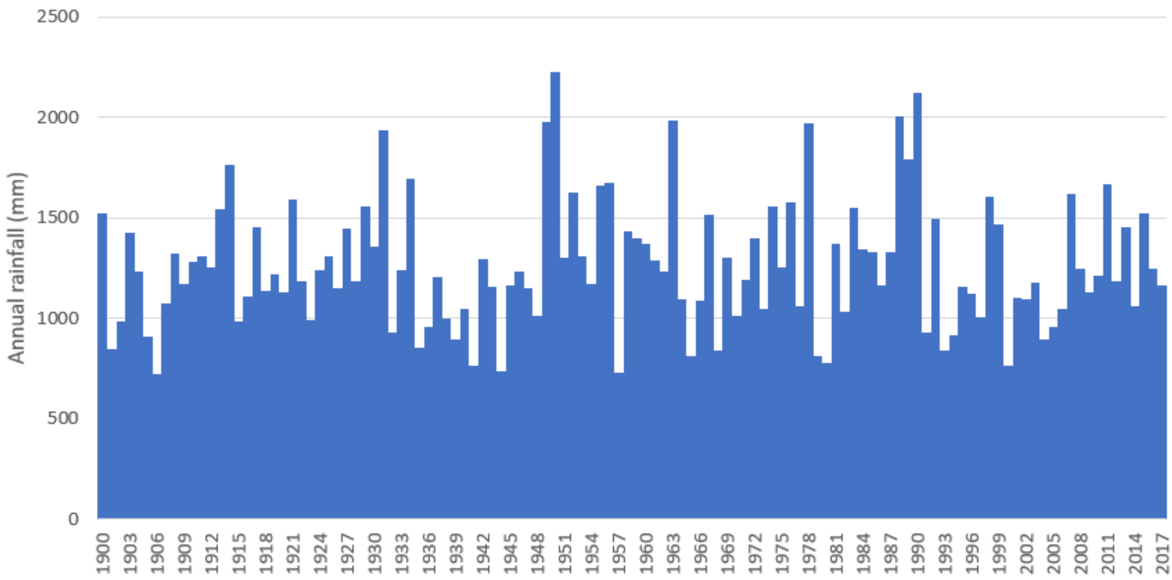


Figure 2.14 Annual composite rainfall (1900-2017)

2.4 Aerial Imagery

Gosford City Council provided DHI an access to a Web Map Service (WMS) developed by the Open Geospatial Consortium. WMS provides the following imageries over the study area.

- Aerials at 2015 December
- Aerials 2015 April
- Aerials 2014
- Aerials 2012
- Aerials 2010
- Aerials 2007
- Aerials 2005

2.5 Drainage Data

Drainage shapefiles were provided by Council.

- WW-DgeBoxCulverts-20180523.shp
- WW-DgeCatchments-20180523.shp
- WW-DgeChannels-20180523.shp
- WW-DgeGrossPollutantTraps-20180523.shp
- WW-DgeHeadwalls-20180523.shp
- WW-DgePipes-20180523.shp
- WW-DgePits-20180523.shp
- WW-DgeSubCatchments-20180523.shp

The drainage assets within the Everglades Catchment were reviewed.

A number of pipes are commented as “dummy pipes” in the drainage network shapefile. Some of them are dummy features to indicate parallel pipes or culverts, while others are pipes designed to connect infiltration type pits. Council confirmed that the latter was not constructed yet. Therefore, unconstructed dummy pipes were removed from the drainage model.

Invert levels were missing from a large number of pipes within the data provided. Some pipes have estimated depth attribute (in metres) which was used in the Drainage Asset Data Capture Project report (1997) as the invert level attribute rather than the level in mAHD. Other pipes are simply missing values.

2.6 Landuse

There is no land use map covering the entire study area. The previously developed landuse map (DHI, 2010) does not cover the extended study area and some streets were not well aligned.

For the coarse-grid (100m) peninsula model (Section 3), the same land use distribution as the previous study was applied. For the refined Everglades model (Section 7), a new land use map was generated manually.

2.7 MIKE SHE model in the 2010 study

MIKE SHE is an integrated hydrological modelling package which includes groundwater, surface water, recharge, and evapotranspiration. MIKE SHE is able to separate rainfall into runoff, evapotranspiration, and recharge in an integrated manner, within a single model, which differentiates to approaches widely used in typical flood studies such initial and continuing loss. One of the strengths of the package is that it can combine different sub-models and different levels of detail, depending on the applications of the model.

The previous flood study in the Woy Woy peninsula (DHI, 2010) developed two MIKE SHE models:

- Long-term model: the model without drainage in the 100m resolution, focused on groundwater to understand the long-term fluctuations of groundwater table. This model was run for 100 years and calibrated against groundwater levels.
- Event model: the long-term model was refined to 10m grid and coupled with a MIKE Urban drainage model to focus on surface water flooding. The model was calibrated against the 1988 flood event.

3 Peninsula groundwater model update

This chapter summarises the changes made to the long-term groundwater model (DHI, 2010).

As described in Section 2.7, the peninsula MIKE SHE model was developed and calibrated in two stages in the previous study:

- Long-term groundwater model
- Event model for flooding

This project included updating the long-term groundwater model to include the Kahibah Creek catchment and to incorporate the newly obtained topographic data and observed groundwater data. The updated model was recalibrated using the new observed groundwater data. Re-conceptualisation of the catchment was not part of this project and the model structures remain unchanged.

3.1 Model Domain

The model domain was extended to include the Kahibah Creek and to the escarpment. The new model domain is represented by the black line in Figure 3.1.The model grid size was maintained at 100m.

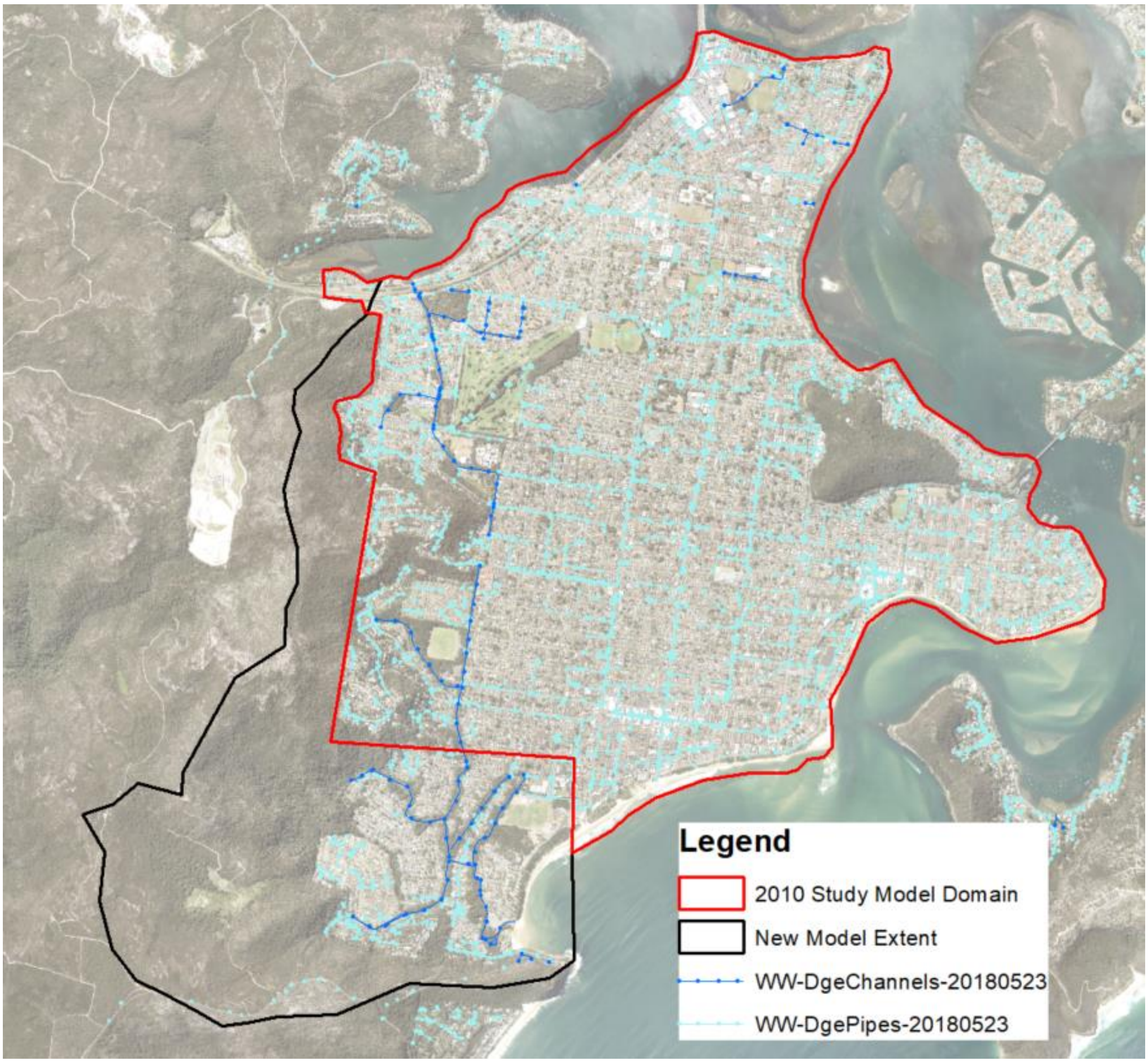


Figure 3.1 Updated model domain

3.2 Open channel network

The Main Drain and Kahibah Creek were modelled in MIKE 11 in the previous study. This model was converted to MIKE HYDRO River, the successor of MIKE 11.

As the Kahibah Creek catchment was included in the model domain, the Kahibah Creek system was further developed to include upstream arms by digitising its major branches. Figure 3.2 shows the updated open channel network coupled to MIKE SHE. The Main Drain is shown in red and the Kahibah system is shown in black. As detailed surveyed cross-sections were not available, cross-sections were derived using LiDAR.

Figure 3.2 Updated open channel network (black: Kahibah Ck System, red: Main Drain)

3.3 Topography

The 1m topography was resampled to a 100m grid for the groundwater model.

Processing of topography data to a large-sized grid often creates local depressions, where a grid cell is lower than the adjacent cell and water gets trapped. This leads to artificial surface water ponding and can slow down computation speed. To avoid artificial water ponding, depressions were filled using MIKE SHE's depression filling tool in the escarpment area. The tool fills local depressions so that water can freely flow into one of the four neighbouring cells. The 100m topography with filled depressions is shown in Figure 3.3.

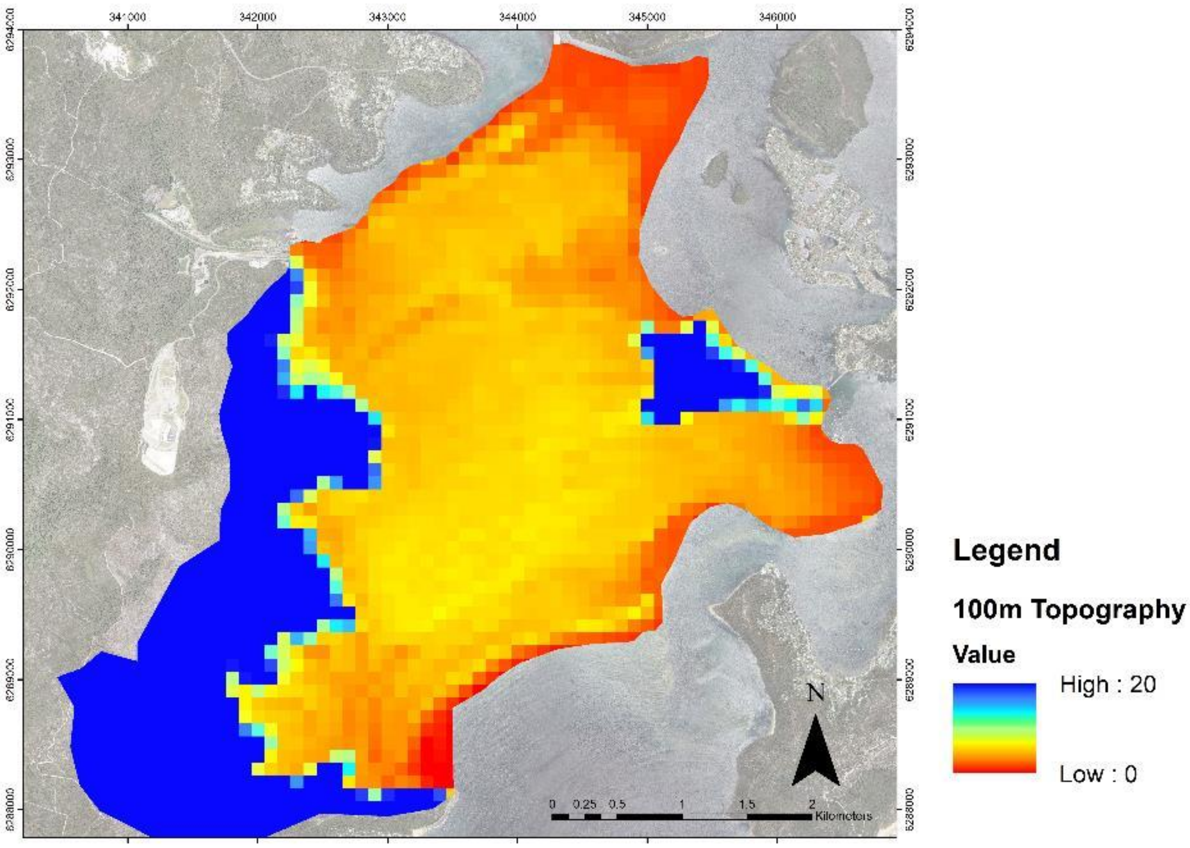


Figure 3.3 100m grid topography processed from LiDAR (depressions filled)

3.4 Aquifer geometry

The model has one aquifer layer, representing the barrier beach sand aquifer underlying most of the peninsula (except Blackwall Mountain and the sandstone escarpment in the west). As the revised model domain was extended towards the escarpment, conceptualisation of the geological layer for this extended area was undertaken for inclusion in the model.

A typical west-east cross-section of the peninsula is presented in Figure 3.4. The unconsolidated sand aquifer lies between the escarpment and Blackwall Mountain. The escarpment and Blackwall Mountain are considered to be mainly sandstone. Mackie (2005) provides an overview of the sand aquifer system as “hosted within an eroded valley comprising relatively impermeable hardrock sandstones and other lithologies of the Hawkesbury Sandstone, Terrigal Formation and Narrabeen Group.”

Considering that the escarpment and Blackwall Mountain are mainly sandstone, it is expected that only a very small portion of rainfall in these areas infiltrates to the deep aquifer layer. Therefore, as per the conceptual model of the previous study, the regional bedrock groundwater system was not explicitly represented in the model. Infiltration on the escarpment is assumed to discharge into the sand aquifer at the base of the escarpment.

A single saturated zone layer was maintained and the bottom level was assumed to be 50cm below the ground surface at the escarpment and Blackwall Mountain. The base of the sand aquifer layer was kept as per Mackie (2005) which interpolated the base of the sand aquifer from deeper exploratory bore findings. The red line in Figure 3.4 represents the lower level of the saturated zone layer in the model.

Hydraulic conductivity of the sand aquifer was a calibration parameters. The hydraulic conductivity details are summarised in Section 4.1.

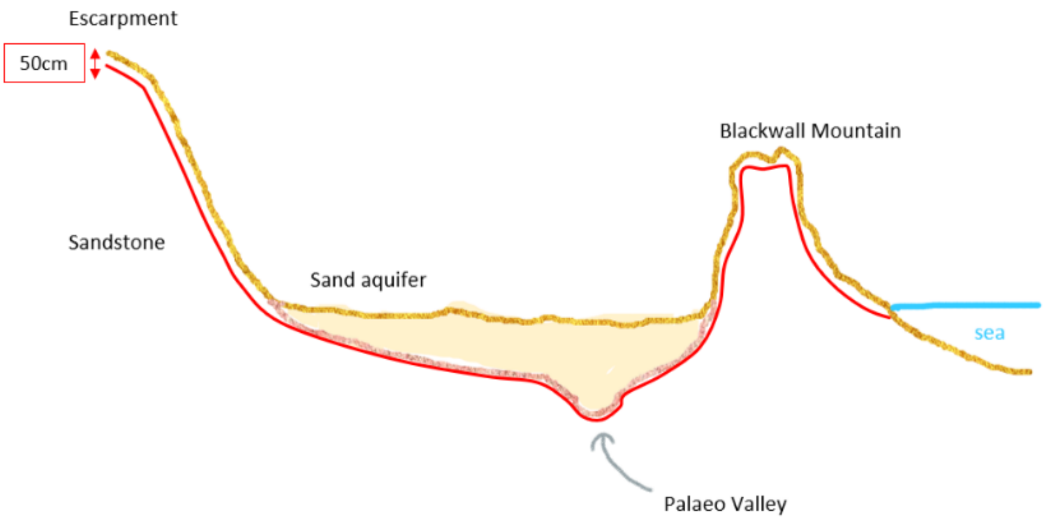


Figure 3.4 Schematic of a typical west-east cross section of the Woy Woy peninsula (red line: the bottom of the saturated zone layer 1 in the model)

3.5 Incorporation of the groundwater levels in the model

Groundwater level records used in the previous study were extended or replaced with both manual measurements and adjusted groundwater level records of the data loggers.

The extended timeseries of groundwater levels was incorporated in the groundwater model as calibration targets.

3.6 Boundary conditions

3.6.1 Shorelines

The existing model used the shoreline boundary condition of 0 mAHD. We adopted 0.1 mAHD as per Mackie (2005) to account for wave action and adjustment for equivalent freshwater head. This sea level is applied in both 2D and 1D models.

3.6.2 Western boundary

The western boundary of the escarpment is set to a zero-flux boundary.

3.7 Surface-subsurface leakage coefficient

The existing model represented the impervious surface as soil with zero conductivity in the unsaturated zone. The newer version of MIKE SHE introduced a parameter called surface-subsurface leakage coefficient, which reduces the infiltration rate and the seepage outflow rate at the ground surface. The parameter is used to account for soil compaction near the ground surface, fine sediment deposits or paved areas.

In the revised model, the surface-subsurface leakage coefficient was used to account for paved areas in the catchment rather than utilising soil parameters in the unsaturated zone. The soil previously set as zero conductivity in the unsaturated zone was converted to sand and the surface-subsurface leakage coefficients were applied for the paved areas in the model.

Figure 3.5 shows a conceptual representation of the impervious areas in the existing model and the updated model.

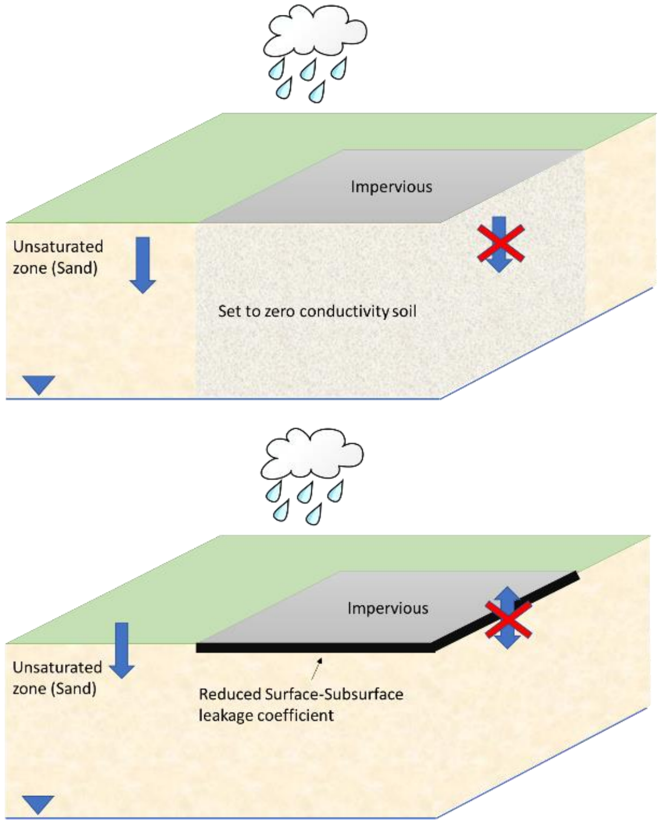


Figure 3.5 Representation of an impervious area in the existing model (top) and in the updated model (bottom)

4 Recalibration of the peninsula groundwater model

The initial run of the updated model produced significant deviations from the newly obtained groundwater levels. Therefore, recalibration of the model was undertaken. It should be noted that re-conceptualisation of the groundwater model is not a part of this study. Therefore, the main model structure and schematisation were maintained

The model was calibrated by manually adjusting hydraulic properties in the model and comparing the simulated groundwater levels against the observed ones. Simulations were carried out from 1970 to 2018:

- 1970 to 1998 was the warm-up period. The warm-up period was used to generate a realistic initial groundwater condition for the calibration period.
- 1998 to 2018 was the calibration period, during which groundwater level measurements were available.

4.1 Calibration parameters

Key calibration parameters were horizontal hydraulic conductivities and specific yield of the aquifer, as well as the surface-subsurface leakage coefficients. it should be noted that hydraulic conductivities measured at the bores in the previous studies were used as reference values for calibration, but not directly used in the model. This is because the model represents the catchment behaviours in a simplified manner and would not necessarily produce realistic predictions when using measured conductivities.

In MIKE SHE, the parameters for the unsaturated zone and saturated zone are separately specified. Table 4.1 shows the parameters of the unsaturated zone and the final values of the specific yield. In MIKE SHE, the specific yield of the top saturated zone layer is set equal to the saturated water content minus the field capacity, which are specified as unsaturated zone parameters. This is to avoid water balance errors at the interface between the saturated and unsaturated zones.

Table 4.1 Specific yields

Area	Specific Yield (-) (SZ)	Water Content at Saturation (-) (UZ)	Water Content at Field Capacity (-) (UZ)	Saturated Hydraulic Conductivity (m/s) (UZ)
Sand Aquifer	0.22	0.25	0.03	5.5e-5
Non-Sand Aquifer (Escarpment, Blackwall Mountain)	0.1	0.3	0.2	1e-7

Figure 4.1 shows the surface-subsurface leakage coefficient applied in the model. With a 100m resolution, it is hard to estimate the exact surface permeability of each grid cell. The previous model (randomly) set the impervious area to be 50% of the total model area. The revised model used the same spatial distribution for the impervious areas. The coefficient in the remaining area was set to 1e-5 (/s) to account for some soil compaction.

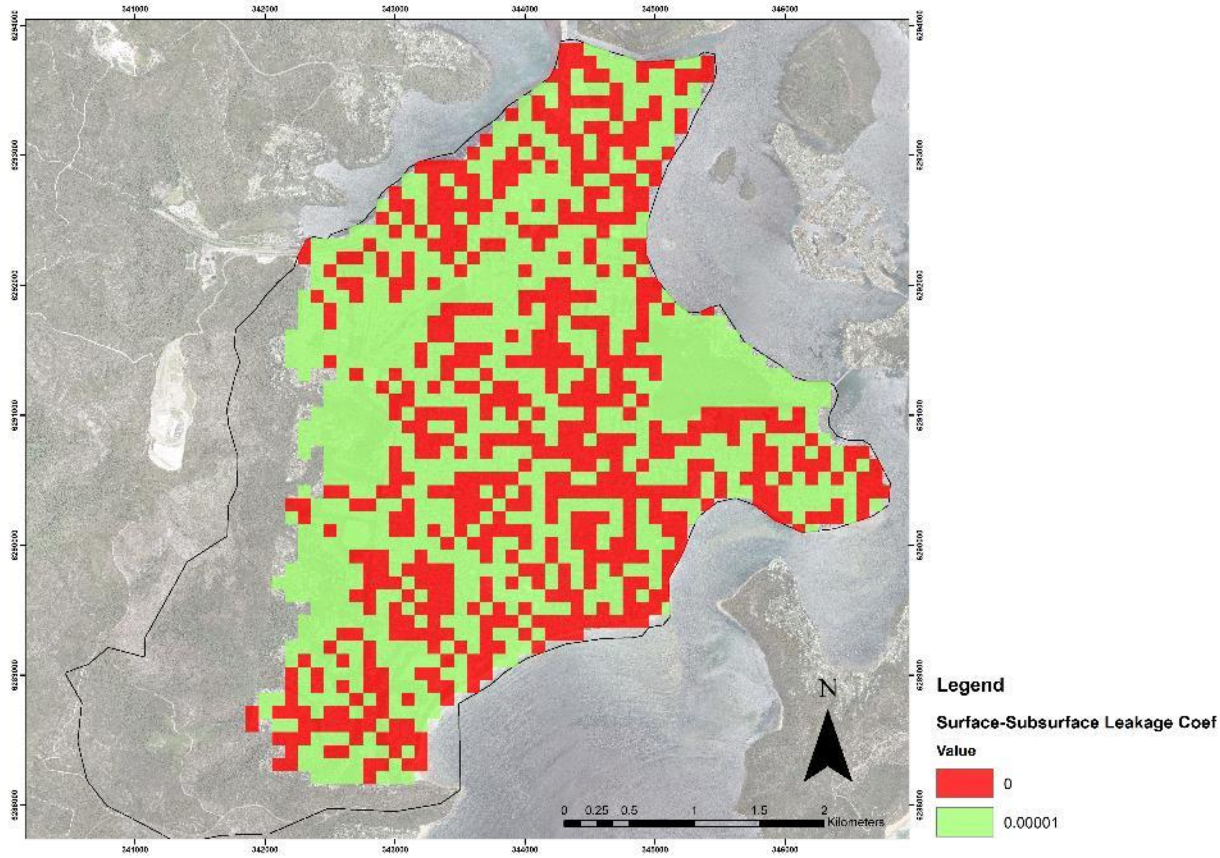


Figure 4.1 Surface-subsurface leakage coefficient

Hydraulic conductivities at the bores WW1 to WW17 were derived from falling head-slug tests (Cook, 1998). Mackie (2005) initially adopted these values to the model but modified during the calibration process. Mackie used PEST for automated optimisation, which is often used in groundwater studies. The revised model used the Mackie (2005) calibrated hydraulic conductivities as the starting point. The conductivities were modified until the model achieved improved matching groundwater levels at the monitoring bores. Figure 4.2 shows the final hydraulic conductivities.

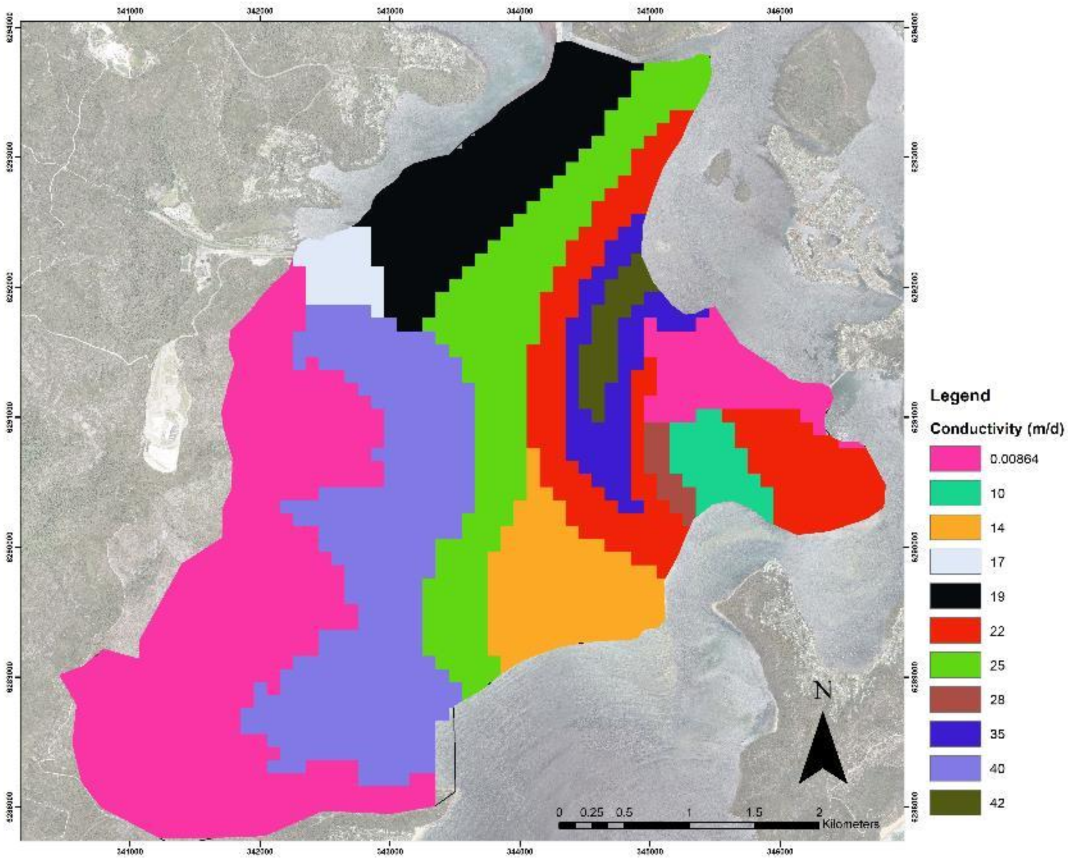


Figure 4.2 Horizontal hydraulic conductivity in the saturated zone of the MIKE SHE model

4.2 Model Performance

4.2.1 Groundwater levels

Simulated and observed groundwater results at the monitoring bores, with data loggers, are shown in Figure 4.3 to Figure 4.12. Simulated groundwater levels are shown in black lines while red crosses show the data logger records and larger red squares show the manually measured standing water levels at the bores. WW56 and WW57, which are likely a record of artificial activities at the Everglades golf course are excluded from the calibration targets, as advised by LCC. Full calibration plots are shown in Appendix B.

Overall, the model produces modelled results that correspond well to observed levels and the model represents the general trends of groundwater levels across the catchment.

High water levels are recorded at WW20 in 2015 and late 2017. Although these blocks were not advised by LCC to be deleted from analysis, these are likely to be data logger errors as the neighbouring monitoring bores, such as WW10, did not record these trends.

At some stations, e.g. WW21 and WW23, the model reproduces the observed groundwater levels well prior to 2012 and underestimates levels between 2013 and 2015. Underestimation of groundwater levels can potentially be explained by an underestimation of rainfall during this period. The BOM rain gauge was used until September 2010 and SILO grid rainfall was used after closure of the gauge.

Groundwater levels are constantly overestimated at WW55 (Figure 4.12). WW55 is located next to Ettalong Creek. Overestimation of water levels is likely to be due to the poor representation of the Kahibah Creek system, where bed levels are not properly captured in the 1D model which is coupled to groundwater model. It is anticipated that improvement of the 1D model in the flood study (Woy Woy FRMP) will improve the groundwater level results around the creek system.

Figure 4.13 shows samples of the simulated groundwater level map in 2007. All plots illustrate groundwater mounding in the south of the Everglades Catchment. Groundwater levels rise and fall in response to rainfall. There was a significant flooding event recorded in 1 June 2007. This is captured in the model; large groundwater level changes are seen between May and June. As stated earlier, the model is intended to represent the sand aquifer and does not represent the bedrock aquifer underlying the escarpment. Therefore, the simulated head elevations outside of the sand aquifer zone are irrelevant.

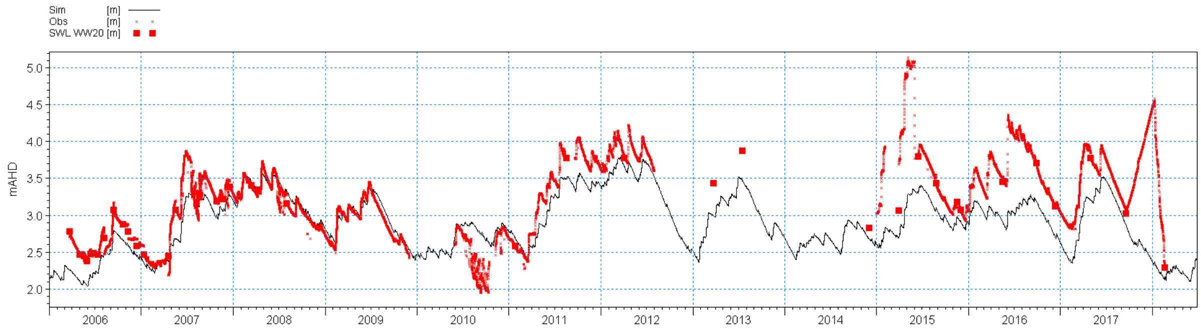


Figure 4.3 Simulated and observed groundwater levels at WW20

Figure 4.4 Simulated and observed groundwater levels at WW21

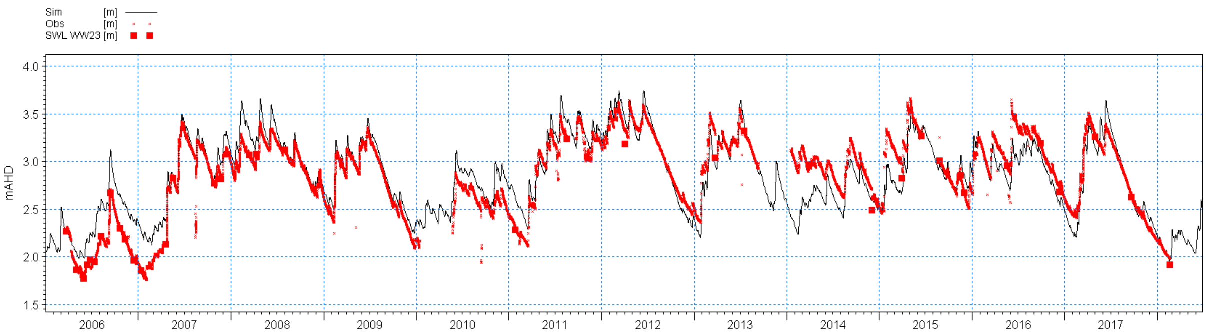


Figure 4.5 Simulated and observed groundwater levels at WW23

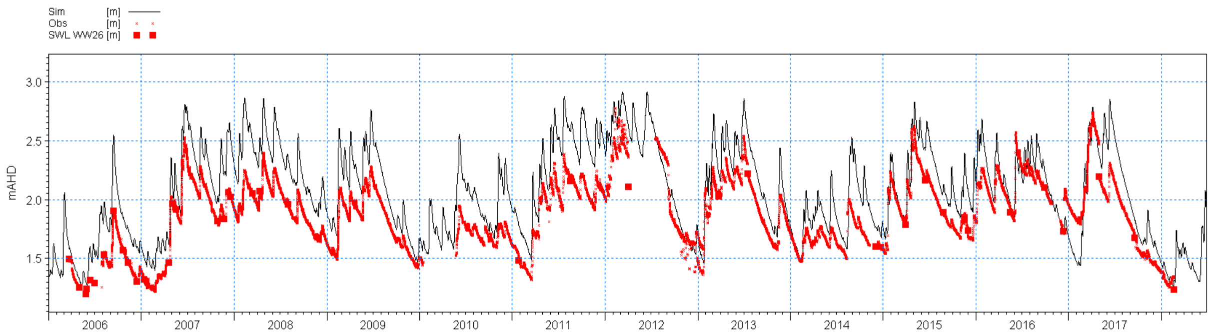


Figure 4.6 Simulated and observed groundwater levels at WW26

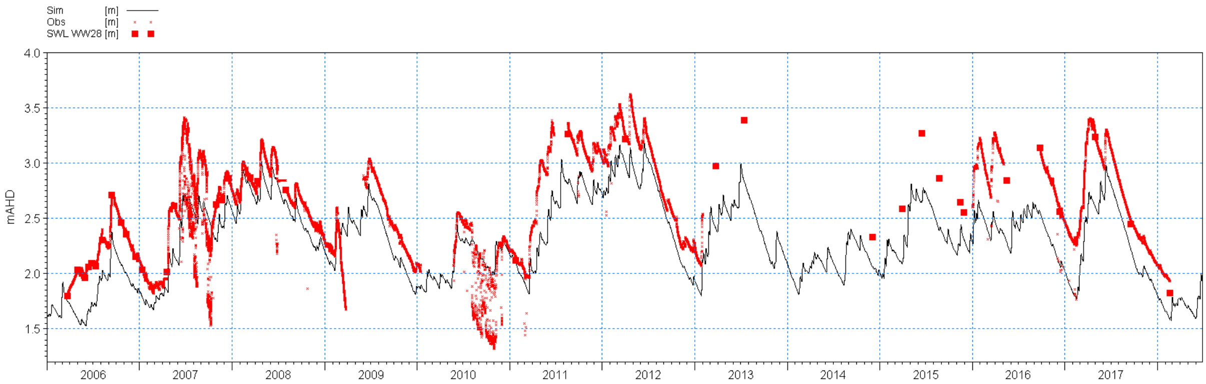


Figure 4.7 Simulated and observed groundwater levels at WW28

Figure 4.8 Simulated and observed groundwater levels at WW33

Figure 4.9 Simulated and observed groundwater levels at WW36

Figure 4.10 Simulated and observed groundwater levels at WW42

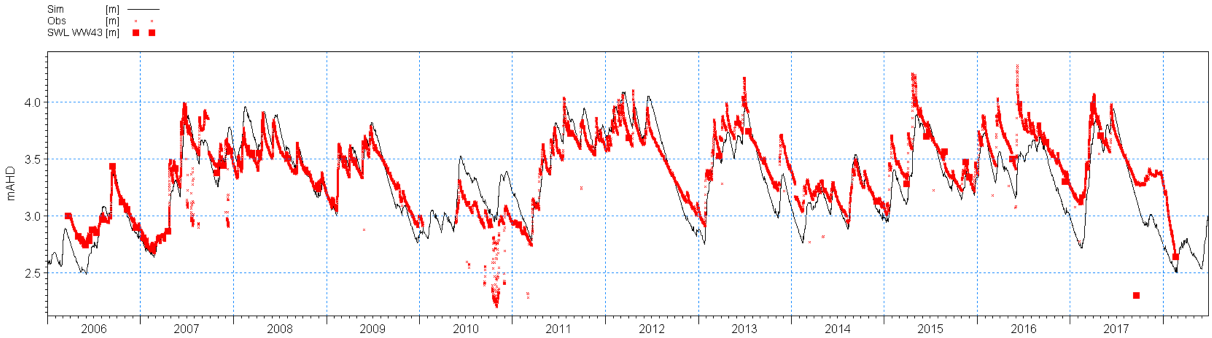


Figure 4.11 Simulated and observed groundwater levels at WW43

Figure 4.12 Simulated and observed groundwater levels at WW55

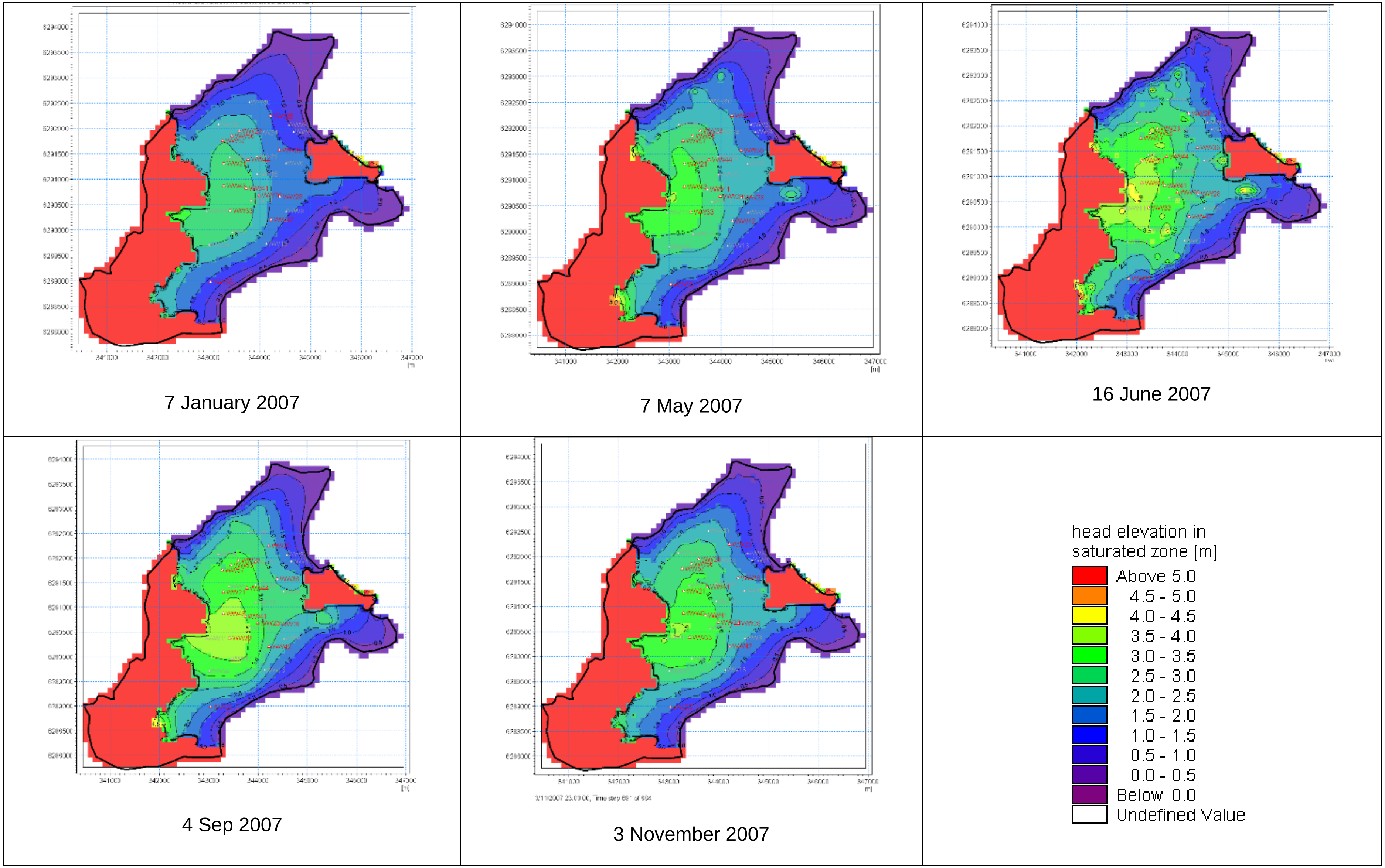


Figure 4.13 Variations of simulated groundwater level over a year (2007)

4.2.2 Water Balance

The water balance of the sand aquifer is calculated from the model results for the period from June 1998 to June 2018. The annual average water balance for this period is shown in Table 4.2.

Table 4.2 Annual average water balance of the sand aquifer[1]

Area	Average annual depth (mm)
Rainfall	1213
Evapotranspiration[2] (*includes direct evaporation from the aquifer)	498 (80)
Surface inflow from boundary	149
Surface outflow to boundary	195
Recharge to Aquifer[3]	593
Pumping	22
Surface flow to open channels	155
Baseflow/Drain flow to open channels	134
Baseflow/Drain outflow to boundary	365
Baseflow inflow from boundary	1
Error	0.003

[1] The total area of the sand aquifer in the model is 1.29ha
[2] Approximately 40% of rainfall evaporates
[3] Approximately 40% of rainfall recharges the shallow sand aquifer

4.3 Summary of the model

The modules and parameters of the recalibrated peninsula groundwater model are summarised in Table 4.3.

Table 4.3 Summary of the peninsula groundwater model

<table>
<tr><th>Model component</th><th>Details</th></tr>
<tr><td>Model Domain</td><td>As per 3.1, includes the Kahibah Creek system</td></tr>
<tr><td>Resolution</td><td>100m x 100m</td></tr>
<tr><td>Simulation Options</td><td>Overland Flow: Finite Difference Method
Unsaturated Zone/Evapotranspiration: Two-layer water balance model
Saturated Flow: Finite Difference Method</td></tr>
<tr><td>Topography</td><td>As per Figure 3.3, LiDAR ground level processed to 100m resolution and local depressions filled</td></tr>
<tr><td>Rainfall</td><td>Daily rainfall, combined SILO grid rainfall and BoM station rainfall as per Section 2.3</td></tr>
<tr><td>Reference Evapotranspiration</td><td>SILO grid evapotranspiration</td></tr>
<tr><td>Land use</td><td>Grass: Leaf Area Index 2, Root Depth 300mm
Trees (random 50%): Leaf Area Index 5, Root Depth 5000mm
Escarpment Area: Leaf Area Index 5, Root Depth 5000mm (this is adjusted to 500mm of the layer thickness)</td></tr>
<tr><td>1D channel</td><td>Main Drain and the Kahibah Creek system</td></tr>
<tr><td>Overland Flow Parameters</td><td>Manning Number: uniform 10 ($m^{1/3}/s$)
Detention Storage: 10mm
Surface-Subsurface Leakage Coefficient: as per Figure 4.1</td></tr>
<tr><td>Unsaturated Zone Parameters</td><td>
<table>
<tr><th>Soil</th><th>θ_{Sat}(-)</th><th>θ_{FC}(-)</th><th>θ_{WP} (-)</th><th>K_{sat} (m/s)</th></tr>
<tr><td>Sand</td><td>0.25</td><td>0.03</td><td>0.05</td><td>5.5e-5</td></tr>
<tr><td>Sandstone</td><td>0.3</td><td>0.2</td><td>0.05</td><td>1e-7</td></tr>
</table>
θ_{Sat}: water content at saturation
θ_{FC}: water content at field capacity
θ_{WP}: water content at wilting point
K_{sat}: Saturated Hydraulic Conductivity</td></tr>
<tr><td>Saturated Zone Parameters</td><td>1 layer as per 3.4
Hydraulic Conductivities as per Figure 4.2
Specific Yield: Sand – 0.22, Sandstone:0.1
Assumed pumping rates as per the previous study (DHI, 2010)</td></tr>
</table>

5 Sustainable Groundwater Extraction Rate

The Council is currently entitled to 4ML/day extraction from the Woy Woy groundwater system and the Council's water supply strategy assumes that this rate can be sustainably extracted during all historical drought conditions.

This study investigates whether this extraction rate is feasible for all historical drought periods. The droughts of interests are:

- The World War II Drought (late 1930s to early 1940s)
- The Millennium Drought (2000s)

An assessment was undertaken with the following approach agreed by DHI and Council:

- The groundwater model was run from 1900 to 2018 which includes the historical drought periods above.
- Although the production bores in Woy Woy would not be operated under Council's water supply operating rules when the water supply dam storage levels are high enough, the constant 4ML/d extraction was applied for the entire simulation period. It assumes operation of production bores is independent of the rest of the water supply system.
- The pumping rate was set to the maximum allocation rate for each bore provided by the Council. The total of these allocation rates is 4ML/d. DHI assumes that these allocated rates were previously assessed by others to be reliable extraction rates for each bore.
- Groundwater response during the drought conditions are to be established, with and without the operation of production bores.

The locations of the production bores with extraction allocation, for this assessment, are shown in Figure 5.1. Test bores are not included. Results of the simulation were compared at the monitoring bore locations.

Figure 5.2 and Figure 5.3 show the simulated minimum groundwater level over the period of 1900 to 2018 under Baseline and the 4 ML/d extraction, respectively. Figure 5.4 shows deviation between the Baseline (calibration run) minimum simulated groundwater level and this pumping scenario. Figure 5.5 and Figure 5.6 show the simulated average groundwater level over the period of 1900 to 2018 under the Baseline and the 4 ML/d extraction scenario, respectively. Figure 5.7 shows the deviation between the baseline (calibration run) average simulated groundwater level and this pumping scenario. The groundwater dependent ecosystems (GDEs) are also shown on the maps. The locations of the largest drawdown in the pumping scenario and indicated in red.

It should be noted that a groundwater model with a 100m x100m computational grid predicts the average drawdown over the 100m grid. The actual drawdown at the pumping bores and nearby monitoring bores will be significantly greater than the model prediction. Therefore, comparison of the groundwater level timeseries of the Baseline and the pumping case were made at the monitoring bores that are not located right next to the pumping bores. Figure 5.8 to

Figure 5.16 compares the groundwater levels during the two drought periods at the locations marked by red circles in Figure 5.1.

Overall, the groundwater system quickly reaches a quasi-steady state due to its high conductivities. Decline of the groundwater level under the 4ML/d extraction varies greatly across different locations of the peninsula and is generally large in the centre of the peninsula while the coastal area is bound by the sea level condition. On average, the groundwater level was 0.5 to 1m lower under the 4ML/d extraction than the Baseline in the centre of the peninsula.

Figure 5.3 indicates the minimum groundwater level becomes lower than the sea level, which has a risk of salinity intrusion, around Woy Woy Oval/PWW 39. Figure 5.17 shows the simulated groundwater levels at WW39 located next to PWW39. As it can be seen from these graphs, the groundwater level becomes below 0m AHD for several months during the dry season (summer) on multiple occasions over the 100 years simulated. In the vicinity of PWW39/Woy Woy Oval is at a risk of saltwater intrusion as the groundwater level in the surrounding areas towards the coastline also becomes below the average sea level. Other areas stay generally above the sea level.

The groundwater level at the Everglades lagoon declines by 0.5-1m as an average which can affect the GDE (Coastal Swamp Forest). The GDE near Woy Woy Oval will potentially be impacted by the salinity intrusion during drought periods.

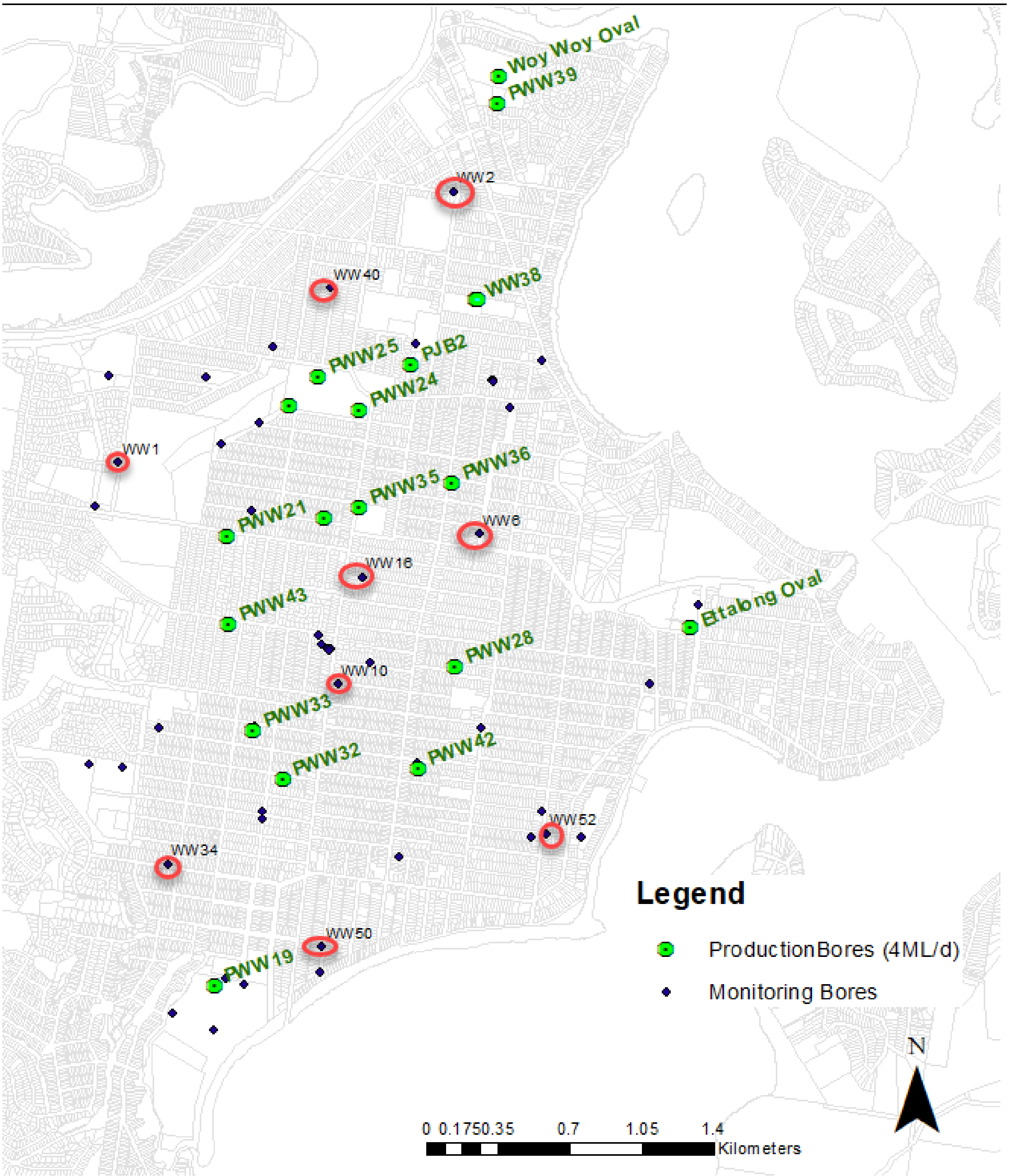


Figure 5.1 Production Bores for portable and recreational purposes and Monitoring Bores

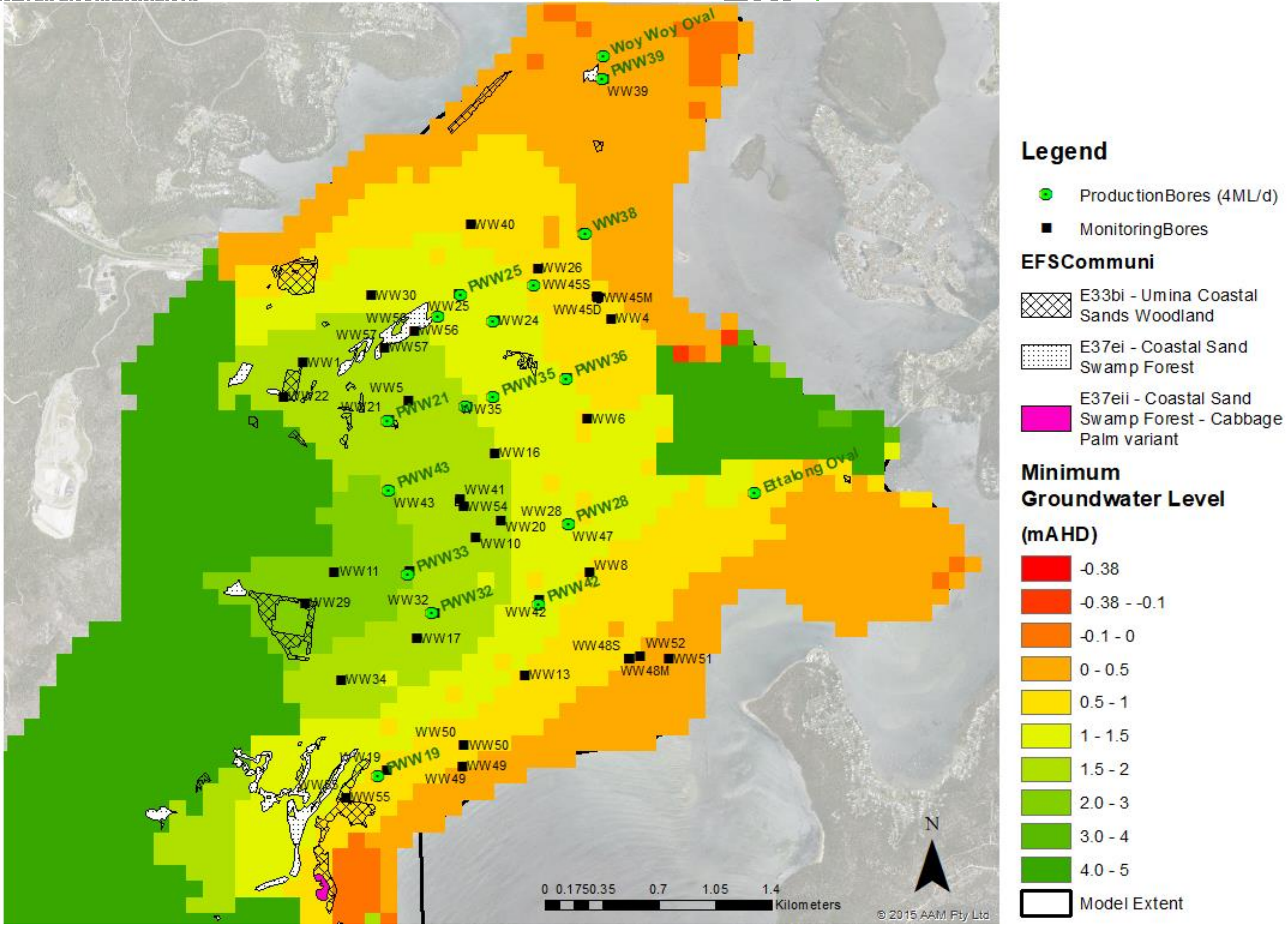


Figure 5.2 Minimum simulated groundwater level from 1900 to 2018 under the existing conditions (Baseline)

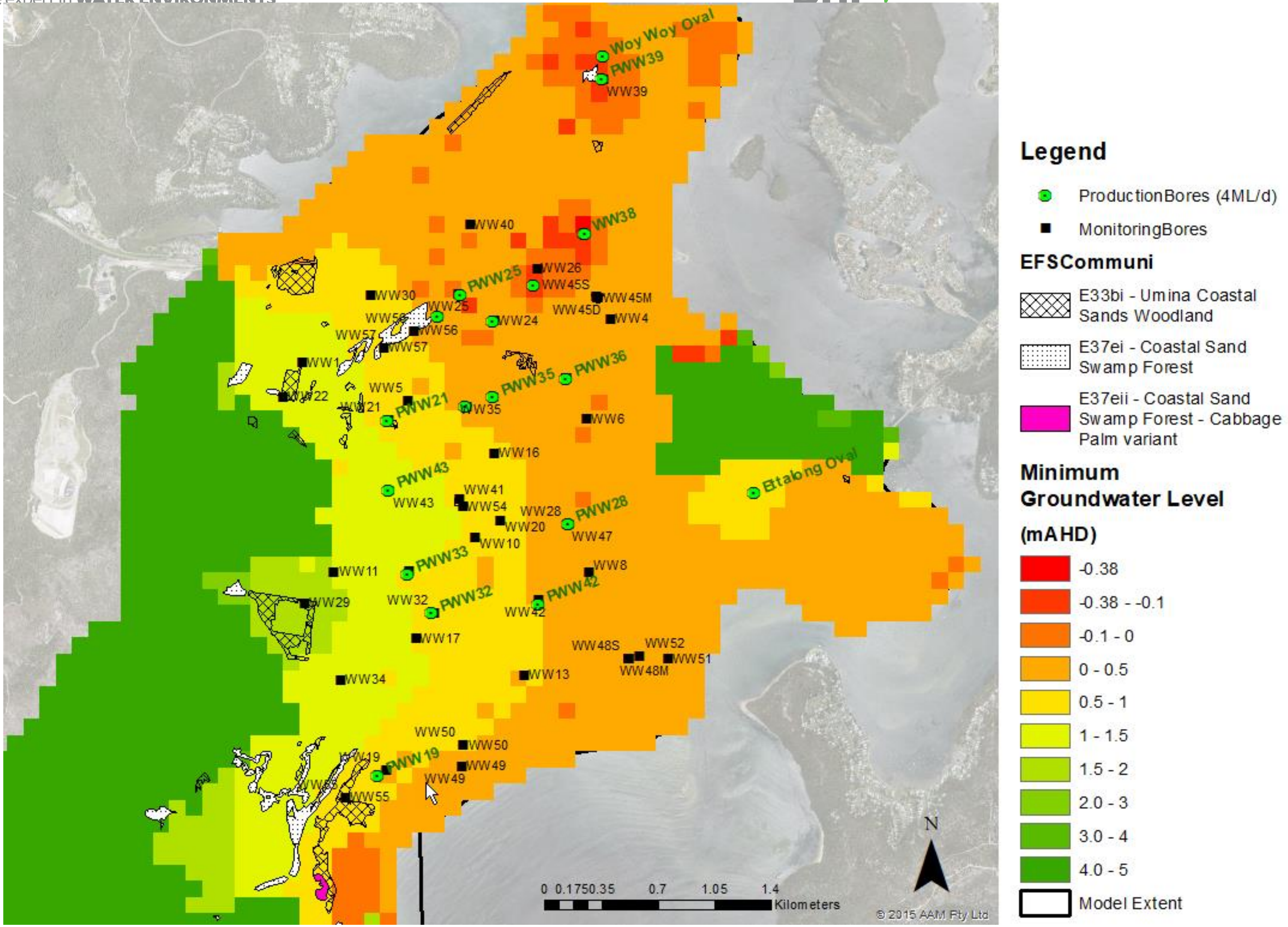


Figure 5.3 Minimum simulated groundwater level from 1900 to 2018 under the 4 ML/d extraction

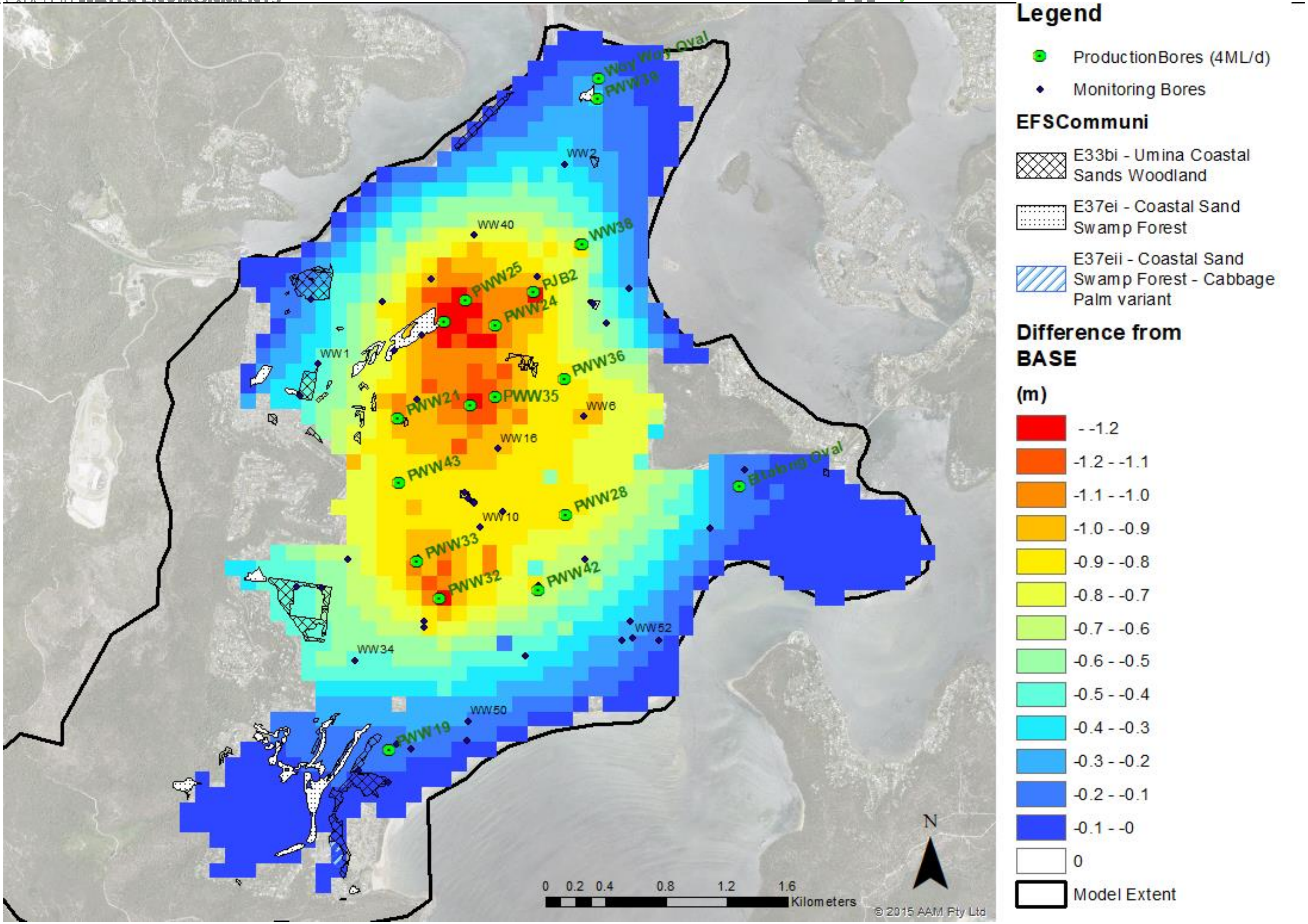


Figure 5.4 Deviation of the minimum groundwater level from 1900 to 2018 compared to Baseline and the Groundwater Dependent Eco Systems

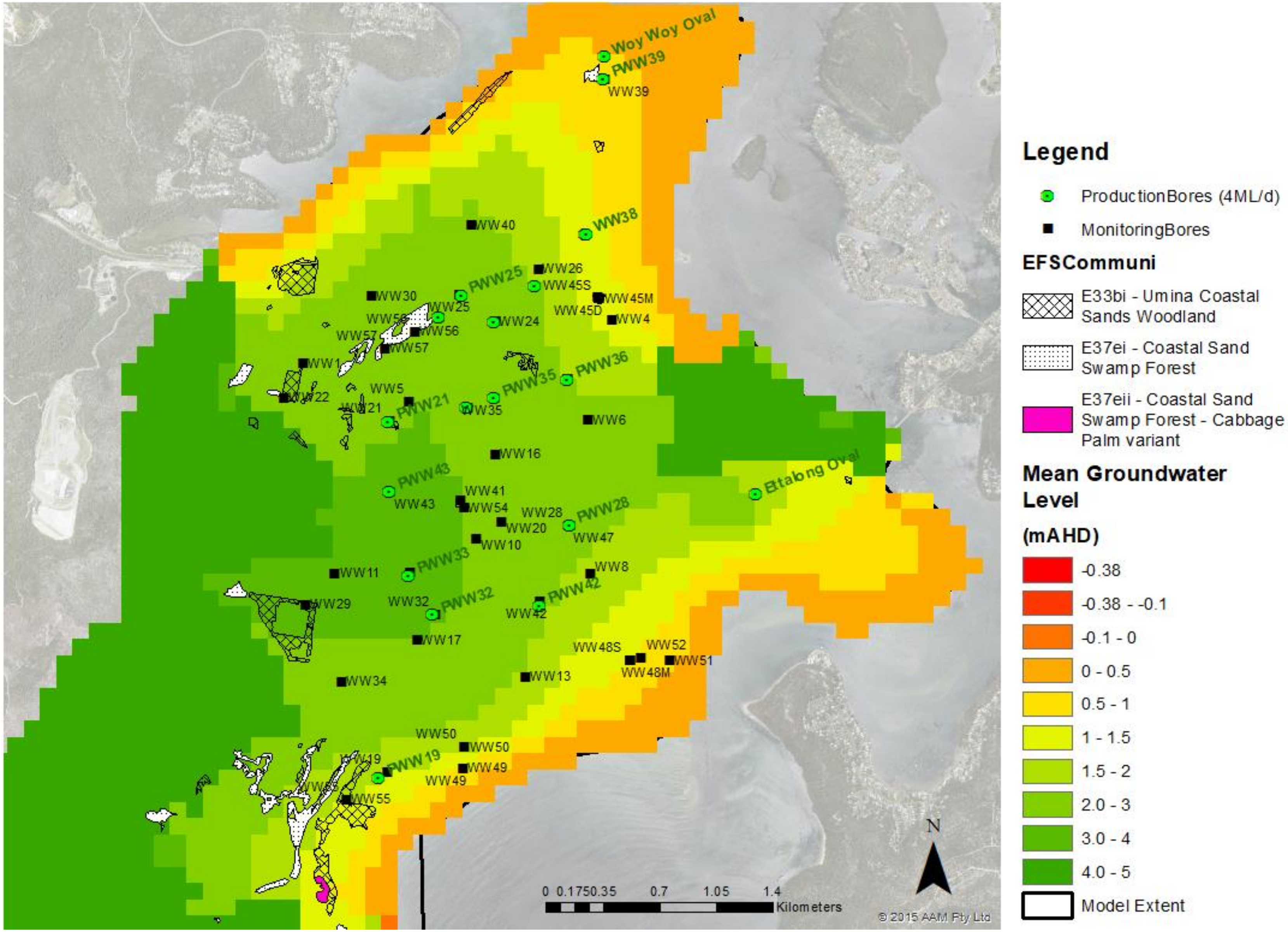


Figure 5.5 Average simulated groundwater level from 1900 to 2018 under the existing conditions (Baseline)

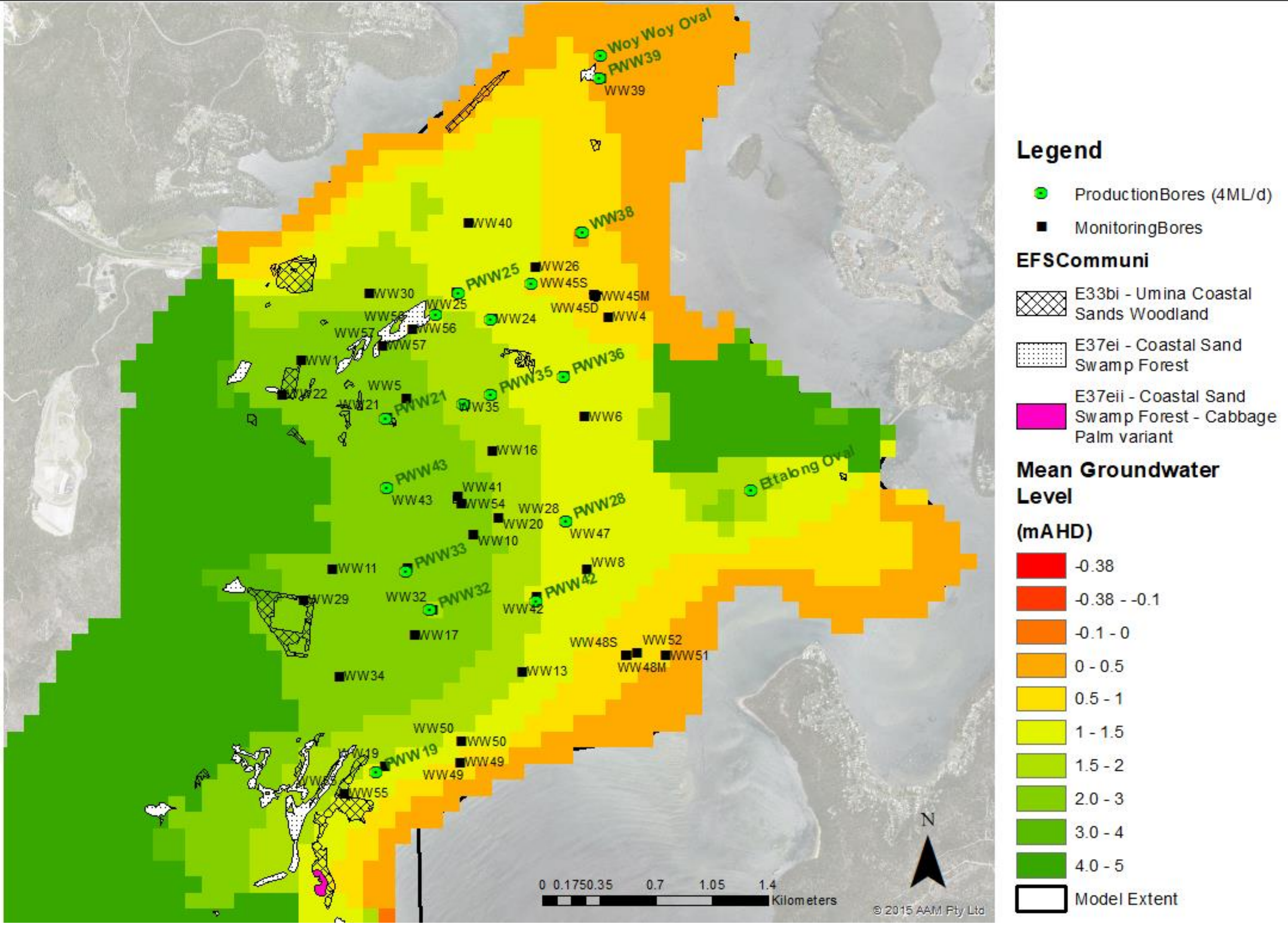


Figure 5.6 Average simulated groundwater level from 1900 to 2018 under the 4 ML/d extraction

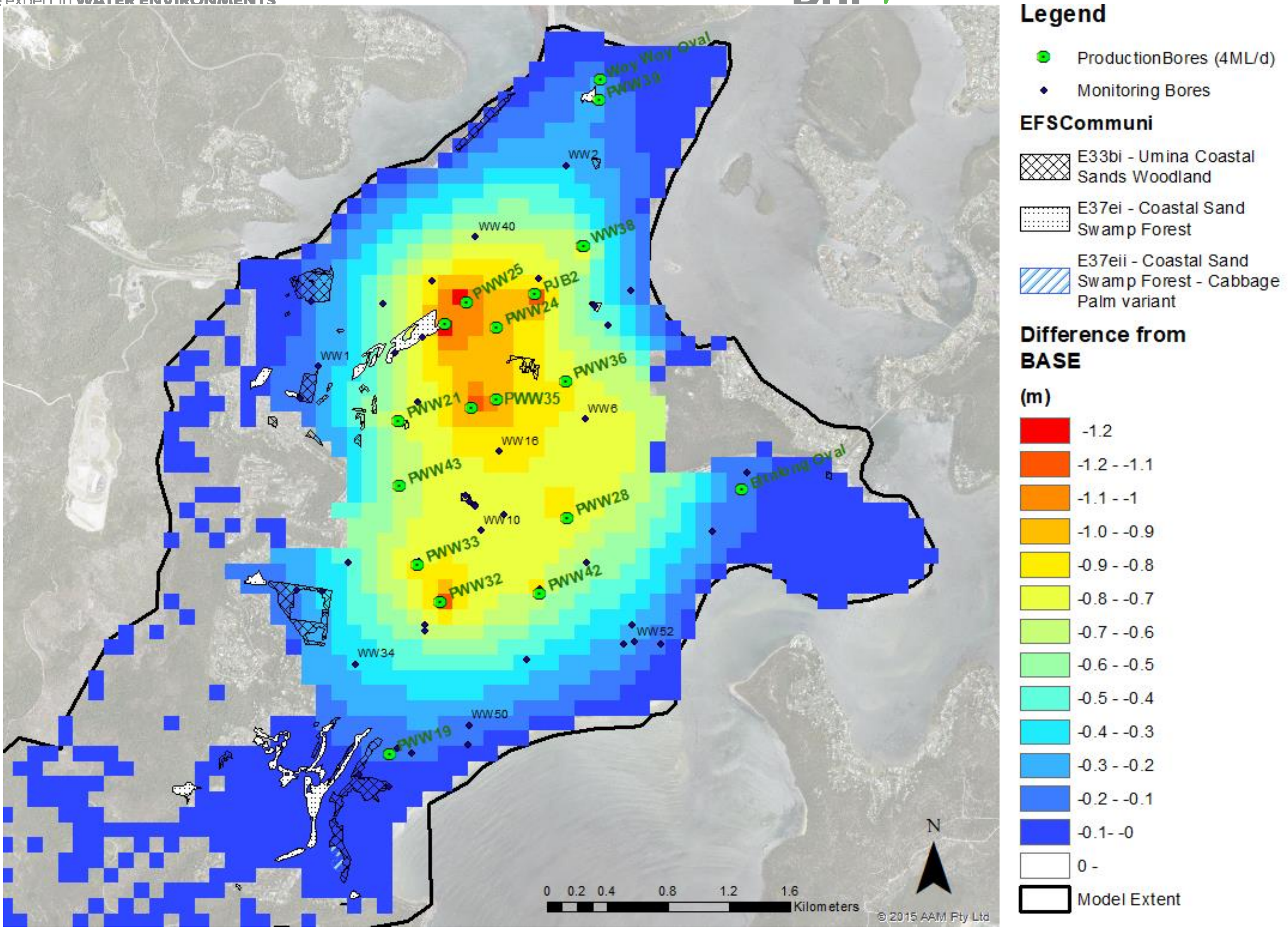


Figure 5.7 Deviation of the average groundwater level from 1900 to 2018 compared to Baseline and the Groundwater Dependent Eco Systems

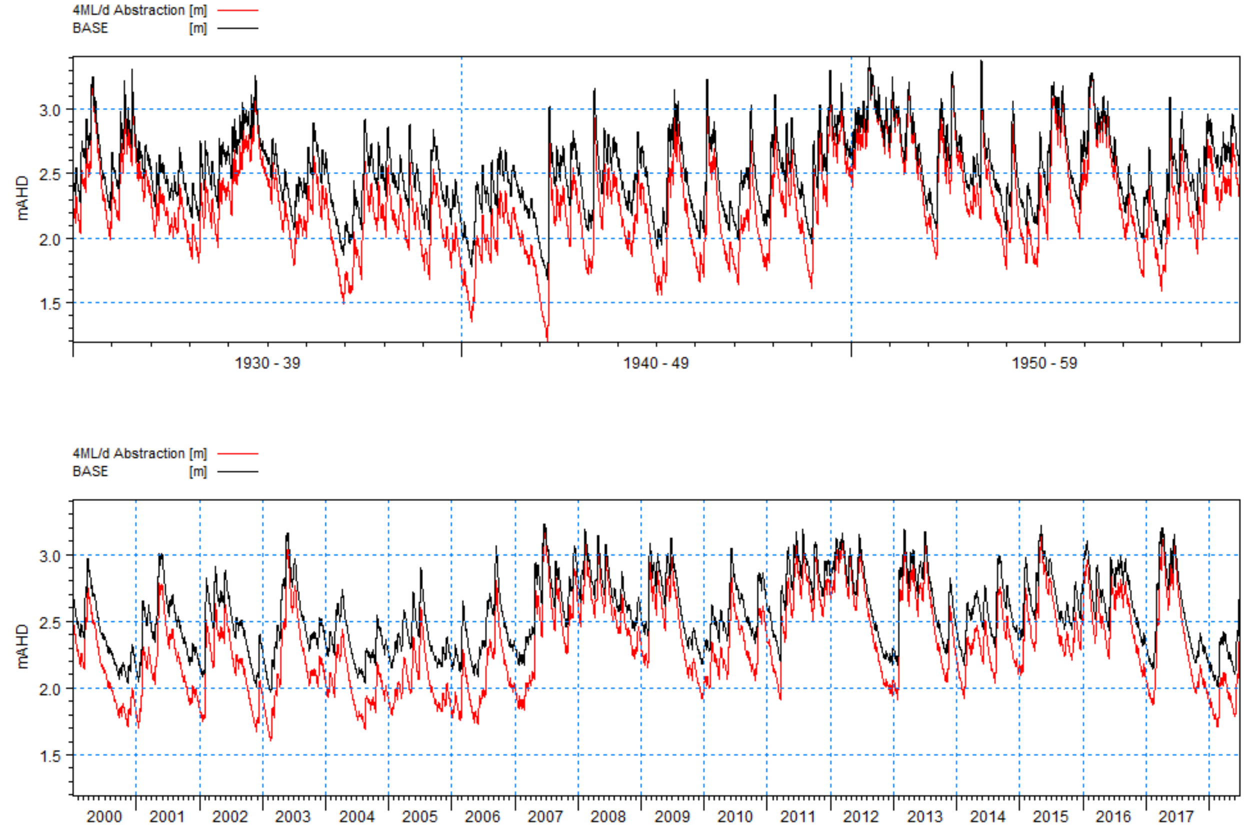


Figure 5.8 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW1 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

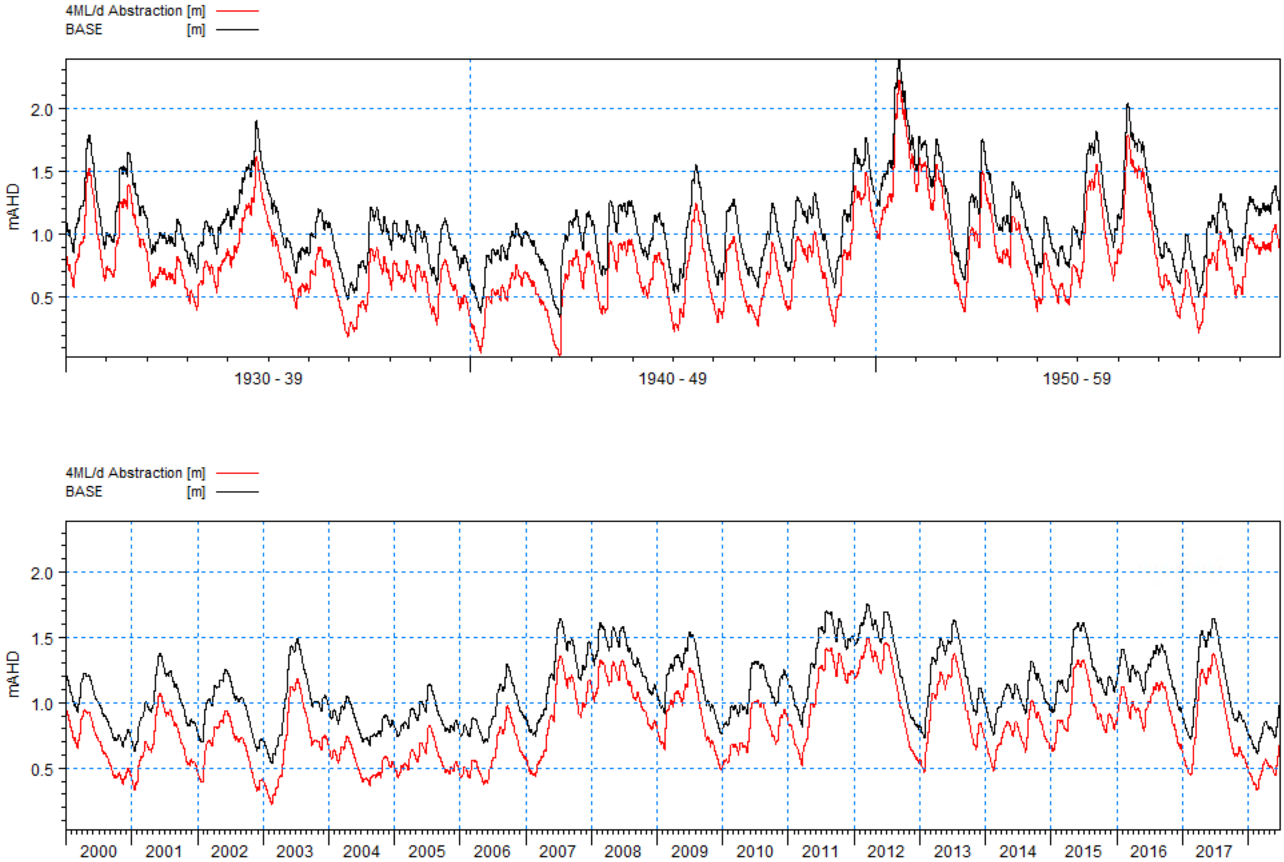


Figure 5.9 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW2 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

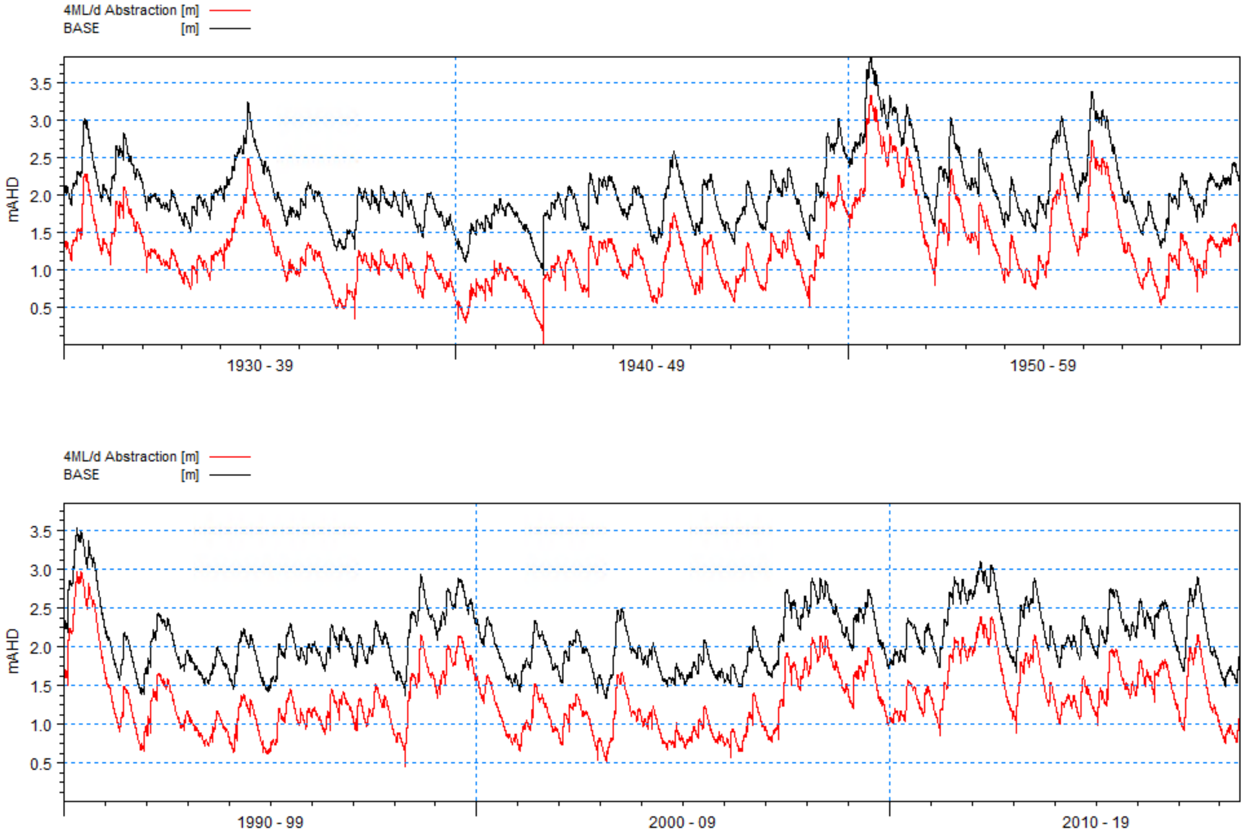


Figure 5.10 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW6 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

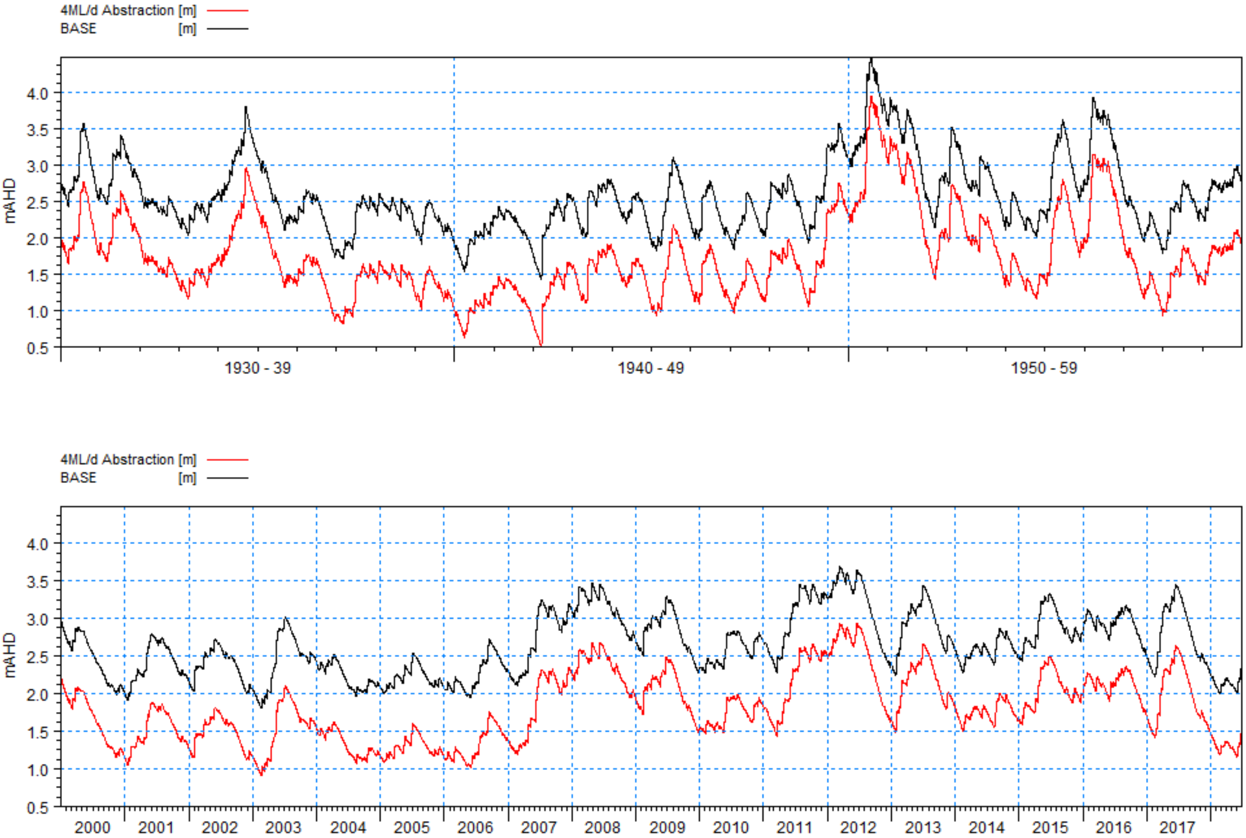


Figure 5.11 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW16 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

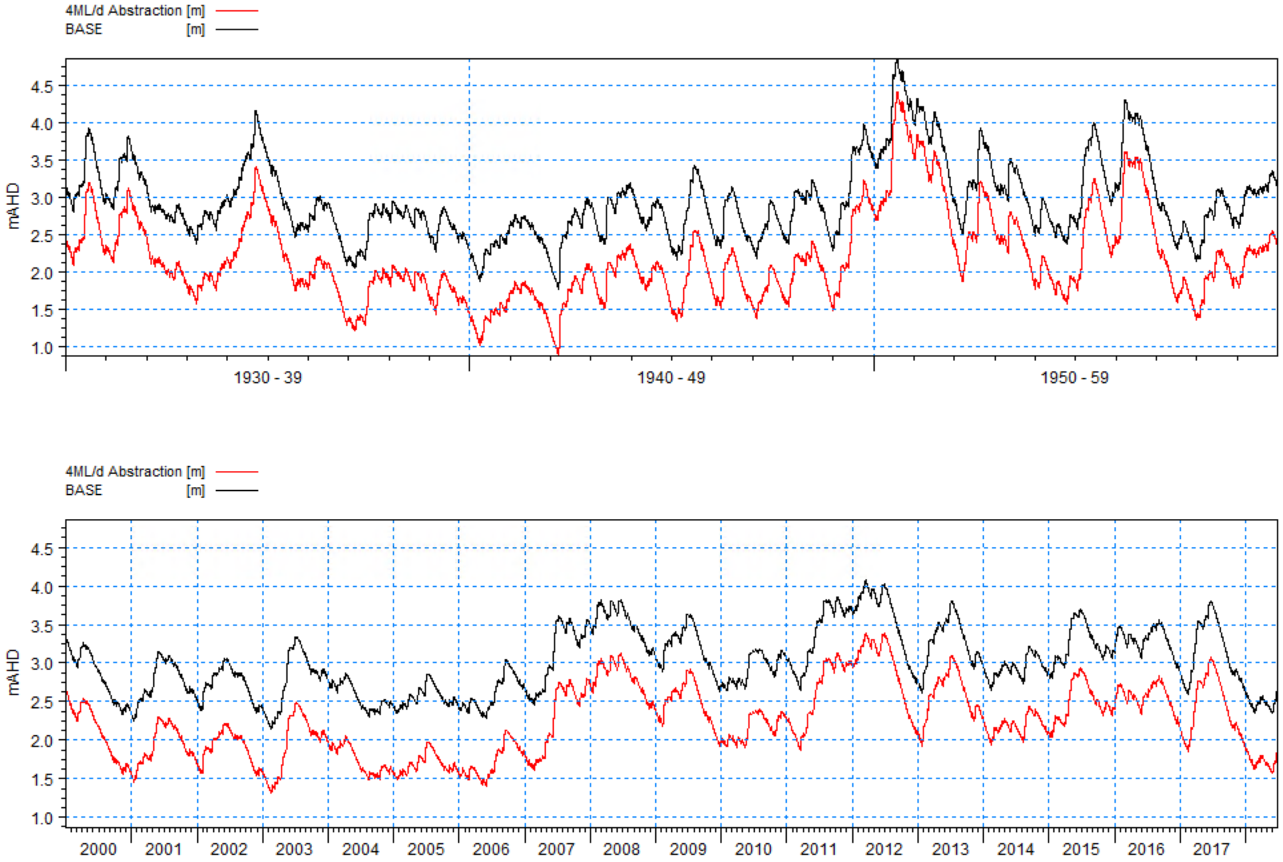


Figure 5.12 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW10 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

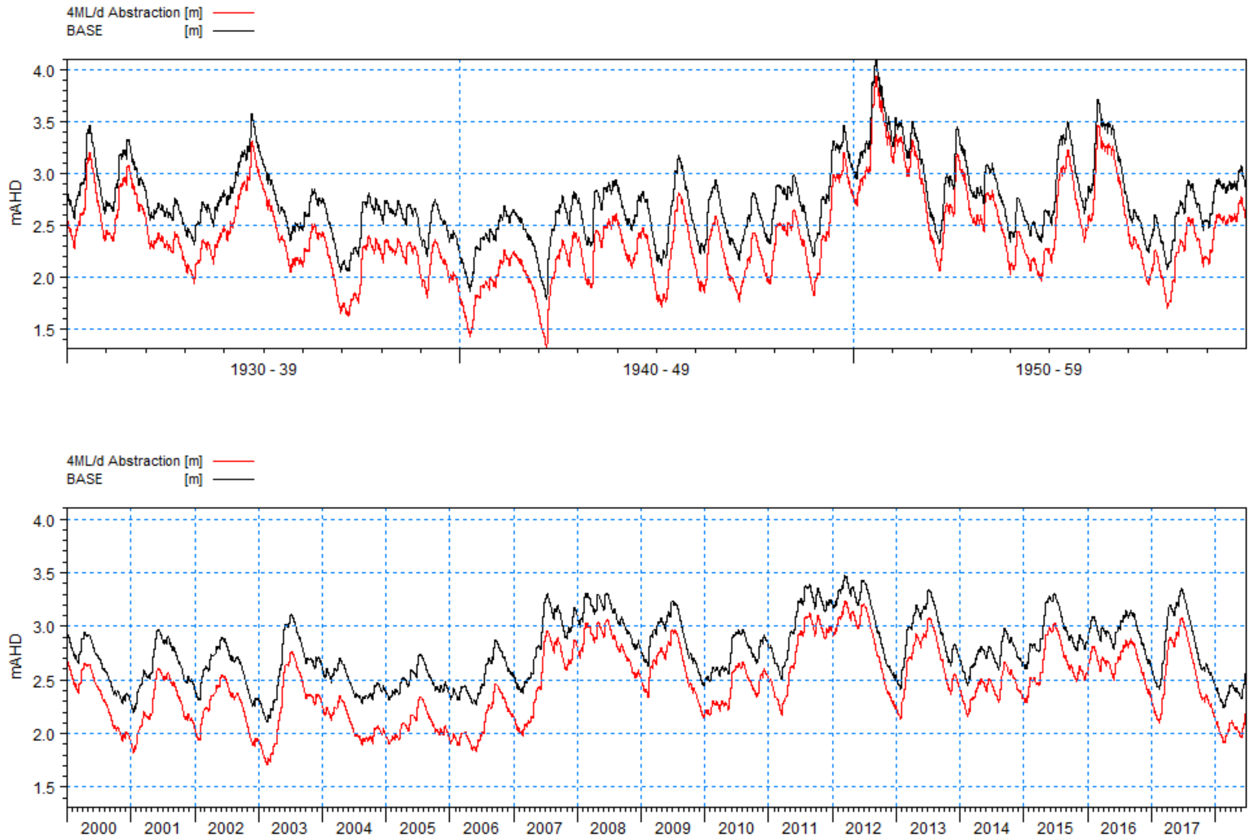


Figure 5.13 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW34 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

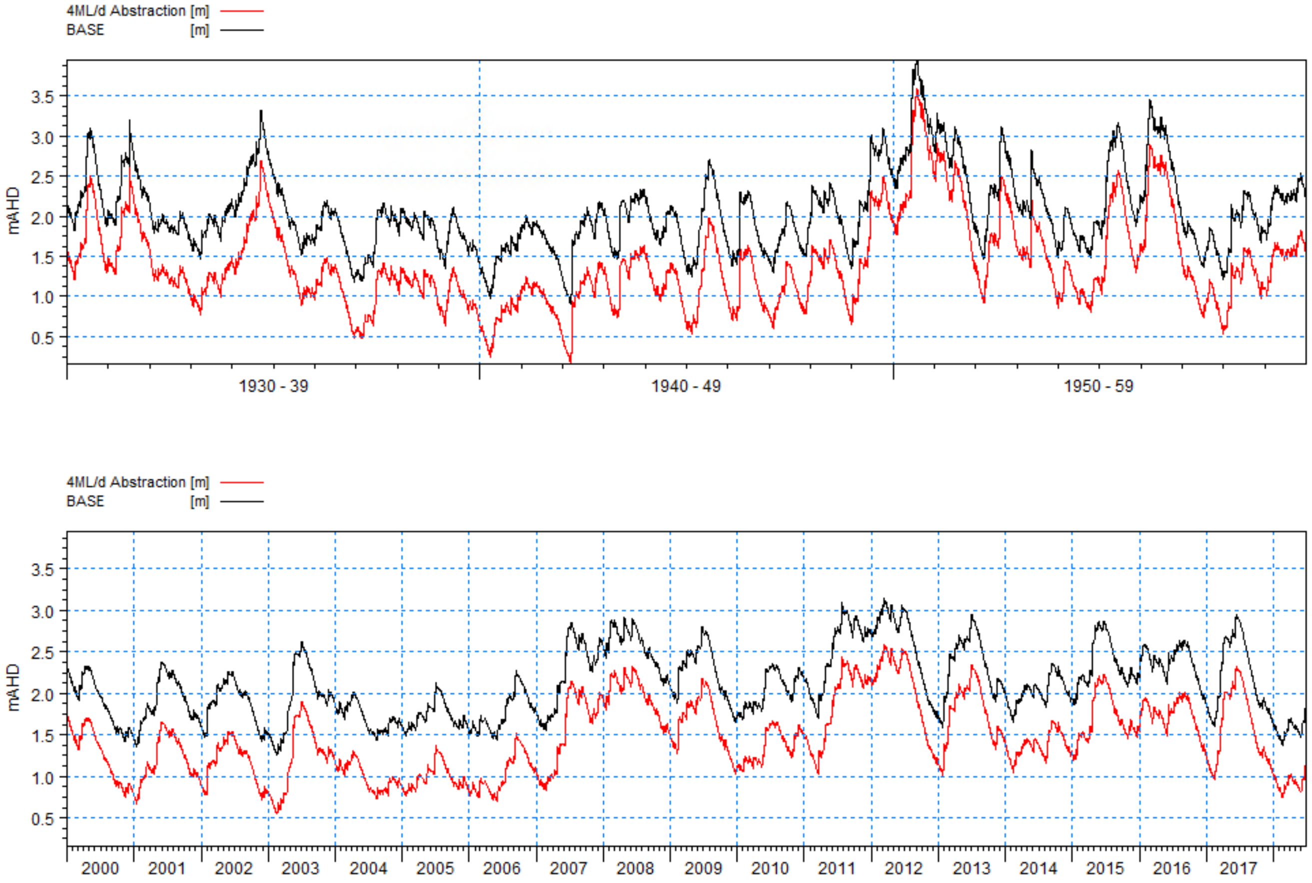


Figure 5.14 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW40 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

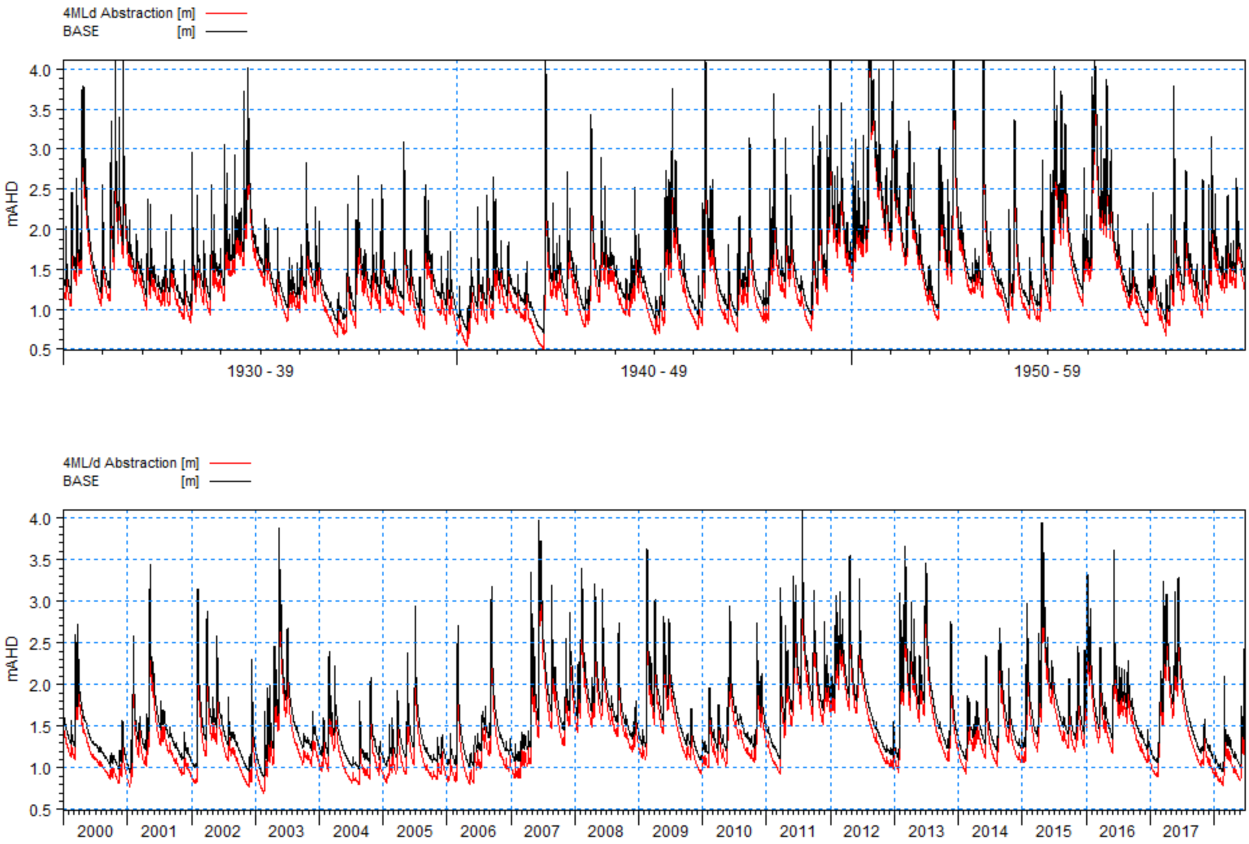


Figure 5.15 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW50 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

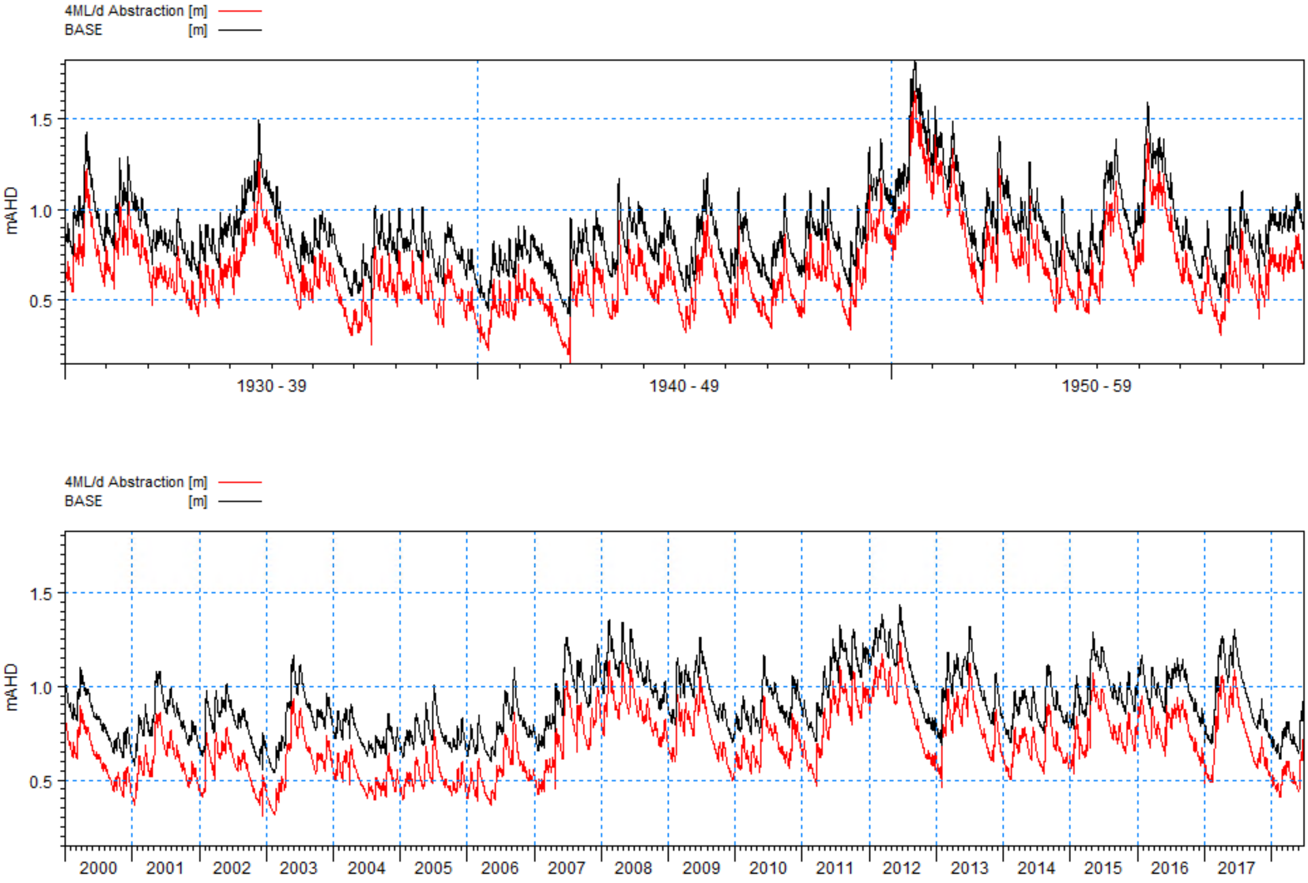


Figure 5.16 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW52 during the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s)

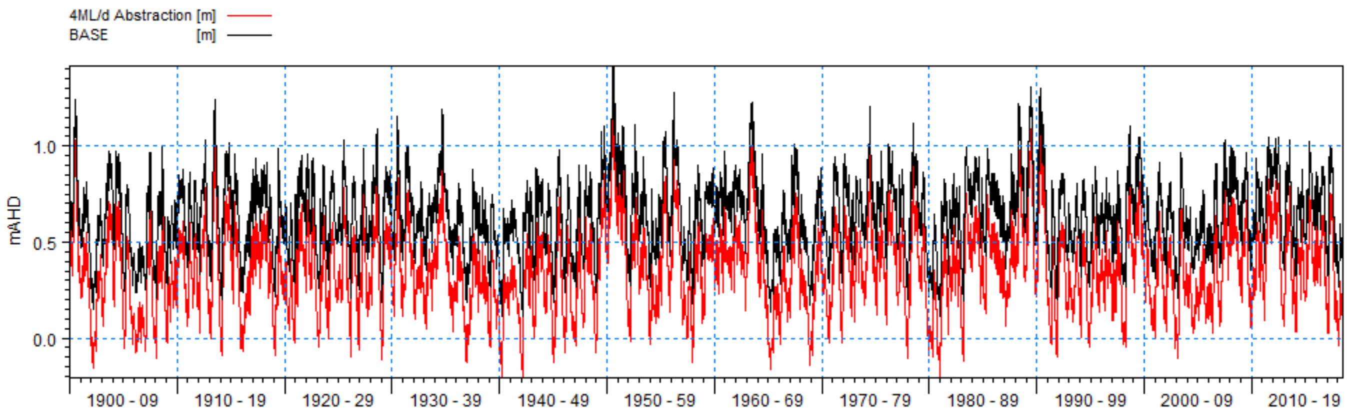


Figure 5.17 Comparison of Base (Black) and Scenario with 4 ML/d extraction (Red) at WW39 next to the production Bore PWW39

6 Everglades Conceptual Models

6.1 Everglades Catchment

The Everglades Catchment is located at north west of the peninsula. It is an artificial storm drainage catchment contributing to the Everglades Main Drain and may differ from the natural surface flow catchment prior urbanisation.

The catchment area is approximately 350ha. The western part of the catchment is a natural forest within the Brisbane Water National Park and the topography can be as high as 150 mAHD. Most other parts of the catchment are relatively flat varying between 4 and 6 mAHD and residential besides the Everglades Golf Course. Previous studies suggest a groundwater mound is located at the southern boundary of the catchment.

The catchment and drainage network is shown in Figure 6.1. The drainage infrastructure is considered to only cater for flow generated by the 1-2 year ARI equivalent rainfall event. (Kahill, 1999).

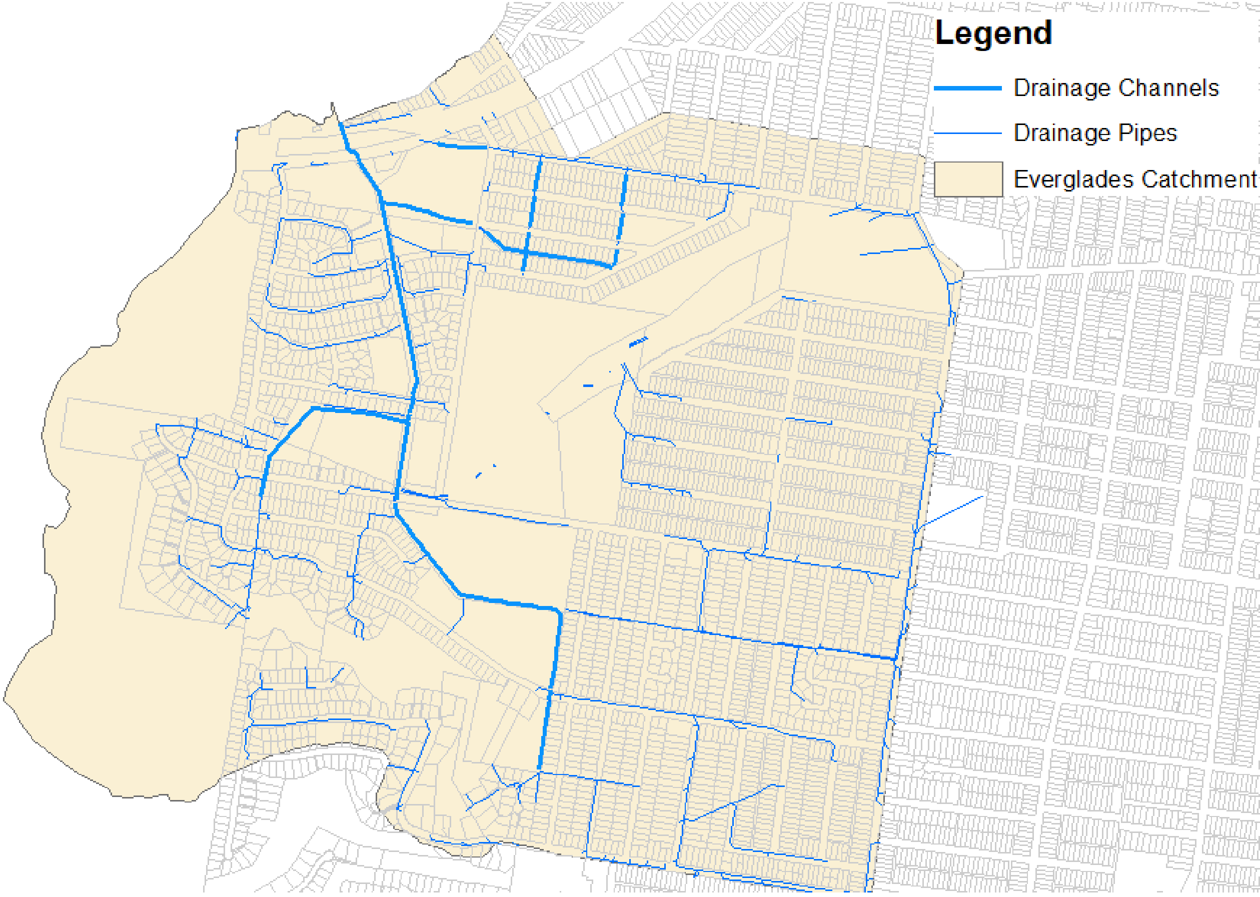


Figure 6.1 Drainage pipes and channels in Everglades Catchment

Many streets in the Everglades Catchment experience frequent small floods known as ‘nuisance flooding’. Typical locations where nuisance flooding is frequently reported include MacKenzie Avenue, Onslow Avenue, Carpenter Street, Veron Road, Connex Road and Shepard Road, Lovell Road.

One of the objectives of this study is to understand the frequent nuisance flooding in the catchment and propose management options which mitigate the nuisance flooding and manage both groundwater and surface water.

6.2 Preliminary Management options

The preliminary integrated water management options (also named “conceptual models” in the study brief and proposal), for the Everglades Catchment, were developed in collaboration with the Central Coast Council and five conceptual management options were presented during a workshop at Council’s Gosford office on 12 September 2018. Each of the options were discussed with Council representatives.

6.2.1 Option 1 – Redirect surface flow

Due to residential development on the Woy Woy peninsula, the surface water flow regime has likely been altered from the natural flow regime. This is particularly apparent in the Everglades Catchment, where the drainage system has designed to convey surface water primarily to the main open channel (western direction), while groundwater flows in an easterly direction.

The redirect surface flow option proposes to connect the Everglades’ stormwater runoff with the adjacent areas by redirecting surface flow towards the east, following the natural groundwater head gradient. A combination of stormwater retention and exfiltration pipes are proposed. This includes pipes along Veron Road and Ryans Road, to establish a connection with the trunk drainage pipe located underneath Trafalgar Avenue (see Figure 6.2). It should be noted that groundwater contours were taken from the preliminary groundwater model simulation for illustration purpose only and the final, calibrated, model may produce different contours.

Key elements considered as part of this option include:

- Efficiency of exfiltration pipes due to large volumes of surface water available for infiltration
- Lessons learned from the trial trunk drainage system at Lane Pine Avenue

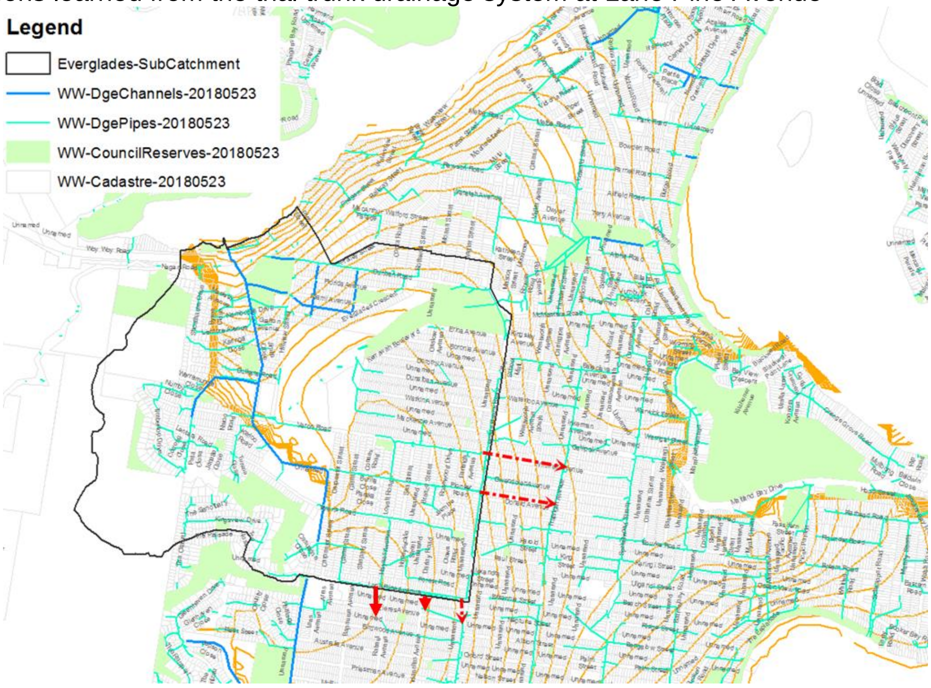


Figure 6.2 Option 1 Conceptualisation: Stormwater runoff is redirected towards the east (indicated by red arrows), following the natural groundwater gradient. The Everglades Catchment is outlined in black, example groundwater contours are shown as orange lines.

6.2.2 Option 2 – Utilisation of potential storage at the existing parks and drainage asset free roads

This option considers utilising storage capacity in existing parks and drainage asset-free roads. The concept is to add underground storage by installing storm traps, soak wells or other types of storage cells underneath roads and traffic intersections, which are then connected to the existing stormwater system.

- Potential locations for park detention storages include MacKenzie Avenue Reserve, Connex Park, Vernon Park, and Ryans Road Reserve (Figure 6.3, left image).
- Potential locations for exfiltration pipes along drainage asset-free roads include Watkin Ave, MacKenzie Ave, Connex Rd, Crown Rd, and Shepard Street (Figure 6.3, right image).

It is also proposed to add swales to road reserves. This will increase the infiltration areas along the roads as well as add further drainage capacity.

The following should be considered in further detail for successful implementation:

- Water quality issues, e.g. contaminated groundwater.
- Duration of construction.
- Location and the need for relocation of utilities.
- Minimum road width and impact on speed limit.
- Reduction of parking areas.
- Local groundwater levels may impact practicability.

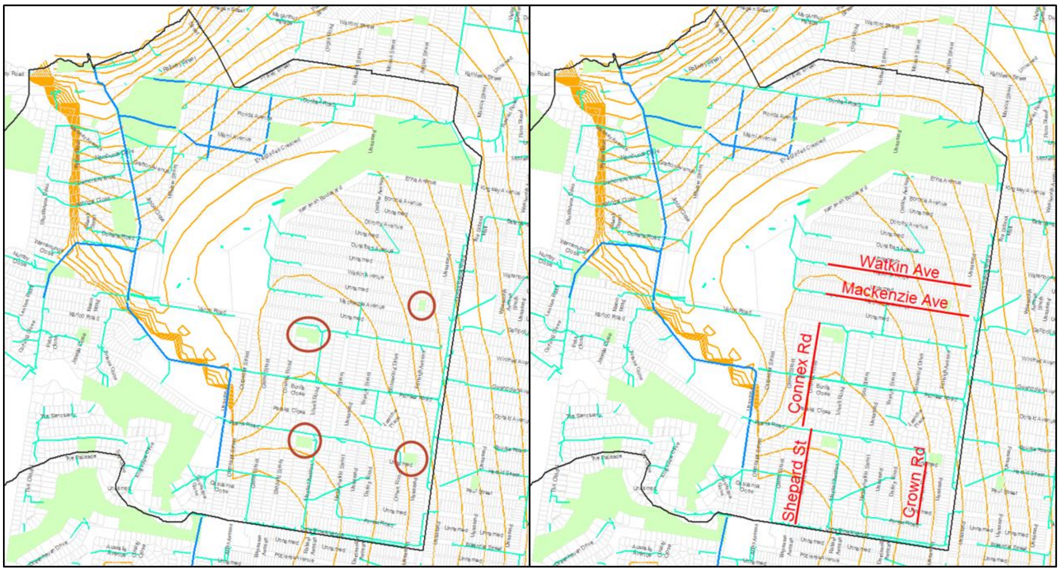


Figure 6.3 Option 2 – Potential locations for water storage (left, indicated by red circles) and exfiltration pipes (right)

6.2.3 Option 3 – Increase storage capacities at existing allotments

Typical dwellings in the Everglades Catchment have very little pervious areas due to construction of granny flats and concrete pavements. As such a large percentage of rainfall falling on the impervious areas will be conveyed to street drainage (and added to the stormwater drainage system, if there is capacity).

The option to increase allotment storage includes the installation of infiltration pads/pits, on-site tanks at the allotments scale. By capturing and storing rainfall at each allotment, runoff from the residential areas can potentially be reduced. Consequently, this can reduce capacity pressure on the existing drainage system. There is also the potential for water supply benefits if incident rainfall can be re-used.

A similar measure was sometimes used to counteract loss of infiltration capacity due to conversion of a relatively small pervious area in an allotment to impervious. This option extends this measure for all allotments in the catchment to test whether it is effective to alleviate existing flooding.

Consideration of building footings and the groundwater table must be given for successful implementation of this option.

A conceptual sketch of a detention tank at the allotment scale is shown in Figure 6.4.

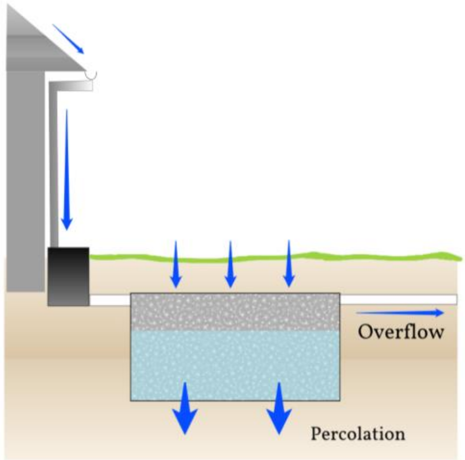


Figure 6.4 Option 3 – Example sketch of detention tank in residential area to increase storage at allotment scale

6.2.4 Option 4 – Strategic reduction of groundwater table prior to a rain event

This option considers extracting groundwater prior to a heavy rainfall event to lower the groundwater table and increase spare infiltration capacity. There are several production bores available within and near the Everglades Catchment (Figure 6.5).

The following should be considered in further detail for successful implementation:

- Pumping can be costly.
- The duration of pumping required and effectiveness of the option is reduced if pumping does not start early enough; increasing the frequency of pumping should be considered.
- Impacts on groundwater-dependent ecosystems (GDEs), namely Paperbark Swamp Forest and Umina Coastal Sandplain Woodland in the Woy Woy catchment (Conacher, 2005).
- Pumping activities are potentially beneficial to water supply activities.
- There is the opportunity to add additional pumps, at strategic locations.

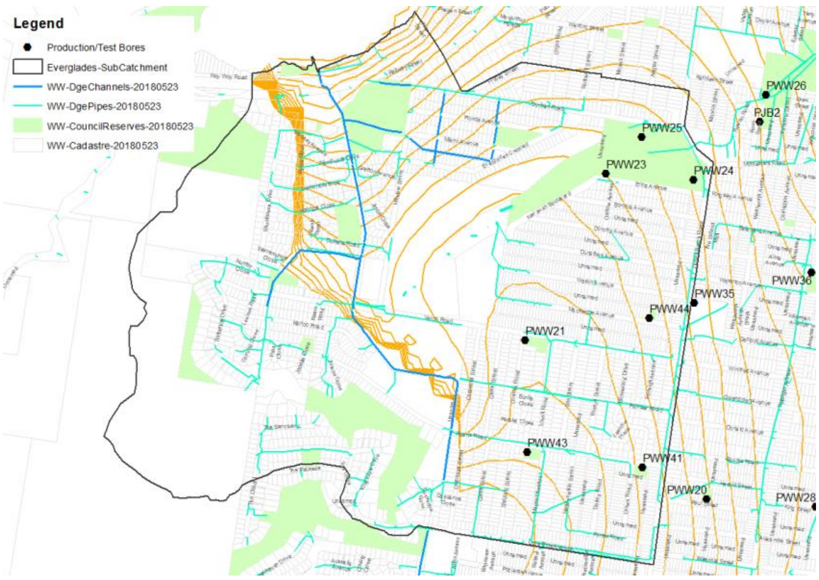


Figure 6.5 Production bores in Everglades Catchment

6.2.5 Option 5 – Rezoning and redevelopment of Everglades Catchment

This option proposes changing the zoning of a sub-area within the Everglades Catchment and redeveloping the area to be more flood resilient. The redevelopment should incorporate green infrastructure that can increase infiltration and storage capacity. Green infrastructure can include wetlands, lagoons, bioinfiltration, raingardens, park avenues, flood corridors, etc.

Figure 6.6 shows the approximate surface drainage catchments Area A, B and C in the Everglades Catchment, following the current layout of streets. Area A is an independent surface flow catchment while Area C flows into Area B through the storm drainage. While the surface drainage catchments can be delineated by mild topographic differences and streets, the groundwater catchment is continuous and covers all three areas, with the groundwater mound sitting between Area A and Area B.

Area B sitting above the groundwater mound is considered as a good location for redevelopment, as rainfall on the site can be locally captured and retained by the green structures in addition to allowing ponded water due to the groundwater rise (Figure 6.6).

At the same time, the number of dwellings can be increased in the redevelopment area. This aligns well with Council's policy to increase population density on the peninsula.

The model results will indicate where possible areas for redevelopment could be located. The following will have to be clarified for successful implementation:

- the number of dwellings and types of green structures that will be most efficient.
- matters around the purchasing of land for rezoning by the State Government.

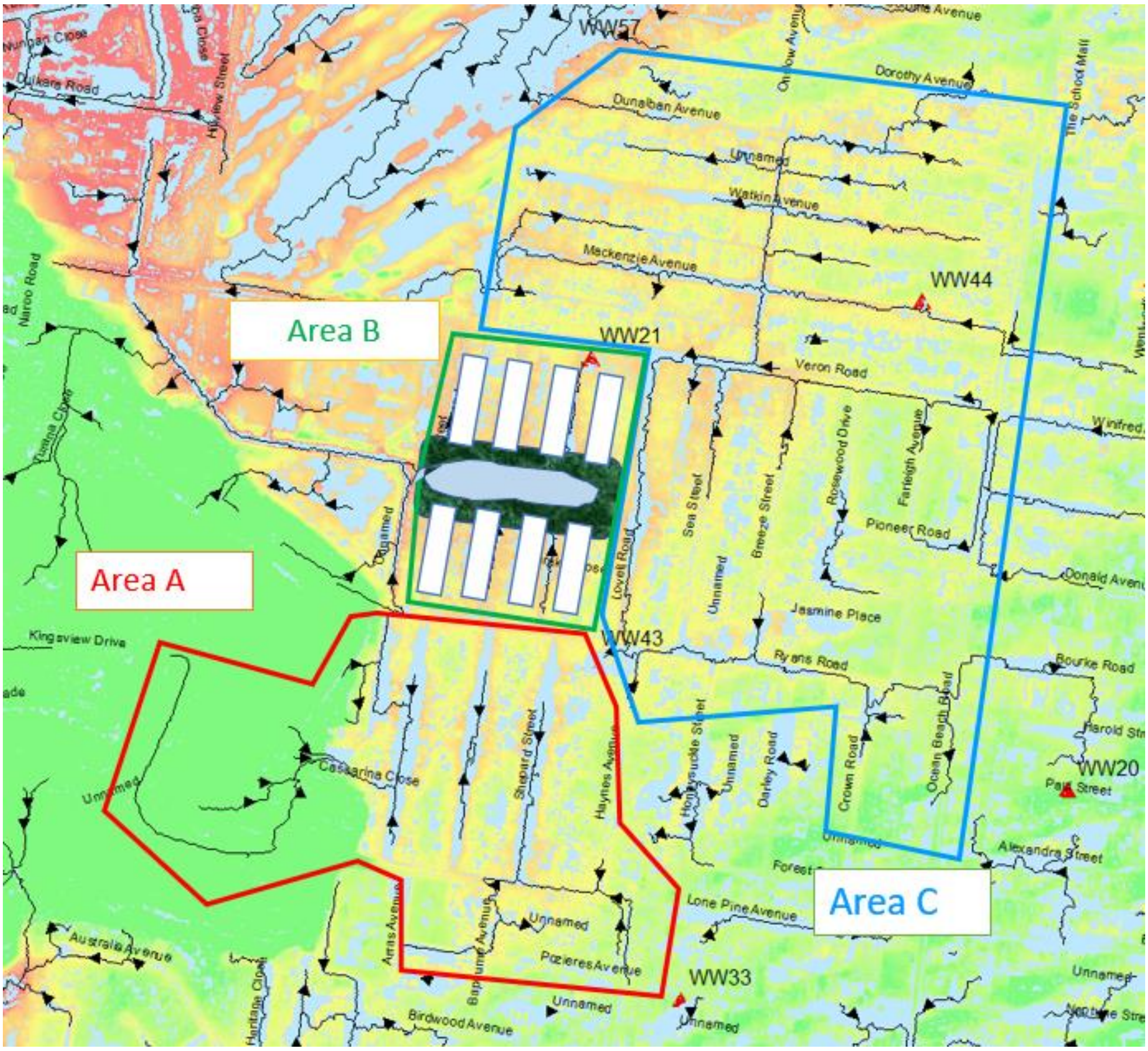


Figure 6.6 Conceptual sketch showing a redeveloped area near the groundwater mound within the Everglades Catchment

7 Development of the Everglades flood model

7.1 Model Setup

The peninsula groundwater model was trimmed to the Everglades Catchment area and the model resolution was increased from 100m of the peninsula groundwater model to 5m grid. Figure 7.1 shows the trimmed model extent with the topography resampled to 5m and the drainage network included in the model.

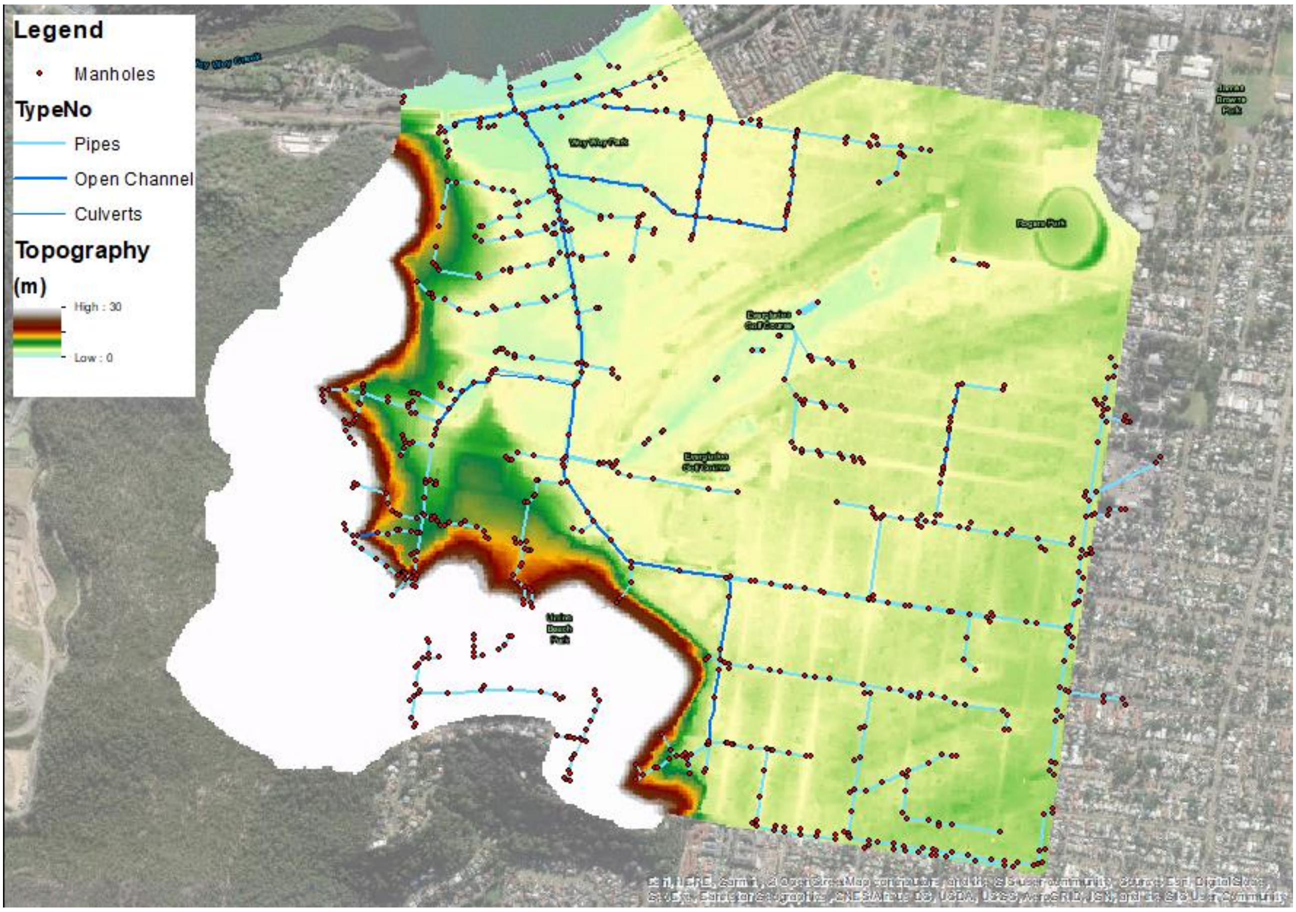


Figure 7.1 Everglades model extent, Topography and Drainage network

7.1.1 MIKE Urban

As shown in Figure 7.1, the drainage network was trimmed to the Everglades Catchment. As described in Section 2.5, the invert levels were often absent from the data provided. Where data was absent, pipe invert levels are estimated from the adjacent pipes with available invert levels or from the estimated pipe depths. The invert levels have been manually adjusted to ensure that a gradient was maintained along the network towards the outlets.

The open channels such as the Main Drain were also modelled in MIKE Urban.

7.1.2 MIKE SHE

The peninsula MIKE SHE model was altered to be more suitable for assessment of the management options.

This update included:

- Refinement of the model to 5m resolution.
- Refinement of the model domain from the peninsula to the Everglades Catchment.
- Alteration of the unsaturated zone module from Two-Layer to Gravity Flow.
  While the two-layer UZ model saves computational time compared to Gravity Flow, it cannot assess reduced infiltration rates depending on the groundwater table. Gravity Flow, a simplified Richards Equation, can assess infiltration based on the groundwater level.

The boundary condition for the saturated zone was extracted from the peninsula model.

7.2 Everglades model calibration

Although it was originally proposed to calibrate the model against the 1988 event, it was discussed with Council that it would be more beneficial to calibrate the model against smaller events which cause nuisance flooding.

7.2.1 Calibration Data

Surface water records in the Woy Woy peninsula are limited. There are no flow or water level records at the Main Drain or stormwater drainage pipes.

Residents in the Woy Woy peninsula have formed a Facebook group which contains posts regarding flood incidents in the Woy Woy peninsula photos. Table 7.1 summarises the events in March and April 2017 which were reported by residents in the Facebook group.

Assuming that these reports were reasonably accurate, the timing of flood incidents have been compared with the surface flooding at nearby groundwater monitoring bores.

Table 7.1 Example of flood events and locations reported by residents in 2017

Date	Approximate time	Locations where ponded water was observed
14/03/2017	15:00	MacKenzie Ave, Connex St, Veron Road near Sea St
15/03/2017	7:50	MacKenzie Ave, Veron Rd
22/03/2017	Not specified	Carpenter St, Veron Rd, Lovell Rd
30/03/2017	Not specified	MacKenzie Ave
4/04/2017	8:40	MacKenzie Ave, Onslow Ave

The Everglades model was run from 13 March 2017 to 6 April 2017. The recorded rainfall at Woy Woy Tip is used as the rainfall input timeseries and is shown in Figure 2.1. The initial groundwater level and the saturated zone boundary were extracted from the 100-year simulation of the peninsula groundwater model.

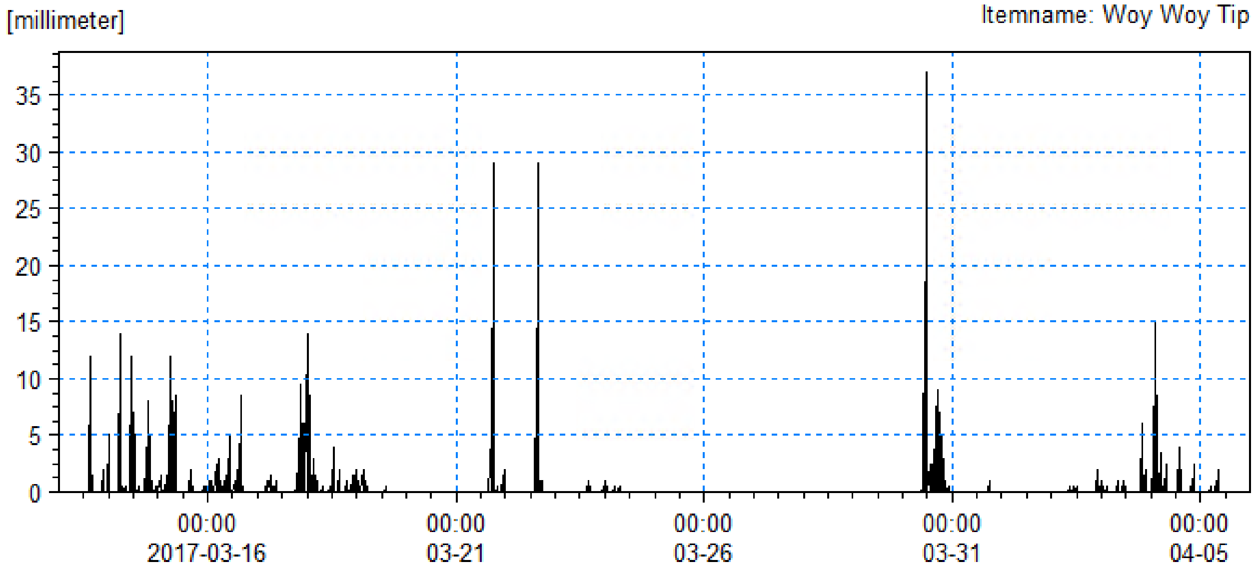


Figure 7.2 Rainfall between 13 March and 6 April 2017

Calibration parameters were 2D Manning's roughness and the exchange coefficient used to calculate MIKE SHE and MIKE Urban exchange flow.

7.2.2 Calibration outputs

Simulated water depth at 4/04/2017 8am is relatively low compared to the photo posted by a resident on the Facebook group. There was no reporting of flooding at Watkins Street but the model simulated frequent flooding at the intersection of Watkins Street and Onslow Ave.

Consistently high water level simulated at the south end of Carpenter Street is due to the boundary condition which was extracted from the peninsula groundwater model.

However, overall flooding at MacKenzie Ave, Onslow Ave, Veron Rd, Carpenter St, Lovell Street and Connex Street was well reproduced, as reported in Table 7.1.

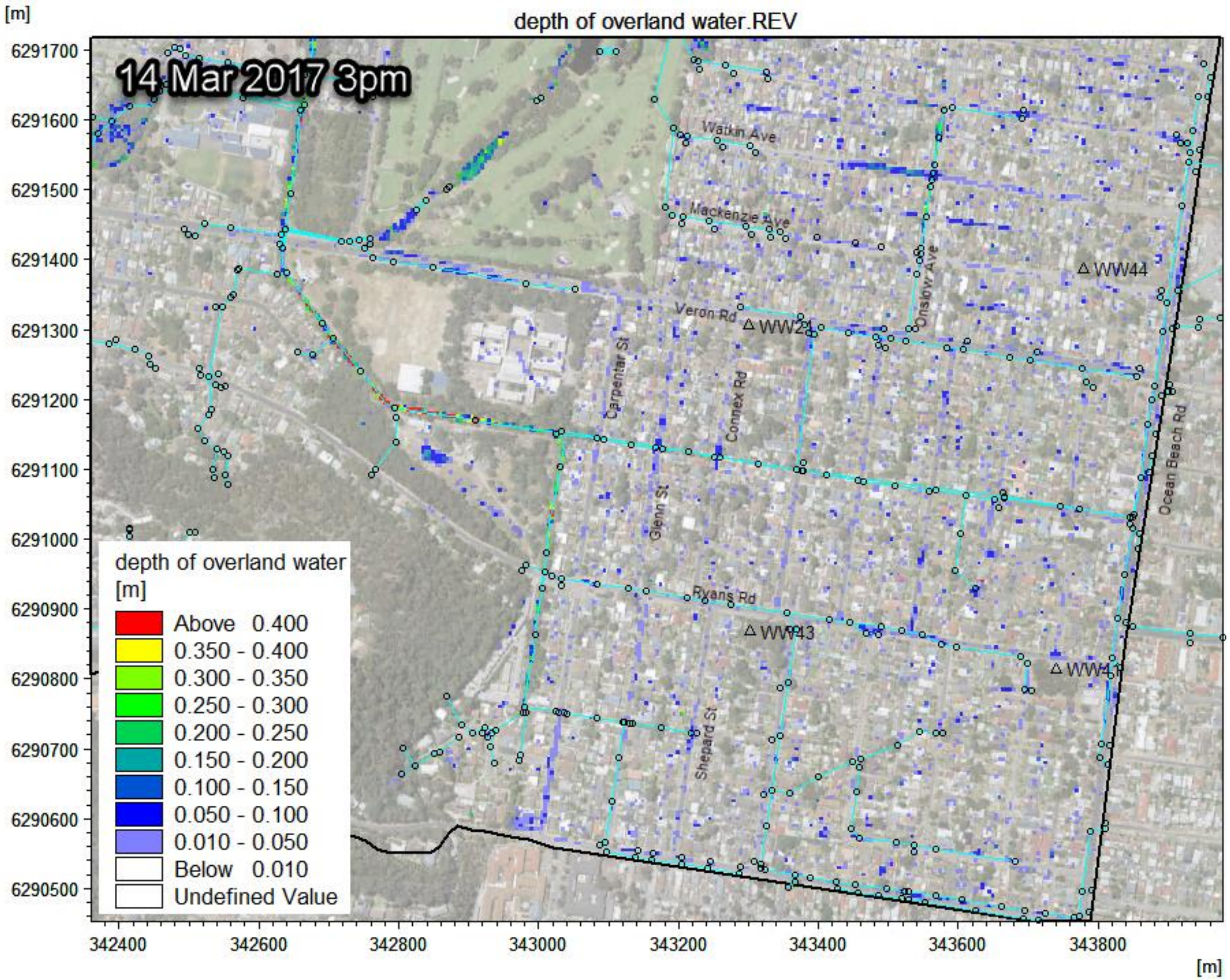


Figure 7.3 Simulated water depth (14 Mar 2017 3pm)

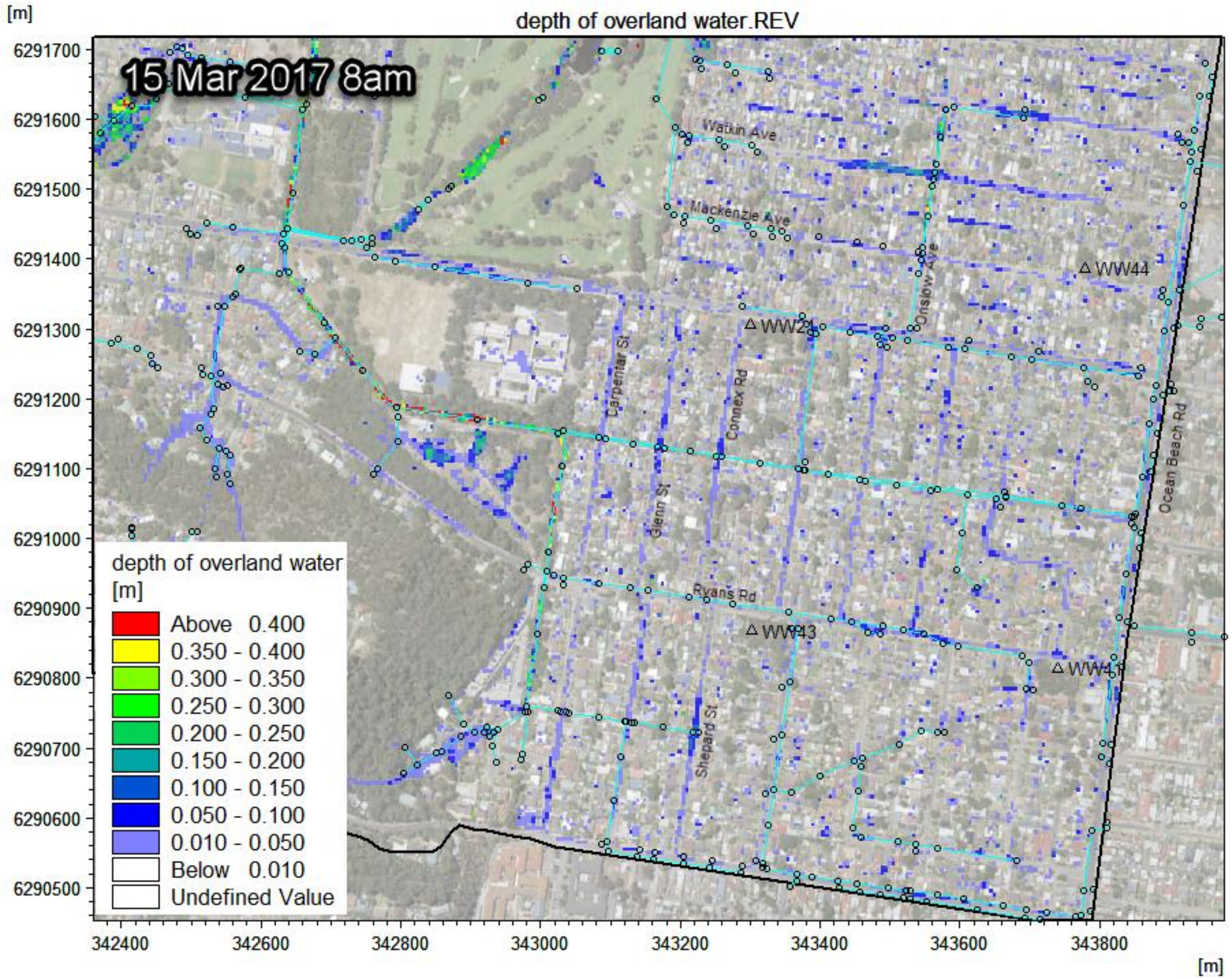


Figure 7.4 Simulated water depth (15 Mar 2017 8am)

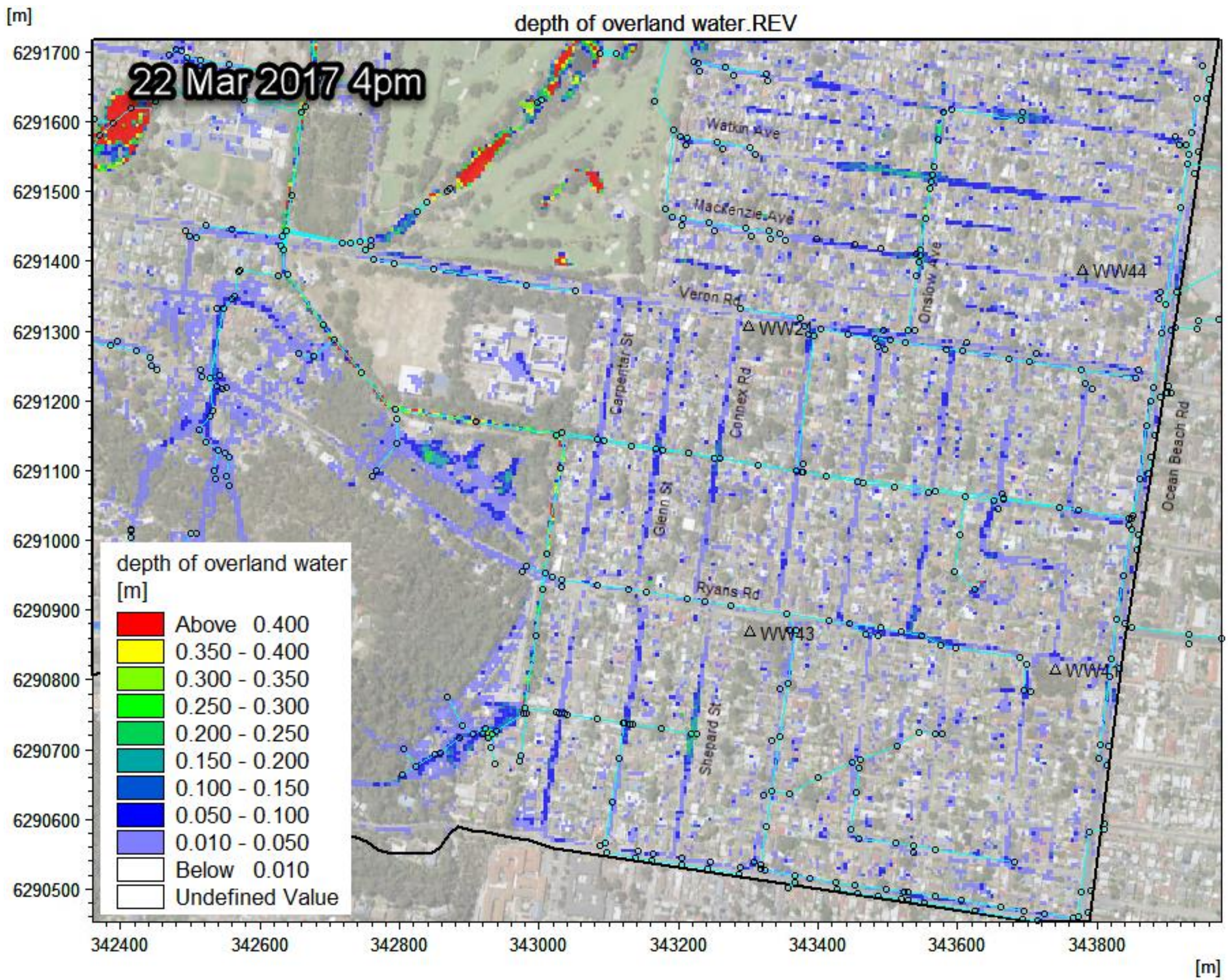


Figure 7.5 Simulated water depth (22 Mar 2017 4pm)

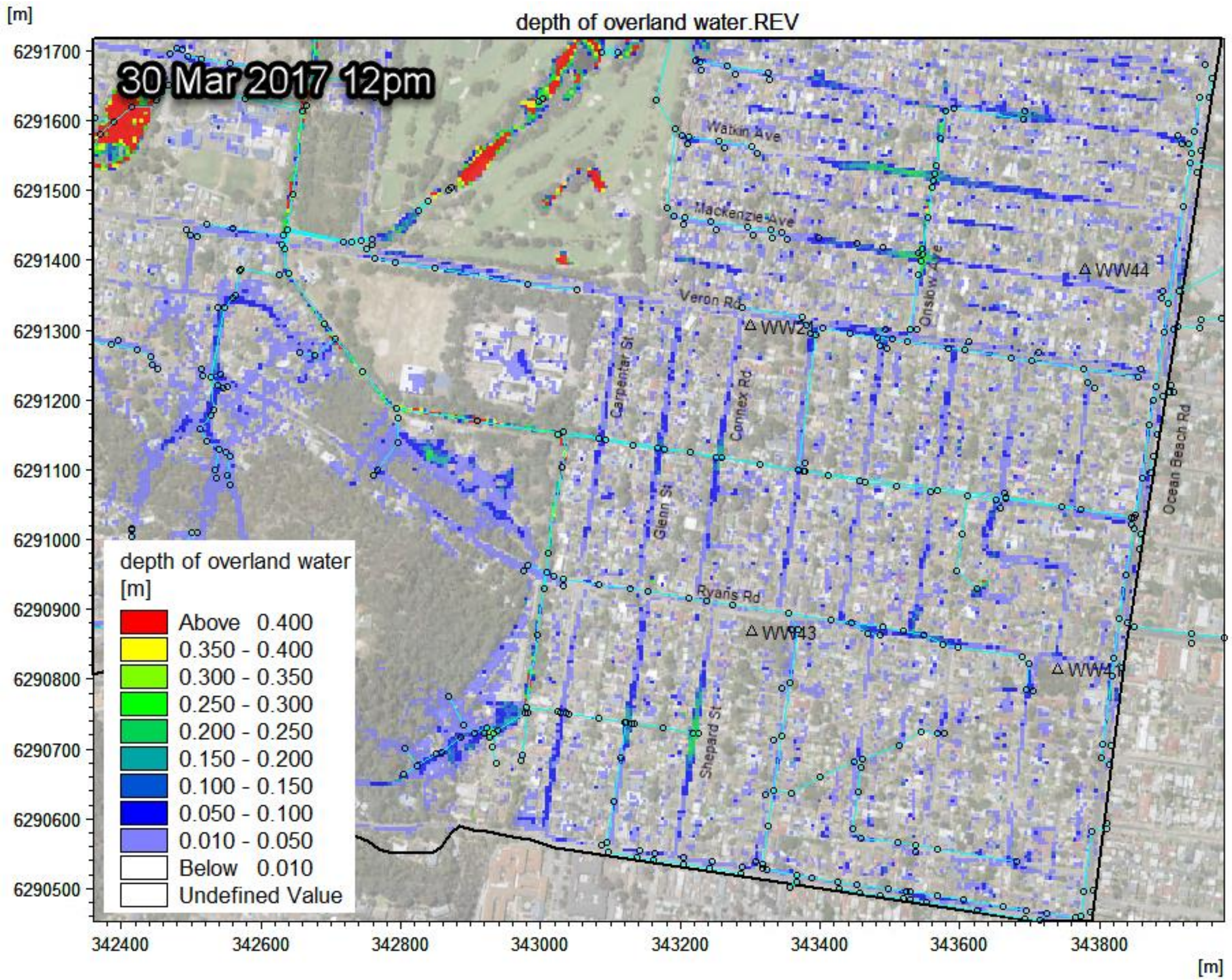


Figure 7.6 Simulated water depth (30 Mar 2017 12pm)

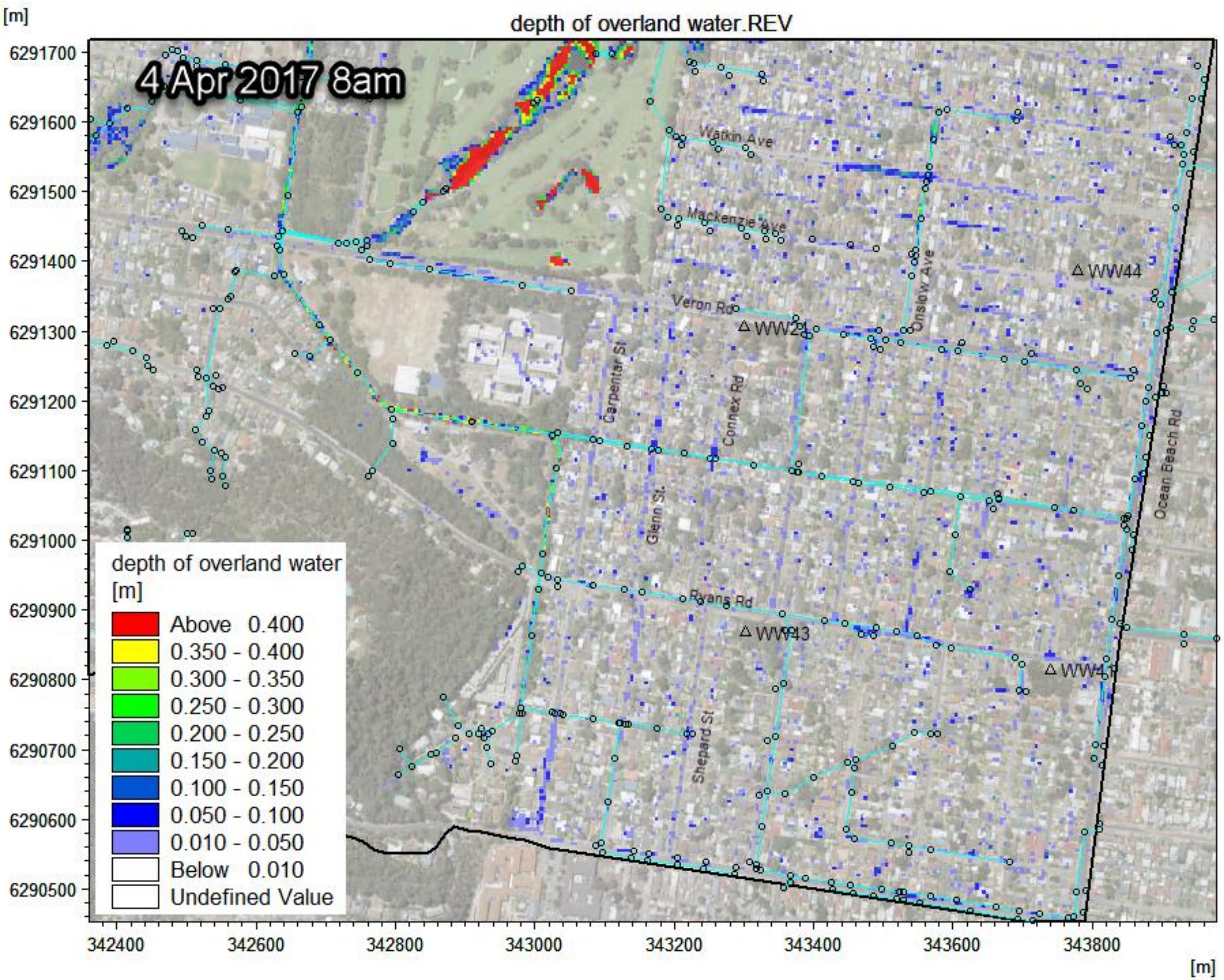


Figure 7.7 Simulated water depth (4 April 2017 8am)

8 Understanding nuisance flooding

As outlined in Section 7.2, residents report flooding incidents in a Facebook group page. Table 7.1 summarises the events in March and June 2017 which were reported by residents in the Facebook group. Figure 8.1 shows the rainfall (resampled to daily) in blue and the reported incidents in red arrows.

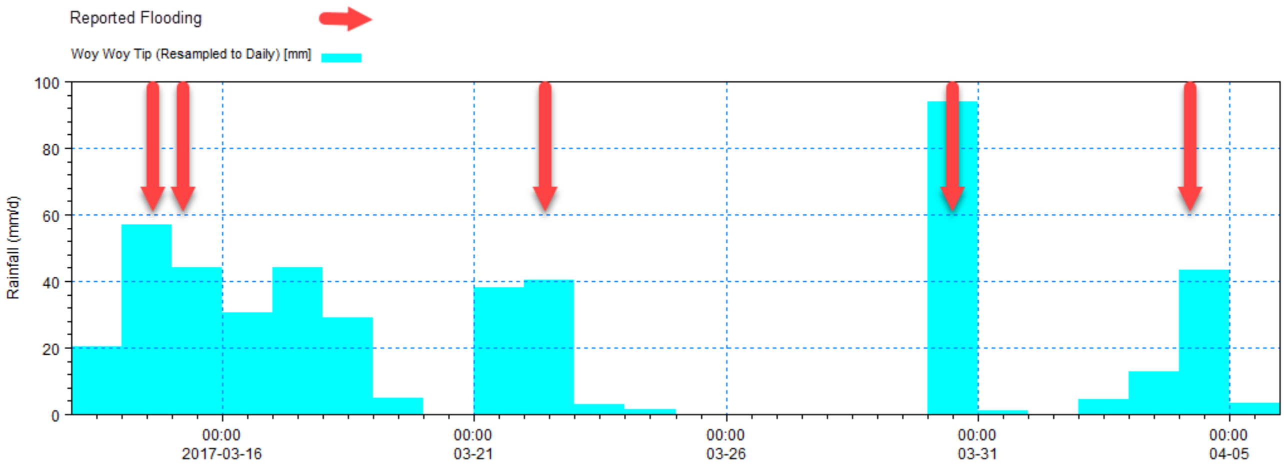


Figure 8.1 Reported flooding with rainfall records (hourly data resampled to daily)

Figure 8.2 to Figure 8.6 show the simulated depth to phreatic surface at the time of the reported flood events. Areas in red indicate where the groundwater table intersects the ground surface. The analysis indicates that the groundwater table rises quickly in response to rainfall and remains at a high level in proximity to Connex Road, Glenn Street, Carpenter Street and Shepard Street.

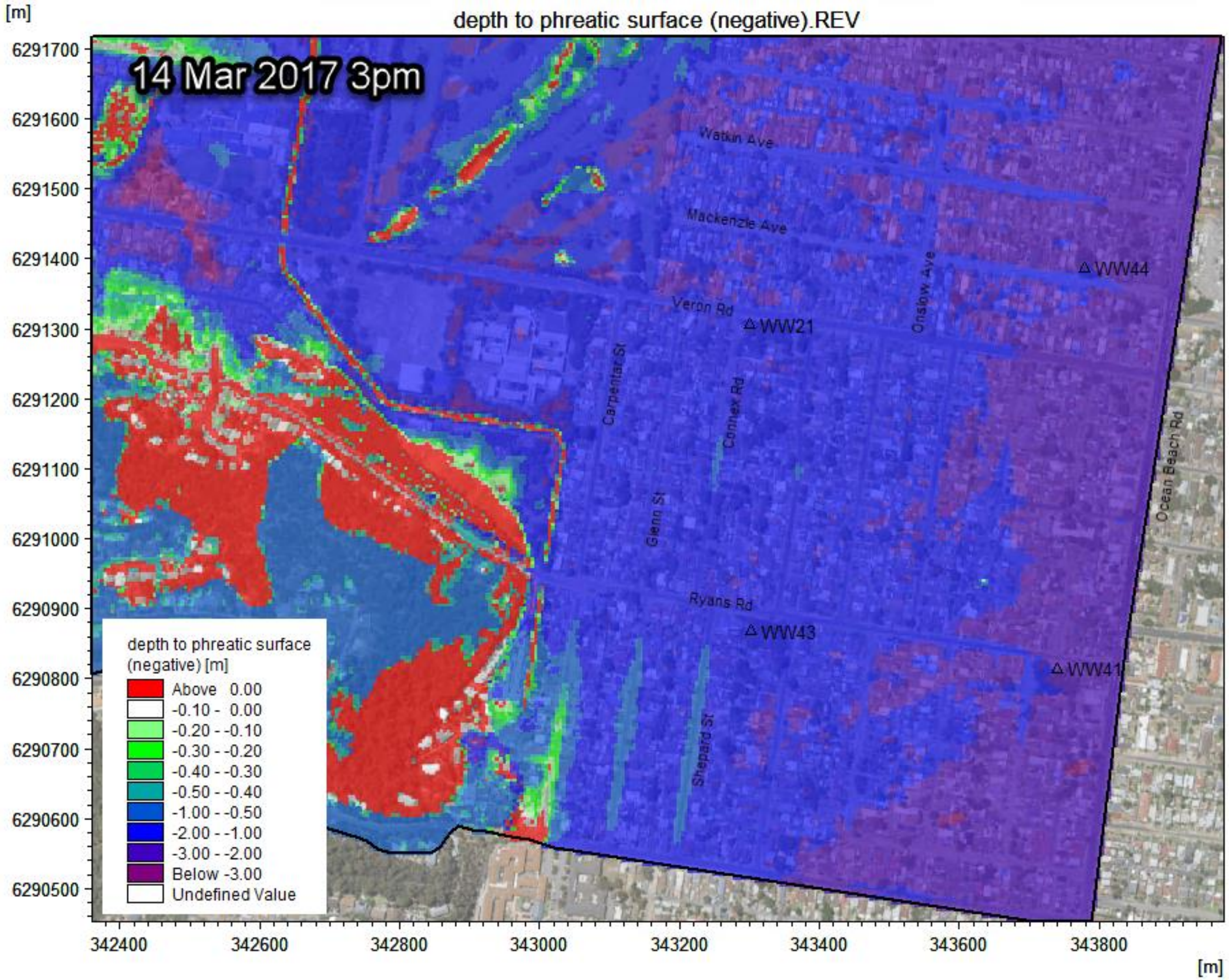


Figure 8.2 Simulated depth to phreatic surface (negative downwards) in Everglades Catchment (14 March 2017 3pm)

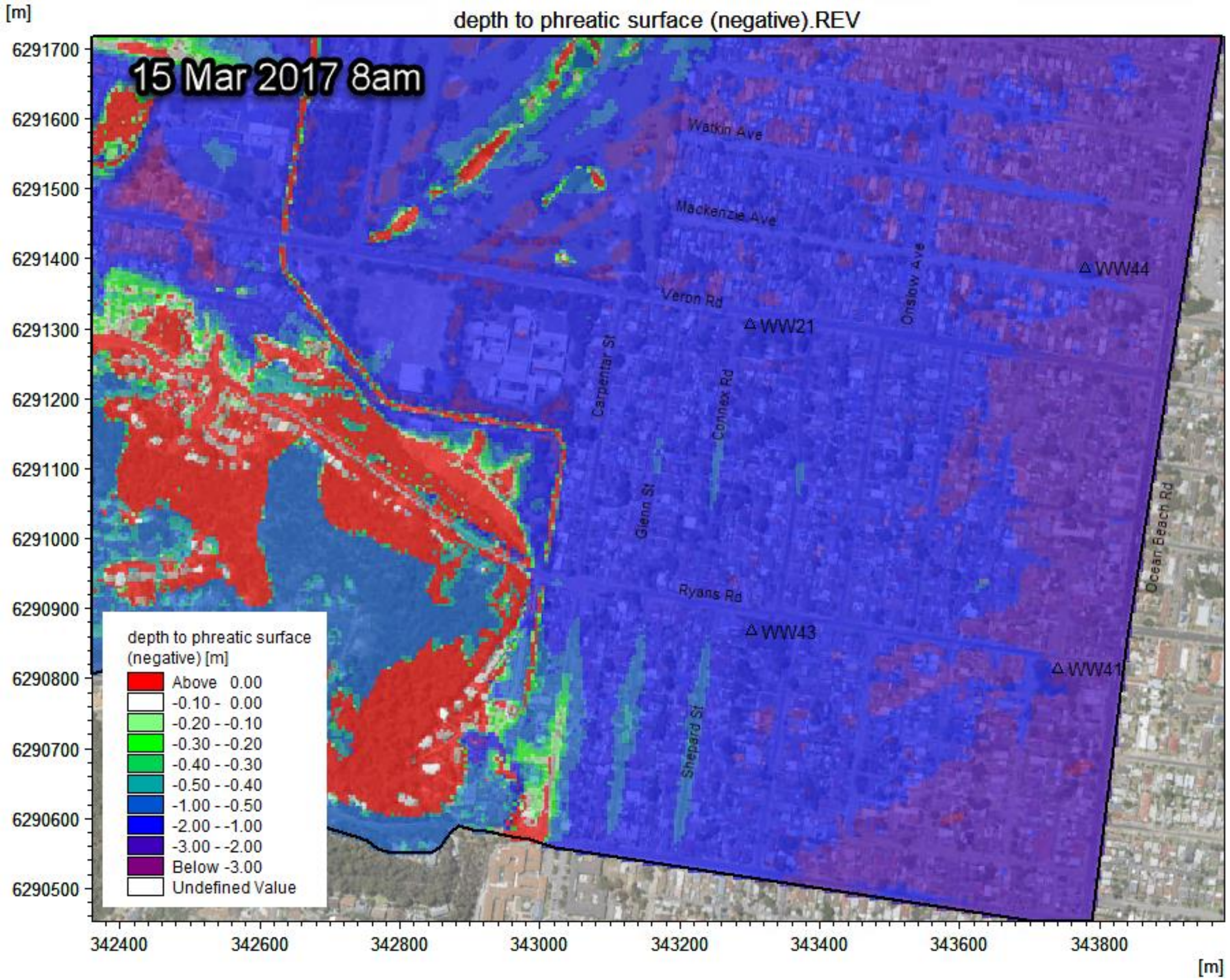


Figure 8.3 Simulated depth to phreatic surface (negative downwards) in Everglades Catchment (15 March 2017 8am)

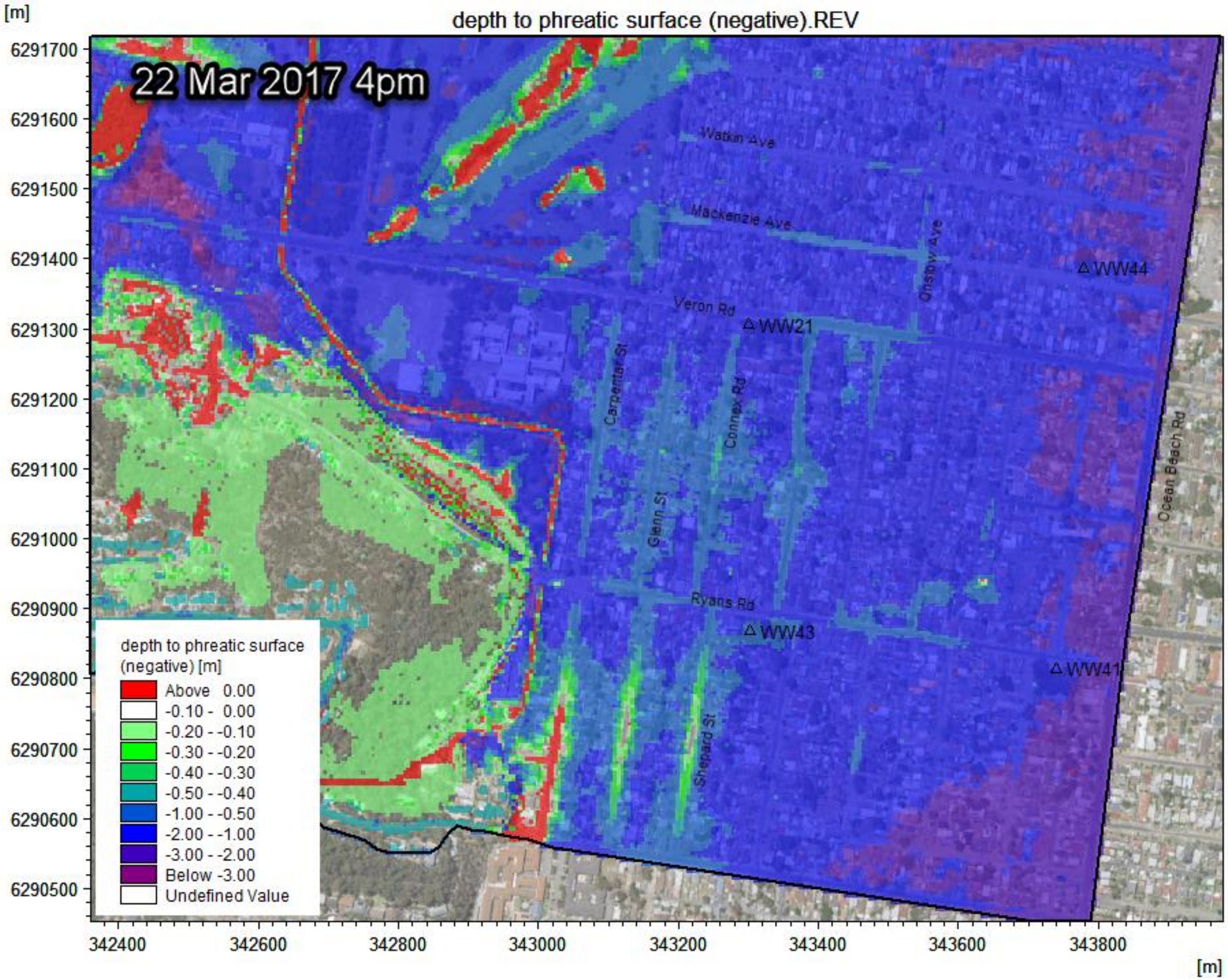


Figure 8.4 Simulated depth to phreatic surface (negative downwards) in Everglades Catchment (22 March 2017 4pm)

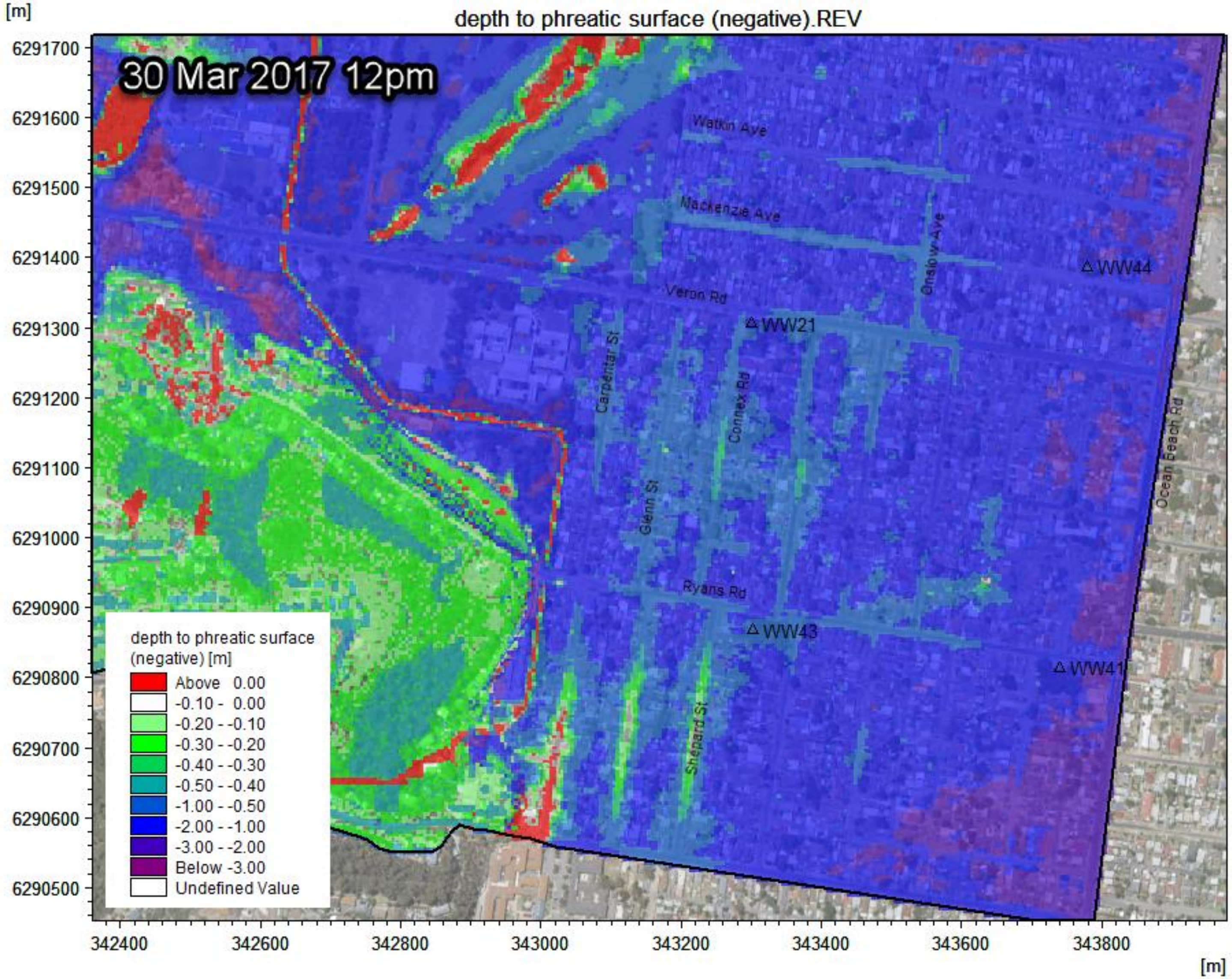


Figure 8.5 Simulated depth to phreatic surface (negative downwards) in Everglades Catchment (30 March 2017 12pm)

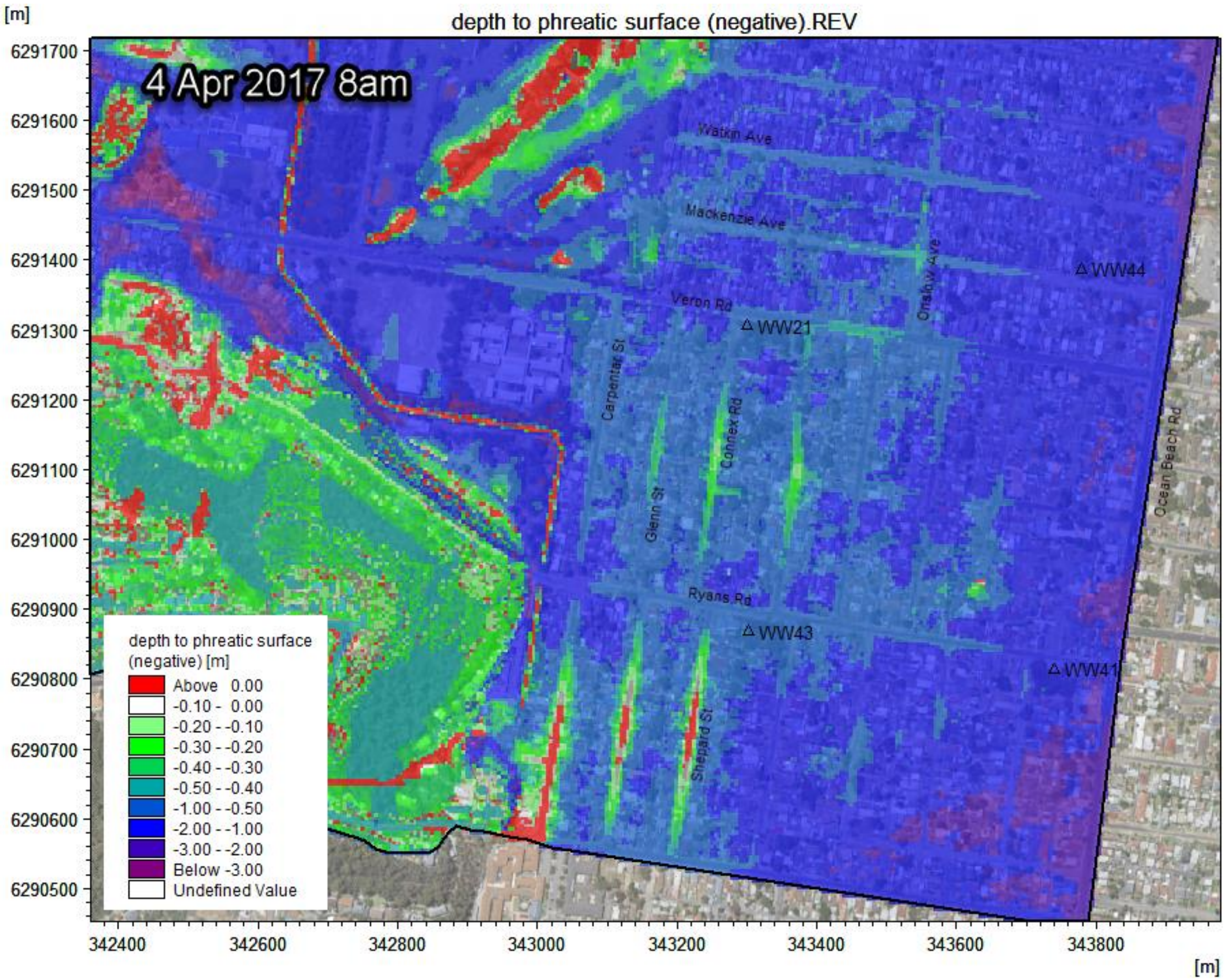


Figure 8.6 Simulated depth to phreatic surface (negative downwards) in Everglades Catchment (4 April 2017 8am)

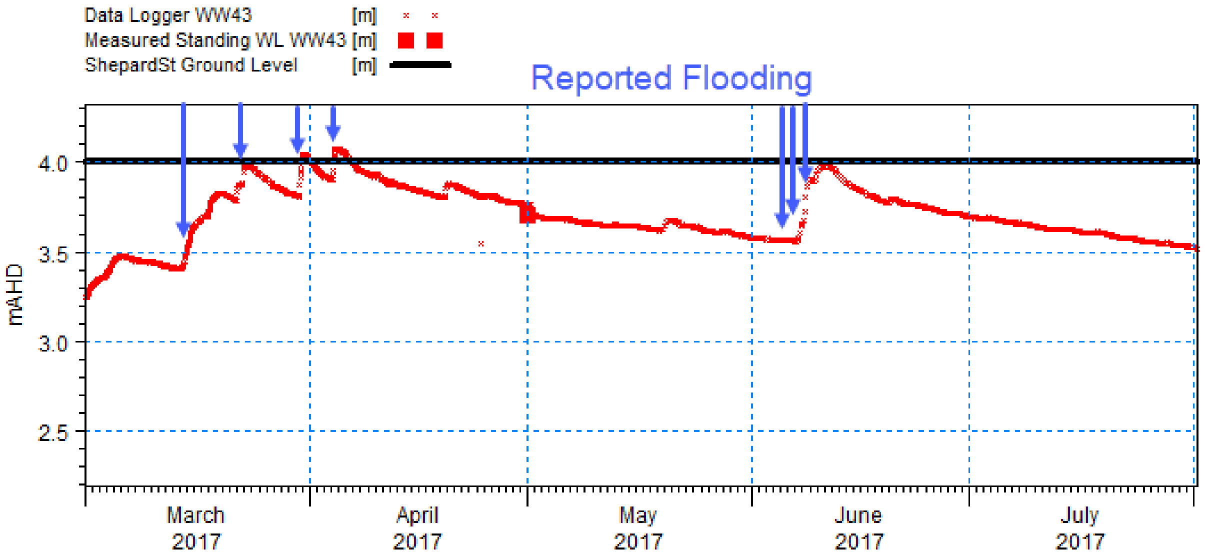


Figure 8.7 Observed groundwater level at WW43 (the closest bore to Shepard St.) and the reported flooding at Shepard St.

Figure 8.7 indicates two elements of flooding behaviour should be considered:

1) Surface runoff from each block quickly flows down to the lowest locations along the streets. Figure 8.8 indicates the main flow paths due to topography. Water ponds at the following locations when the drainage infrastructure lacks sufficient capacity:

    a. The intersection of Onslow Avenue and MacKenzie Avenue.

    b. Veron Road between Onslow Avenue and Lovell Road.

    c. The low points (at the midpoint) of Carpenter Street, Glenn Street, Connex Road and Lovell Road between Veron Road and Ryans Road.

    d. The low points (at the midpoint) of Carpenter Street, Glenn Street, and Shepard Street between Ryans Road and Lone Pine Avenue.

2) The groundwater level quickly rises, fed not only by rainfall on the residential blocks but also by rainfall from the escarpment. While the groundwater level rise is responsive to rain events it is then slow to decline compared to the rise, depending on any subsequent rainfall. In instances when the groundwater table is above the ground surface, increasing the drainage capacity will have only a limited impact on reducing the ponded water. This is seen at Connex Road, Glenn Street, Lovell Road, Carpenter Street and Shepard Street. This is consistent with the information that several swamps existed in this location, prior to urbanisation.

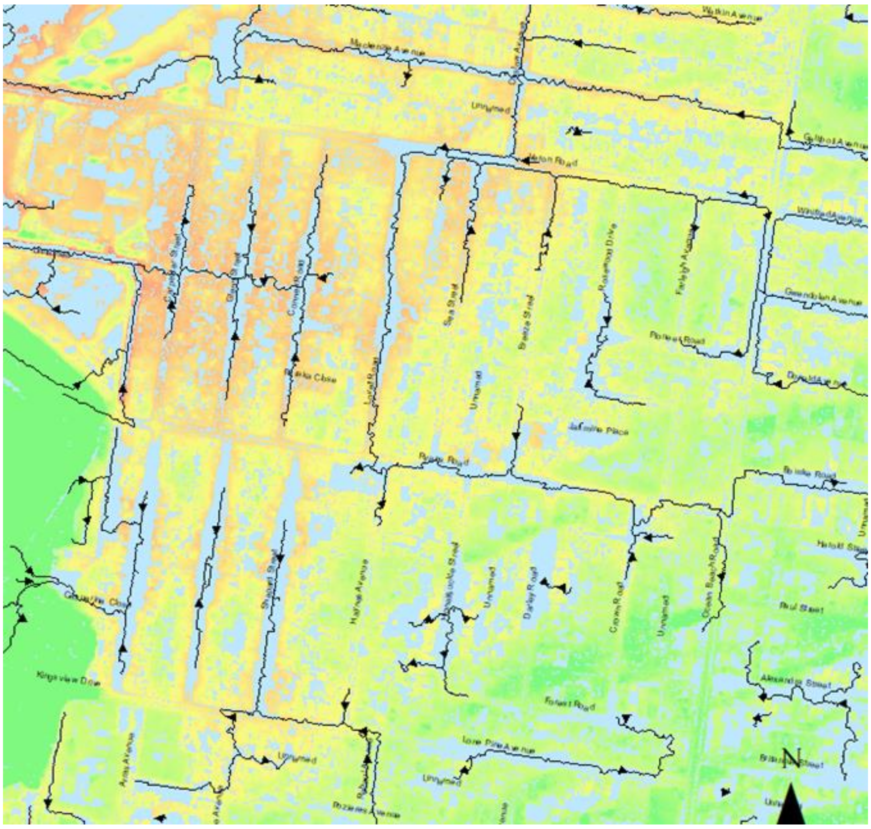


Figure 8.8 Estimated surface flow paths in the Everglades Catchment

9 Assessment of Management Options

9.1 Assessed events

Council originally requested that assessment of the management options was undertaken using the February 1990 event which is equivalent to approximately the 0.5% to 1% AEP design event. Section 9.1.1 describes the details of the February 1990 event.

Following the initial assessment of Option 3 (Section 6.2.3), it was agreed that it is more relevant to evaluate options against the nuisance flooding represented by small rainfall events in March and April 2017 that were used for calibration. Therefore, the majority of assessments were primarily undertaken using the 2017 nuisance flooding events described in Sections 7.2.1 and Section 8.

9.1.1 February 1990 Flood event

The February 1990 event was a large rainfall event with a total of 701 mm of rainfall over 12 days, peaking at 309.8 mm/day on 2 Feb 1990. The hyetograph can be seen in Figure 9.1.

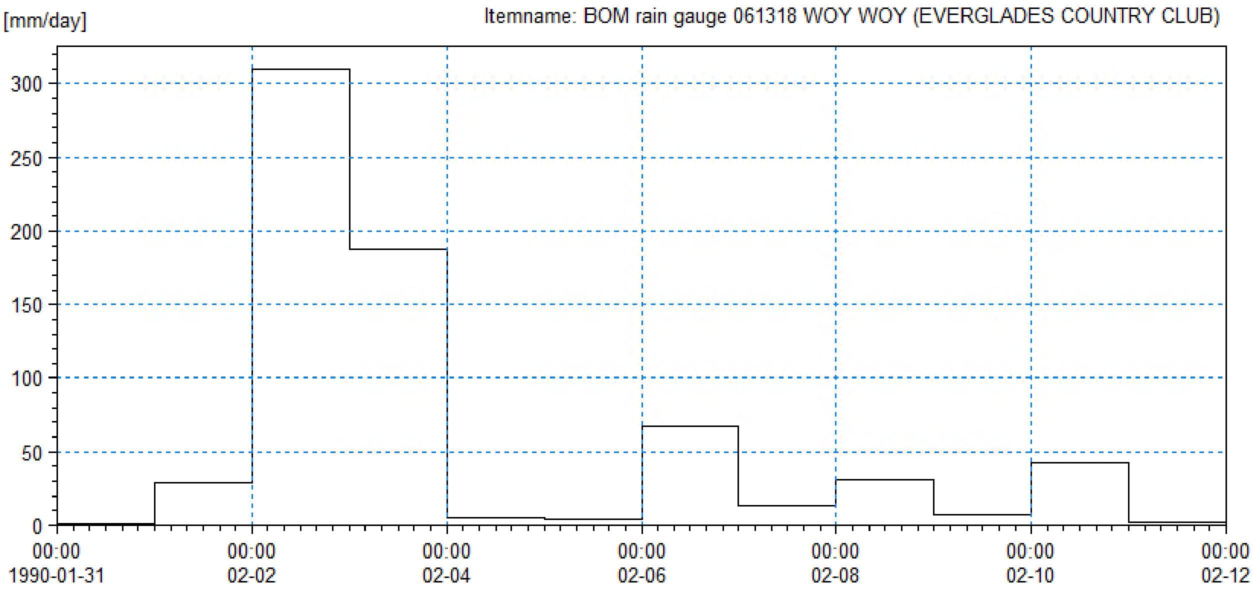


Figure 9.1 Rainfall recorded at Everglades Country Club (BoM) between 31 Jan and 12 Feb 1990

9.1.1.1 Flood depth and depth to the groundwater table

The Baseline simulation of the Feb 1990 event showed that typical locations in the Everglades Catchment, such as: MacKenzie Avenue, Onslow Avenue, Carpenter Street, Glenn Street and Shepard Street were flooded, as indicated in Figure 9.2. Figure 9.3 shows dynamic water depth at a selection of the identified flooding locations. Figure 9.4 shows the minimum depth to the groundwater (negative downwards) and Figure 9.5 shows the depth to groundwater table (negative downwards) at the typical flooding locations over time. These indicate that the groundwater table reached the ground surface in several locations and remained at an elevated height for more than a week at several locations. This likely resulted in ponded water for an extended period.

It should be noted that the peak flood depth at the intersection of MacKenzie Avenue and Onslow Avenue occurred prior to the groundwater table reaching the ground surface. This indicates that the initial flooding at the intersection of MacKenzie Avenue and Onslow Avenue was caused by surface runoff and then prolonged ponding is caused both by the high groundwater table and the lack of drainage. The timing of the peak flood depth and the peak groundwater table coincided at Shepard Street. This indicates that peak flooding at Shepard Street is caused by the combination of surface runoff and the high groundwater table.

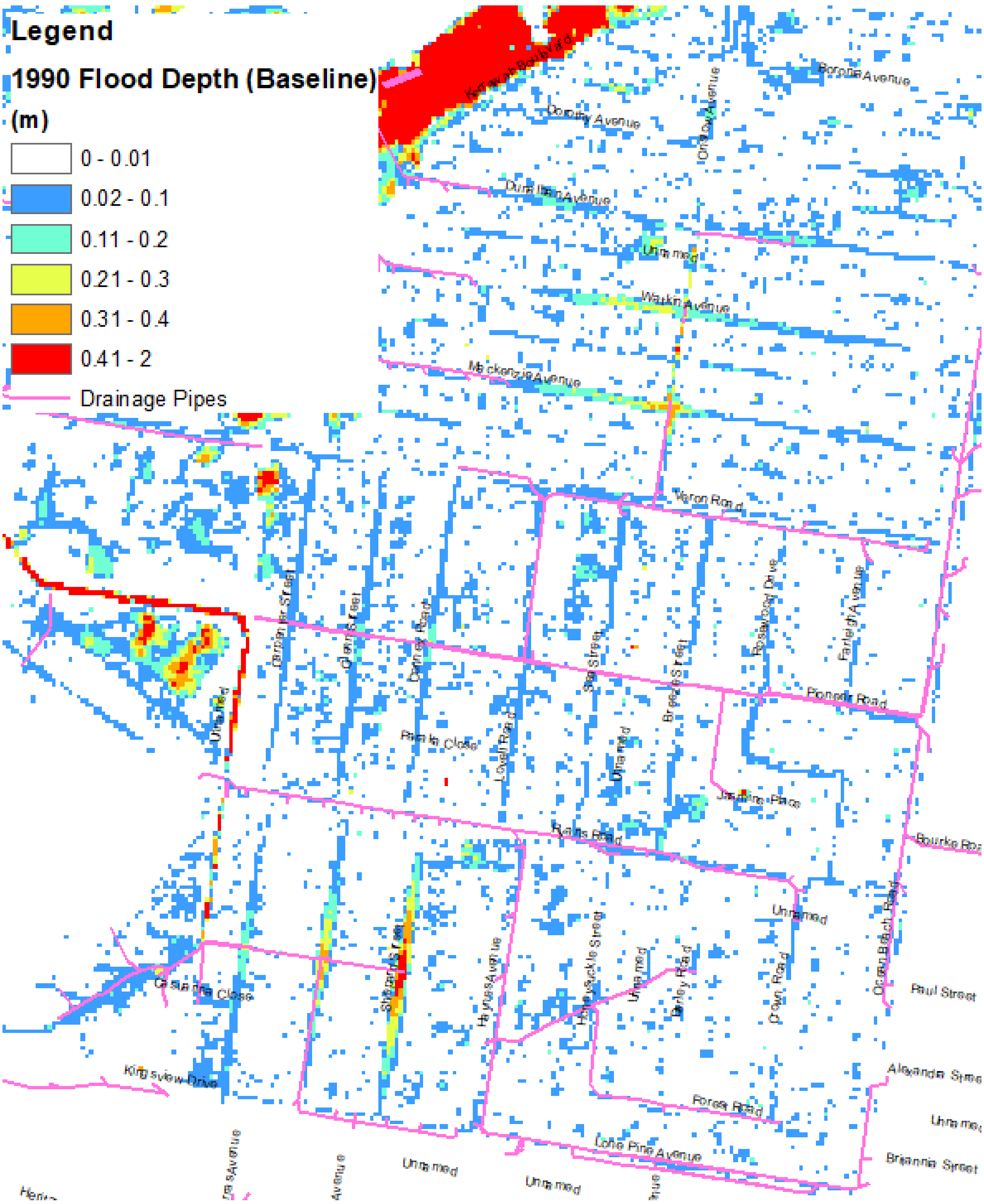


Figure 9.2 Maximum Water Depth of February 1990 event

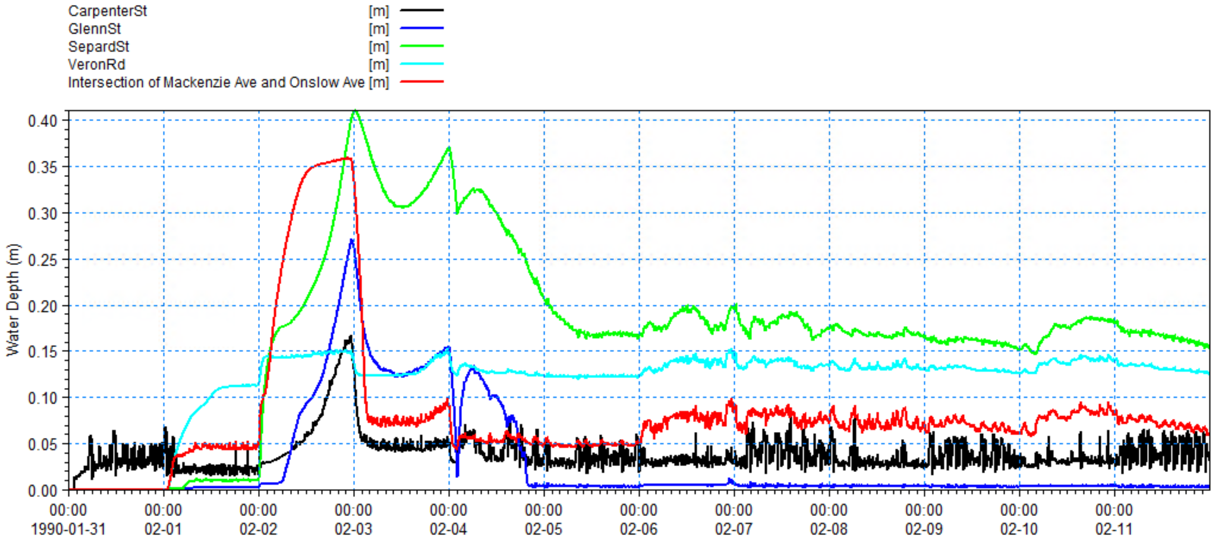


Figure 9.3 Water Depth at Carpenter Street, Glenn Street, Shepard Street Veron Road and at intersection of Makenzie Avenue and Onslow Avenue

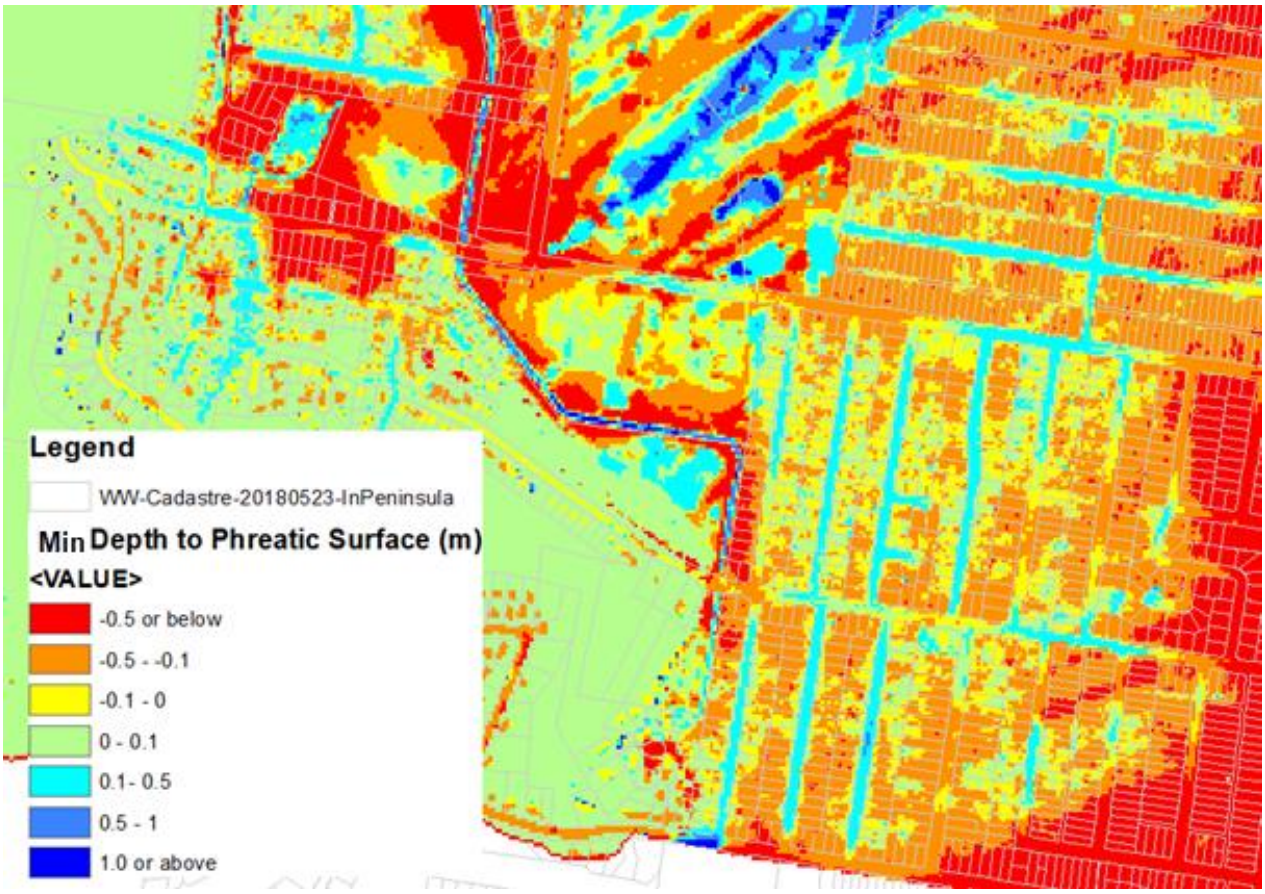


Figure 9.4 Minimum Depth to Phreatic Surface (m) (negative downwards)

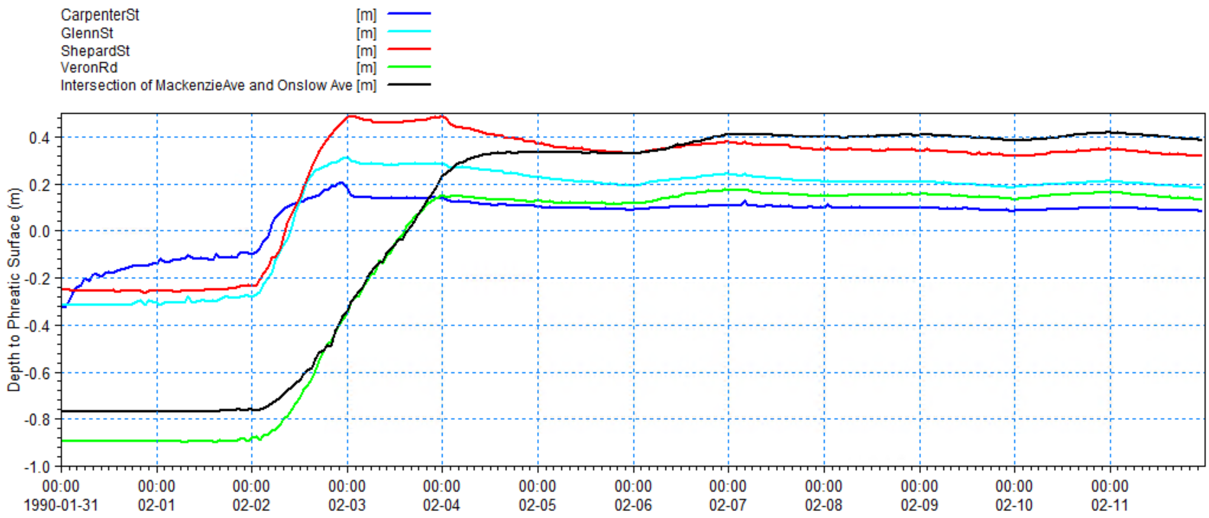


Figure 9.5 Depth to Phreatic Surface (Negative downwards) at Carpenter St, Glenn St, Shepard Street Veron Road and at intersection of Makenzie Avenue and Onslow Ave

9.1.1.2 Existing drainage capacity

PI17872 to PI15207, the 450mm to 750mm alignment from the intersection of MacKenzie Avenue and Onslow Avenue to Veron Road and then to the middle of Lovell Road, are at full capacity during the peak of the February 1990 event, while the downstream 900mm pipe and its parallel 900mm pipe towards the Main Drain remain under-capacity.

Similarly, the 1200mm pipe through Ryans Road does not reach full capacity during the February 1990 event.

The 450mm to 750mm pipes (PI10805 to PI5184) on an alignment through the middle of Shepard Street, Glenn Street, and Carpenter Street towards Main Drain indicate they are also at full capacity during the 1990 event.

9.1.2 Comparison with Council’s black spots

The simulated flood extent was visually compared against the black spots map provided by Council in the Everglades catchment (Appendix C). While all the simulated flood locations are not marked as black spots, the black spot locations in the Everglades catchment generally match the simulated flood locations shown in Figure 9.2 and align with areas where the groundwater table reaches or gest close to the ground surface. This indicates that flooding

9.2 Screening of options for numerical modelling

Conceptual options described in Sections 6.2 were further examined and modelling has been undertaken. Table 9.1 summarises the manual assessment of the conceptual options prior to numerical modelling.

Table 9.1 Screening of potential conceptual options for numerical modelling

Breakdown strategies considered	Conceptual option	Manual assessment prior to numerical modelling

Additional inlets	Option1 Option2	As per Section 8, some ponding is caused by the lack of inlets and drainage. This is a potential solution particularly relevant at MacKenzie Avenue, Watkin Avenue, Ryans Road and Veron Road.
Exfiltration pipes	Option2	This option is a potential solution in the area outside of the indicated groundwater mound e.g. MacKenzie Avenue and Watkin Avenue.
Divert the surface water to the east	Option1	This could improve flooding where the existing drainage infrastructure is at full capacity. The trunk drainage level outside of the Everglades Catchment is a key consideration if this option can be implemented.
Utilisation of underground storage at the existing parks	Option2	Most of the existing parks are not located along a main surface flow path except Connex Park and Vernon Park located near the existing drainage infrastructure. While this option can release some capacity in the existing drainage in small flood events, the groundwater table rises quickly in these areas, especially in a large flood event, which will encroach upon the storage and infiltration effectiveness of an excavated storage basin.
Drainage infrastructure or storage along asset free roads	Option2	As per Section 8, some ponding is caused by the lack of inlets and stormwater drainage infrastructure. This could potentially work at MacKenzie Avenue, Watkin Avenue, Ryans Road and Veron Road.
Allotment scale storage	Option3	This could potentially reduce the effective contributing runoff area and consequently reduce runoff to streets and the drainage infrastructure.
Strategic pumping of the groundwater table	Option4	The manual assessment showed that pumping for a short period prior to a flooding season is not effective. For example: analysis indicated that continuous pumping at the nearest 7 pumping bores at their pump duty rates for one month would lower the groundwater table by 5cm only around the bores and the drawdown from the surrounding areas would be minimal. However, the assessment of sustainable groundwater extraction rate (Section 5) showed that the long-term strategic pumping could reduce the groundwater table by 0.5m to 1m in proximity to the groundwater mound. This may also improve the flood depth in this region.
Rezoning and redesign	Option5	The ground level of Shepard Street, Glenn Street, Carpenter Street and Connex Road are above the groundwater mound and are impacted by the

		groundwater table. Rezoning and reforming of the streets and the surrounding blocks may facilitate the low-lying areas to function as a naturally ponded area. The exact reforming and rezoning design is unknown and was decided not to be implemented in numerical modelling.

From the preliminary screening in Table 9.1, the following options were modelled:

Table 9.2 Summary of the numerically modelled management options

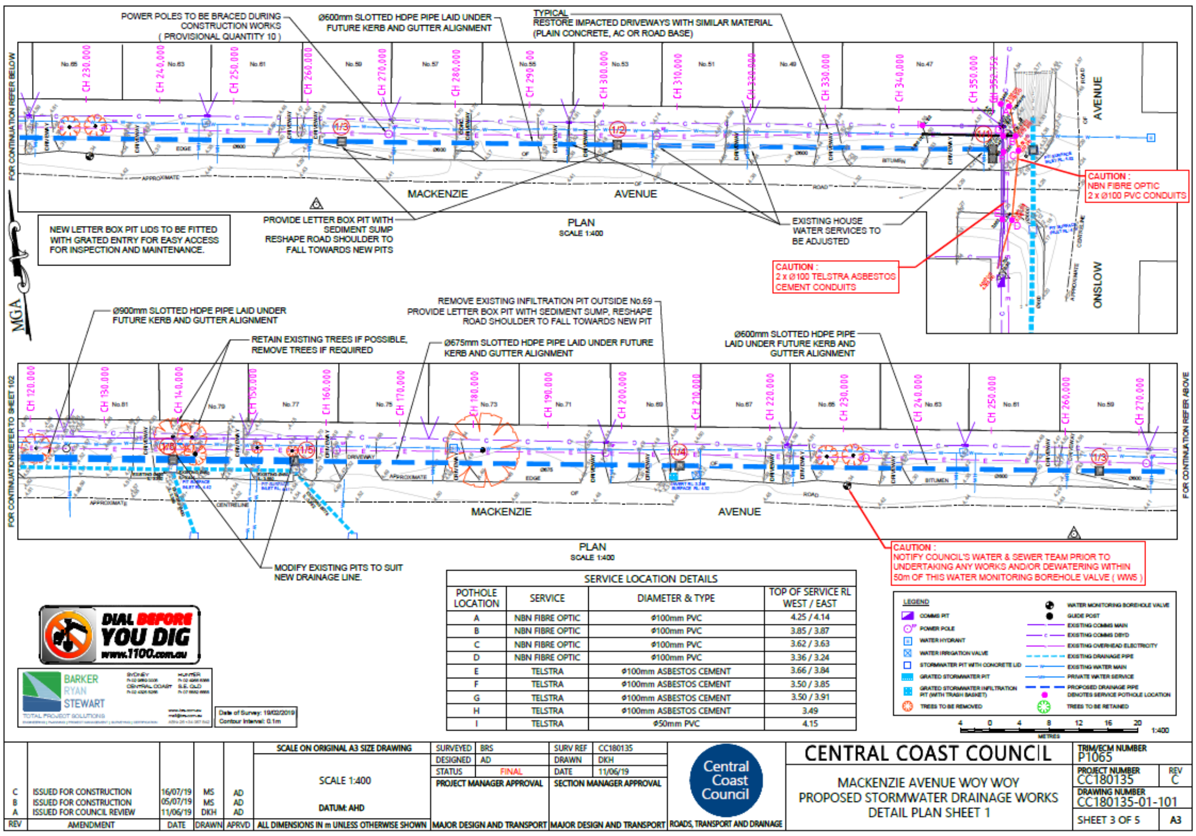
Option ID	Modelled option	Description	Event modelled
Mackenzie	MacKenzie Avenue Drainage upgrade (Additional inlets + Drainages at the drain free asset road)	Council has already installed additional inlets and exfiltration pipes at MacKenzie Avenue west of Onslow Avenue. This was modelled and preliminary results have been delivered.	1990 2017
Option1	Additional Inlets + Additional storage (sumps) + Divert surface water to east	This option looked at the combination of additional inlets and sumps at ponding locations and the diversion of the existing flow from Veron Road, where it is often at its maximum capacity (assuming that diversion is possible). The following scenario was modelled: • Additional inlets at the ponding locations • Increase temporal storage capacity by installing sumps • Divert the drainage flow from Veron Rd	2017
Option2-1	Utilisation of Connex Park	Connex Park is located close to the existing drainage at Veron Road which often at its maximum capacity. A small detention storage at Connex Park is modelled.	2017
Option2-2	Exfiltration pipes	The new parallel exfiltration pipe and inlet structures at MacKenzie Avenue improved flooding on the street. To test the effectiveness of the exfiltration pipes, all the existing pipes in the model area were converted to slotted pipes.	2017
Option2	Swales along the road	The introduction of swales at the streets where surface water is typically conveyed to the low points.	2017

Option3	Allotment scale tanks + infiltration devices	8000L water tank and a percolation pad are installed at each allotment. This corresponds to Option3 in Section 6.2.	1990 2017
Option4	Strategic reduction of groundwater	The antecedent groundwater condition was utilised from the long-term groundwater simulation. 4ML/d was extracted via pumping from the production bores. This corresponds to Option4 in Section 6.2.	1990

9.3 MacKenzie Avenue drainage upgrade

The 2019 design of the proposed MacKenzie Avenue drainage upgrade work (completed in 2020) was provided by Council (CC180135-01). The preliminary results of this scenario were delivered to Council on 6 September 2019 prior to the installation.

The existing pipe ended at approximately 78 MacKenzie Avenue. A new slotted pipe (600mm to 900mm) was proposed to be laid and extended to Onslow Avenue, in parallel to the existing pipe. The screenshot of the proposed design can be seen in Figure 9.6.



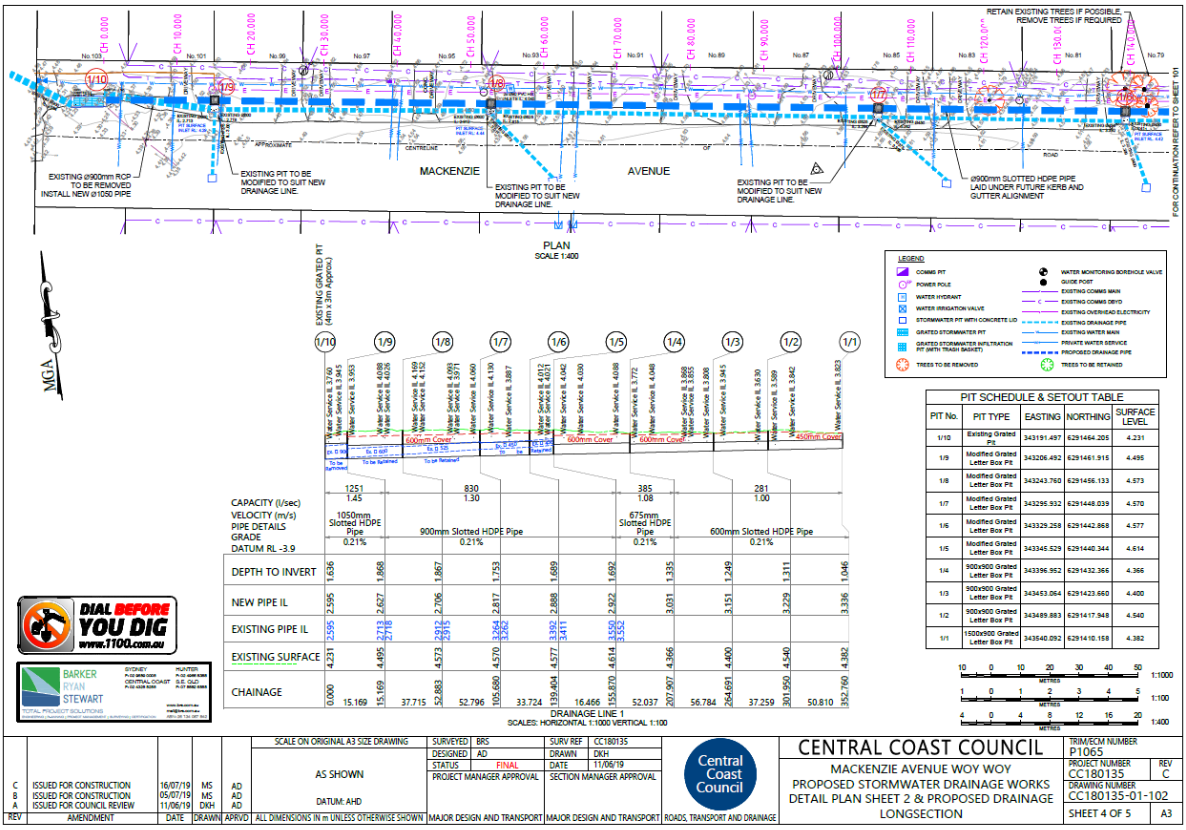


Figure 9.6 The proposed drainage upgrade at MacKenzie Avenue (Central Coast Council, 2019, CC18015 REVC.pdf)

Figure 9.7 shows the difference of flood depth during the February 1990 event. A reduction of 0.1 to 0.2m in flood depth is expected along MacKenzie Avenue due to installation of the new drainage infrastructure at the low-lying location where the existing north-south drainage infrastructure is at capacity. Figure 9.8 shows the water depth over the event at the intersection of MacKenzie Avenue and Onslow Avenue. This also demonstrates the peak depth is reduced.

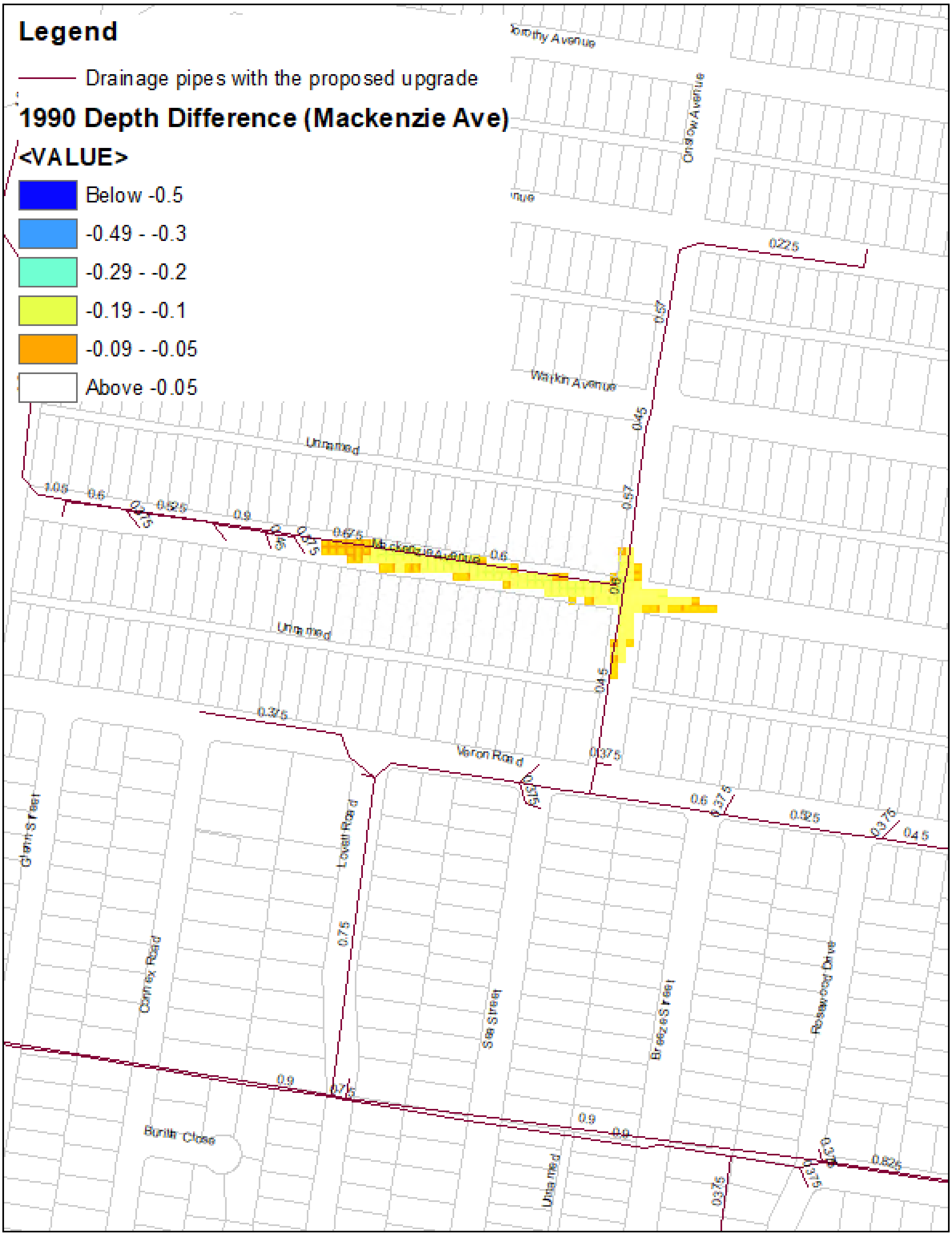


Figure 9.7 MacKenzie Avenue drainage upgrade - Flood depth difference from the baseline (Feb 1990 event)

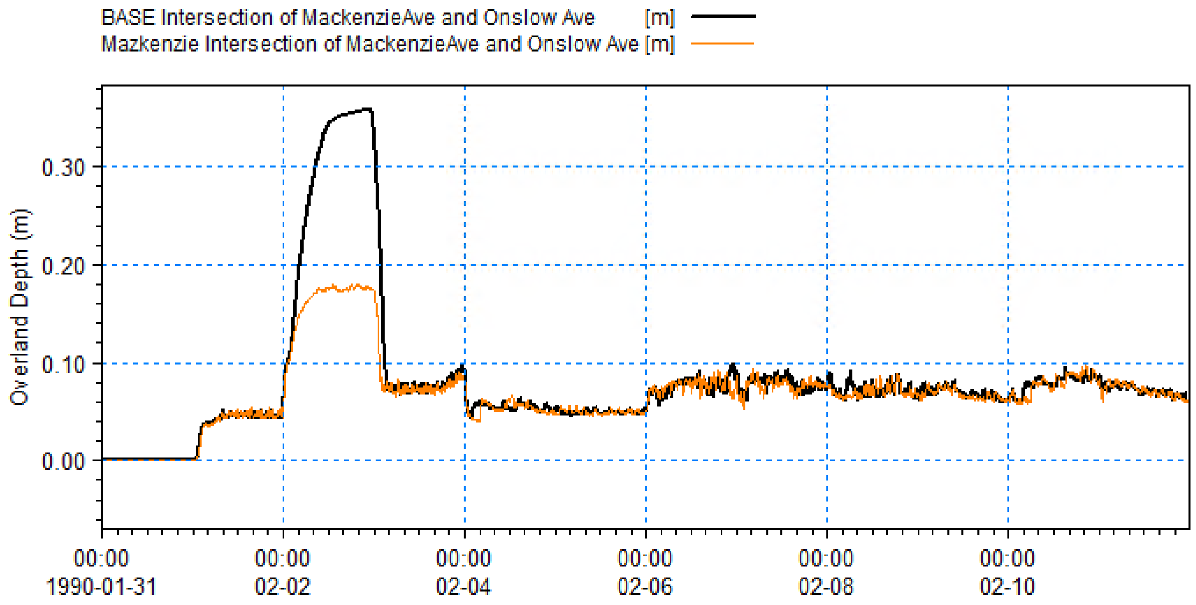


Figure 9.8 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Feb 1990 event, Black: Baseline, Orange: with upgrade work)

Figure 9.9 shows the difference of flood depth during the March to April 2017 events. A reduction of 0.05 to 0.1m in flood depth is expected at a similar location along MacKenzie Avenue during the larger February 2017 event. Figure 9.10 compares the Baseline and modelled option water depth in three relatively large events between March and April 2017 at the intersection of MacKenzie Avenue and Onslow Avenue. This also demonstrates the peak depth is reduced.

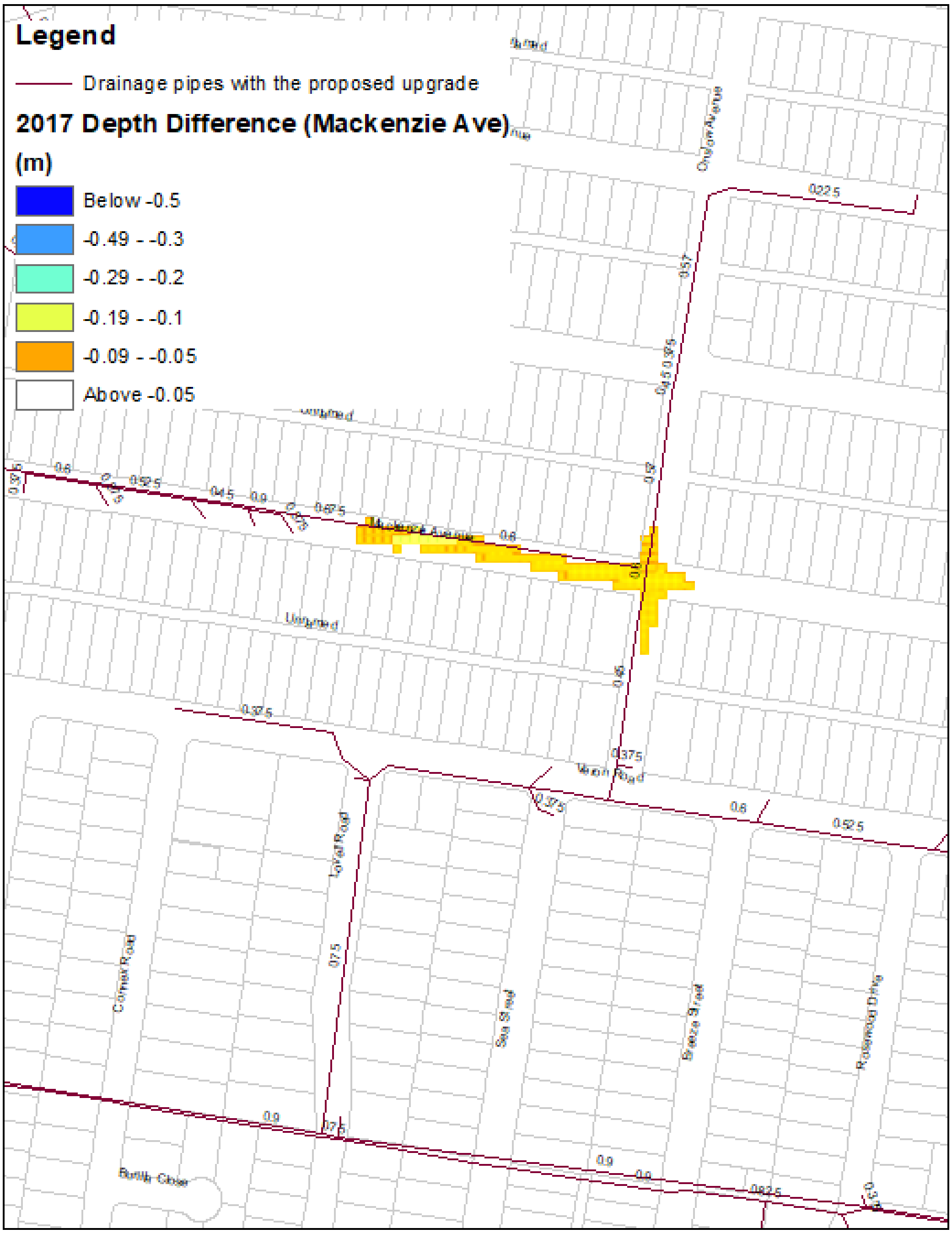


Figure 9.9 MacKenzie Avenue drainage upgrade - Flood depth difference from Baseline (Mar-Apr 2017)

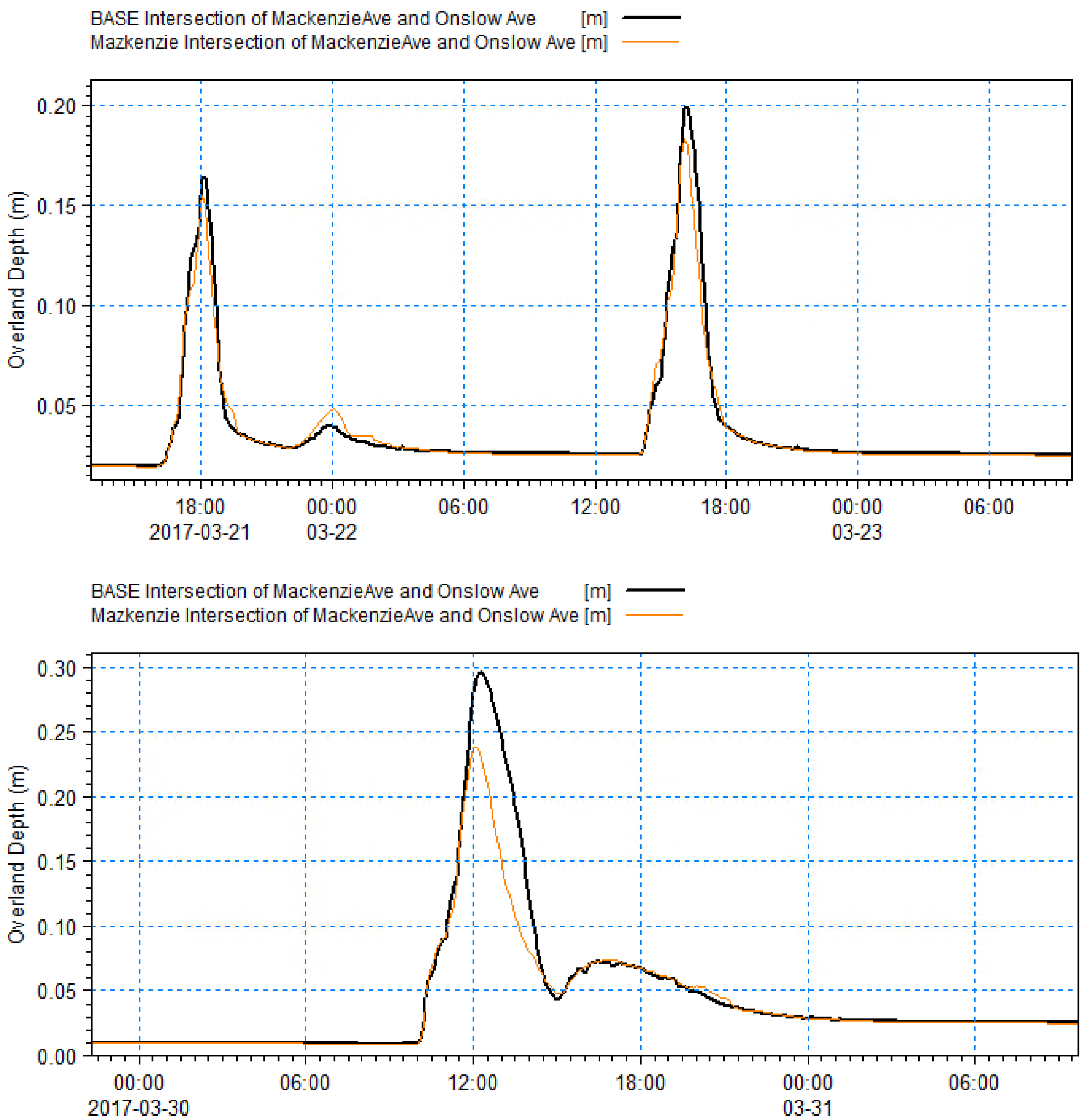


Figure 9.10 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Mar-Apr 2017 event, Black: Baseline, Orange: with upgrade work)

9.4 Option 1 – Redirect surface flow

This option attempts to drain the surface flow following the natural groundwater gradient and considers diverting stormwater away from the Main Drain, in the west, to east. This option could reduce pressure on the existing drainage infrastructure in the Everglades Catchment.

9.4.1 Additional Inlets + Additional storage (sumps) + Divert surface water

This option combines installation of additional inlets and sumps together with diverting a section of the catchment away from the existing network. Sumps were placed at locations where relatively high flood depths were observed but no direct inlets are currently installed. A sump with a plan area of 5 m^2 x approximately 1 m deep (the depth varies depending on the invert levels of the neighbouring pipe) was assumed.

In addition, the pipe along Lovell Road south of Veron Road was disconnected and diverted east. The Baseline simulation showed that the pipe along Lovell Road was often at its maximum capacity. Since the Everglades model does not include trunk drainage outside the model domain, it was assumed that the downstream pipe would have sufficient capacity and would not restrict flows.

In Figure 9.11, the pink nodes represent locations of the modelled sumps and the dotted lines show potential diversion drainage paths.

The difference of maximum flood depth between this option and the Baseline during Mar to Apr 2017 is shown in Figure 9.11.

While the capacity of the drainage pipe at Lovell Road was increased by diverting flow to the east, this did not reduce flooding at Veron Road. The results indicated that drainage infrastructure at Veron Road is still at full capacity during the peak of the event.

The inclusion of storage sumps improved flooding at Connex Road, Glenn Street and Carpenter Street.

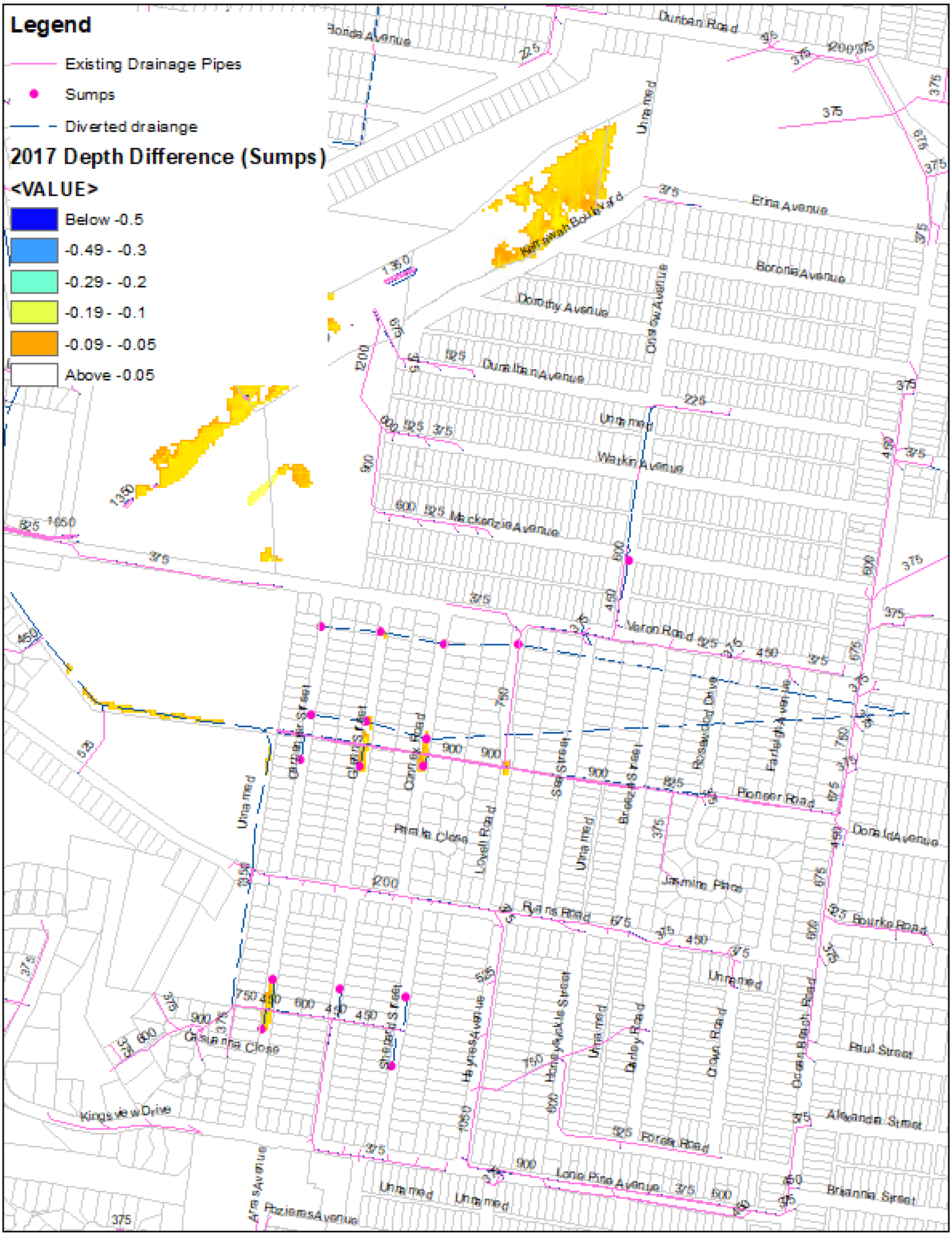


Figure 9.11 Additional inlets, sumps and diversion of the pipe -Flood depth difference from BASE (Mar-Apr 2017)

9.4.2 Consideration of trunk drainage levels

The exact invert levels of the majority of the drainage network are unknown in the Woy Woy peninsula and the levels were estimated from a combination of the topography and the infrastructure where invert information is available.

The topography at Trafalgar Avenue truck drainage is between 5.6 – 6.2 mAHD and is approximately 1-2m higher than streets in the Everglades Catchment as shown in Figure 9.12. Assuming that the pipes are laid approximately 2m below the ground surface, diverting water from the drainage in the Everglades Catchment to the east may not be feasible.

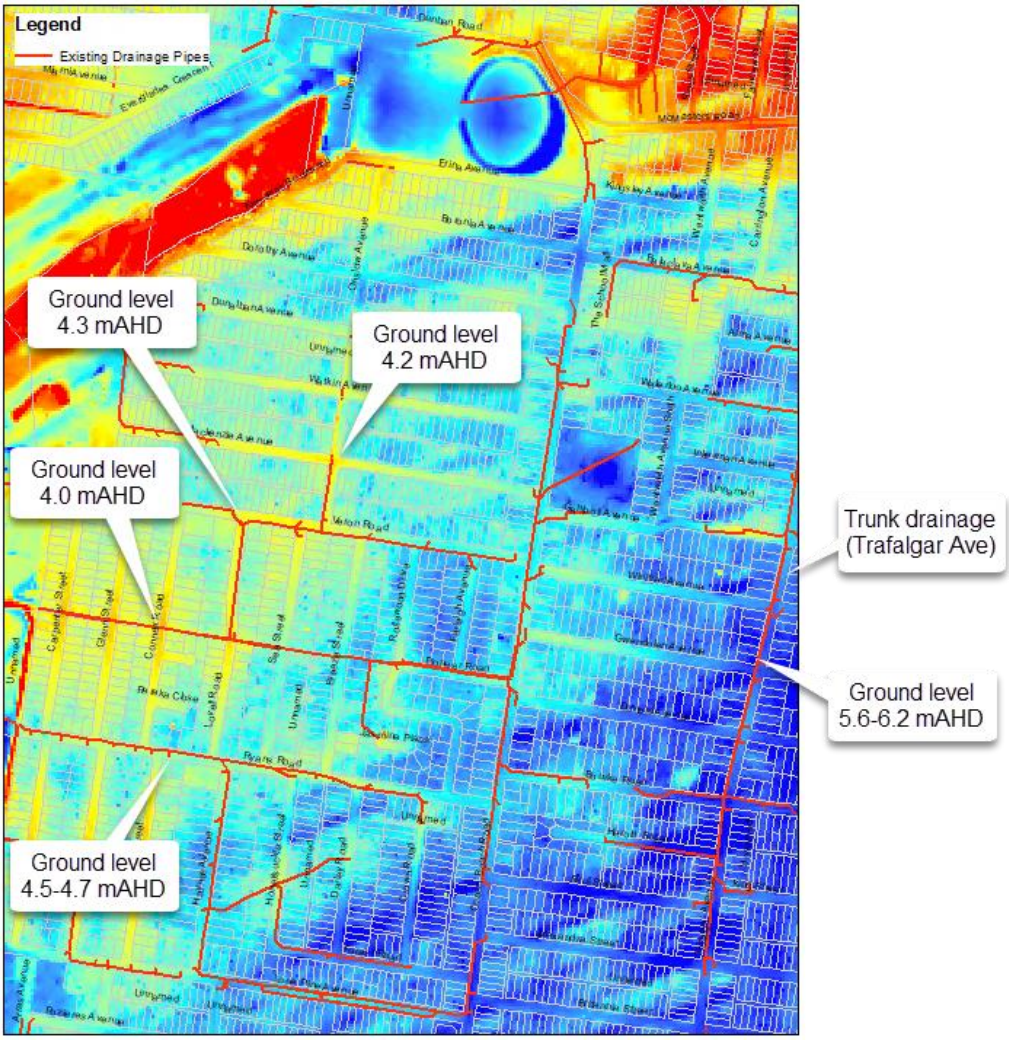


Figure 9.12 Surface level in the Everglades Catchment and Trafalgar Avenue

9.5 Option 2 – Utilisation of potential storages at the existing parks and drainage asset free roads

Figure 9.13 and Figure 9.14 show the flood depth and the maximum depth to the phreatic surface during flooding events in 2017 and 1990 as well as locations of the existing parks (Council Reserves).

The existing parks are not located at the low points where flooding typically occurs. Installation of storage at existing park locations is unlikely to improve flooding on streets.

The exception could be Connex Park located at the corner of Veron Road and Connex Road/Lovell Road. The existing drainage pipes along Veron Road towards Lovell Road reaches maximum capacity during rainfall events and the area experiences ponding on the streets. Connex Park is located next to the intersection of Veron Road and Lovell Road where ponding is often observed. In the baseline simulation of Mar-Apr 2017 events, the groundwater table remains below 50cm below the ground surface.

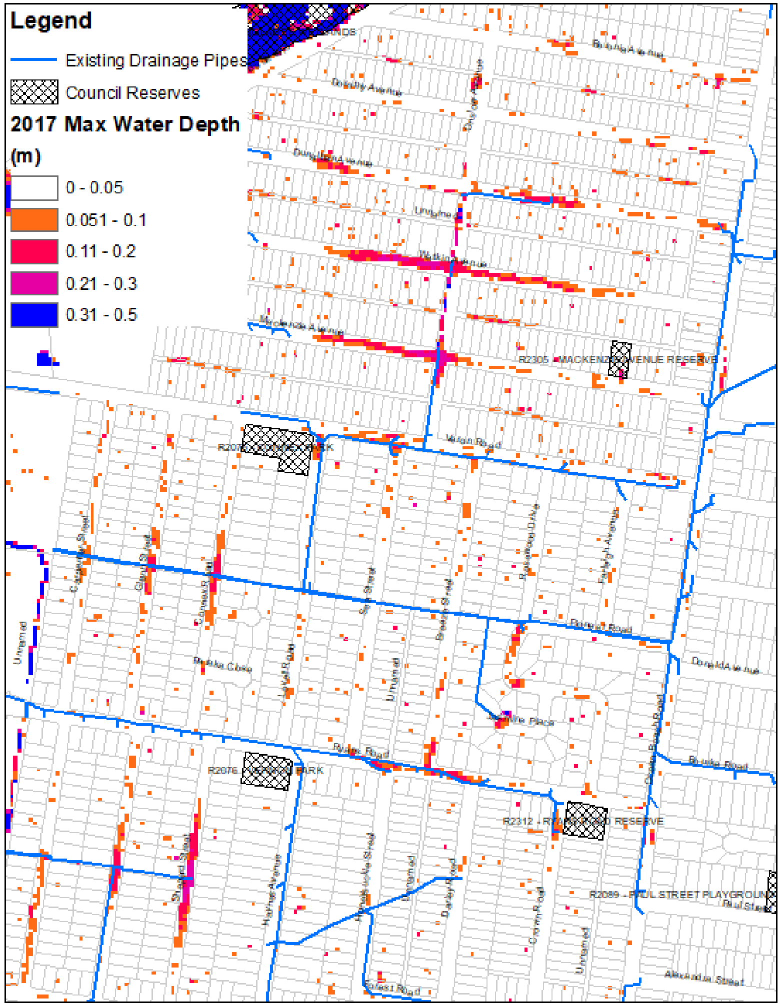
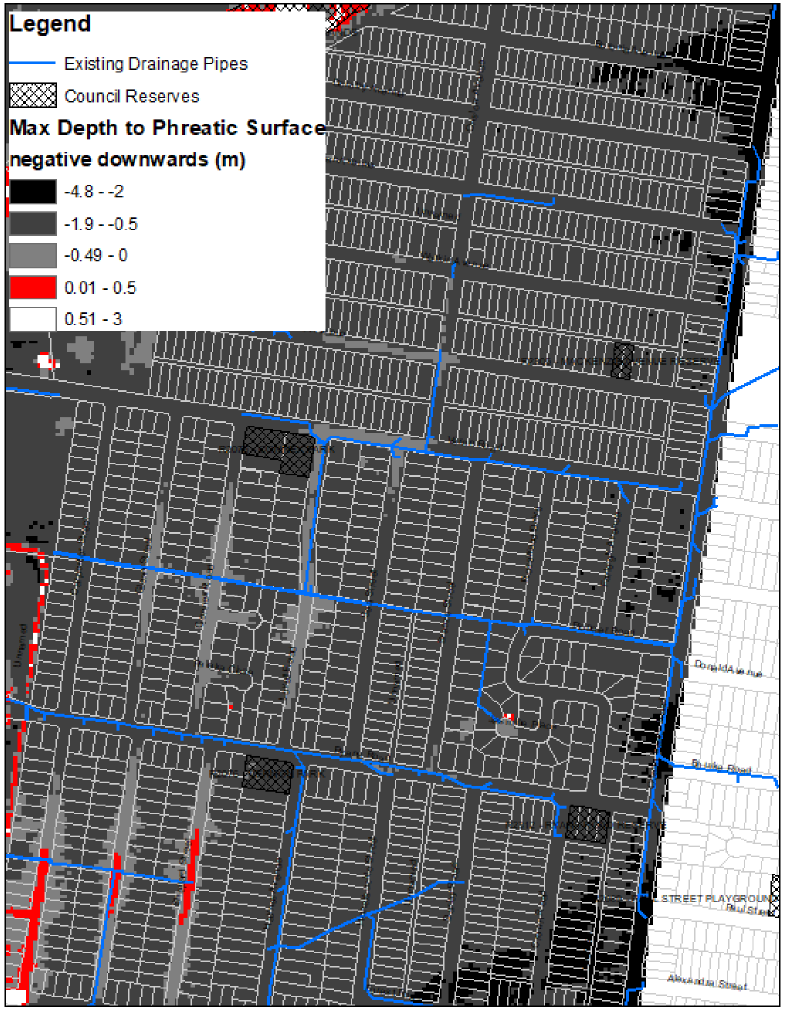
Flood depth	Depth to Phreatic Surface (negative downwards)
	

Figure 9.13 Mar-Apr 2017 flooding and council reserves

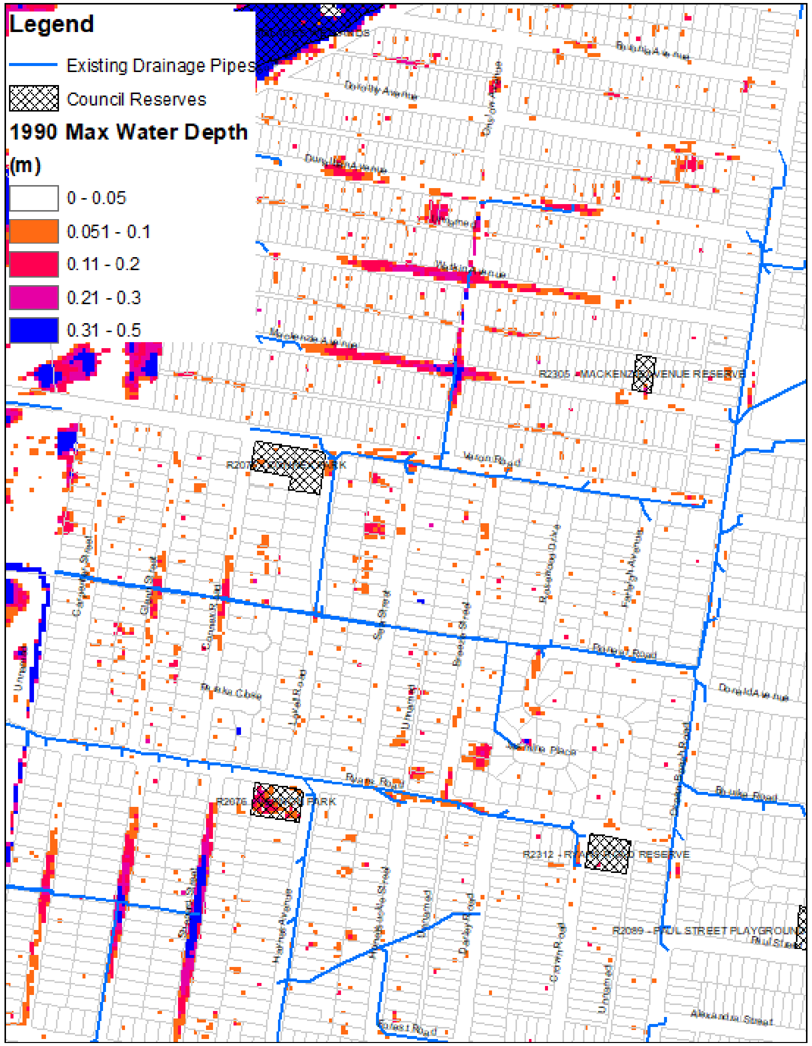
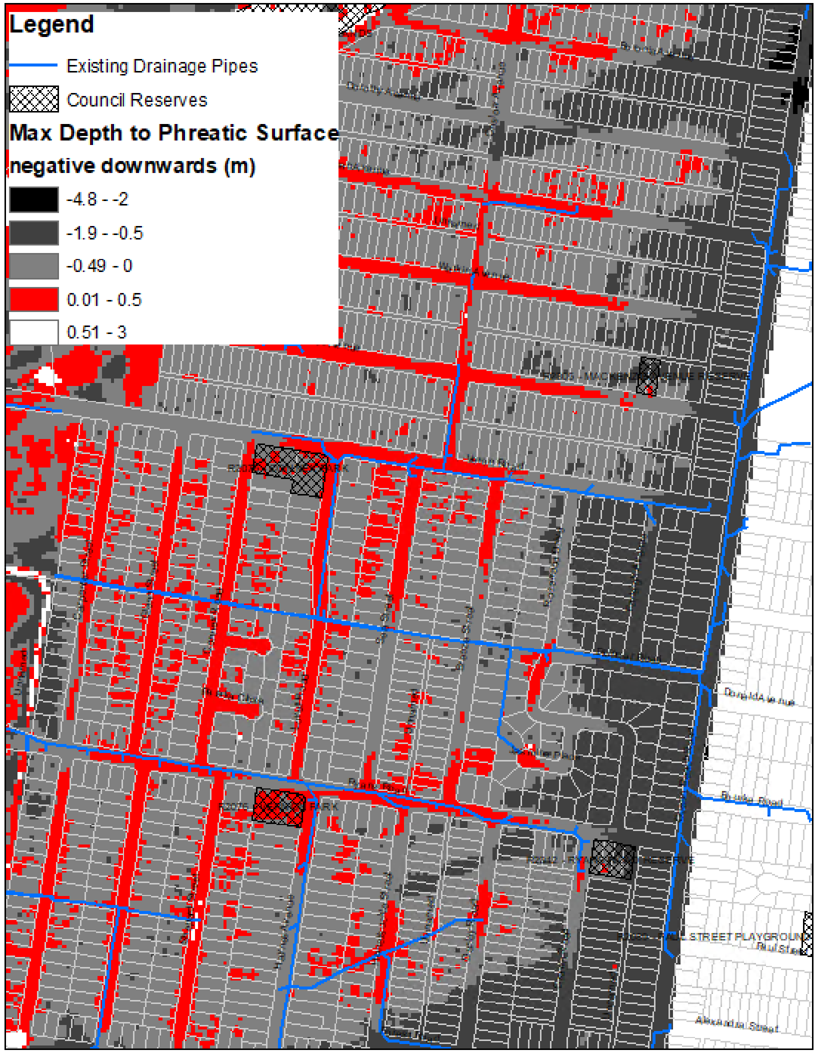
Flood depth	Depth to Phreatic Surface (negative downwards)
	

Figure 9.14 Feb 1990 flooding and council reserves

9.5.1 Storage at Connex Park

This option assessed the impact of diverting flow from existing drainage infrastructure to storage within Connex Park.

A W40m x L25m x D1.5m storage with infiltration capacity at Connex Park was model. The storage inlet is diverted from PT4354 and an invert level of 3.2 mAHD. The dimension and representation of storage in the model was testing of the potential capability of the option and should not be considered for design purposes.

Figure 9.15 indicates the difference in maximum flood depth between the tested option and the Baseline during Mar to Apr 2017. Figure 9.16 and Figure 9.17 compare the water depth of Baseline and this option on 30 April 2017, the largest event in this simulation period.

Limited impact on the flood depth was simulated at Veron Road. A minor reduction in the flood depth at MacKenzie Avenue was indicated. This is likely a result of the new storage allowing additional capacity in the Veron Road drainage infrastructure and additional inflow at MacKenzie Avenue can be accommodated.

Considering that the groundwater table reaches the ground surface during a large event such as the Feb 1990 event, this storage option is likely to be effective only for small events where the groundwater table stays below the base of the storage zone.

Figure 9.15 Storage at Connex Park, Flood depth difference from BASE (Mar-Apr 2017)

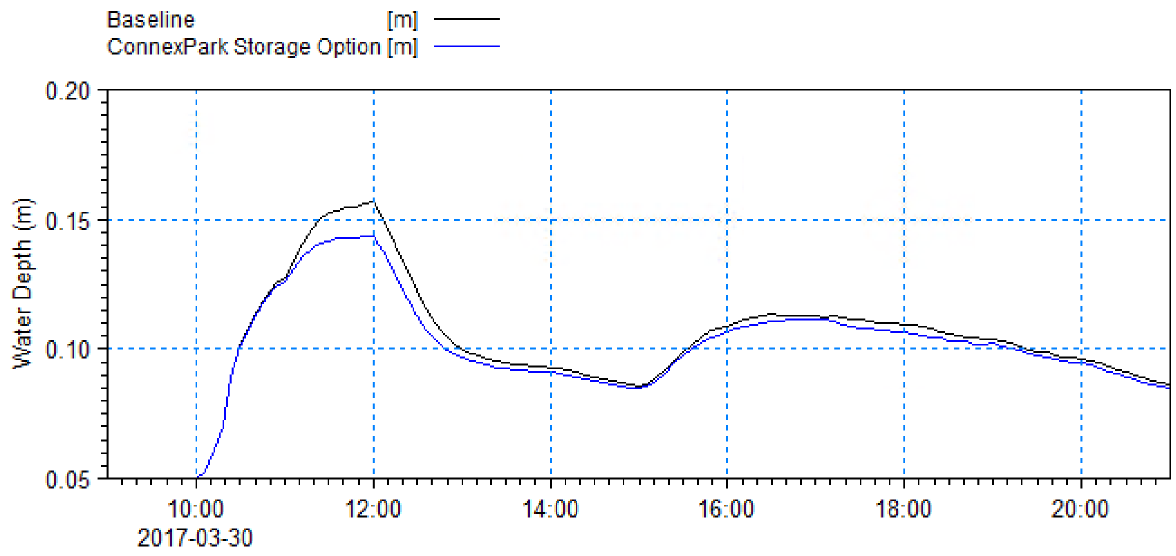


Figure 9.16 Comparison of water depths at the intersection of Veron Road and Sea Street (Black: Baseline, Blue: OPTION with Storage at Connex Park) (30 March 2017)

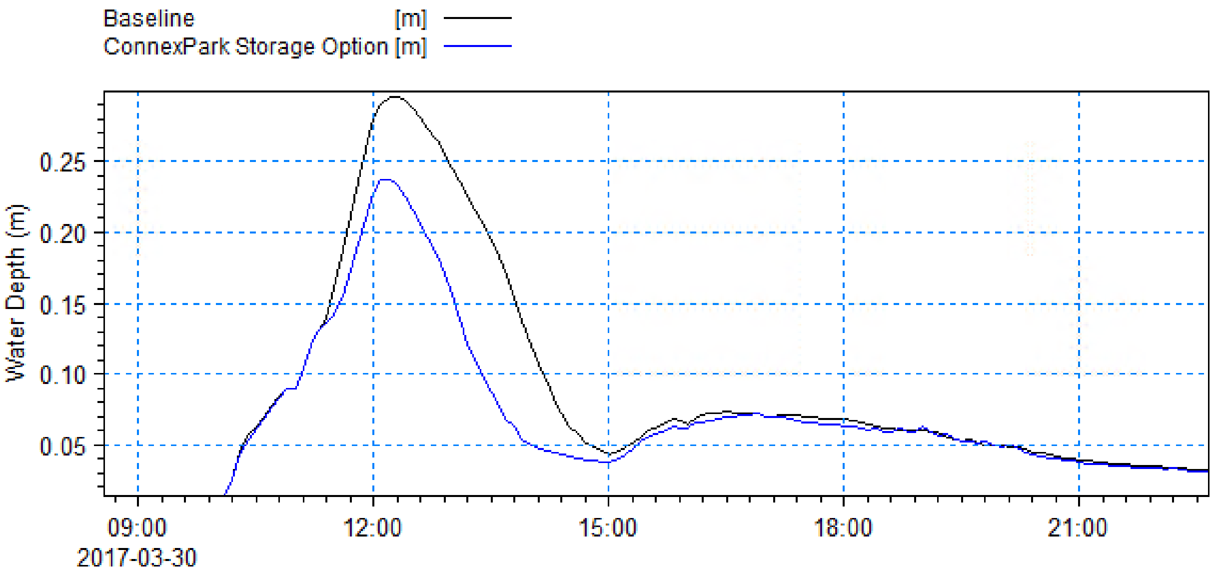


Figure 9.17 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Black: Baseline, Blue: OPTION with Storage at Connex Park) (30 March 2017)

9.5.2 Exfiltration pipes

The positive impact of the MacKenzie Avenue drainage upgrade work (Section 9.3) demonstrated that new inlets and a new slotted pipe were effective on a road that previously had only limited positive drainage infrastructure. To test the impact of slotted pipes for reduction of flood depth, the existing drainage pipes were converted to slotted pipes. Although this is an extreme scenario, it can help identify the effectiveness of slotted pipes and if so, where this option can be effective. Infiltration capacity of the slotted pipes were taken from an example product Plastream SRP Slotted Pipe (Rocla). The infiltration capacity of the pipes increases from 33 to 148 (L/s per meter of pipe) for a 600mm pipe and from 58 to 258 (L/s per meter of pipe) for 1050mm pipe, when the clear height of water above the top of the pipe is 0.1m to 2m. While water exchange is factored by the head difference between in the drainage and MIKE SHE, the leakage coefficient in modelling cannot be varying based on the head difference. Therefore, the clear height of water above the top of the pipe was assumed to be 0.5m for modelling. Pipes can intercept the groundwater as well.

Figure 9.18 shows difference of maximum flood depth of the option with exfiltration pipes and the Baseline during Mar to Apr 2017. No significant improvements in flood depths were observed and the pipe itself is not sufficient to reduce the peak flooding. This can be explained by the infiltration capacity relatively small compared to the inflow rates to the pipes during the peak of rainfall event. It is also possible that the shallow depth to groundwater at the peak, combined with the invert of the drainage infrastructure will mean that the exfiltration from the pipe system may be limited.

Figure 9.19 to Figure 9.21 compare the water depth of Baseline and this option over time at the intersection of MacKenzie Avenue and Onslow Avenue, Shepard Street and Glenn Street. These graphs show proportionally larger reductions in smaller events between the 21st and 23rd of March at the intersection of the intersection of Mackenzie Avenue and Onslow Avenue and Glenn Street.

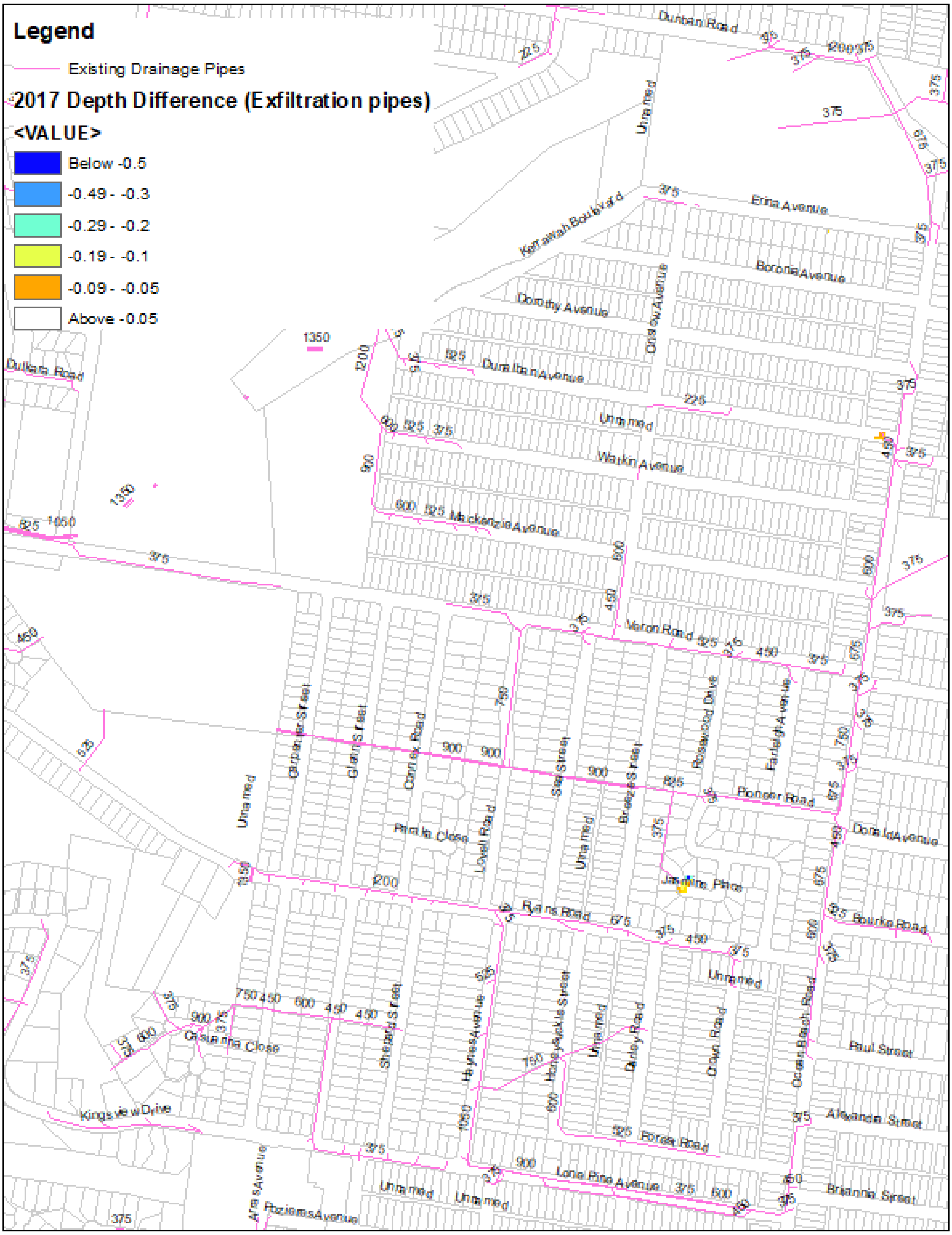


Figure 9.18 Exfiltration pipes -Flood depth difference from BASE (Mar-Apr 2017)

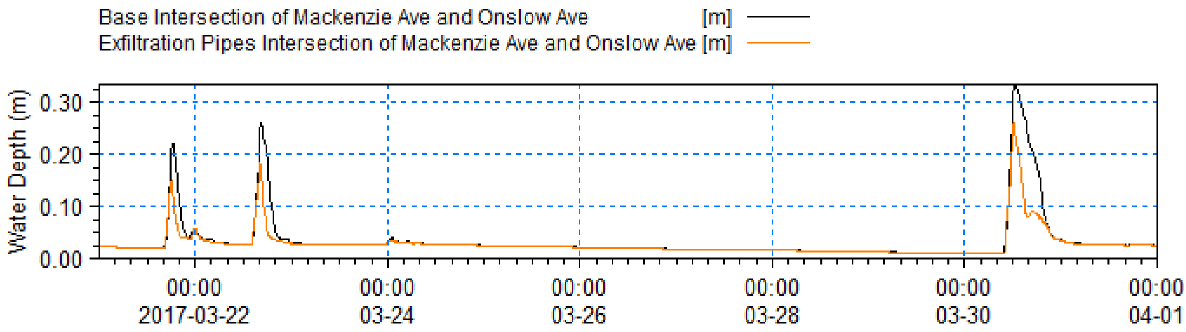


Figure 9.19 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Mar-Apr 2017 event, Black: Baseline, Orange: with Exfiltration Pipes)

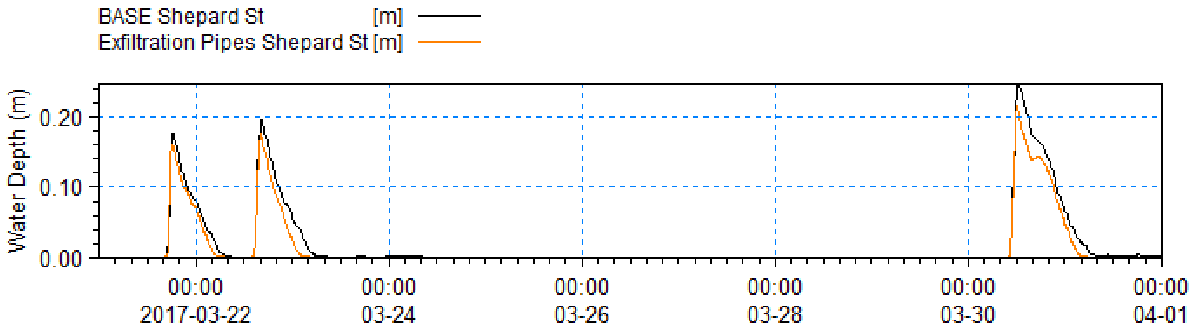


Figure 9.20 Comparison of water depths at Shepard Street (Mar-Apr 2017 event, Black: Baseline, Orange: with Exfiltration Pipes)

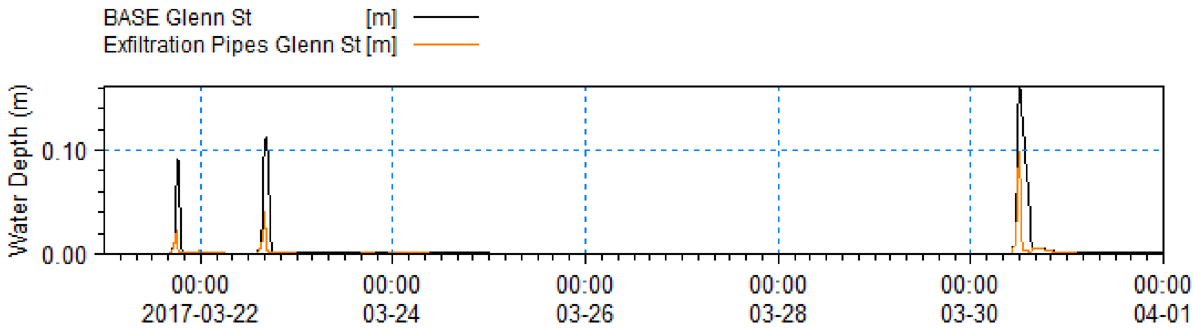


Figure 9.21 Comparison of water depths at Glenn Street (Mar-Apr 2017 event, Black: Baseline, Orange: with Exfiltration Pipes)

9.5.3 Swales

Swales can be installed is the streetscape and would particularly relevant option along roads where is the is no existing formal drainage infrastructure. The functioning of a swale is achieves multiple benefits in stormwater management by delaying peaks of storm events by retaining water prior to draining into the low point on streets as well as promoting water quantity and quality objectives. Swales were incorporated in the model by applying a higher roughness coefficient and 0.2m deep x 5m wide ditches along edges of the major streets (Erina Avenue, Boronia Avenue, Dorothy Avenue, Dunalban Avenue, Watkin Avenue, MacKenzie Avenue, Sea Street, Lovell Road, Connex Road, Glenn Street, Carpenter Street, Haynes Avenue and Shepard Road) in the Everglades

Catchment. The locations of these ditches are indicated in purple in Figure 9.22. Figure 9.22 also shows the difference in flood depths between this option and the Baseline. It can be seen that flooding at the typical low points such as MacKenzie St, Shepard Street and Veron Road is improved. More water is retained in swales before flowing down into the local low points.

Design and sizing of swales to be effective would need to be explored further, prior to implementation.

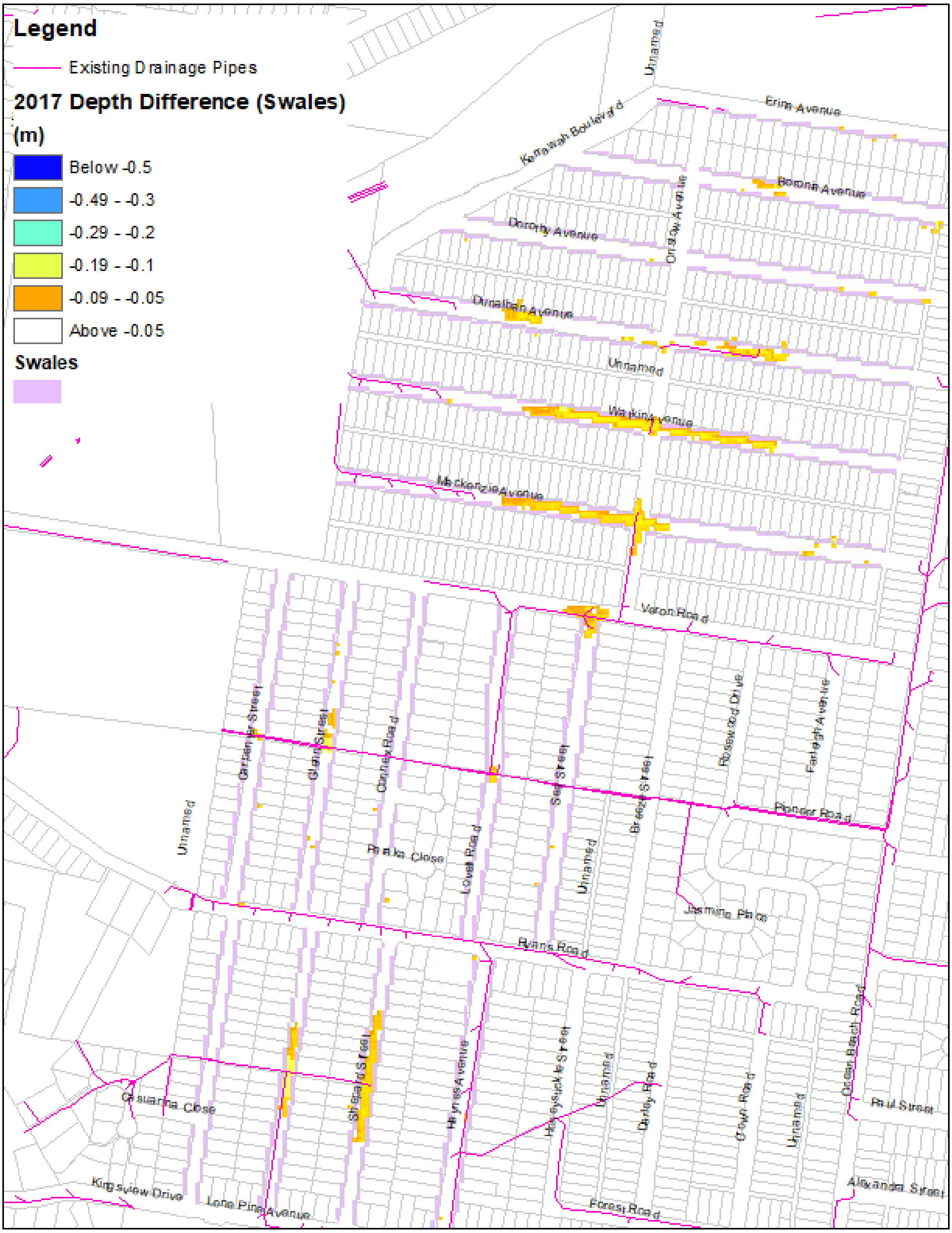


Figure 9.22 Swales along the drainage asset-free streets -Flood depth difference from BASE (Mar-Apr 2017)

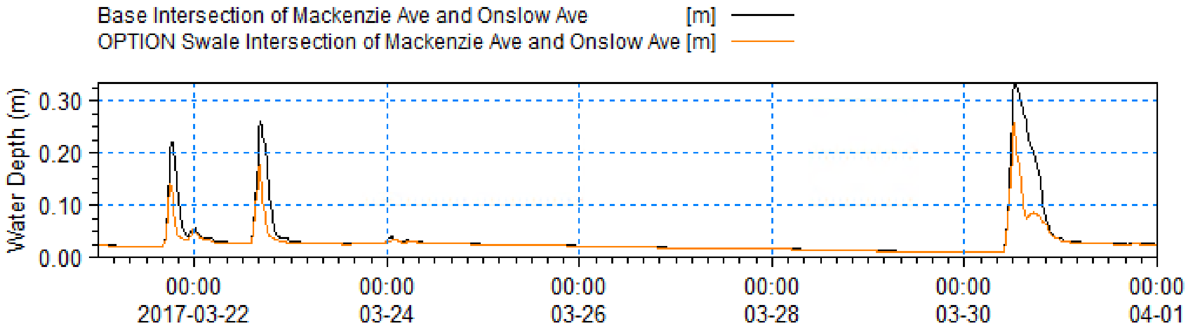


Figure 9.23 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Mar-Apr 2017 event, Black: Baseline, Orange: with Swales)

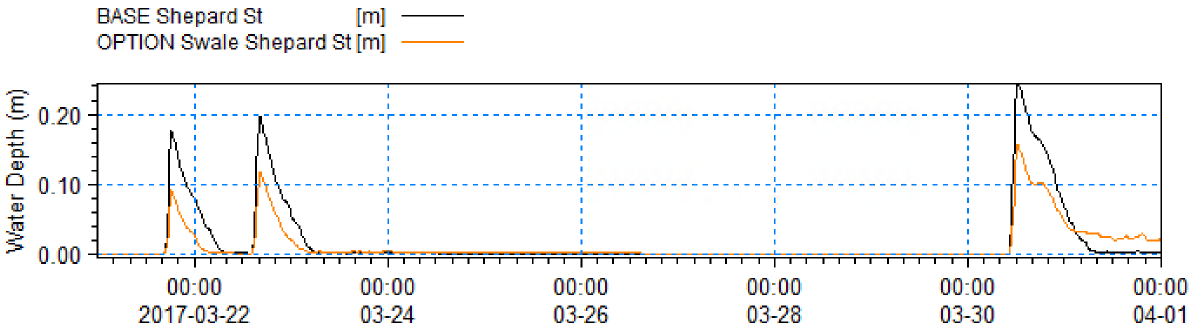


Figure 9.24 Comparison of water depths at Shepard Street (Mar-Apr 2017 event, Black: Baseline, Orange: with Swales)

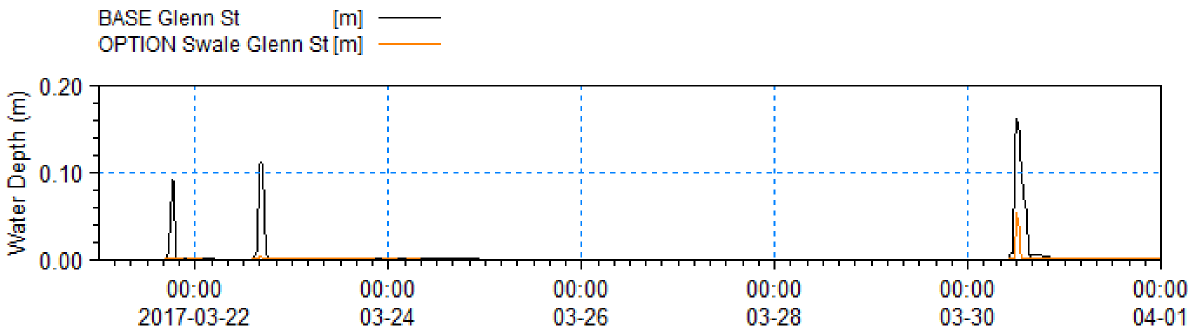


Figure 9.25 Comparison of water depths at Glenn Street (Mar-Apr 2017 event, Black: Baseline, Orange: with Swales)

9.6 Option 3 - Increase Storage Capacities at Allotment scale

To incorporate option 3 into the model, the following assumptions were made:

- A 8000L tank is installed at each lot.
- The tank collects water from the roof. The roof area at each lot is 200m^2.
- Water usage from the tank includes outside use, toilet, washing machine, hot water usage. This has been adopted from *DEUS-Rainwater Tank Model SILO Data 1985-2005.xls* provided by Council. The average load of washing and the average usage of toilet per household were estimated based on the average number of people per household in Woy Woy per 2016 Census and the average water usage (Turner et al., 2010)

- An outlet is connected to an infiltration pad within the lot. Infiltration rate is controlled by the actual groundwater table and the hydraulic conductivity.
- Residual rainfall contributes to runoff.

Figure 9.26 shows the difference in flood depths between this modelled option and the Baseline Feb 1990 event. It shows that the allotment scale tanks did not significantly reduce the peak water depth. Figure 9.27 to Figure 9.29 show the comparison of water depths between Baseline and OPTION 3 at identified flooding locations. Minor reductions can be seen at Shepard Street and Glenn Street while almost no reduction was achieved at the intersection of MacKenzie Avenue and Onslow Avenue.

It can be seen in Figure 9.26 and Figure 9.27 to Figure 9.29 that the implementation of the lot level storage devices had a limited impact on the peak flood levels (approximately 3rd of Feb 1990). This could be explained by the peak water depth being primarily driven by incident rainfall on the road catchments. The lot level drainage option would not impact the road catchments nor flood depths related to these catchments. It can be seen however that as the Feb 1990 event progressed there is a reduction in flood depths over an extended period of time (Figure 9.28 and Figure 9.29 4th of February). This may be explained by the responsiveness of the sub-catchments at individual locations and in some instances the lot level catchments contributing to flood depths during longer duration events. The addition of lot level drainage appears to will help alleviate total flooding impacts (as opposed to just the peak) during longer duration events.

While this study considered 8000 L tanks for reduction of the existing flooding, further investigations of this option can be done for counteracting the impact of new development on the existing flooding.

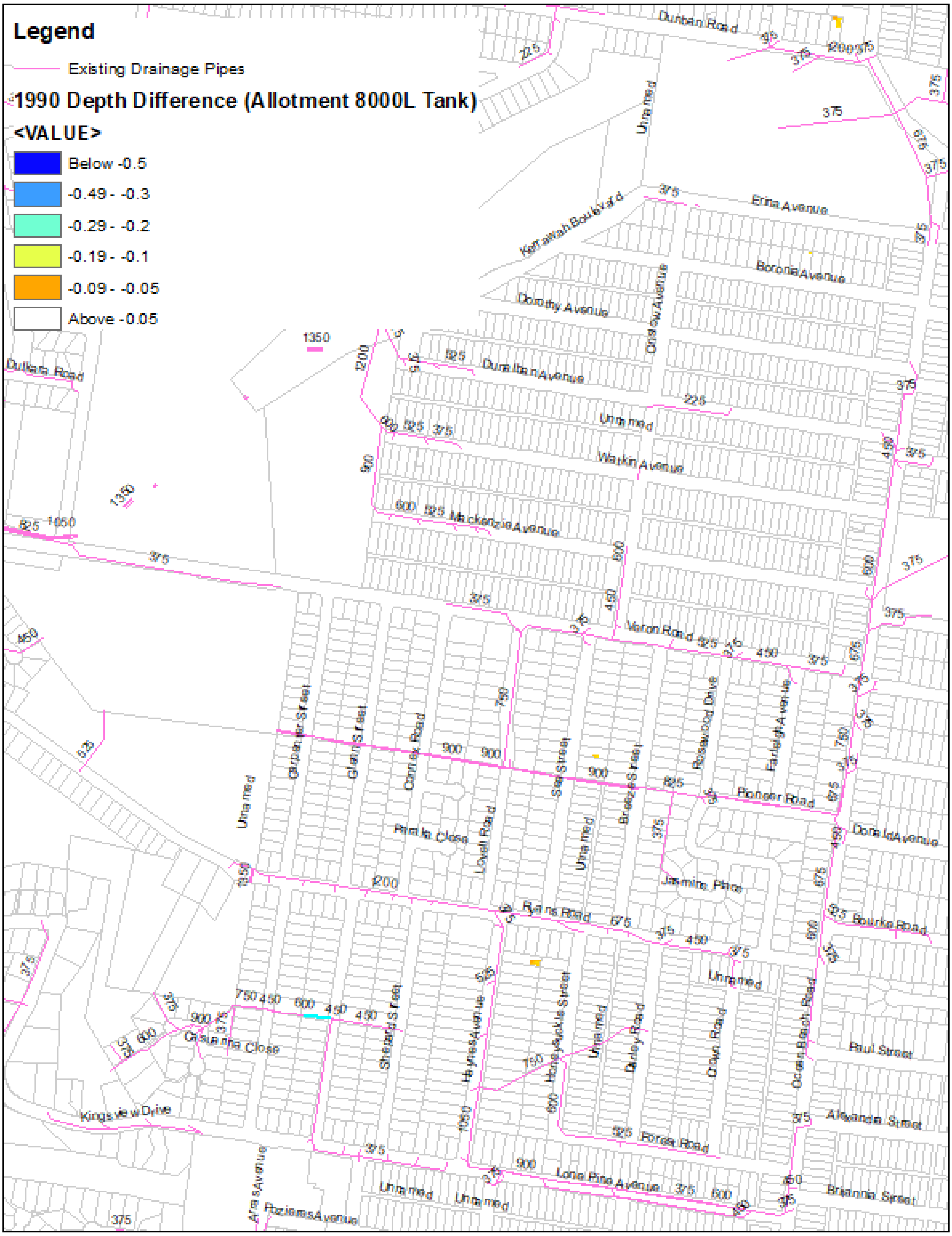


Figure 9.26 Allotment Scale tanks -Flood depth difference from BASE (Feb 1990 event)

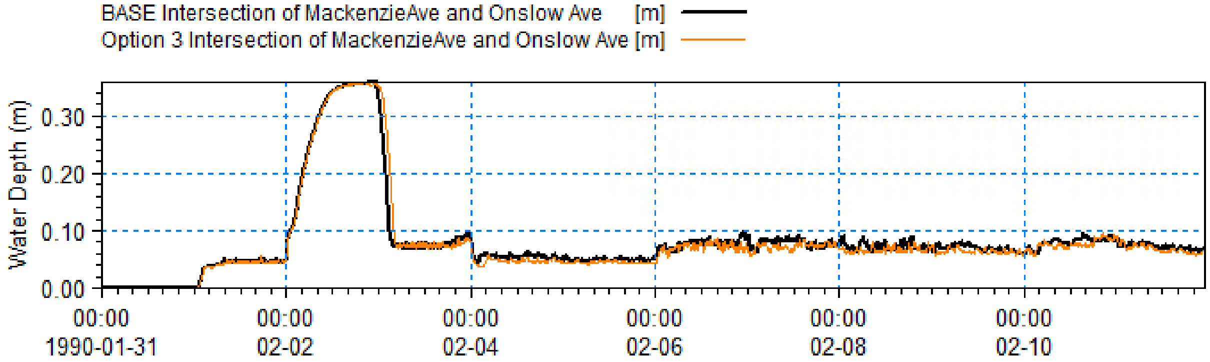


Figure 9.27 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Black: Baseline, Orange: OPTION 3) (Feb 1990)

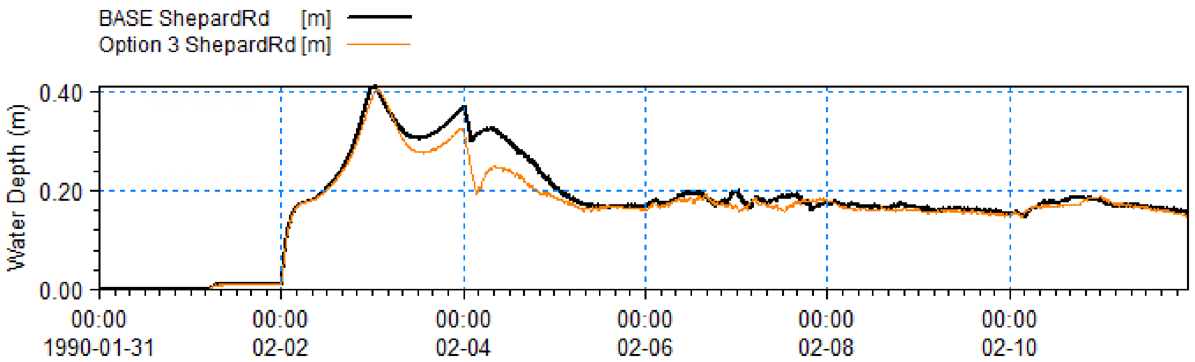


Figure 9.28 Comparison of water depths at Shepard Street (Black: Baseline, Orange: OPTION 3) (Feb 1990)

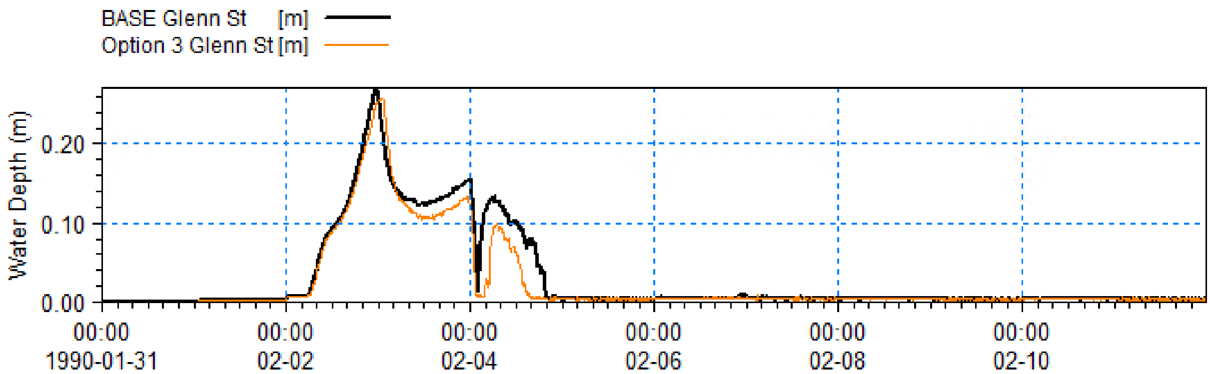


Figure 9.29 Comparison of water depths at Glenn Street (Black: Baseline, Orange: OPTION 3) (Feb 1990)

Following this assessment, Council requested to see the effectiveness of Option 3 for a more frequent event. Option 3 was tested against the series of 2017 nuisance flooding events. Figure 9.30 shows the difference of maximum flood depth Option 3 and the Baseline during Mar to Apr 2017. While small reductions in water depth are seen at Glenn Street, the overall impact of the allotment scale tanks on the flood depths is limited.

This can be explained by:

- The total roof area is relatively small compared to the catchment area. Reduction in the effective runoff is relatively small (a few percent)

- 8000L is equivalent of 40mm rainfall on the 200 m² roof. This quickly fills up and the infiltration rate is not as high as the rainfall rate.

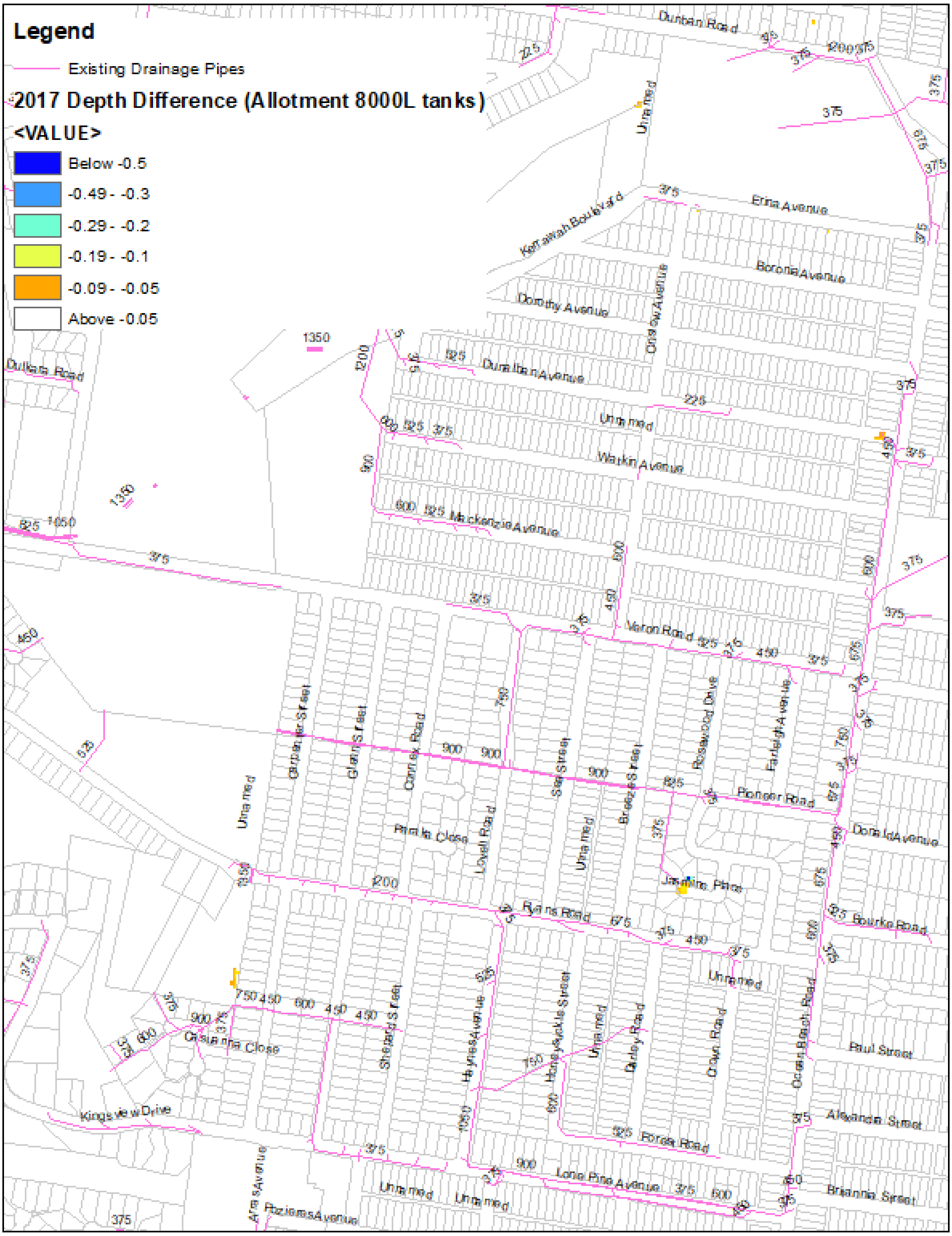


Figure 9.30 Allotment scale tanks -Flood depth difference from BASE (Mar-Apr 2017)

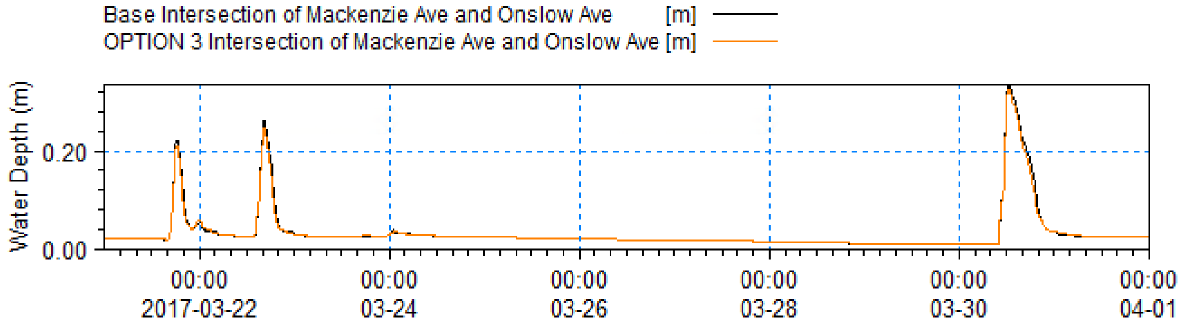


Figure 9.31 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Black: Baseline, Orange: OPTION 3) (Mar-Apr 2017)

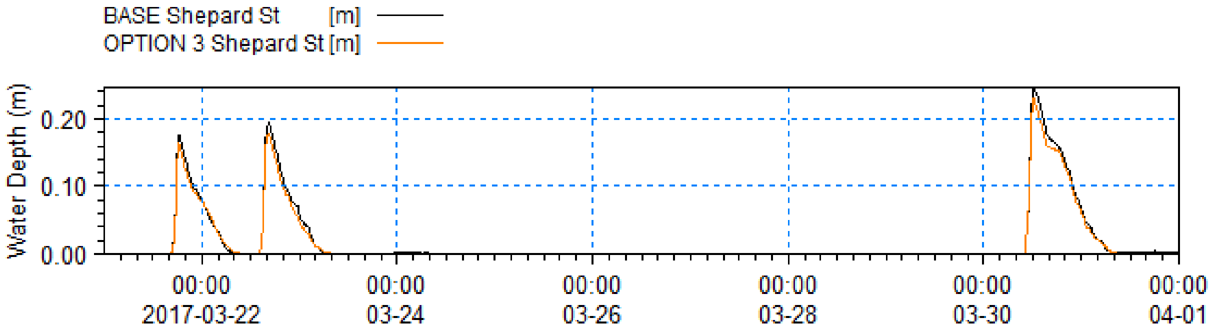


Figure 9.32 Comparison of water depths at Shepard Street (Black: Baseline, Orange: OPTION 3) (Mar-Apr 2017)

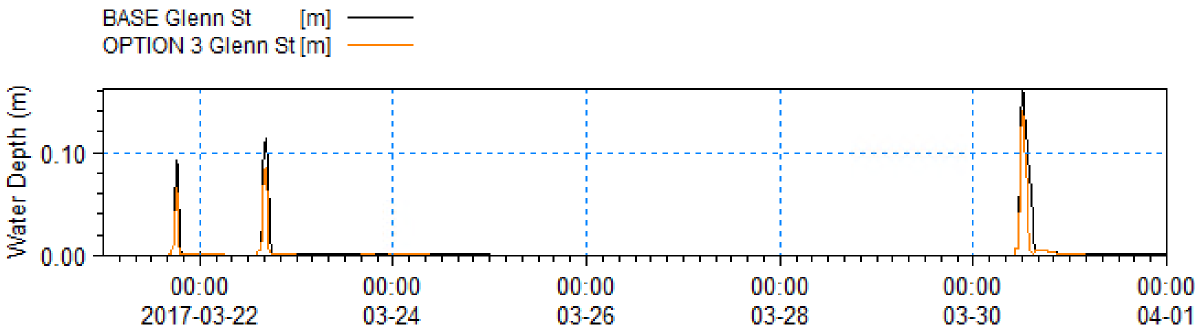


Figure 9.33 Comparison of water depths at Glenn Street (Black: Baseline, Orange: OPTION 3) (Mar-Apr 2017)

9.7 Option 4 - Strategic reduction of groundwater

The antecedent groundwater condition was extracted from the long-term groundwater simulation and combined with a constant 4ML/d pumping rate which was run for assessment of sustainable groundwater extraction rate as per Section 5. Figure 9.34 shows the difference in maximum flood depth between Option 4 and the Baseline in Feb 1990. Figure 9.35 to Figure 9.37 indicate the water depth at identified flooding locations. A reduction in flood depth was simulated at Shepard Street, Glenn Street, Carpenter Street and the golf course where the groundwater mound is located, while reduction in the peak flood depth in other locations is limited.

This indicates that the strategic lowering of groundwater increases the storage capacity of the sandy layer and flooding impacts can be improved in the areas impacted by the high groundwater table.

The following points should be further investigated for suitability of adaptation of this option.

- Impact on the groundwater dependent ecosystem
- Impact on soil settlement by reduction of the groundwater table
- Impact on the salinity intrusion
- Impact of the groundwater pattern change in conjunction with the sea level rise associated with the climate change

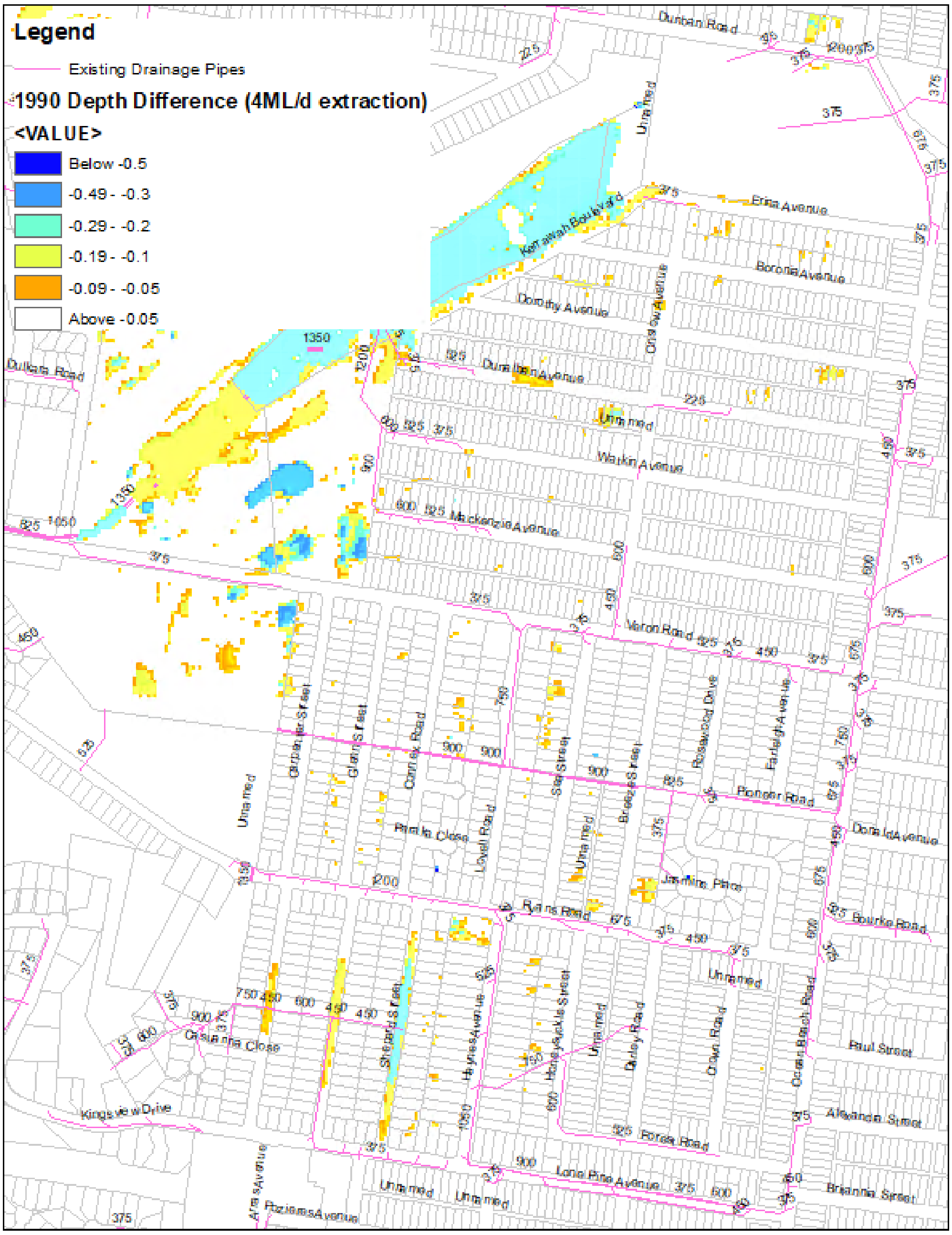


Figure 9.34 Strategic groundwater reduction - Flood depth difference from BASE (Feb 1990)

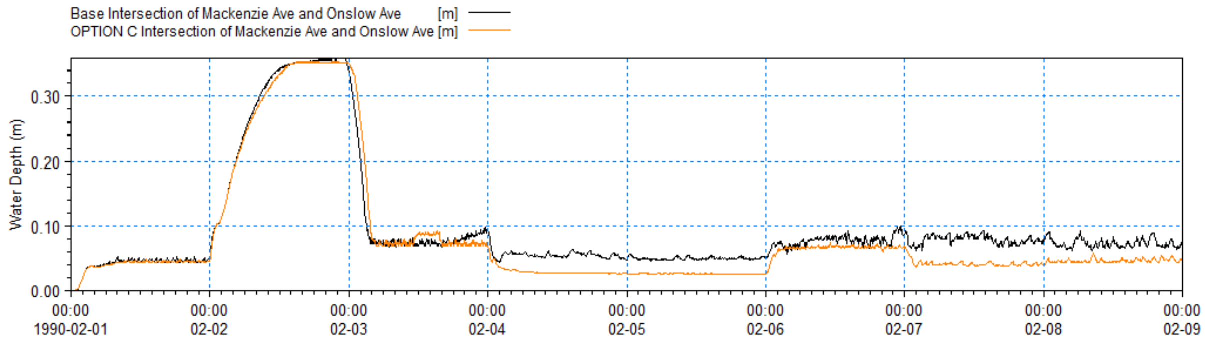


Figure 9.35 Comparison of water depths at the intersection of MacKenzie Avenue and Onslow Avenue (Black: Baseline, Orange: OPTION 4) (Feb 1990)

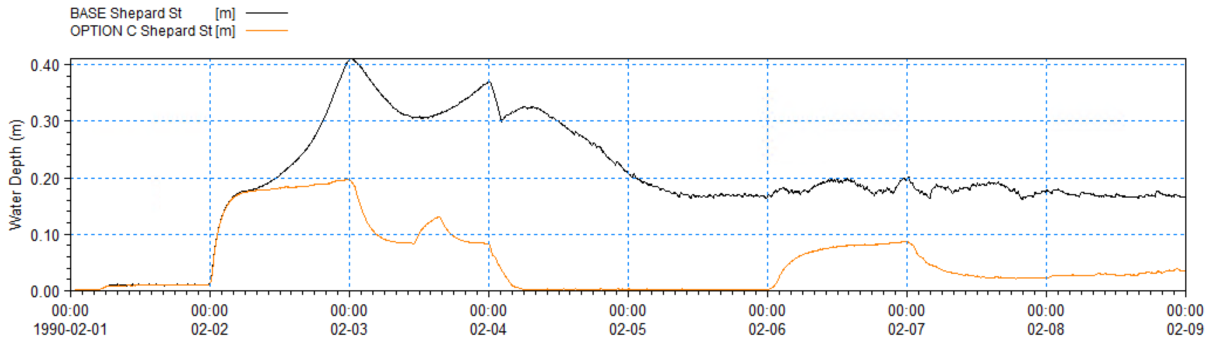


Figure 9.36 Comparison of water depths at Shepard Street (Black: Baseline, Orange: OPTION 4) (Feb 1990)

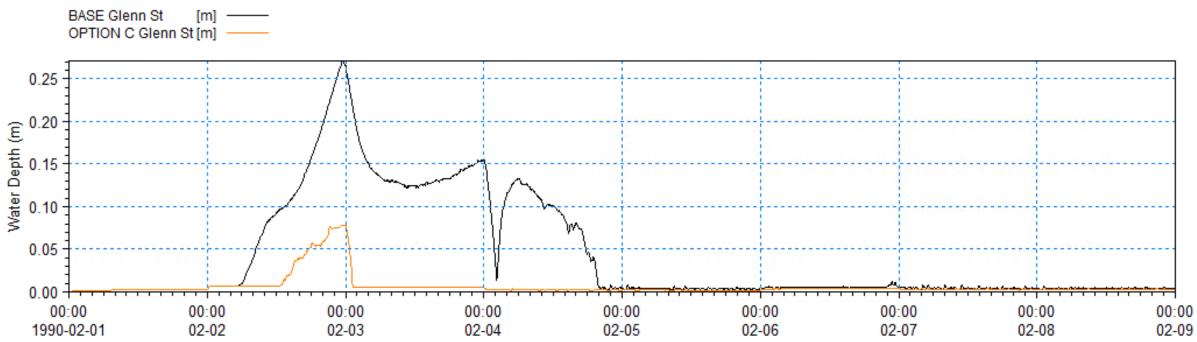


Figure 9.37 Comparison of water depths at Glenn Street (Black: Baseline, Orange: OPTION 4) (Feb 1990)

9.8 Option 5 - Rezoning and redevelopment

Shepard Street, Glenn Street, Carpenter Street and Connex Road are located above the groundwater mound and flooding at these locations is often a result of the high groundwater table. This flooding behaviour aligns with the understanding that wetlands/lagoons existed at the base of the escarpment around the Everglades Catchment prior to urbanisation. Rezoning and redevelopment allow the low-lying areas to function as naturally ponded areas.

10 Summary

Literature review of stormwater infiltration and flood studies on the Woy Woy peninsula since 1990 was undertaken. Groundwater bore data on the peninsula collected since the previous study (DHI, 2010) were also reviewed and compiled as well as other data such as climate, topographic and drainage data.

Review of the literature and data provided understanding of necessary inputs and assumptions to be incorporated in updating the Peninsula groundwater model such as boundary conditions, soil parameters and calibration targets.

The Peninsula groundwater model developed in the previous study (DHI, 2010) was expanded to include the Kahibah catchment and revised to incorporate the new LiDAR data.

The initial test runs showed recalibration of the upgraded model was required, particularly to incorporate the newly obtained groundwater records. The available data was manually adjusted to be as realistic as possible, using the best available information. The model was calibrated against the groundwater level records at the monitoring bores. The model reproduced the known groundwater pattern of a groundwater mound at the Everglades Catchment and surface water flows toward the bounding sea. The peninsula groundwater model was run with the long-term rainfall timeseries and the average sea level for more than 100 years to estimate the groundwater trend in the catchment.

The updated model was used to assess sustainable groundwater extractions. This was undertaken by running the model with Council's entitlement of 4ML/day pumping at the production bores from 1900 to 2018 which includes two historical drought periods, namely the World War II Drought (late 1930s to early 1940s) and the Millennium Drought (2000s). Decline of the groundwater level under the 4ML/d extraction varies greatly across different locations of the peninsula and is generally large in the centre of the peninsula while the coastal area is bound by the sea level condition. On average the groundwater level becomes 0.5 to 1m lower under the 4ML/d extraction than the Baseline at the centre of the peninsula. At some locations, the groundwater levels fall below 0mAHD for several months during the dry season on multiple occasions over the 100 years simulated.

Outcomes of the groundwater model were handed over to another study "Woy Woy Flood Risk Management Study and Plan".

Conceptual models of preliminary management options in the case study catchment Everglades were developed in collaboration with key stakeholders in Council.

To assess the selected options quantitively, a numerical model was developed. The Everglades Catchment flood model was derived by trimming and refining the peninsula groundwater model. The drainage infrastructure also was added to the model. The Everglades catchment flood model was calibrated using nuisance flooding available from 2017. While no records of flood depth or water level/discharge at Main Drain were available the reported occurrence of flooding at streets was replicated in the model. The Everglades flood model was used to simulate nuisance flooding records, in 2017, and a larger event, in February 1990. This revealed the following characteristics of flooding at the Everglades catchment:

- Surface runoff flows down streets and ponds at the low points. This is particularly evident at the intersection of MacKenzie Avenue and Onslow Avenue, the middle sections of Connex Road, Lovell Road, Glenn Street, Shepard Street and Carpenter Street.

- Lack of drainage assets (for example, the intersection between MacKenzie Avenue prior to the 2020 drainage work) or limited drainage capacity (around Veron Road) causes ponding of water at local sag points.
- The shallow sandy aquifer level is responsive to runoff from both local residential blocks and the escarpment.
- The groundwater level reaches the ground surface after a series of minor rainfall events (April 2017) or a large rainfall event (February 1990 event) at some low-lying locations.
- The high groundwater table coincides with the surface water peak in locations along Shepard Street, Connex Road, Glenn Street and Carpenter Street.
- The high groundwater table potentially causes prolonged ponding at these locations.

The interaction of groundwater and surface water contributing to flooding indicates that mitigation options such as increasing the stormwater drainage capacity is unlikely to solve flooding in the Everglades catchment. Several management options were numerically modelled for the nuisance flooding in 2017 or the Feb 2019 event. Findings of the assessment and recommendations of each option are summarised as follows:

- The MacKenzie Avenue drainage upgrade works (completed in 2020) were assessed prior to commencement of construction. The simulation confirmed that additional inlets and the extended duplication of pipes improves local flooding during the nuisance flooding events and the larger rainfall event.
- The drainage pipes at Veron Road and Lovell Road are often at maximum capacity. Redirection of flows away from Main Drain, combined with the addition of drainage inlets and sumps was effective in alleviation of capacity constraints and contributes to a reduction in nuisance flooding at local sag points. However, this may not be effective for a large flood event at Shepard Sreett, Connex Road, Glenn Street and Carpenter Street where the high groundwater table also contributes to flooding. The progression of this option would require survey of exact drainage levels which were not available in this study. The topography of Trafalgar Avenue, where the easterly trunk drainage is located, is typically higher than the topography of the Everglades Catchment, it may not be feasible to redirect flow to this trunk drainage.
- An additional storage, with infiltration capacity, at the existing Connex Park will assist in alleviating capacity issues of drainage infrastructure on Veron Road and Lovell Road during nuisance flooding events and potentially improve the flooding at upstream locations such as Mackenzie Avenue and Onslow Avenue. However, the storage and infiltration capacity are likely to be impacted during larger rainfall events where the groundwater table rises above the invert level of the storage.
- Exfiltration pipes have a limited impact on improvement of peak flooding. However, it could reduce minor ponding on some streets.
- Installation of swales along the drainage asset free streets can improve flooding at topographic low points. Road design should consider swales as an option to ensure the permeability of road reserves.
- Allotment scale tanks (8000L) collecting rainfall from the roof were tested. While this reduces flood depth slightly during smaller events, it is not effective for reduction of flooding of larger rainfall events. While this study considered 8000L tanks for reduction of the existing flooding, further investigations of this option can be done for counteracting the impact of new development on the existing flooding.
- Strategic reduction of groundwater would be ineffective if pumping is undertaken for only short periods of time (e.g. 1 month) prior to a flood season. However, a permanent reduction in the groundwater table through

constant 4 ML/d pumping for portable water uses can improve flooding significantly at Shepard Street, Glenn Street and Carpenter Street where the high groundwater table contributes to flooding impacts. Further assessment is required for feasibility of this option as lowering the groundwater level can impact groundwater dependent ecosystems, increase the risk of salinity intrusion and may have soil settlement implications.

Council's Black Spot Policy currently restricts developments in the vicinity of the historically reported drainage issues. Any amendments to the current Black Spot policy would need to carefully consider any site specific black spot in the context of the flooding mechanics (e.g. groundwater driven flooding) and should utilise the groundwater information from this study and information in the on-going Woy Woy Floodplain Risk Management Study and Plans. Considerations of the latest flood risk management study and plans were outside the scope of this integrated water study.

11 Recommendations

The simulations undertaken as part of this study indicates that the following are the most promising options for alleviation of nuisance flooding.

- Option 2 Swales on drainage asset free roads
- Option 4 Strategic reduction of groundwater table
- Option 5 Rezoning and redevelopment

Option 4 Strategic reduction of groundwater table and Option 5 Rezoning and redevelopment are also considered effective for alleviation of a larger flood event. At a low point experiencing frequent flooding like MacKenzie Avenue which was missing drainage capacity, additional inlets and drainage capacity can also improve flooding.

It is recommended that further investigations as part of more detailed examination of these options to confirm suitability for adaptation. This includes:

- Option 2 – site specific implementation in the context of roadside infrastructure requirements and road standards, sizes and, design of swales for effectiveness.
- Option 4 – the impact of permanent lowering of the shallow groundwater on groundwater dependent ecosystems, salinity intrusion and soil settlement in conjunction with climate change.
- Option 5 – any existing development conditions/standards and the ability to incorporate new policies/regulations and the site specific constraints of sizing and design requirements for rezoning and redevelopment

The following are also recommended for future studies:

- To review the options in this study in the future Flood Risk Management Study and Plan.
- To maintain the groundwater monitoring program and to process the data at a regular basis. A large number of monitoring bores have been installed in the Woy Woy peninsula which collect water quality and pressure data of the shallow groundwater which are useful for further investigations of management options and groundwater assessment. It should be noted that downloading of a raw data is not sufficient if the bores are not maintained and the data is not compiled for an extended period of time. Lack of regular compilation of the collected data significantly increases uncertainties and quality of data over time as the information about the monitoring conditions degrades over extended periods of time.
- To share the updated groundwater model and the outcome of the assessment of the sustainable groundwater extraction rate with relevant Directorates of Council for evaluation of future water supply policies of the Peninsula and potential synergies with the groundwater management.
- To survey drainage levels for more accurate representation of the drainage system in the model.
- To collect more information about the surface flow regimes as well as the storm drainage flow. Limited information about the surface flow as well as the storm drainage flow were available in the peninsula for calibration of the model. The developed Everglades flood model can be further improved by incorporating by surveyed drainage levels or the water level/discharge records at an open channel such as Main Drain.
- To review the relevance of the Black Spot Policy in the current Development Control Plans considering the updated groundwater model and the outcome of this study as part of a future Floodplain Risk Management Plan in the Peninsula.

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APPENDICES

APPENDICES

APPENDIX A

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16th February 2019
Ref: 19016-A

DHI Water and Environment Pty Ltd
PO Box 4503
SYDNEY NSW 2001

Re: **Status Report – Water level Data Compilation and Assessment**
Woy Woy Groundwater Project

1. INTRODUCTION

In accordance with our Woy Woy project proposal 15048 dated 5th July 2018, the following tasks were undertaken:

- Acquire pressure (water level) and temperature data and calibration files from Central Coast Council for the 13 monitoring bores equipped with pressure transducers (water level sensors/loggers installed in 13 dedicated monitoring bores on the Woy Woy peninsula. The loggers were commissioned in about 2006 and the data downloaded manually by a Council officer on a semi regular basis. The raw data was archived in Council's IT system but apparently never reviewed, checked or interrogated.
- Compile the raw water level data (PRN files – *Data Flow*) in a 'stand-alone' data base (spread sheet) for each monitoring bore. The compilation work revealed that the data set for each monitoring bore had on average 50 data blocks. Manual water level measurements taken by Council over the ensuing 14 years, when downloading the loggers and/or batteries were changed or repairs undertaken, were manually appended to each data base. The average number of data rows is 45,000.
- Interrogate each data block manually for each subject monitoring bore and append to the previously-constructed spread sheet.

  The interrogation of each of the 13 data sets revealed apparent errors, data glitches, outliers, multiple data shifts and apparent sensor drift. The drift was identified by comparing the water levels logged by each sensor with the manual water level measurements for those dates.
- Construct a set of hydrographs for each monitoring bore.

During the initial data compilation, it became apparent that more time was required to compile the large amounts of data (14 years and 45,000 rows per bore). In this regard, a variation was submitted to DHI to cover this additional time (Variation I).

An algorithm was applied to the water level data in each data set in an attempt to correct the apparent drift and data shifts revealed by comparing the recorded water levels in the logger data with manual water level measurements for the same dates. The corrections were successful for the majority of the data but some significant data shifts were difficult to reach convergence. The data was sent to DHI for review and input into the numerical groundwater model.

Subsequent discussions with DHI and Council confirmed that some of the adjusted water levels do not appear to correlate with intermittent manual water levels taken by Council in ‘nearby’ monitoring bores over the same period. Larry Cook Consulting did not at this time hold any water level data for the neighbouring monitoring bores.

To progress the assessment of the integrity and usefulness of the water level data, a further variation was proposed (Variation II). It was recommended that the hydrographs already constructed from the above-mentioned logger data (13 monitoring bores) be compared/correlated with the manual water level measurements for any neighbouring bores held by DHI/Council. This process would quickly identify parts/blocks of the automated water level data that may require adjustment or deletion.

2. ADDITIONAL WORK UNDERTAKEN – VARIATION II

The following work was undertaken as per Variation II:

- Reviewed comments and questions in email correspondence from DHI regarding the water level data (emails Dec 10 2018 and Feb 5, Jan 30 2019) and in a detailed memo report to Council dated 232 January 2019.
- Reassessed the previously compiled water level data for all 13 monitoring bores with sensors/data loggers and identify actual periods of data shifts, outliers and data sensor/recorder failure.
- Convened a meeting with DHI in Sydney (Keiko Yamagata) on 15th February 2019 to discuss apparent issues with the water level data and assess reliability of the data for use in the numerical groundwater model. The apparent issues with each data set were assessed and a way forward discussed.
- Prepared this report detailing the parts of each data set considered reliable for the computer model and parts requiring adjustment in the model or deletion from the process.
- This report also describes the hydrogeological setting of the Woy Woy Peninsula and provides clarification of possible reasons for data inconsistencies and issues relevant to the assessment of the water level data.

3. HYDROGEOLOGY SETTING

Fourteen test production bores were constructed to an average depth of 23.2m on the Woy Woy Peninsula, a three-kilometre-wide composite Pleistocene-Holocene beach barrier system which hosts a large, unconfined, rainfall-recharged groundwater mound (**Figure 1**).

The Peninsula is situated within the northern part of a 2-kilometre-wide, north-south trending valley hosted by the Terrigal Formation which is dissected by Broken Bay where the Hawkesbury River enters the Tasman Sea. Pittwater forms the southern part of the valley structure. The dunes and intervening swales trend north-east to south-west parallel to the present shoreline on Ocean Beach and orthogonal to the prevailing direction of south-east swell waves entering Broken Bay. The ridge system north and north-west of the line of wetlands including the Everglades wetland in the north of the Peninsula is believed to be a Pleistocene inner barrier system (Hails, 1969). The sand ridges south of these wetlands through to Ocean Beach are considered to be of recent age formed in response to eustatic changes.

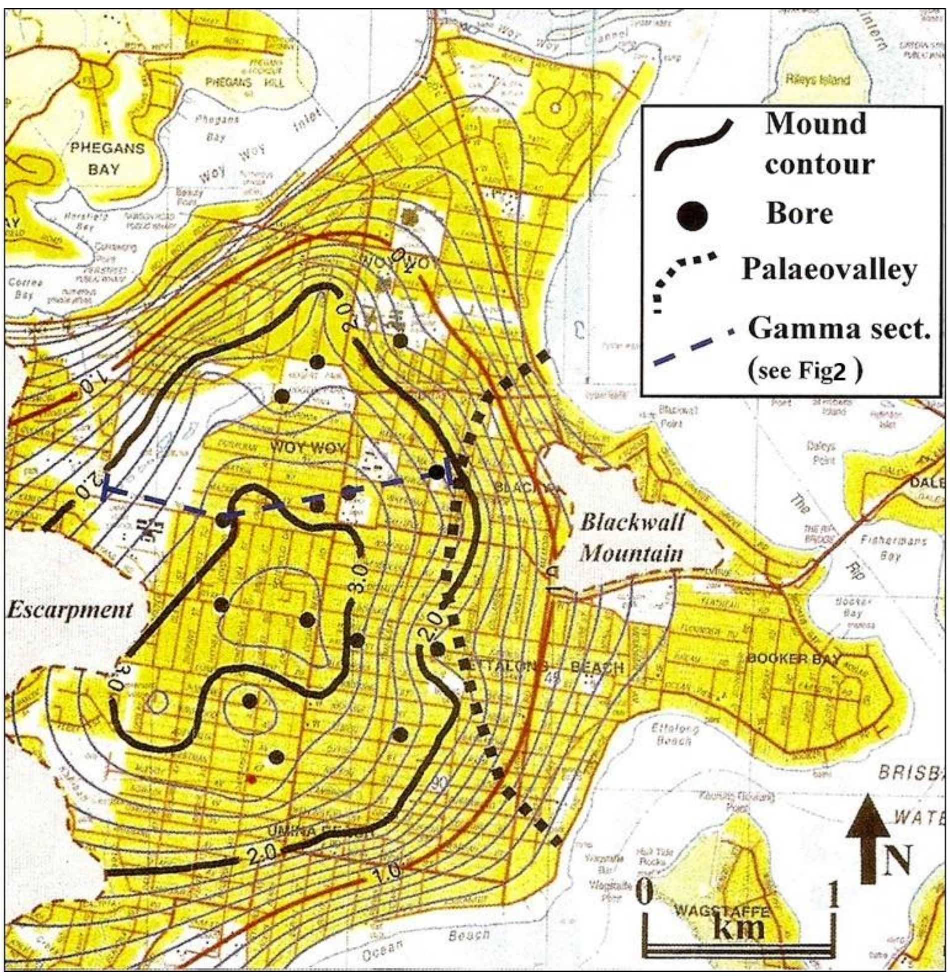

Figure 1 Woy Woy beach barrier sand dune aquifer with contours on the watertable mound

Several campaigns of test and monitoring bore drilling since 1998 combined with geophysical bore logging and stratigraphic correlations reveal a set of five Holocene dominantly stacked and interlensed, north-east trending sand bodies ranging in total thickness of between approximately 20 and 25m. The sequence overlies strongly weathered Terrigal Formation basement.

Gamma logging indicated that relatively 'clean' fine to coarse sand dominates the eastern half of the Peninsula and silty to clayey, in part peaty, fine to medium sand in the west. A representative E-W gamma section located in the central part of the Peninsula (**Figure 1**) shows this distribution.

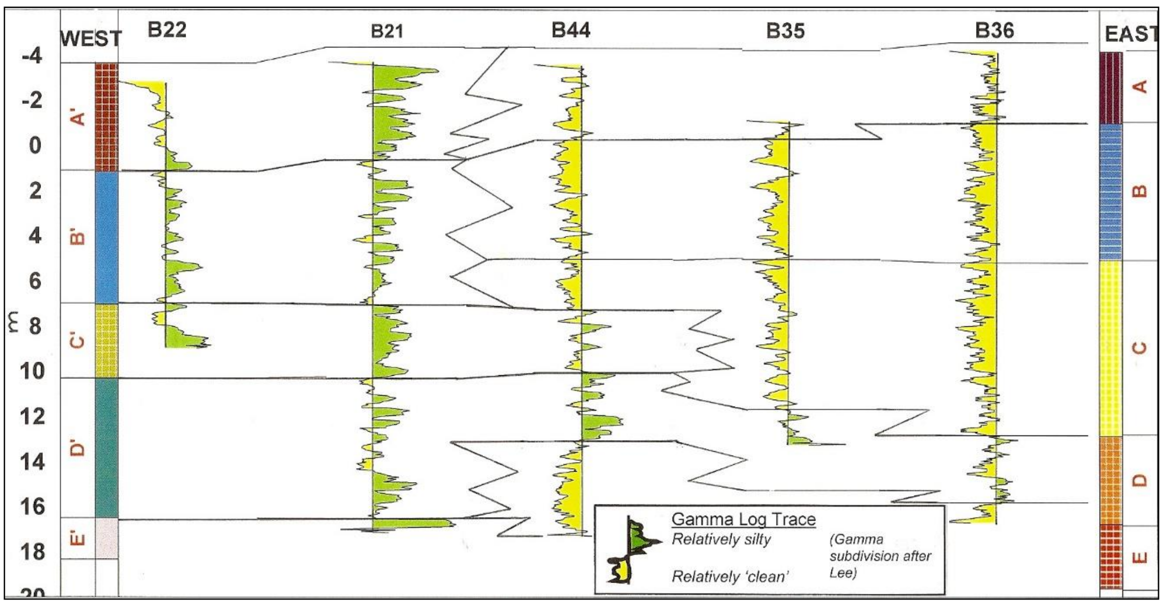

Figure 2 Representative gamma section across the Woy Woy sand dune aquifer

The sand complexes are dominantly transgressive sheet-like forms and distributed along a meridional depositional axis flanked to the west by lagoonal and wetland environments. The thickest sequences of 'clean' sand are developed in the central parts of the Peninsula extending south to Ocean Beach and thinning to the north. This sand sequence constitutes the most prospective aquifer and is essentially a 'wedge' bounded to the east by estuarine deposits and the sea and to the west by lagoonal-wetland deposits.

The groundwater mound is broadly located in the 6m-high central part of the Peninsula with the crown generally between about 3.0 and 4.0m AHD (**Figure 1**). The fluctuations in water table are directly related to rainfall recharge events. The majority of test production bores were strategically positioned on the mound to target the more prospective of the Holocene sand bodies and to take advantage of the positive head. Elevation-controlled 'pump to' levels have been developed by Council in order to avoid any impact on the aquifer from artificially-induced saltwater encroachment.

4. CLARIFICATION

In order to provide clarification and more certainty with the water table measurements recorded in the logged monitoring bores, the following points are made:

- The elevations (and coordinates) of observation bores were determined from an accurate ground survey by Barry Hunt Associates in the mid 2000s. Elevations and coordinates were calculated to three decimal places.
- The casing (monuments) and ‘stickups’ of the observation bores have not been changed since installation/construction. Some observation bores are in ‘road boxes’ and therefore level with the ground surface.
- Water level measurements, logger downloads and any maintenance was always carried out by one Council officer – Phil Cranidge. That is, manual water level measurements were taken using an electronic water level dipper (Herron) and always used the same reference mark on the respective bores.
- Although errors are always possible when deploying data loggers, the monitoring bores are 50 mm inside diameter. The logger is 39 mm diameter and is easily deployed to its correct depth with a cap that neatly fits the 50 mm diameter casing. The semi flexible vent tube is 8 mm diameter and doubles as a support ‘cable’. It is almost impossible to ‘coil’ or ‘hang-up’ the logger cable. The 39 mm-dia logger has to be fed into the casing vertically and directly and lowered to its dedicated depth. Unless there is an obstruction in the casing (PVC pipe), the logger freely lowers to its nominated position.
- Manual water level measurements were/are always taken in the casing prior to extraction of the logger for downloading. The plug on the end of the vent tube is lifted from the top of casing by just 6 to 10 cm to provide access for the electronic water level dipper.
- Uncorrected drift in the pressure (water table) measurements did occur due to either logger failure and/or power loss (flat batteries). More frequent water level measurements and regular data interrogations would help to address these issues in a timely manner.
- The download procedure for the ‘Odyssey’ loggers includes the removal of the logger string from the bore, remove the sealed screw cap from the top of the logger and plug in a data transfer cable. When the data is downloaded, the logger ceases to log automatically. In the event that the logger is removed but not downloaded, the pressure measurements would be surface level pressures as there is no water above the logger.
- The pressure ranges were selected to manage the increase in water pressures/levels that may arise from intense rainfall events. In any case, the water tables are relatively shallow (close to surface). The burst pressure cannot be exceeded in the bores.
- The loggers will record any interference from proximal production bore pumping and/or extraction from spear points (basic use rights). It is noted that Phil Cranidge did correctly, from time to time, operate the production bores for small periods in order to ‘turn’ them over.

- As DHI correctly identified, the loggers will also record any proximal mechanical 'loading' and 'unloading' (compression/decompression) of locally confined sand aquifers caused by such events as movement of 'heavy' construction vehicles and/or localized ponding of water following intense rainfall events.

5. ANALYSIS, DISCUSSION ANS RECOMMENDATIONS

WW20 – PAUL STREET

The hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- The recorded water level data between commencement of logging in March 2006 and end November 2009 is considered reliable and representative of the hydrogeological conditions at this site during this period.
- Multiple short-term drawdown events of approximately 0.2 m observed in the hydrograph are not considered data anomalies (glitches) and considered to be responses to local spear point (basic use rights bores) extraction.
- Spurious data anomalies recorded on 5th January 2015 and 16th December 2018 were deleted.
- Significant deviation is noted between the shape of the hydrograph and hydrographs for proximal monitoring bores with manual water level measurements. In this regard, it is recommended that the data blocks listed below be adjusted or deleted from the analysis:
    - Period Dec 2009 and May/June 2010
    - Period July 2012 and end January 2015

  These periods include three steep drawdown of the water table (between approximately 2.0 and 5.0 m) followed by a lack of water level data. These are interpreted to be systematic of logger failure (possibly low power issues-flat batteries).

WW21 – VERON STREET

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores generally correlate with the data logger pressures (water level). Therefore, the hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- The overall shape and trend of the hydrograph is similar to hydrographs from proximal monitoring bores.
- Rapid rises (spikes) in the water table are considered to be due to the effects of instantaneous recharge from rainfall events which are enhanced by its location close to the top of the groundwater mound in the central part of the

peninsula. However, the trend of the hydrograph remains representative of local near-bore hydrogeological conditions

- Steep drawdown of the water table (between approximately 1.0 and 3.4 m) followed by a lack of water level data were recorded over five events between mid-2014 and early 2017. These are interpreted to be systematic of logger failure (possibly low power issues-flat batteries). In this regard, it is recommended that the data for the periods listed below be deleted from the analysis:
  - ➢ Period 18/6/17-23/6/14
  - ➢ Period 8/7/15-9/7/15
  - ➢ Period 18/3/16-25/3/16
  - ➢ Period18/8/16-24/8/16
  - ➢ Period 4/4/17-7/4/17

WW23 – ROGERS PARK

The hydrograph reveals that the manual measurements of the water table in proximal monitoring bores generally correlate with the data logger pressures (water level). The shape of the hydrograph is consistent with trends observed in neighbouring monitoring bores and therefore considered to be appropriate for use in the model.

WW26 – JAMES BROWN OVAL

The hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- The overall shape and trend of the hydrograph is similar to hydrographs from proximal monitoring bores.
- Steep, sharp but relatively small amounts of drawdown of the water table (approximately 0.2 m) were observed in the data, for example between April 2012 and January 2013. The drawdown events are regular and consistent. These are interpreted to be minor interference from spear points (basic use rights bores). However, the trend of the hydrograph remains representative of local near-bore hydrogeological conditions.
- Significant deviation is noted between the shape of the hydrograph and hydrographs for proximal monitoring bores with manual water level measurements in early to late April 2012. In this regard, it is recommended that the data block listed below be adjusted or deleted from the analysis:
  - ➢ Period April 2012 to August 2012

WW28 – KING STREET

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores in the main correlate with the data logger pressures (water level). The hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- Steep, sharp but relatively small amounts of drawdown of the water table (between approximately 0.4 and 0.6 m) were observed throughout the data. The drawdown events are regular and consistent. These are interpreted to be minor interference from spear points (basic use rights bores). However, the trend of the hydrograph remains representative of local near-bore hydrogeological conditions.
- The water level data recorded between early 2013 and late 2015 includes ‘flat lining’, data gaps and unusual recharge events (spikes) that are not reflected in the hydrographs for neighbouring monitoring bores. In this regard, it is recommended that the data block listed below be deleted from the analysis:
    - Period February 2013 to end 2015
- It is also recommended that the data block listed below be adjusted or deleted from the analysis:
    - Period May 2016 to September 2016

WW33 – POZIERS STREET

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores in the main correlate with the data logger pressures (water level). The hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- Significant data shifts are observed during four periods between early 2015 and late 2017. These shifts may be due to errors introduced during downloads of the data logger where the sensor/logger may have inadvertently repositioned at a different level in the monitoring bore or different reference levels used?
- It is therefore recommended that the data blocks listed below be adjusted or deleted from the analysis:
    - Period June to December 2016
    - Period May to October 2016. It is noted that the trend of the hydrograph during this period is plausible, but the data has shifted ‘up’
    - Period August to September 2017
- A gradual and significant 3 m rise in the water table is observed between about mid-December 2016 and early April 2017. A steep decline in the water table follows. We cannot guarantee the integrity of this data even though a 0.5 m rise is noted during the end of the same period in neighbouring monitoring bores WW11, WW17 and WW 34.

  It is therefore recommended that this data block be deleted from the analysis.

WW36 – ALMA STREET

The hydrograph shows 'flat lining' of the water table between late 2008 and 2018. A review of the collated data revealed a calculation glitch in the spread sheet in October 2008. This glitch has been duly corrected.

A review of the corrected data and reconstructed hydrograph suggests that the hydrograph is considered to be useful for use in the groundwater model

The following comments are provided:

- Multiple steep, sharp but relatively small amounts of drawdown of the water table were observed throughout the data. The drawdown events are regular and consistent. These are interpreted to be minor interference from spear points (basic use rights bores). However, the trend of the hydrograph remains representative of local near-bore hydrogeological conditions.

WW42 – ALBION STREET

Although the hydrograph reveals that the measurements of the water table generally correlate with the data logger pressures (water level), there are unexplained data shifts that require adjustment or deletion from the analysis. These events easily identified on the hydrograph and occur about:

- May 2006
- June 2009
- October 2009
- November 2010
- January 2011

WW43 – RYANS ROAD

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores generally correlate with the data logger pressures (water level). The hydrograph is considered to be generally useful for use in the model with the following comments and caveats:

- Rapid rises (spikes) in the water table are considered to be due to the effects of instantaneous recharge from rainfall events which are enhanced by its location close to the top of the groundwater mound in the central part of the peninsula. However, the trend of the hydrograph remains representative of local near-bore hydrogeological conditions
- Rare erratic values of water level in the data (example March 2017) do not compromise the overall shape of the hydrograph
- There are however, unexplained data shifts that require deletion from the analysis. These events easily identified on the hydrograph and occur about:
    - September 2007

- November 2010
- June 2015

WW44 – MACKENZIE STREET

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores generally correlate with the data logger pressures (water level). Although the hydrograph reveals that the measurements of the water table generally correlate with the data logger pressures (water level), there are unexplained data shifts that require adjustment or deletion from the analysis. These events are easily identified on the hydrograph and occur on or about:

- 21/8/07
- September to November 2010
- 2/12/04
- 12/12/16

- Frequent rises (and less common falls) in the water table (average 0.5 m) were observed in the logger data between early September and mid November 2010. Although this phenomena is difficult to explain, useful discussions with DHI indicate that they may be due to mechanical loading and unloading at the nearby production bore PWW44 on a local confined aquifer.
- Rare erratic values of water level in the data (examples September 2006, June 2015 and September 2016) do not compromise the overall shape of the hydrograph

WW55 – UMINA OVAL

The hydrograph reveals that the manual measurements of the water table in proximal neighbouring bores correlate with the data logger pressures (water level). The shape of the hydrograph is consistent with trends observed in neighbouring monitoring bores and therefore considered to be appropriate for use in the model.

It is noted however that there are possible minor data shifts may occur that may require adjustment. These are on or about:

- End April 2017
- September 2017

WW56 – BORONIA AVENUE

Monitoring Bore WW56 is located on the southern side of the Everglades Country Club, an active but disturbed wetland system. The country club incorporates a network of licensed production bores which regularly extract groundwater for the irrigation of the golf course.

The hydrograph displays relatively erratic fluctuations in the water table and several unexplained data shifts that are believed to be the response to artificial groundwater interference associated with the production bores and pumps.

- It is recommended that the data for WW56 not be used in the groundwater model.

WW57 – DUNALBAN AVENUE

The elevation of the ground surface in the data base was incorrect and has been corrected. The shape of the hydrograph is consistent with trends observed in neighbouring monitoring bores and therefore considered to be appropriate for use in the model.

- The observed fluctuations (minor shifts) in the water table may be slightly influenced by artificial interference from bores and pumps in the nearby Everglades Country Club.

6. CLOSURE

If you require any further information or wish to discuss the report, please do not hesitate to contact Larry Cook on 0428 884645.

For and on Behalf of
Larry Cook Consulting Pty Ltd

Larry Cook
Senior Hydrogeologist

APPENDIX B–Calibration Results

Groundwater levels

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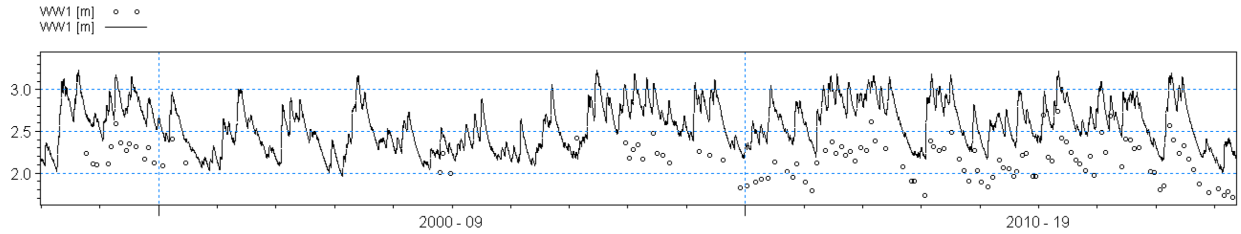
Simulated and observed groundwater levels at the monitoring bores

B.1 Everglades drainage catchment

WW1



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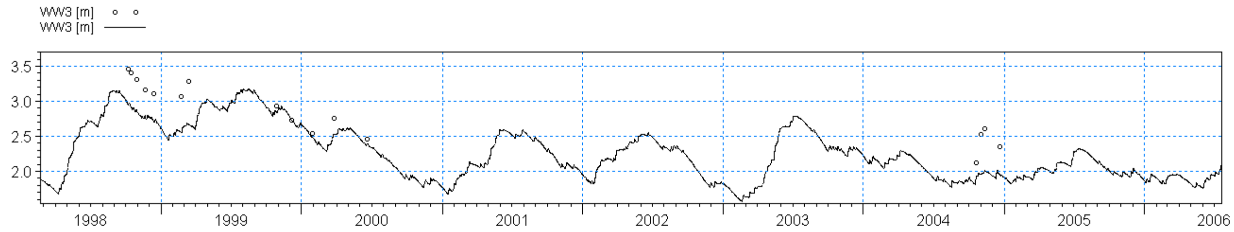
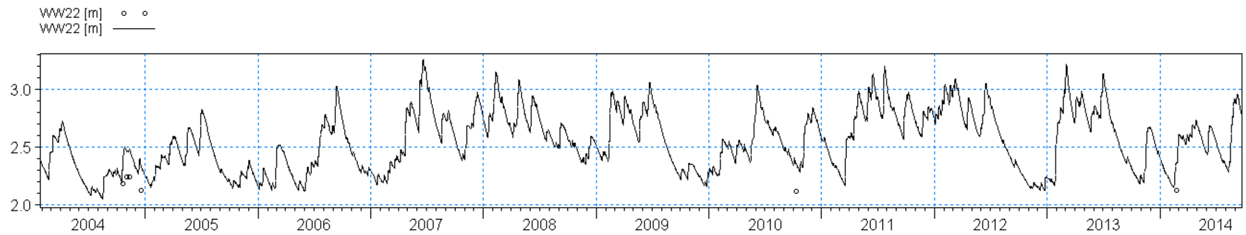


WW5

WW22



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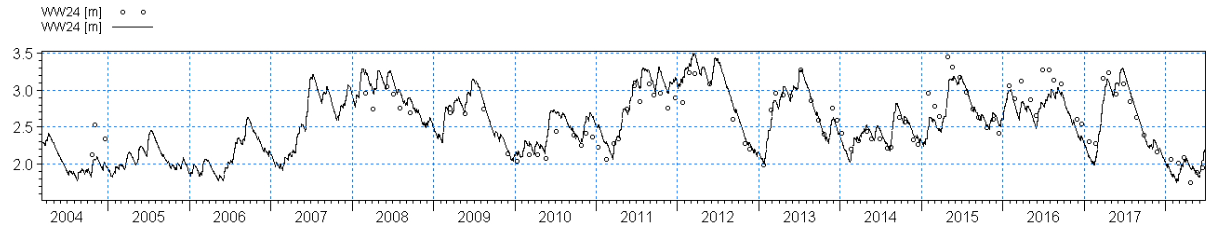
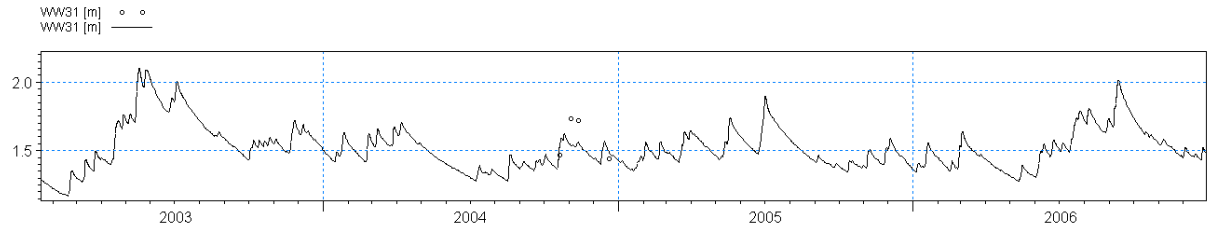


WW25

WW30

WW31

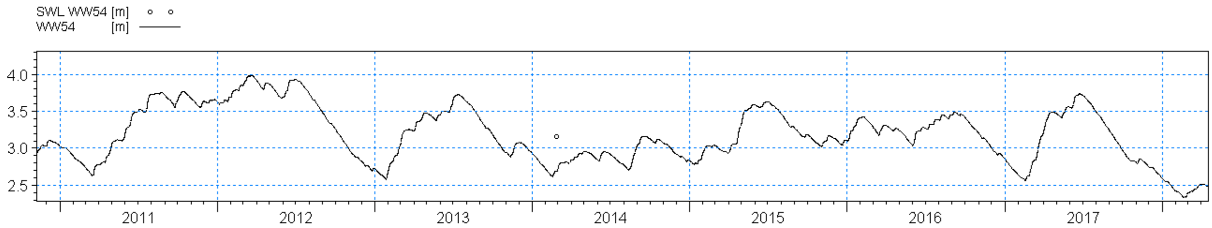


WW39

WW40

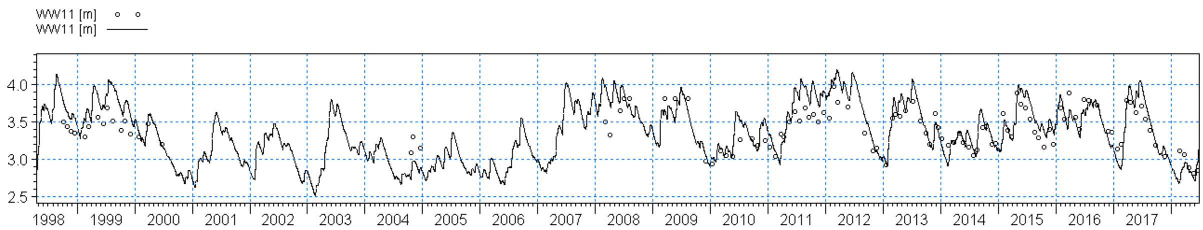
WW41

WW54



B.2 Kahibah Creek drainage catchment

WW11



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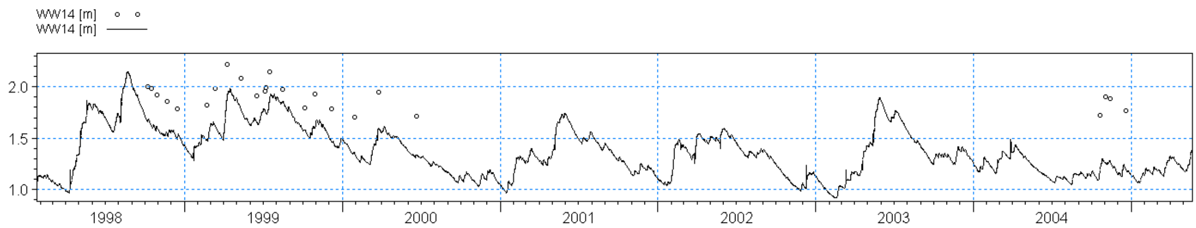

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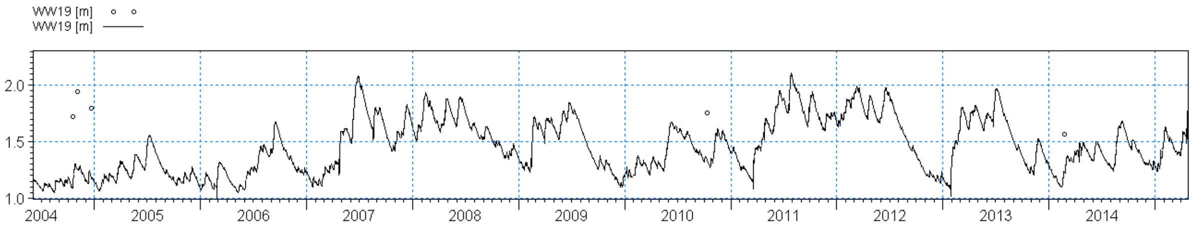

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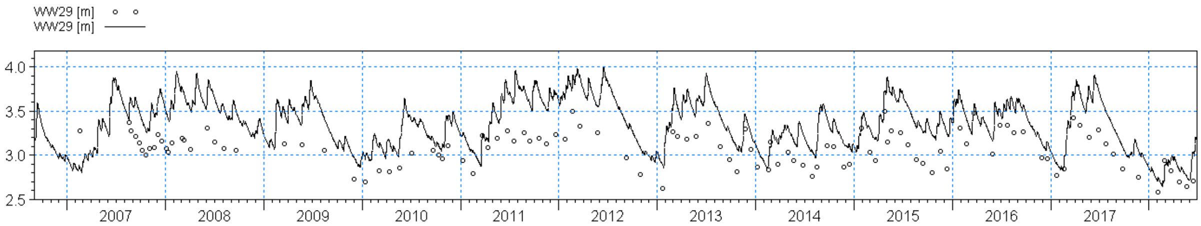
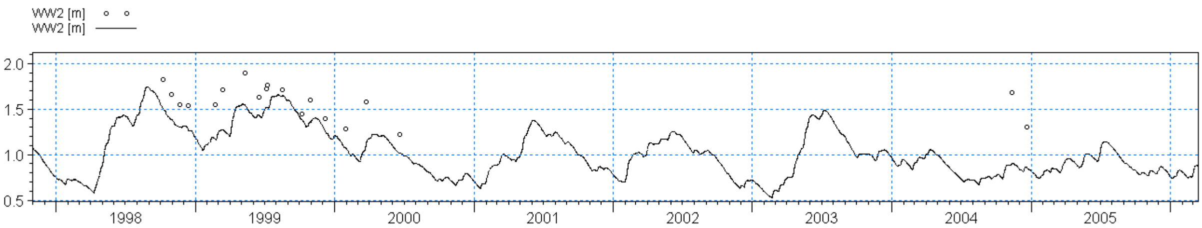


WW34

B.3 Woy Woy Peninsula East drainage catchment

WW2



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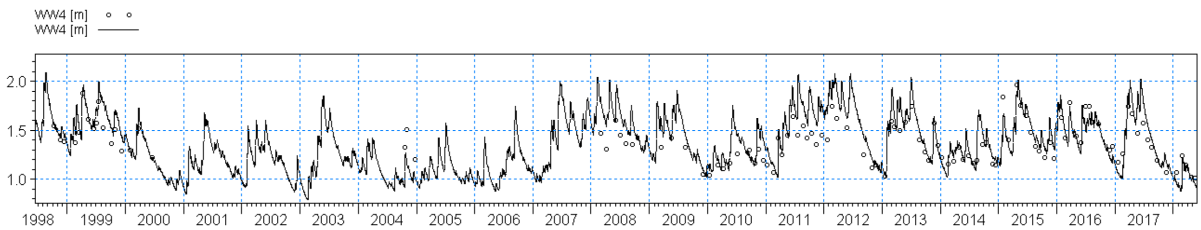

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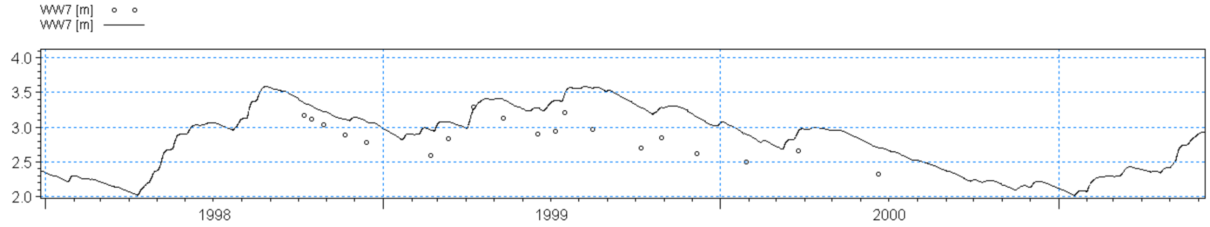
WW7



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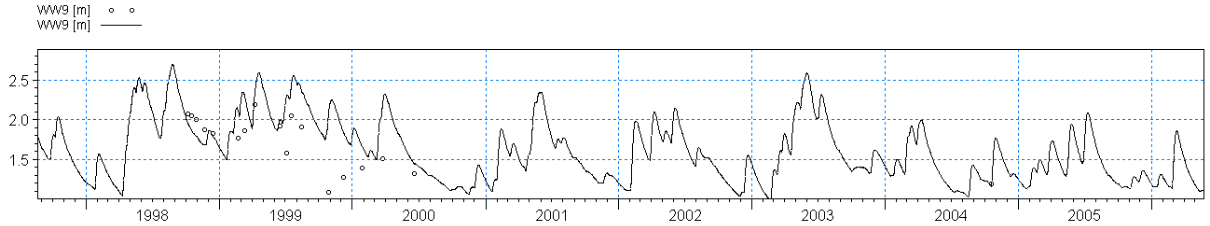
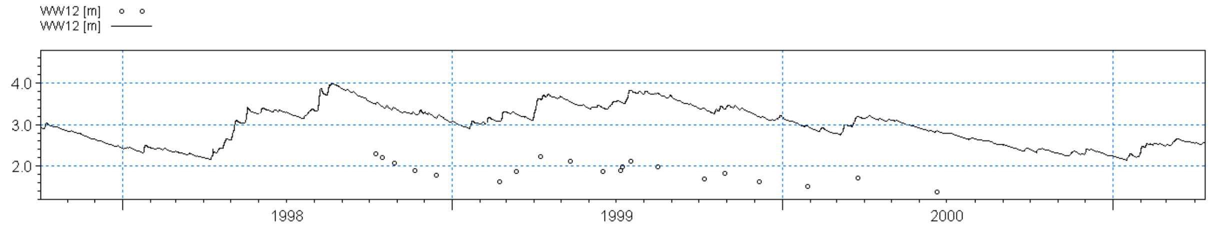


WW10

WW12



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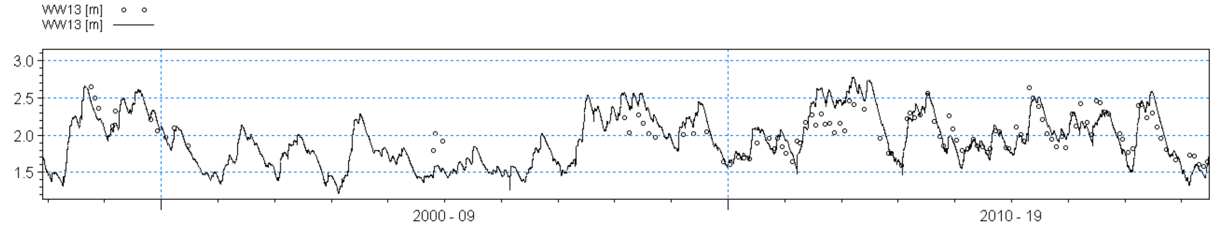

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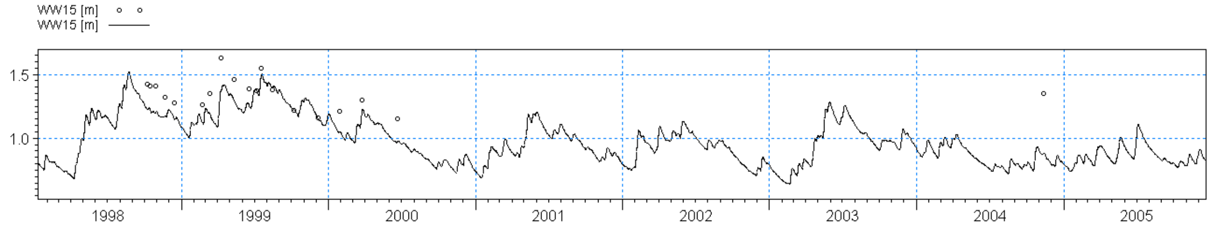

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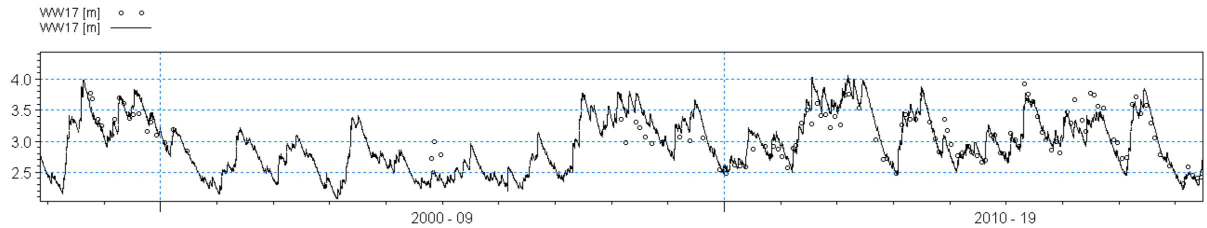

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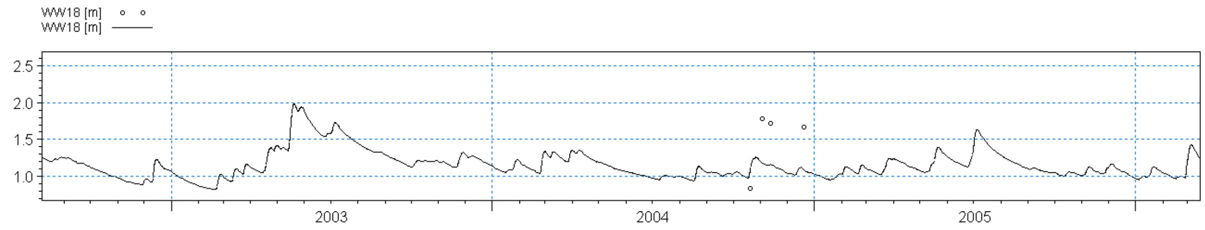

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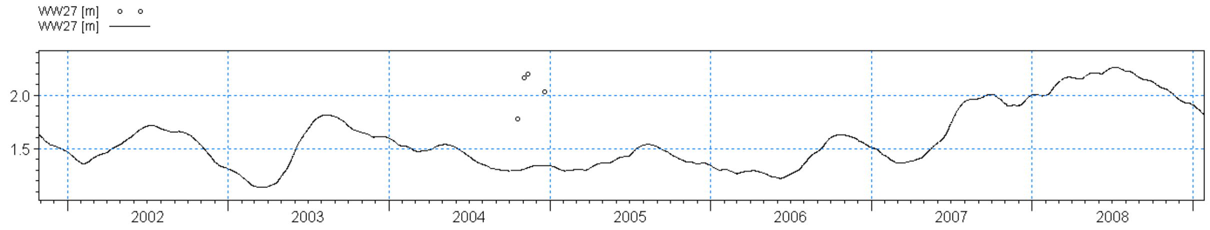

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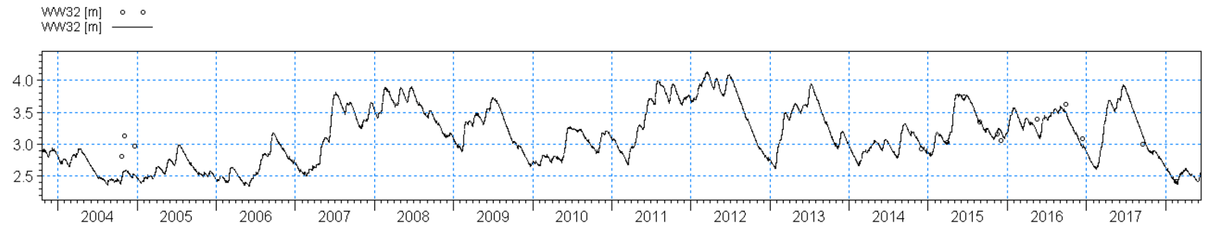

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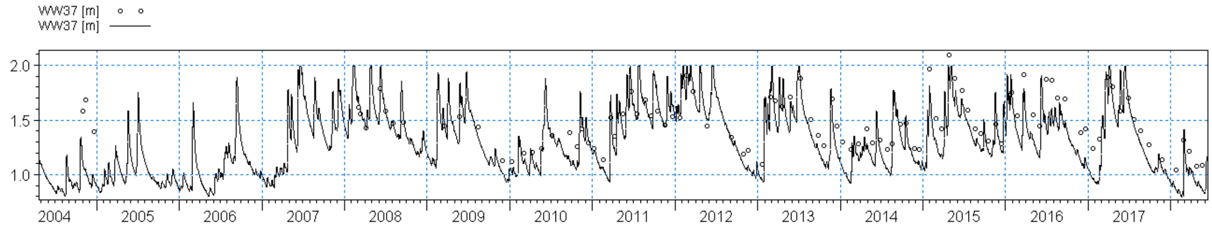

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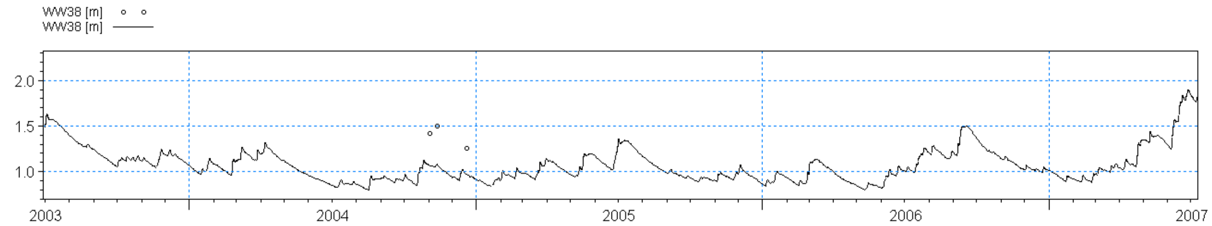
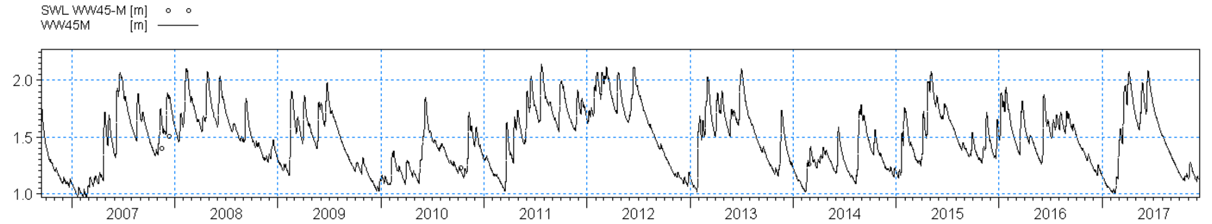


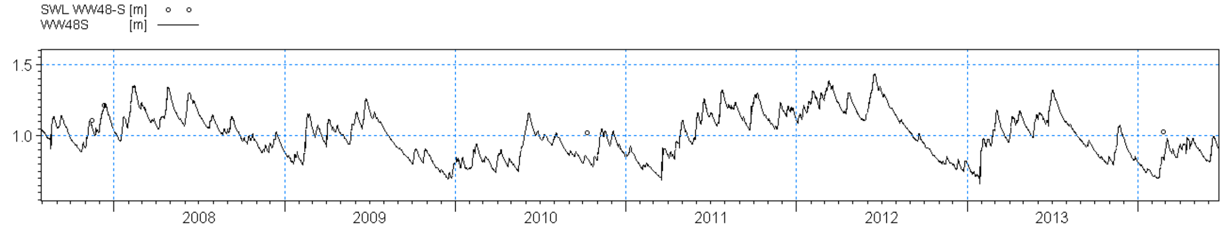
WW45-M



WW46

WW47

WW48-S



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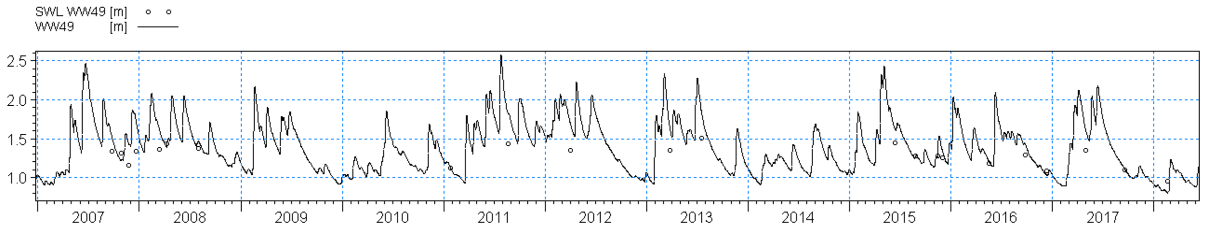

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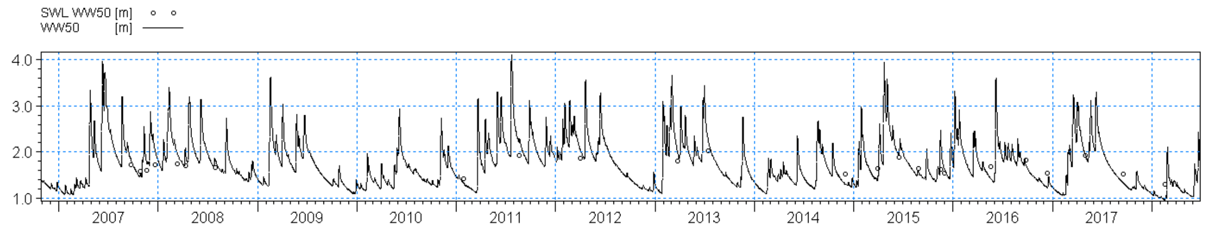

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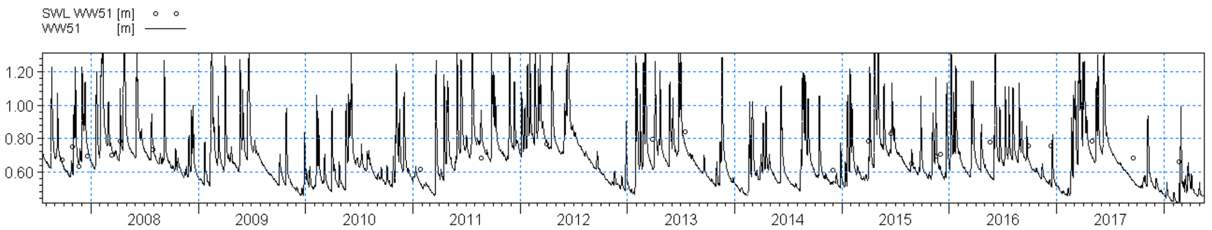

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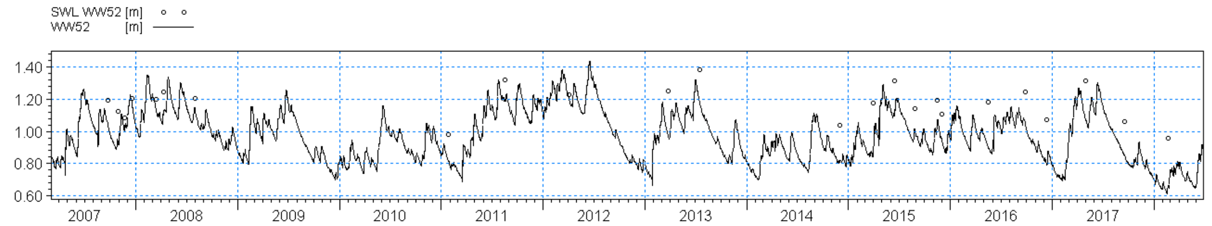

APPENDIX C–Council's Black Spots

Scanned Map provided by Council

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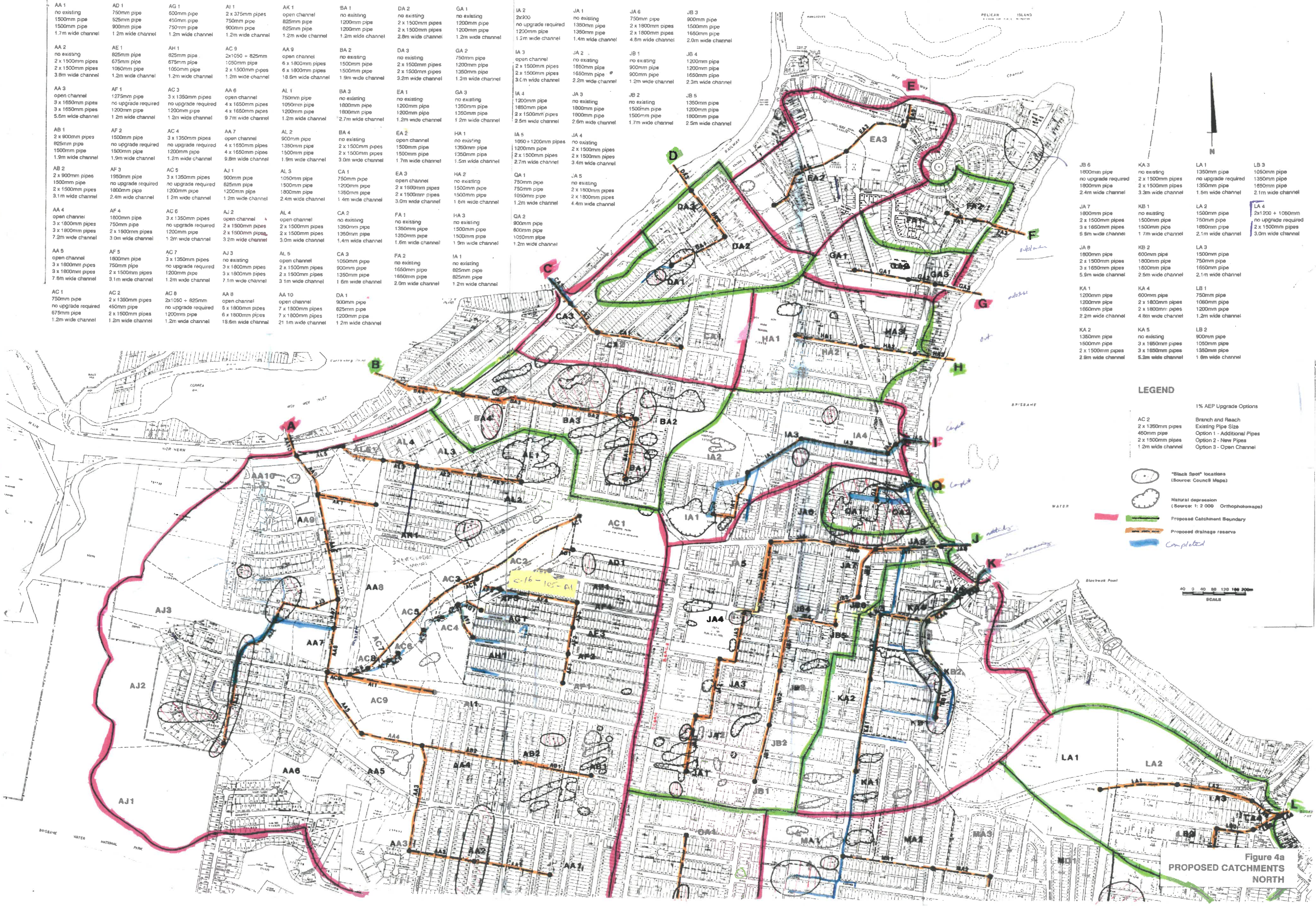
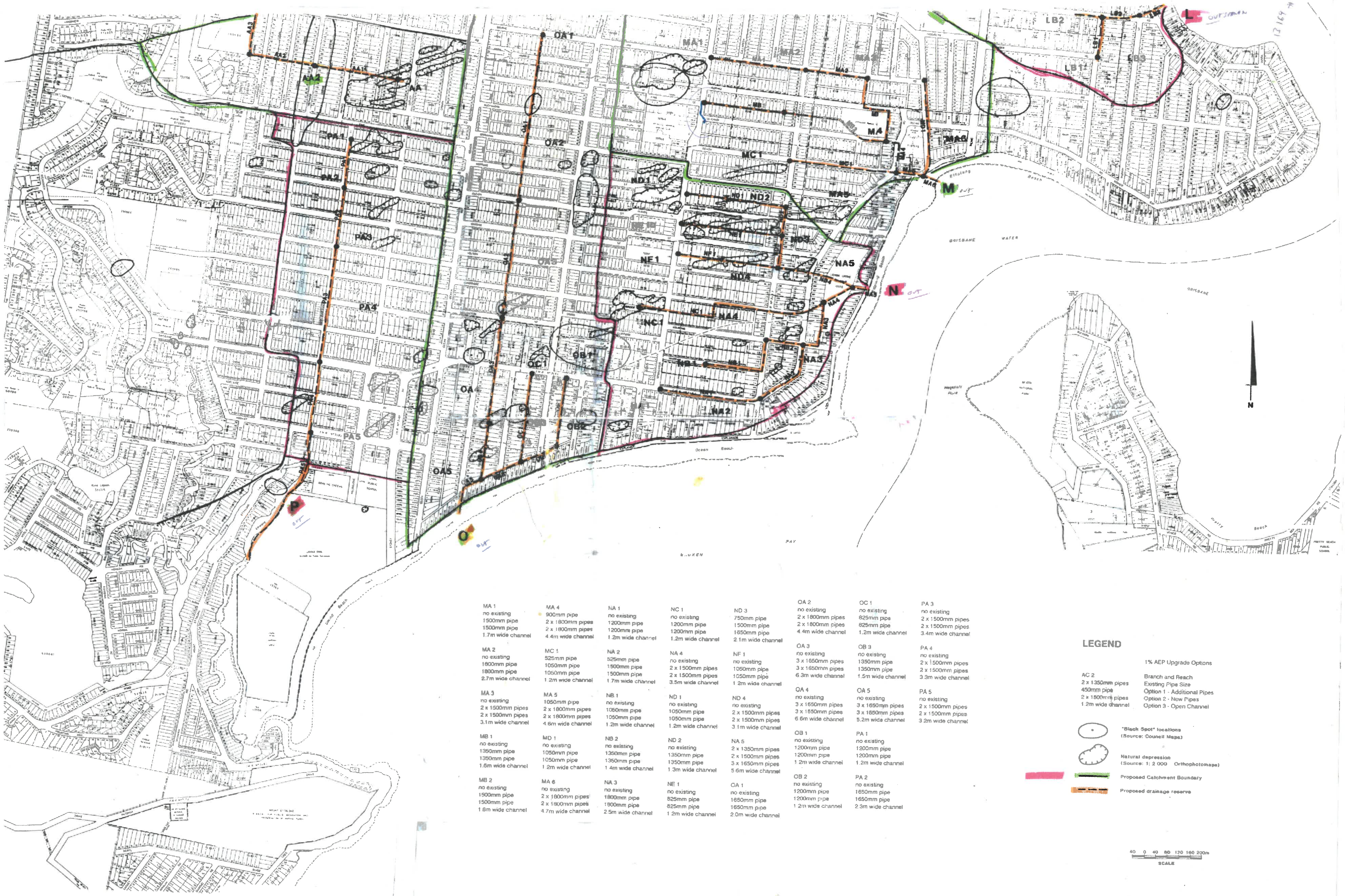


Branch and Reach	Existing Pipe Size	Option 1 - Additional Pipes	Option 2 - New Pipes	Option 3 - Open Channel
AA 1	no existing	1500mm pipe	1500mm pipe	1.7m wide channel
AA 2	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.8m wide channel
AA 3	open channel	3 x 1650mm pipes	3 x 1650mm pipes	5.6m wide channel
AB 1	2 x 900mm pipes	825mm pipe	1500mm pipe	1.9m wide channel
AB 2	2 x 900mm pipes	1500mm pipe	2 x 1500mm pipes	3.1m wide channel
AA 4	open channel	3 x 1800mm pipes	3 x 1800mm pipes	7.2m wide channel
AA 5	open channel	3 x 1800mm pipes	3 x 1800mm pipes	7.8m wide channel
AC 1	750mm pipe	no upgrade required	675mm pipe	1.2m wide channel
AD 1	750mm pipe	525mm pipe	900mm pipe	1.2m wide channel
AE 1	825mm pipe	675mm pipe	1050mm pipe	1.2m wide channel
AF 1	1275mm pipe	no upgrade required	1200mm pipe	1.2m wide channel
AF 2	1500mm pipe	no upgrade required	1500mm pipe	1.9m wide channel
AF 3	1950mm pipe	no upgrade required	1800mm pipe	2.4m wide channel
AF 4	1800mm pipe	750mm pipe	2 x 1500mm pipes	3.0m wide channel
AF 5	1800mm pipe	750mm pipe	2 x 1500mm pipes	3.1m wide channel
AC 2	2 x 1350mm pipes	450mm pipe	2 x 1500mm pipes	1.2m wide channel
AG 1	600mm pipe	450mm pipe	750mm pipe	1.2m wide channel
AH 1	825mm pipe	675mm pipe	1050mm pipe	1.2m wide channel
AC 3	3 x 1350mm pipes	no upgrade required	1200mm pipe	1.2m wide channel
AC 4	3 x 1350mm pipes	no upgrade required	1200mm pipe	1.2m wide channel
AC 5	3 x 1350mm pipes	no upgrade required	1200mm pipe	1.2m wide channel
AC 6	3 x 1350mm pipes	no upgrade required	1200mm pipe	1.2m wide channel
AC 7	3 x 1350mm pipes	no upgrade required	1200mm pipe	1.2m wide channel
AC 8	2x1050 + 825mm	no upgrade required	1200mm pipe	1.2m wide channel
AI 1	2 x 375mm pipes	750mm pipe	900mm pipe	1.2m wide channel
AC 9	2x1050 + 825mm	1050mm pipe	2 x 1500mm pipes	1.2m wide channel
AA 6	open channel	4 x 1650mm pipes	4 x 1650mm pipes	9.7m wide channel
AA 7	open channel	4 x 1650mm pipes	4 x 1650mm pipes	9.8m wide channel
AJ 1	900mm pipe	825mm pipe	1200mm pipe	1.2m wide channel
AJ 2	open channel	2 x 1500mm pipes	2 x 1500mm pipes	3.2m wide channel
AJ 3	no existing	3 x 1800mm pipes	3 x 1800mm pipes	7.1m wide channel
AA 8	open channel	6 x 1800mm pipes	6 x 1800mm pipes	15.6m wide channel
AK 1	open channel	825mm pipe	825mm pipe	1.2m wide channel
AA 9	open channel	6 x 1800mm pipes	6 x 1800mm pipes	18.6m wide channel
AL 1	750mm pipe	1050mm pipe	1200mm pipe	1.2m wide channel
AL 2	900mm pipe	1350mm pipe	1500mm pipe	1.9m wide channel
AL 3	1050mm pipe	1500mm pipe	1800mm pipe	2.4m wide channel
AL 4	open channel	2 x 1500mm pipes	2 x 1500mm pipes	3.0m wide channel
AL 5	open channel	2 x 1500mm pipes	2 x 1500mm pipes	3.1m wide channel
AA 10	open channel	7 x 1800mm pipes	7 x 1800mm pipes	21.1m wide channel
BA 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
BA 2	no existing	1500mm pipe	1500mm pipe	1.9m wide channel
BA 3	no existing	1800mm pipe	1800mm pipe	2.7m wide channel
BA 4	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.0m wide channel
CA 1	750mm pipe	1200mm pipe	1350mm pipe	1.4m wide channel
CA 2	no existing	1350mm pipe	1350mm pipe	1.4m wide channel
CA 3	1050mm pipe	900mm pipe	1350mm pipe	1.6m wide channel
DA 1	900mm pipe	825mm pipe	1200mm pipe	1.2m wide channel
DA 2	no existing	2 x 1500mm pipes	2 x 1500mm pipes	2.8m wide channel
DA 3	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.2m wide channel
EA 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
EA 2	open channel	1500mm pipe	1500mm pipe	1.7m wide channel
EA 3	open channel	2 x 1500mm pipes	2 x 1500mm pipes	3.0m wide channel
FA 1	no existing	1350mm pipe	1350mm pipe	1.6m wide channel
FA 2	no existing	1650mm pipe	1650mm pipe	2.0m wide channel
GA 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
GA 2	750mm pipe	1200mm pipe	1350mm pipe	1.3m wide channel
GA 3	no existing	1350mm pipe	1350mm pipe	1.2m wide channel
HA 1	no existing	1350mm pipe	1350mm pipe	1.5m wide channel
HA 2	no existing	1500mm pipe	1500mm pipe	1.6m wide channel
HA 3	no existing	1500mm pipe	1500mm pipe	1.9m wide channel
IA 1	no existing	825mm pipe	825mm pipe	1.2m wide channel
IA 2	2x900	no upgrade required	1200mm pipe	1.2m wide channel
IA 3	open channel	2 x 1500mm pipes	2 x 1500mm pipes	3.0m wide channel
IA 4	1200mm pipe	1650mm pipe	2 x 1500mm pipes	2.5m wide channel
IA 5	1050+1200mm pipes	1200mm pipe	2 x 1500mm pipes	2.7m wide channel
QA 1	750mm pipe	750mm pipe	1050mm pipe	1.2m wide channel
QA 2	900mm pipe	600mm pipe	1050mm pipe	1.2m wide channel
JA 1	no existing	1350mm pipe	1350mm pipe	1.4m wide channel
JA 2	no existing	1650mm pipe	1650mm pipe	2.2m wide channel
JA 3	no existing	1800mm pipe	1800mm pipe	2.6m wide channel
JA 4	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.4m wide channel
JA 5	no existing	2 x 1800mm pipes	2 x 1800mm pipes	4.4m wide channel
JA 6	750mm pipe	2 x 1800mm pipes	2 x 1800mm pipes	4.8m wide channel
JB 1	no existing	900mm pipe	900mm pipe	1.2m wide channel
JB 2	no existing	1500mm pipe	1500mm pipe	1.7m wide channel
JB 3	900mm pipe	1500mm pipe	1650mm pipe	2.0m wide channel
JB 4	1200mm pipe	1200mm pipe	1650mm pipe	2.3m wide channel
JB 5	1350mm pipe	1200mm pipe	1800mm pipe	2.5m wide channel
JB 6	1800mm pipe	no upgrade required	1800mm pipe	2.4m wide channel
JA 7	1800mm pipe	2 x 1500mm pipes	3 x 1650mm pipes	5.9m wide channel
JA 8	1800mm pipe	2 x 1500mm pipes	3 x 1650mm pipes	5.9m wide channel
KA 1	1200mm pipe	1200mm pipe	1650mm pipe	2.2m wide channel
KA 2	1350mm pipe	1500mm pipe	2 x 1500mm pipes	2.9m wide channel
KA 3	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.3m wide channel
KB 1	no existing	1500mm pipe	1500mm pipe	1.7m wide channel
KB 2	600mm pipe	1800mm pipe	1800mm pipe	2.5m wide channel
KA 4	600mm pipe	2 x 1800mm pipes	2 x 1800mm pipes	4.8m wide channel
KA 5	no existing	3 x 1650mm pipes	3 x 1650mm pipes	5.2m wide channel
LA 1	1350mm pipe	no upgrade required	1350mm pipe	1.5m wide channel
LA 2	1500mm pipe	750mm pipe	1650mm pipe	2.1m wide channel
LA 3	1500mm pipe	750mm pipe	1650mm pipe	2.1m wide channel
LB 1	750mm pipe	1050mm pipe	1200mm pipe	1.2m wide channel
LB 2	900mm pipe	1050mm pipe	1350mm pipe	1.6m wide channel
LB 3	1050mm pipe	1350mm pipe	1650mm pipe	2.1m wide channel
LA 4	2x1200 + 1050mm	no upgrade required	2 x 1500mm pipes	3.0m wide channel

Figure 4a
PROPOSED CATCHMENTS
NORTH



Branch and Reach	Existing Pipe Size	Option 1 - Additional Pipes	Option 2 - New Pipes	Option 3 - Open Channel
MA 1	no existing	1500mm pipe	1500mm pipe	1.7m wide channel
MA 2	no existing	1800mm pipe	1800mm pipe	2.7m wide channel
MA 3	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.1m wide channel
MB 1	no existing	1350mm pipe	1350mm pipe	1.6m wide channel
MB 2	no existing	1500mm pipe	1500mm pipe	1.8m wide channel
MA 4	900mm pipe	2 x 1800mm pipes	2 x 1800mm pipes	4.4m wide channel
MC 1	525mm pipe	1050mm pipe	1050mm pipe	1.2m wide channel
MA 5	1050mm pipe	2 x 1800mm pipes	2 x 1800mm pipes	4.6m wide channel
MD 1	no existing	1050mm pipe	1050mm pipe	1.2m wide channel
MA 6	no existing	2 x 1800mm pipes	2 x 1800mm pipes	4.7m wide channel
NA 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
NA 2	525mm pipe	1500mm pipe	1500mm pipe	1.7m wide channel
NB 1	no existing	1050mm pipe	1050mm pipe	1.2m wide channel
NB 2	no existing	1350mm pipe	1350mm pipe	1.4m wide channel
NA 3	no existing	1800mm pipe	1800mm pipe	2.5m wide channel
NC 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
NA 4	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.5m wide channel
ND 1	no existing	1050mm pipe	1050mm pipe	1.2m wide channel
ND 2	no existing	1350mm pipe	1350mm pipe	1.3m wide channel
NE 1	no existing	825mm pipe	825mm pipe	1.2m wide channel
ND 3	750mm pipe	1500mm pipe	1650mm pipe	2.1m wide channel
NF 1	no existing	1050mm pipe	1050mm pipe	1.2m wide channel
ND 4	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.1m wide channel
NA 5	2 x 1350mm pipes	2 x 1500mm pipes	3 x 1650mm pipes	5.6m wide channel
OA 1	no existing	1650mm pipe	1650mm pipe	2.0m wide channel
OA 2	no existing	2 x 1800mm pipes	2 x 1800mm pipes	4.4m wide channel
OA 3	no existing	3 x 1650mm pipes	3 x 1650mm pipes	6.3m wide channel
OA 4	no existing	3 x 1650mm pipes	3 x 1650mm pipes	6.6m wide channel
OB 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
OB 2	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
OC 1	no existing	825mm pipe	825mm pipe	1.2m wide channel
OB 3	no existing	1350mm pipe	1350mm pipe	1.5m wide channel
OA 5	no existing	3 x 1650mm pipes	3 x 1650mm pipes	5.2m wide channel
PA 1	no existing	1200mm pipe	1200mm pipe	1.2m wide channel
PA 2	no existing	1650mm pipe	1650mm pipe	2.3m wide channel
PA 3	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.4m wide channel
PA 4	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.3m wide channel
PA 5	no existing	2 x 1500mm pipes	2 x 1500mm pipes	3.2m wide channel