THE UNIVERSITY OF NEW SOUTH WALES
water research laboratory
Manly Vale N.S.W. Australia

GROUNDWATER CHARACTERISATION AND NUMERICAL MODELLING FOR RAINBOW BEACH ESTATE

by

S E Pells and S Mehrabi

Technical Report 2009/32
March 2010

THE UNIVERSITY OF NEW SOUTH WALES
SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
WATER RESEARCH LABORATORY

GROUNDWATER CHARACTERISATION AND NUMERICAL MODELLING FOR RAINBOW BEACH ESTATE

WRL Technical Report 2009/32 March 2010

by

S E Pells and S Mehrabi

Water Research Laboratory
School of Civil and Environmental Engineering
University of New South Wales ABN 57 195 873 179
King Street
Manly Vale NSW 2093 Australia

Telephone: +61 (2) 8071 9800
Facsimile: +61 (2) 9949 4188

Technical Report No	2009/32
Report Status	Final
Date of Issue	March 2010
WRL Project No.	09056
Project Manager	Steven Pells

Title	Groundwater Characterisation and Numerical Modelling for Rainbow Beach Estate
Author(s)	Steven E Pells and Sara Mehrabi
Client Name	Tierney Property Services on behalf of St Vincents Foundation Pty Ltd
Client Address	PO Box 493 Port Macquarie NSW 2444
Client Contact	James Dunn / Brian Tierney
Client Reference	MP06-0085 & MP07-0001

EXECUTIVE SUMMARY

The St Vincents Foundation owns property adjacent to Rainbow Beach, between the coastal villages of Bonny Hills and Lake Cathie on the New South Wales Mid-North Coast. A Part 3A Concept Plan and Project Application for development of residential lots on this land has been put forward and is currently being assessed.

Management of groundwater resources will be addressed in both the Concept Plan and Project Applications. Prior to this study, Tierney Property Services (TPS), acting on behalf of the St Vincents Foundation, engaged various consultants to undertake field investigations to characterise the geology, soils and groundwater resources on the site. Most recently, TPS undertook a 3 month baseline groundwater characterisation study which featured routine monitoring of groundwater levels and groundwater quality from 29 locations across the site. Routine groundwater level monitoring was still ongoing at time of writing.

The Water Research Laboratory (WRL) of the University of New South Wales was engaged by TPS to compile and review the available information and to comment on the nature and potential value of these groundwater resources. Through numerical groundwater modelling techniques, WRL was also asked to assess the impacts from construction of a proposed open waterbody on the site, as featured in the current Concept Plan. This study follows previous groundwater studies presented in the Water Engineering and Environment DGR Assessments (WEDGRA), Cardno (2008). The WEDGRA was referenced and used by WRL, and this current study by WRL was undertaken on the premise of augmenting previous studies, providing additional detail to the groundwater investigations undertaken in the WEDGRA. WRL have also provided additional detail to some aspects of groundwater and Acid Sulfate Soils characterisation over the site, and it is the intention of TPS that this study by WRL is read as a complementary and more recent study to the WEDGRA.

The site is located in a small coastal basin, which is infilled with sedimentary sequences of estuarine, marine and Aeolian origins. Within these sedimentary deposits, three groundwater aquifer systems are identified:

1. Saturated organic / estuarine clays, which dominate low lying regions to the west of the site;
2. An unconfined aquifer within deposits of silty sands throughout low lying areas in the centre of the site, and;

3. Perched freshwater aquifers within coastal dune systems in the east of the site, adjacent to the coast.

Water quality within the first two systems is typical of an Acid Sulfate Soil (ASS) environment, with low pH and elevated concentrations of iron and aluminium. In isolated samples, water from the silty sand aquifer fulfils requirements for longer term irrigation and stock watering. For the majority of samples, water quality is not suitable for drinking, short or long term irrigation and does not fulfil identifiable beneficial usage categories in terms of the relevant guidelines.

From experience at other similar sites, water quality in the perched coastal aquifer is expected to be fresh and of good quality. This groundwater is expected to play a role in sustaining a small littoral rainforest found at the north eastern perimeter of the site. Samples taken from within this aquifer to the south east of the site indicate that the aquifer has been impacted by the presence of the Bonny Hills Sewage Treatment Plant (STP) which has disposed treated effluent by infiltration to the aquifer since the 1980's. Groundwater mounding near the STP indicates flow of treated effluent onto the St Vincents Foundation site, and the water quality exhibits elevated nutrients and contamination from faecal coliforms. Within the vicinity of the STP, groundwater may technically fulfil requirements for short term irrigation. However, with respect to risks of contamination, such usages would generally not be recommended.

A numerical groundwater model of this site was previously established by Cardno in 2008 using the MODFLOW code using data that was available at the time. WRL updated the model with additional water level monitoring data that is now available. The model was shown to offer robust steady-state representations of groundwater levels across the site and was used to present groundwater conditions across the site for scenarios of low, medium and high rainfall. The model highlighted the role that Duchess Gully, the key surface water feature in the site, had in draining groundwater across the site. It is also clear that an existing wetland on the site maintains water levels slightly below the surrounding groundwater levels, indicating net recharge to the wetland.

The new wetland, proposed as part of the Concept Plan, is of similar nature to the existing wetland and will also have a standing water level that is maintained below the surrounding groundwater levels. The numerical model was used to simulate changes (drawdown) in groundwater across the site once this new wetland is established. The results of this analysis are clearly presented in Figure 29 of this report. Predicted drawdowns are primarily confined to the silty sand aquifer. The modelling results show that the proposed wetland will not impact upon the perched freshwater aquifer within the coastal dunes to the east of the site.

A region of "marshy" land adjacent to the existing wetland has been identified by previous studies as a frog habitat. The standing groundwater level at this location is close to the existing lake water level, approximately 1.6 m below ground level. Hence the 'marshy' nature at the surface occurs as an unsaturated zone, or a perched groundwater system within thick deposits of high plasticity clays. Based on consideration of the available data and modelling results, it is WRL's opinion that the proposed wetland will not impact on the moist 'marshy' nature of the surface soil conditions in this location.

Acid Sulfate Soils (ASS) have been identified on the site. In Section 7.4 of this report longer-term or post-construction risks are identified and discussed[1]. In summary, many of the existing higher risk ASS deposits will remain below the water table following development. Such ASS deposits do not present a potential risk. However, a zone of shallow ASS to the north west of the proposed wetland may be subject to some drawdown with the possibility of subsequent pyrite oxidation. Consideration was given to the management of water quality within the proposed wetland following inward seepage of any ASS-affected groundwater into the proposed wetland from this region, including undertaking water quality modelling. It was also noted that the region will be buried under engineered fill, which may assist with limiting exposure, and is expected to result in development of a perched water table that may maintain saturation. A discussion of these risks, supported by water quality modelling, concluded that the risks are small, but a monitoring plan should be implemented and a response plan prepared.

Routine groundwater and surface monitoring is recommended for the site, as set out in Appendix B of this report. The objective is to monitor impacts to groundwater levels and / or quality, and any development of acidic conditions within the wetland. Preliminary trigger levels are presented along with an action plan to be undertaken if trigger levels are exceeded. This plan should be reviewed after 2 years of monitoring. This surface water (wetland) monitoring component is strictly for assessment of ASS impacts, and should complement any other general monitoring requirements stipulated by other parties.

[1] Management of the disturbance of ASS during construction phases is covered by an Acid Sulfate Soils Management Plan (ASSMP).

CONTENTS

EXECUTIVE SUMMARY		i
1. INTRODUCTION		1
2. SITE OVERVIEW AND AVAILABLE DATA		3
2.1	Development Planning and Related Studies	4
2.2	Existing Surface Water and Lakes	4
2.3	Proposed Wetland	5
2.4	Climate, Rainfall and Runoff	5
2.5	Ground Investigations	5
2.6	Acid Sulfate Soils	7
2.7	Groundwater Levels	7
2.8	Groundwater and Surface Water Quality	11
2.9	Operation of Bonny Hills STP, and Associated Groundwater Investigations	13
2.10	Previous Groundwater Numerical Model	14
3. REVIEW OF HYDROGEOLOGY		15
3.1	Hydrogeological Setting	15
3.2	Aquifers and Groundwater Flow	16
3.3	Groundwater and Surface Water Quality	18
3.4	Summary of the Value (Beneficial Usage) of Existing Aquifers	19
4. ESTABLISHMENT OF GROUNDWATER MODEL		22
4.1	Modelling Objectives and Complexity	22
4.2	Model Code	22
4.3	Model Structure	22
	4.3.1 Model Domain	23
	4.3.2 Model Layers	23
4.4	Hydrogeological Conceptualisation	24
5. SIMULATION OF EXISTING CONDITIONS		26
5.1	Steady State Approximations	26
	5.1.1 Calibration	27
	5.1.2 Results	28
5.2	Transient – Verification by Replication of Monitoring Period	29
6. SIMULATION OF PROPOSED DEVELOPMENTS		30
7. DISCUSSION OF IMPACTS		31
7.1	Drawdown	31
7.2	Identified Protection Areas	31
7.3	Impacts to Aquifer Water Quality	32
7.4	Acid Sulfate Soils	32
8. CONCLUSIONS		36
9. REFERENCES		38

APPENDIX A – WRL BORE LOGS
APPENDIX B – GROUNDWATER MANAGEMENT PLAN

LIST OF TABLES

1. Summary of Site Ground Investigations
2. Summary of Acid Sulfate Soil Investigations
3. Details of Groundwater Monitoring Network
4. Summary of Groundwater Level Measurements
5. Water Quality Sampling Locations
6. Suite 1 Parameters
7. Suite 2 Parameters
8. Average Water Quality Values, Existing Wetland (Sept 2005 to Nov 2007)
9. Water Neutralisation Capacity, Existing Wetland
10. Estimates of Hydraulic Conductivity from Slug Tests, AWACS 1996
11. Mean Measured Water Quality
12. Values of Hydraulic Conductivity and Storage Adopted in the Model
13. Values of Recharge Adopted in Steady State Models
14. Calibration Statistics
15. Groundwater Characteristics used in PHREEQC
16. Predicted pH in the Proposed Wetland

LIST OF FIGURES

1. Site Location
2. Overview of Existing Site
3. Overview of Concept Plan for the Site
4. Surface Water Features
5. Rainfall and Evaporation
6. Locations of Site Ground Investigations
7. Groundwater and Surface Water Monitoring Locations
8. Timeseries of Recorded Groundwater Levels
9. Geological Units Found at the Surface
10. Orientation of Hydrogeological Cross Sections
11. Hydrogeological Cross Section EW1
12. Hydrogeological Cross Section EW2
13. Hydrogeological Cross Section EW3
14. Hydrogeological Cross Section NS1
15. Hydrogeological Cross Section NS2
16. Hydrogeological Cross Section NS3
17. Recorded Groundwater Levels – August 2009
18. Groundwater Model Domain and Surface Topography
19. Groundwater Model Conceptualisation – Layer 1

20. Groundwater Model Conceptualisation – Layer 2
21. Steady State Simulation of Existing Conditions – Median Rainfall
22. Steady State Simulation of Existing Conditions – Lower Rainfall
23. Steady State Simulation of Existing Conditions – Higher Rainfall
24. Steady State Calibration
25. Verification of Model Against Monitoring Period
26. Steady State Simulation of Post Development Conditions – Median Rainfall
27. Steady State Simulation of Post Development Conditions – Lower Rainfall
28. Steady State Simulation of Post Development Conditions – Higher Rainfall
29. Groundwater Drawdown – Pre Minus Post Development, Average Rainfall
30. Acid Sulfate Soils Risk Zone
31. Acid Sulfate Soils Risk Zone Showing Proposed Fill and Development Locations

1. INTRODUCTION

Tierney Property Services (TPS) have prepared a Part 3A Concept Plan (MP06-0085) for the proposed residential development of 'Rainbow Beach Estate', on a property in the coastal suburb of Bonny Hills, New South Wales (NSW). In addition a Part 3A Project Application (MP07-0001) has been prepared for the central corridor, incorporating open space, district playing fields, existing and proposed wetlands. TPS are acting on behalf of the St Vincents Foundation, who are the property owners.

TPS have engaged the Water Research Laboratory (WRL) of the University of New South Wales to undertake a review of the groundwater system over the site, including an assessment of the potential value of existing groundwater resources and the impacts that the proposed developments may have on these groundwater resources. Consideration is also given to the role of Acid Sulfate Soils (ASS) on groundwater resource management. Specific plans for a proposed large wetland were examined in detail.

In Section 2 of this report, an overview of the site and the available data is presented. A summary of the hydrogeology over the site is then given in Section 3. Details of the numerical groundwater model are described in Section 4, and the results from the model are given in Sections 5 and 6 for the simulation of existing and post-development conditions respectively. In Section 7, a discussion of the potential impacts of the proposed developments on groundwater resources is given with reference to the numerical model simulations. The findings of the study and recommendations are summarised in Section 8.

A Groundwater Management Plan is presented in Appendix B of this report. This provides a specification for ongoing monitoring which is required in response to the risks to groundwater that are identified in this report. The Groundwater Monitoring Plan also includes some recommendations for monitoring from the selected surface water sources as a means to monitor any activation of ASS. The Groundwater Monitoring Plan is to support rather than supersede other required management or monitoring plans such as an Acid Sulfate Soils Management Plan (ASSMP), which pertains primarily to the construction phase, and Surface Water Management Plan.

This study follows previous groundwater studies presented in the Water Engineering and Environment DGR Assessments (WEDGRA), Cardno (2008). The WEDGRA was referenced and used by WRL, and this current study by WRL was undertaken on the premise of augmenting previous studies, providing additional detail to the groundwater investigations undertaken in the WEDGRA. WRL have also provided additional detail to some aspects of groundwater and Acid Sulfate Soils characterisation over the site, and it is the intention of TPS that this study by WRL is read as a complementary and more recent study to the WEDGRA.

2. SITE OVERVIEW AND AVAILABLE DATA

The study area is located on Rainbow Beach, between the coastal suburbs of Lake Cathie and Bonny Hills, on the New South Wales Mid North Coast. The location of the property is shown in Figure 1. A closer view of the site, as it currently exists, is shown in Figure 2.

The site was cleared in the past for pastoral usages, and in the 1950's and 1960's bulk earthworks and various changes to drainage lines were made to improve its pastoral capacity (EDAW, 2009). In the 1980's, an approval for development of an 'international sports and leisure facility' was granted to the site. Subsequent to this, further bulk earthworks were undertaken, including the initial stages of development of a golf course throughout the central portion of the site.

The existing wetland on site (as marked on Figure 2) was also constructed in the 1980's, with spoil from excavation of the wetland used in development of the residential lots adjacent to the southern site boundary (*ibid*). The wetland was constructed online to the main drainage channel. The outlet of this wetland is at its eastern edge, and flows directly to Duchess Gully via a constructed channel. Prior to this, surface flows used to travel northwards, linking with Duchess Gully at the north eastern region of the site (Cardno, 2006). While development of the sporting facility was abandoned, the site and wetland are actively maintained by its current owner.

The Bonny Hills Sewage Treatment Plant (STP) is found on an adjacent property to the south east of the site (Figure 2). The STP was constructed in the mid 1980's, and services the towns of Lake Cathie and Bonny Hills. Since its inception, secondary treated effluent has been discharged to the dunes east of Duchess Gully via two exfiltration basins and a 1 km long exfiltration trench.

An overview of the currently proposed development Concept Plan is shown in Figure 3. The Concept Plan features the development of residential lots, located along the northern portion of the site. In many places, these lots would be placed on fill, to bring them above the design flood level. The subsequent project application also features the construction of a series of treatment wetlands, shown as blue outlines on Figure 3. Spoil from excavation of Wetland 'W1' (as marked on Figure 3) is proposed to be used for provision of filling material for the proposed developments. Wetland 'W1' will receive inflow from the existing constructed wetland (i.e. at its southern tip), and will discharge via a weir to Duchess Gully at its north eastern extremity.

2.1 Development Planning and Related Studies

The following data is available relating to site features and planning:

- Surface elevation data of the existing site, including surface contours prepared at 0.2 m intervals, and a digital elevation model (DEM) developed from surveys on a 15 m grid
- Cadastral data
- Aerial photography (July 2009)
- Contours of planned developments, including land filling and excavations for proposed wetland W1
- Detailed plans of proposed excavations, as set out in "Rainbow Beach Earthworks Report", Luke and Company (October 2008)
- Water Engineering and Engineering and Environment Report (WEDGRA), Cardno (2008).

These data are shown in Figures 2 and 3. There are also a number of studies undertaken related to planning and management for the proposed Concept Plan.

2.2 Existing Surface Water and Lakes

The surface water catchment to Duchess Gully has an area of approximately 780 ha and is shown in Figure 4. Surface water channels to the west of the site are man-made and divert surface flows into the existing artificial wetland. The artificial outlet from the existing wetland run eastwards to Duchess Gully, with the pre-development flow path heading north. The channels associated with Duchess Gully (in the east of the site) are the original (pre-development) alignment.

The water level in the existing wetland is stated to remain relatively constant, between 3.2 and 3.4 m AHD, typically 3.3 m AHD (Cardno 2006). The water level is controlled by a weir, but is also occasionally lowered to assist with ongoing site landscaping / restoration works along the banks of the existing wetland.

Man-made channels to the west of the site are typically dry, flowing only briefly during rainfall events. Standing water is typically found in Duchess Gully, which is believed to reflect seepage of groundwater into the gully.

2.3 Proposed Wetland

The footprint of the proposed wetland W1 is shown in Figure 3. The new wetland will be maintained at 3.0 m AHD using a constructed low-flow channel, discharging to Duchess Gully at its northern end.

A secondary weir will be set at 3.7 m AHD with 25 m crest length, to allow overflow directly towards Duchess Gully during minor flood events. This weir will be placed on the Eastern edge of the proposed wetland.

2.4 Climate, Rainfall and Runoff

Long term regional average rainfall and pan evaporation data for Port Macquarie are shown in Figure 5a (taken from Table 9 in Cardno 2006). The annual average rainfall is reported as 1440 mm, and the average annual pan evaporation is 1361 mm. Also shown are monthly rainfall totals calculated for 2009, using data from BoM station 60139 "Port Macquarie AWS". The total rainfall for this period was 2323 mm, which is above the long term annual average.

A groundwater monitoring program was recently undertaken at the study area for the period August to October 2009. Daily rainfall data for a period corresponding to (and preceding) this period are shown in Figure 5b. The data shown was sourced from the BoM Port Macquarie station.[2]

Surface water modelling undertaken by Cardno (2008) assessed an average annual runoff of 240 mm. The total catchment area for existing wetland was 662 ha, indicating an annual inflow of approximately 1590 ML per annum. For the proposed wetland, an 'effective' catchment area of 354 ha (allowing for bypassing during peak events) is indicative of an annual average surface water inflow of 850 ML per annum (Table 18, Cardno 2008).

2.5 Ground Investigations

A series of ground investigations have been undertaken on or adjacent to this site for characterisation of acid sulfate soil risks, geotechnical investigations and groundwater investigations. Test pits and boreholes undertaken from these investigations are summarised in Table 1. The locations of the bores, test pits and piezometers are shown in Figure 6.

[2] Local Bureau of Meteorology (BoM) stations Lake Cathie and Bonny Hills are no longer operational.

Bore and test pits logs have been provided to WRL for all of these investigations, and have been used in characterising the hydrogeological features. WRL provided supervision and undertook detailed borehole logging for the standpipes installed in August 2009. Borelogs for the investigations by WRL are attached in Appendix A of this report.

Of these investigations, those by AWACS (1996) and Holmes and Holmes (2003) and WRL (2009) included installation of standpipe piezometers for monitoring of groundwater levels and quality.

Table 1
Summary of Site Ground Investigations

Date	ID	Type	No.	Comment
Nov 1993	BH1 – BH26	Test Pit	26	Undertaken by Holmes and Holmes for Luke and Company as part of a geotechnical site appraisal
	BH27 – BH40	Augered Bore	14	
Jul 1995	LC1 – LC11	Augered Bore with standpipe	13	Piezometers and multi-levels piezometers installed as part of hydrogeological investigations for Bonny Hills STP, by AWACS. One detailed water quality round on Nov 1995. Levels logged from Aug 1995 to Jan 1996.
Dec 1998	BH101 – BH106	Augered Bore	6	Further geotechnical / ASS characterisation by Holmes and Holmes for Luke and Company
Nov 2002	W1 – W13	Augered Bore with standpipe	13	By Holmes and Holmes for Luke and Company. Borehole logs indicate standpipes were installed. Water quality sampling undertaken on Dec 2002. Water levels measured in Dec 2002, Jan 2003 and Mar 2003.
Mar 2003	BH107 – BH111	Augered Bore	5	Further geotechnical / ASS characterisation by Holmes and Holmes for Luke and Company
Apr 2003	29448 – 29498	Augered Bore	13	Further geotechnical / ASS characterisation by Holmes and Holmes for Luke and Company
Apr 2004	BHC1 – BHC4	Augured Bore	4	Further geotechnical / ASS characterisation by Chandler for Luke and Company
Aug 2005	TPC1 – TPC25	Test Pit	25	Further geotechnical / ASS characterisation by Chandler for Luke and Company
Aug 2009	GW1 – GW9	Augered Bore with standpipe	10	Undertaken by WRL for establishment of a baseline groundwater quality monitoring network.

2.6 Acid Sulfate Soils

A summary of the information currently available for characterisation of ASS on this site is summarised in Table 2.

Table 2
Summary of Acid Sulfate Soil Investigations

Date	ID	Type	No.	Comment
Nov 1993	BH1 – BH26	Test Pit	26	Borelogs include marking of 'ASS' and 'PASS' where encountered, but not supported with test results.
	BH27 – BH40	Augered Bore	14	Sample pH and pH change on oxidation reported in the field for some units encountered in BH's 3, 7, 11, 17, 19, 21, 26, 31, 33, 34, 36, 38 and 40.
Dec 1998	BH101 – BH106	Augered Bore	6	5 samples per bore tested in laboratory according to POSA methods.
Mar 2003	BH107 – BH111	Augered Bore	5	3 samples per bore tested in laboratory according to POCAS methods.
Apr 2003	29448 – 29498	Augered Bore	13	ASS risk classified on borelogs for all materials, but source laboratory test data not found.
Apr 2004	BHC1 – BHC4	Augured Bore	4	8 samples per bore tested in laboratory according to POCAS methods.

In addition, water quality sampling described in Section 2.8 tested for constituents indicative of ASS impacts.

2.7 Groundwater Levels

Groundwater level monitoring has been undertaken from the groundwater standpipe piezometers. Details of these groundwater monitoring piezometers are shown in Table 3, and their locations are shown in Figure 7. A summary of the available groundwater level measurements undertaken from these piezometres is given in Table 4.

Plots of the available groundwater level data are shown in Figure 8. Figure 8a shows groundwater data recorded between December 2002 and March 2003. Figure 8b shows data recorded between the August 2009 and December 2009. For reference, daily rainfall data for these periods is also shown.

For the 2002 – 2003 monitoring period, groundwater levels were seen to increase generally over the site following large rainfall events in February and March 2003, including an event of over 90 mm on the 13th March 2003. Prior to this, groundwater levels were relatively static, corresponding to a period of lower rainfall.

At the commencement of the 2009 monitoring, groundwater levels across the site were observed to elevated to a level similar to the post-rainfall levels observed in 2003. It is noted from Figure 5 that the site had received well above average rainfall in the prior months, and it is known that large scale regional flooding occurred in February. Between August and October 2009 groundwater levels were observed to be in decline, falling generally by 0.35 m over a period of 42 days. There was only very minor rainfall during this period, and falling levels may be indicative of draining of the groundwater over the site, in the absence of significant rainfall, and subsequent to flooding earlier in the year. A large (1-2 yr ARI) rainfall event on the 5th to 9th November 2009 resulted in re-elevation of groundwater levels.

Table 3
Details of Groundwater Monitoring Network

Bore ID	Easting♠	Northing♠	RL (m AHD)
W1	484281.59	6506841.14	5.700
W2	483940.17	6506864.86	5.175
W3	483710.82	6506852.09	5.200
W4	483640.70	6506679.40	5.100
W5	484862.90	6507358.70	4.480
W6	484929.20	6507172.13	5.400
W7	484705.53	6507300.68	4.75
W8	484456.97	6507057.97	4.810
W9	484702.94	6507039.40	5.020
W10	484651.60	6506878.67	4.755
W11	484422.71	6506868.14	5.885
W13	483868.24	6506513.50	5.125
L11/1	484880.00	6506967.80	5.465
L11/2	484881.48	6506967.10	5.200
GW1	485007.51	6506846.14	7.700
GW2	485098.96	6507099.89	5.080
GW3	484758.12	6507191.45	5.560
GW4	484433.50	6507116.48	5.510
GW5	484051.05	6506894.33	5.520
GW6	484401.39	6506799.19	5.835
GW7a	484812.83	6506844.88	6.345
GW7b	484812.84	6506842.77	6.290
GW8	483753.20	6506503.55	6.160
GW9	484126.28	6506637.36	5.170
2F1	484604.48	6506965.40	5.690
2F2	484819.30	6507198.46	5.975

♠ Coordinates are in MGA Zone 56 GDA 94.

Table 4
Summary of Groundwater Level Measurements

Bore ID	**RL ToC▲**	**Measured Standing Water Level (m AHD)**												
		31-Jul 1995▲	06-Dec 2002♠	21-Jan 2003♠	31-Mar 2003♠	10-Aug 2009♣	29-Aug 2009♦	19-Sep 2009♦	10-Oct 2009♦	11-Nov 2009◙	2-Dec 2009◙	23-Dec 2009◙	13-Jan 2010◙	3-Feb 2010◙
W1	5.7		3.6	3.59	3.8		4.36	3.68	3.51	5	3.65	3.51	3.87	4.6
W2	5.175		3.51	3.73	4.77		3.905	3.62	3.52	4.755	3.795	3.295	4.575	4.435
W3	5.2		3.7	3.87	4.68		4.63	4.33	4.01	4.4	4.07	3.63	4.47	4.34
W4	5.1		3.53	3.77	4.64		4.7	3.17	3.6	4.73	3.91	3.4	4.39	4.72
W5	4.48		3.21	3.19	3.83		3.63	3.42	3.25	3.97	3.29	3.03	3.74	3.65
W6	5.4		3.63	3.72	4.25		4.12	3.95	3.83	3.99	3.79	3.67	3.97	3.79
W7	4.75		3.23	3.34	4.03		3.82	3.56	3.36	4.46	3.48	3.2	3.92	3.63
W8	4.81		3.74	3.74	4.06		4.25	4.04	3.81	3.98	3.98	3.71	4.11	4.01
W9	5.02		3.71	3.85	4.43		4.27	4.09	4.02	4.46	3.98	3.82	4.21	4.18
W10	4.755		3.91	3.81	4.49		4.325	3.96	3.98	4.455	3.765	3.625	4.105	4.205
W11	5.885		3.63	3.59	4.25		4.505	4.02	4.01	5.055	4.135	3.745	4.505	4.205
W13	5.125		3.94	3.925	4.24		4.505	4.33	4.16	4.505	4.425	4.225	4.665	
GW1	7.7					6.28	6.16	6.06	5.98					
GW2	5.08					2.88	2.65	2.49	2.37	2.98	2.46	2.28	2.79	2.42
GW3	5.56						3.93	3.84	3.76					
GW4	5.51						4.31	4.11	3.92	4.06	4.02	3.74	4.15	4.07
GW5	5.52						3.9	3.7	3.43	3.89	3.41	3.03	3.82	3.69
GW6	5.835					4.205	4.055	3.84	3.63					
GW7a	6.345					4.415	4.255	4.14	4.02	4.315	4.055	3.875	4.275	4.105
GW7b (deeper)	6.29					4.27	4.15	3.98	3.76	3.96	3.84	3.75	4.09	3.94
GW8	6.16						4.59	4.46	4.35	4.7	4.49	4.32	4.73	4.69
GW9	5.17						3.5	3.41	3.37	3.7	3.44	3.33	3.59	3.6
LC11/1 (deeper)	5.465	4.17					4.265	3.87	4.03	4.265	3.975	3.845	4.185	4.115
LC11/2	5.2	3.8					3.78	3.78	3.58	3.59	3.54	3.47	3.66	3.63
2F1	5.69						4.16	4.01	3.86	4.38	3.92	3.67	4.55	4.13
2F2	5.975						4.155	4.04	3.93	4.175	3.915	3.775	4.105	3.985

▲Elevation of Top of Piezometer casing (ToC) in m AHD
* Recorded by AWACS September 1996
♠ Recorded by Holmes and Holmes, as reproduced in Luke and Co. October 2008
♣ Recorded by WRL subsequent to installation of new piezometers
♦ Recorded in Laxton and Laxton, November 2009
◙ Recorded by Wildthings Native Gardens staff

2.8 Groundwater and Surface Water Quality

Water quality sampling was undertaken from the ground and surface water monitoring locations shown in Figure 7. Three rounds of water quality sampling were recently undertaken in conjunction with water level monitoring – 29th August 2009, 19th September 2009 and 10th October 2009. A summary of the water quality constituents and sampling locations is given in Tables 5 to 7 below.

Table5
Water Quality Sampling Locations

ID	Sampling Parameters (see Tables 6 and 7)
W1 – W13	Suite 1
SW 1 - 3	
LC11/2	
GW1 – GW9	Suite 2
LC11/1	

Table 6
Suite 1 Parameters

Parameter Type	Parameters
Physical Properties	pH, EC, Temperature, DO, Eh
Major Anions	Cl, SO_4^{2-}
Heavy Metals	Fe (total and soluble), Al (total and soluble)

Table 7
Suite 2 Parameters

Parameter Type	Parameters
Physical Properties	pH, EC, Temperature, DO, Eh
Major Anions	Cl, SO_4^{2-}
Trace Metals	Fe (total and soluble), Al (total and soluble), Ca, Na, K, Mg As, Cd, Co, Pb, Mn, Hg, Zn
Nutrients	TKN, Total N, Total Phosphorous
Coliforms	E.coli

Full details of the water quality sampling results are given in Laxton and Laxton (2009), and results are discussed in Section 3.3.

Water quality sampling within the existing wetland was undertaken on 11 occasions, between September 2005 and November 2007 (presented in Cardno (2008)). A summary of the average values from this sampling is presented in Table 8.

Table 8
Average Water Quality Values, Existing Wetland (Sept 2005 to Nov 2007)

Depth m	Temp Deg C	DO % sat	pH	ORP (Redox Potential)	Cond mS/cm
0	22.2	124.1	7.6	119.0	0.19
0.5	22.2	116.5	7.3	116.3	0.19
1	22.1	116.7	7.2	121.0	0.19
1.5	21.8	119.8	7.1	124.6	0.19
2	20.7	85.3	6.9	133.5	0.19
2.5	19.4	59.8	6.8	226.6	0.19

Tests were also undertaken to characterise the neutralisation (buffering) capacity of surface water within the existing wetland to examine the risks of generation of acidic conditions in the proposed wetland due to inward seepage of ASS affected groundwater (see Section 7.4). These tested results of these tests are presented in Table 9 below.

Table 9
Water Neutralisation Capacity, Existing Wetland

Measured at 6/03/2010	Alkalinity (mg/L)	Bicarbonate (mg/L)	pH
SW3	19	23	7.29
SW4	25	31	7.38
SW5	24	30	7.21
SW6	19	23	7.18
Average	21.75	26.75	7.26

The location of SW3 is the current outlet to the existing lake. SW4 to SW6 are various locations around the existing lake.

2.9 Operation of Bonny Hills STP, and Associated Groundwater Investigations

The Bonny Hill STP, shown in Figures 2 and 3, has been in operation since the mid 1980's. Since this time, treated effluent has been disposed at the site via exfiltration into the underlying aquifer. The exfiltration system comprises two large unlined 'balancing ponds' ("EP3" and "EP4"), and a (approximately) 1000 m long exfiltration trench system, which runs parallel to the beach, extending from near the STP southwards to near the location that Duchess Gully discharges to the ocean. According to a review of the STP undertaken by ERM in 2005, the STP (at the time of writing) treated approximately 1.0 ML/d of treated effluent on an ongoing basis.

A groundwater investigation at the STP site was undertaken by AWACS in 1996. The study set out to investigate the operation of the exfiltration system and the impacts to regional groundwater resources. For the study, 13 piezometers were installed at 9 locations adjacent to the STP. The locations are shown in Figure 6 (see bores 'LC1 – LC11'). Two of these bores (LC 11/1 and LC 11/2) are located on the St Vincents Foundation land and have been included in the current monitoring network.

AWACS undertook slug testing to estimate hydraulic conductivity of various materials. The results are summarised in Table 10.

Table 10
Estimates of Hydraulic Conductivity from Slug Tests, AWACS 1996

Material	Estimated Hydraulic Conductivity (m/day)
Clayey sand, light grey	0.01
Fine to med light grained sand, brown	4
Fine to med sand light grey	0.4 to 5
Gravelly sand	29

The AWACS study found that a layer of iron-indurated sands ("Coffee Rock") generally between 1 and 4 m AHD (just below the invert of Duchess Gully) created an aquiclude separating upper and lower aquifer systems. The coffee rock impeded the downward flow of effluent, leading to occasional springs of effluent water discharging above the coffee rock face along Rainbow Beach and within Duchess Gully. The coffee rock reduced the effectiveness of the exfiltration systems. Water levels in the upper aquifer were stated to be strongly influenced by the operation of the STP, and were close to 6 m AHD adjacent to infiltration ponds. Piezometric water levels in the lower aquifer were 2 to 3 metres lower, indicating downward flow.

The influence of the Bonny Hills STP on water quality was observed in the AWACS (1996) study, as well as subsequent studies by other parties (Public Works, 2000; ERM, 2001). It was noted in all studies that the operation of the STP had impacted groundwater quality and groundwater levels, creating mounding in the vicinity of the STP. In the ERM (2001) study, it was stated that monitoring subsequent to the AWACS study "confirmed that the groundwater under and within the vicinity of the STP is impacted by microbial contaminants to levels above the acceptable criteria".

Figures attached to the AWACS report noted water levels in the infiltration ponds to be 6.3 m AHD and 5.5 m AHD for EP3 and EP4 respectively.

2.10 Previous Groundwater Numerical Model

A three-dimensional (3D) numerical groundwater model was previously developed for the study area by Cardno (2008). The model files were provided to WRL, and were used as a basis for development of the groundwater modelling undertaken by WRL. Details of this modelling are provided in Section 4, 5 and 6 of this report. Details regarding the groundwater modelling undertaken by Cardno are provided in Cardno 2008.

3. REVIEW OF HYDROGEOLOGY

3.1 Hydrogeological Setting

The site is set within a small coastal basin. This basin has been infilled with a complex combination of soils from various coastal, estuarine and man-made processes. The major superficial geological units are mapped in Figure 9, based on examination of borelogs from investigations (shown in Figure 6), as well as publically available geological and soil landscape sheets.

Over the north and north western periphery of the site, the topography is elevated along the edge of the basin. Shallow deposit of residual clays and serpentine intrusions are found here above the underlying sedimentary formations. Test pits and bores undertaken in these formations found yellow-brown gravelly clays / clayey gravels with rock boulders and high plasticity clays. The depth of material was generally 2-3 m before refusal (of the test pit excavator) upon bedrock. Some minor groundwater seepage was found occasionally above the bedrock layer, but generally these units were dry.

The southern periphery of the site is similarly elevated, with similar residual shallow clayey materials being found. A mound of this material is also found in the centre of the site, between the existing lake and the STP. Ground investigations undertaken on this mound (BH37) found mottled red / brown / yellow residual clays, which were well drained and with low permeability. These units are also expected to be primarily dry.

Throughout the south western and central portion of the site, and at the foot of the bounding hills, the land is low lying, and high plasticity clays with high organic content are found to overlay the bedrock (and their associated residual clays). These organic clays may have been deposited under a process of infilling of a previous coastal estuary which dominated this part of the site. These areas are subject to seasonal waterlogging and represent an acid sulfate soil risk. Ground investigations in this region found the clays to be grey to dark grey, sometimes greenish with very high plasticity and a thickness of approximately 2 to 3 m. These organic clays were underlain by orange / red residual high plasticity sandy clays. The clayey materials in this region may also have been disturbed or modified in regions by previous land uses. These materials are marked on Figure 9 as ‘organic clays’ and are expected to be generally saturated.

In the central – eastern portion of the site (in the vicinity of the existing and proposed wetlands but west of Duchess Gully) sandy soils are found. Ground investigations undertaken on site found these to be light grey medium to fine sands and silty sands, relatively loose, and with a defined water table at generally 2 m depth.

East of Duchess Gully, coastal dune formations are found. An elevated dunal ridge follows parallel to the coast, with medium well sorted sub-angular sand of Aeolian origins. Soil landscape mapping also show that, in the south eastern corner of the site, these dunal deposits extend westward past the STP site up to the eastern edge of the existing wetland. The extents are shown in Figure 9.

The dune formations appear to overlay the silty sand formations found to the west of Duchess Gully. Investigations in this region also found that layers of iron-induration (coffee rock) were found generally at RL of 1 to 4 m AHD – corresponding to an elevation just above the intertidal zone, and also the invert of Duchess Gully. These indurated layers visibly outcrop along the beach and, as found by AWACS (1996), represent a confining layer between an upper and lower aquifer. Ground investigations indicate that the indurated layers are thickest near the ocean, but thin out to the west of Duchess Gully. They are not encountered by bores near the existing and proposed wetlands.

The surface expressions of these geological formations are mapped in Figure 9. However, ground investigations showed that layering is more complex in 3 dimensions. To assist with interpretation, a series of hydrogeological cross sections were produced across the site. The orientation of the cross sections are shown in Figure 10, and the cross sections are shown in Figures 11 to 16. ASS field and laboratory test data is included on the cross sections, where available.

The Aeolian silty sand formations, which are found in the vicinity of the existing and proposed wetlands, are found to extend further westwards, underlying a surface layer of organic and residual clays. The approximate extent of the silty sands is shown with a dashed line in Figure 9.

3.2 Aquifers and Groundwater Flow

Monitored groundwater levels across the site are presented in Table 3 and Figure 8. Groundwater levels are noted to be dynamic, responding to rainfall events. It is noted that the groundwater levels were uniformly declining across the site between August to October 2009, as this period featured very low rainfall and was preceded by a period of high rainfall.

Groundwater levels increased over the site in November, following a large (approx 1 to 2 yr ARI) rainfall event between the 6th to 8th November 2009.

Groundwater levels recorded in August 2009, at the start of the recent monitoring, are shown in Figure 17. In general terms, groundwater levels show a gradient falling towards the surface water features (i.e. toward the ocean, Duchess Gully and the existing wetland). Duchess Gully incises deeply into the adjacent aquifers and is also generally set below the level of the regional water table. As such, Duchess Gully is understood to operate as a drain to the aquifer. Duchess Gully also represents a divide in the aquifer system. To the east of Duchess Gully, groundwater levels are elevated within the dunal ridge. This is typical, with higher rainfall recharge into the sandy formations and ground water being elevated from wave runup processes. The groundwater is also particularly elevated adjacent to the STP, which is due to the disposal of effluent to the aquifer at that location. Within the dune system, it is seen that a groundwater mound exists, with groundwater flow onto the St Vincents Foundation property and towards Duchess Gully (westwards) and the ocean.

Bore GW2 is located in a depression between the dunal ridge and Duchess Gully. Seepage was noted at the interface between this depression and the toe of the elevated dune, suggesting flow from the dunal aquifer toward Duchess Gully. However, the lowest groundwater levels were recorded within GW2, at approximately 2.5 m AHD (approx 2m below ground). At this site, drilling encountered a band of well rounded pebbles, up to 40 mm size. The sample was difficult to identify due to the nature of drilling, but it is possible that a previous alignment of Duchess Gully was intercepted that may be associated with a high-conductivity region. This may account for the lower groundwater levels here, with efficient drainage from the depression towards Duchess Gully.

The decline of groundwater levels observed during the recent monitoring period may be due partly to evapotranspiration, but also from drainage of the whole site towards the ocean via Duchess Gully. Some loss of groundwater may occur vertically to deeper formations, but with respect to the low permeability of the underlying clays, this is expected to be relatively small.

The water levels in the existing wetland are below the water table in the adjacent aquifers, indicating flow generally toward the existing wetland. The proposed wetland, with water level at RL3.0, will similarly be below the current ground water table. Even when the wetlands are charged from surface flooding events, the water level in the wetlands is expected to be below the adjacent groundwater levels.

3.3 Groundwater and Surface Water Quality

WRL have reviewed the water quality data presented in Laxton and Laxton 2009. In general terms, the groundwater quality across the site is consistent with the acid sulfate soils (ASS) known to exist, with low pH values and high concentrations of aluminium, iron and sulphates.

The data also shows a very high degree of variability, possible due to the turbidity of samples, as described in Laxton and Laxton 2009. With consideration to the short monitoring period and this variability it is not possible to identify clear trends in the data. As such, averaged data values have been used for site characterisation. Groundwater quality testing is currently ongoing at this site, which may support more detailed analyses in the future.

Environmental responsibilities associated with any proposed works include ensuring that the 'beneficial usage category' of existing groundwater is not adversely affected. The beneficial usage is typically characterised by referencing observed water quality parameters against guidelines relevant to possible usages of water, including usages as drinking water, for irrigation or stock watering, or for the benefit of the regional environment. Reference has been made to the following guidelines to assist in characterising the beneficial usage category of the groundwater:

- ANZECC & ARMCANZ (2000) Australian and New Zealand Guidelines for Fresh and Marine Water Quality, Australian and New Zealand Environment and Conservation Council
- NHMRC (2005) Australian Drinking Water Guidelines, Australian Government National Water Quality Management Strategy

A summary of the mean water quality values for selected constituents is shown in Table 11. The constituents chosen are those for which a guideline value exists. Relevant guidelines have also been summarised in Table 11.

None of the samples taken from across the site in the recent groundwater monitoring program exhibited water quality suitable for usage as drinking water, or long term irrigation. Many of the constituents concentrations were too high, but it was characteristically metals (Pb, Zn, Mn, Fe) that were too elevated. The pH of water samples was generally less than 6.5, which is unsuitable for drinking water.

Groundwater samples from bores W6 and LC11/2 fulfilled requirements for usage of water for short term irrigation. Surface water samples from SW1 (upstream in Duchess Gully) and SW3 (existing wetland) also fulfilled requirements for short term irrigation usages. The elevated iron concentrations precluded samples from W9, GW1,GW9, LC11/1, SW2 and 2F2 from achieving the same (short term irrigation) beneficial usage.

There is no guideline value for Iron concentrations pertaining to stock watering usages. Hence, 20% (6) of the sampled locations were found to be suitable for usage in stock watering for the constituents sampled. Concentrations of lead and aluminium precluded such usages from the remaining locations. In some places, the salinity was also too high.

Guidelines pertaining to ecosystem preservation (ammonia, phosphorous and nitrogen) were exceeded in the samples tested. This indicates that such water would not be suitable for release into upland river systems.

Note that further guidelines also exist for water quality constituents not sampled. Hence, the commentary provided above is indicative only.

In general terms, the highest salinity waters were associated with the clay dominated portions of the site. To the east, within the sandy aquifers, water was generally fresh. The highest total aluminium values were found in bores around the north western periphery of the site, at the foothills.

Surface water samples from the existing lake and from upstream of Duchess Gully were generally superior to groundwater samples, being fresher, with lower iron and aluminium and more neutral pH. Samples from SW2 in Duchess Gully were poor, and are believed to reflect their proximity to the STP, indicating flow of effluent toward Duchess Gully in this location.

3.4 Summary of the Value (Beneficial Usage) of Existing Aquifers

In a review of the proposed development, DWE were concerned about the presence of broad coastal aquifers of high quality that may be impacted. Site investigations and water quality sampling do not support this view. Rather, such aquifers are of limited extent and, where high quality aquifers potentially exist, they have been significantly impacted by current land uses. The key groundwater resource that has a beneficial usage designation requiring upholding is the protection of the littoral rainforest to the north east of the site.

Table 11
Mean Measured Water Quality

Location	Constituent Concentration (mg/L unless stated)																
	TDS	**pH**	**Cl-**	**S0^4**	**Fe Total**	**Al**	**Na**	**Arsenic**	**Cadmium**	**Pb**	**Mn**	**Hg**	**Zn**	**Ca**	**Ammonia - N**	**Total N**	**Total P**	**E-coli**
W1	415	5.75	142	27	47	42												
W2	1201	5.59	520	104	40	108												
W3	1092	6.83	373	43	13	24												
W4	1425	5.76	673	72	66	55												
W5	2101	5.09	960	145	70	46												
W6	41	4.57	24	5	0.44	3.8												
W7	260	4.93	313	36	69	58												
W8	10222	5.58	4900	930	77	79												
W9	141	5.79	50	6	17	18												
W10	118	4.94	36	24	24	41												
W11	382	5.49	160	27	58	56												
W13	935	7.16	335	171	15	30												
GW1	213	4.75	84	10	1	1.8	52	0.005	0.0007	0.014	0.007	0.00007	0.054	5.5	0.254	1.866	0.0637	3
GW2	172	5.67	64	22	122	500	41	0.172	0.0016	0.247	0.733	0.00027	0.737	4.6	0.387	1.601	0.2323	1
GW3	111	6.25	31	5	127	231	21	0.08	0.001	0.124	0.56	0.00007	0.217	5.1	0.356	2.028	0.5768	1
GW4	6600	7.15	2743	257	377	437	1490	0.0059	0.0007	0.12	3.173	0.0001	1.797	84	0.159	0.459	0.1239	2
GW5	4581	5.71	2103	720	109	260	1120	0.024	0.0007	0.261	1.333	0.00013	0.13	123	0.152	1.414	0.0323	1
GW6	779	5.98	267	126	476	300	167	0.043	0.0027	0.537	3.6	0.00047	0.607	18	0.303	1.158	0.026	2
GW7a	77	5.42	29	6	20	310	18	0.006	0.0007	0.175	0.132	0.00047	0.49	7.2	0.523	1.897	0.135	4
GW7b	111	6.36	25	20	15.7	94	37	0.025	0.0012	0.164	0.063	0.00006	0.123	6.2	0.259	1.694	0.1335	2
GW8	847	7.16	407	175	49	90	407	0.0063	0.0007	0.256	0.377	0.00007	0.097	13	0.207	0.667	0.0412	1

Location	Constituent Concentration (mg/L unless stated)																
	TDS	pH	Cl-	S0[4]	Fe Total	Al	Na	Arsenic	Cadmium	Pb	Mn	Hg	Zn	Ca	Ammonia - N	Total N	Total P	E-coli
GW9	1582	6.42	617	232	46	12.5	400	0.0072	0.0007	0.243	0.153	0.00063	0.088	30	0.198	1.057	0.024	2
LC11/1	127	5.44	43	7	1.7	2.6	33	0.005	0.0007	0.004	0.029	0.00003	0.392	3.1	0.548	2.42	0.07	1
LC11/2	345	7.05	94	5	6.7	0.51												
SW1	291	6.72	96	4	9.6	0.42												
SW2	2427	6.48	1127	133	2.7	0.25												
SW3	119	7.51	48	13	1.7	1.5												
2F1	361	6.02	133	7	25	43												
2F2	56	5.83	31	14	8	20												
Guideline Values																		
Drinking	500	6.5	250	500	0.3	0.2	180	0.007	0.002	0.01	0.1	0.001	0.005	-	0.5	-	-	0
Irrigation	1300-3000	-	700	-	0.2, 10	5, 20	115, 460	0.1, 2	0.01, 0.05	2, 5	0.2, 10	0.002	2, 5	-	-	2, 25	0.5	-
Stock	2000	-	-	1000	-	5	-	0.5	0.01	0.1	-	0.002	20	1000	-	-	-	-
Ecosystems	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0.013	0.25	0.02	-

Notes:
- Irrigation guidelines are for long and short term irrigation respectively.
- Variation in stock values depends on stock
- E-coli measured in number per 100 mL. Results were noted as ‘dubious’ by Laxton and Laxton, 2009, due to high turbidity.

4. ESTABLISHMENT OF GROUNDWATER MODEL

4.1 Modelling Objectives and Complexity

A numerical groundwater model was used to assist with assessing the impacts of the proposed wetland. The model was set up to replicate observed groundwater conditions over the site (referred to as the 'existing conditions model'). The model was then re-run with the proposed wetland in place (referred to as the 'post-development model'). Differences between the existing and the post-development models were used to comment on the impacts to groundwater.

The existing conditions model was set up to create a steady-state approximation of the observed groundwater conditions. That is, (infinitely) long term and steady climatic conditions were applied to the model. Calibration was achieved by ensuring that the 'steady-state' climatic conditions resulted in groundwater levels that matched those observed on site. As groundwater levels on site are actually dynamic, this steady state approximation was undertaken to simulate three assumed conditions – low, medium and high rainfall. The existing conditions model was also validated in transient (non steady state) mode by checking that the groundwater response over time was appropriate.

The calibrated and validated model was then modified by inclusion of the wetland, with a fixed water level at RL3.0 m AHD.

4.2 Model Code

The numerical groundwater model applied the MODFLOW 2000 code. This modelling code is capable of simulating three dimensional groundwater flow, and is an internationally accepted modelling tool. The MODFLOW 2000 code was solved using *Groundwater Vistas* as the modelling interface, and ArcGIS for pre- and post-processing.

4.3 Model Structure

A MODFLOW groundwater model of the site was previously assembled by Cardno (Cardno, 2006). This model was provided to WRL, and was used as the basis for WRL's modelling presented in this report. Specifically, the model domain (extents) and layer elevations set up by Cardno (2006) were used by WRL and were not modified. However, WRL modified the properties and extent of geological units; the model boundary conditions and the model's hydrologic parameters to calibrate against the water level data that is now available.

4.3.1 Model Domain

The model domain (extents) is shown in Figure 18. The model covers an region 1800 m (east-west) by 1600 m (north-south), centred over the proposed wetland. The eastern boundary extends into the ocean and the northern and southern boundaries extend past the flood-prone low lands, onto the edges of the basin. The western boundary extends past the western limit of the sandy clay aquifers, but does not cover the full extents of the property. This is because impacts to groundwater at this western extremity were not expected. The model uses a 10 m grid throughout the model domain.

4.3.2 Model Layers

The model supplied by Cardno featured two layers. Layers in the model allow for representation of changes in geology in the vertical dimension. More layers allows for more detailed representation of geology, but increased modelling complexity.

WRL undertook a review of the established layering to verify that it is suitable for representation of the geology at this site. The orientation of these layers is seen in cross sections prepared by WRL, shown in Figures 11 to 16. The top of layer 1 represents the surface topography, which is shown in Figure 18. The bottom of layer 2 represents the base of the numerical model. The bottom of this layer, as established by Cardno, was observed to correspond closely with high plasticity clays, and demarcates, in the model, an assumed boundary through which vertical flow does not pass. In the east of the site, this refers to the high plasticity grey 'marine' clays, and in the west, to the location of high plasticity residual clays that are expected to reside above the sedimentary bedrock of the local basin. The base of layer 2 was observed to change in elevation significantly throughout the model, creating natural barriers to horizontal flow. This presents some challenges for model stability, as regions where the base of the model is elevated effectively dry up.

Layer 1 (upper layer) and layer 2 (lower layer) were separated at a location corresponding approximately to an observed interface between geological units. Throughout the centre of the model, this corresponded to an interface between silty sand aquifers and organic clays. The model was thus effective in demarcating these units in these regions. In the east of the model, within the dune sands, this layer allowed for a simplified representation of the layers of induration (coffee rock). However, the complex geology in this region may have been better represented by three layers.

In summary, the two layers set up by Cardno were found to allow for sufficient flexibility for simplified representation of the geology at this site. This was suitable for the objectives and complexity of the original model. However, the layering may be too simplified to allow for more detailed transient models.

4.4 Hydrogeological Conceptualisation

Five geological units were represented in the model, referred to hereafter as Zones. Values of hydraulic conductivity and storage were assigned to each of these zones in accordance to the geological unit being represented. The locations of these zones are shown in Figures 19 and 20 for Layer 1 and Layer 2 respectively. A summary of the parameters used is shown in Table 12. The values shown in Table 9 were used in the calibrated existing condition and post-development models. Note that storage values are not applied in steady-state model and were only used in the transient validation described in Section 5.2.

Table 12
Values of Hydraulic Conductivity and Storage Adopted in the Model

Zone	Geologic Unit	Hydraulic Conductivity (m/d)	Specific Yield (%)	Specific Storage (m^{-1})
1	Sand Dunes	10	0.25	1×10^{-5}
2	Silty Sand	3.4	0.15	1×10^{-5}
3	Residual Clay	0.012	0.02	1×10^{-5}
4	All Other Clays	0.004	0.02	1×10^{-5}
5	Coffee Rock	2	0.07	1×10^{-5}

The values shown in Table 12 were selected to achieve an appropriate calibration and are chosen to be representative of the geological units for the manner in which they are represented in the model. For example, indurated sands (coffee rock) may generally be expected to have a hydraulic conductivity less than 2 metres per day, but due to limitations in the model (i.e. the number of layers available) a value was chosen that represented a thin layer of induration *within* a model layer otherwise comprising sand.

The ocean boundary was modelled as a constant head. Studies have shown that wave action can cause a superposition of fresh groundwater in the aquifer adjacent to the ocean (Nielsen *et al.* 1988; Turner *et al.* 1997). Hence in the steady state model, a constant head of +0.5 m AHD was used, which is slightly elevated above mean sea level. The model did not include simulation of tides, wave action or density differences due to salinity.

The groundwater model simulated groundwater within the Duchess Creek surface water catchment. Model cells that were outside of the Duchess Creek catchment were de-activated. General head boundaries were applied around the perimeter of the model at locations where inflow and outflow may be expected and may be important (see Figures 19 and 20). The remainder of the model perimeter employed no-flow boundaries.

The interaction of groundwater with Duchess Gully is a key feature of this site. Examination of elevation data (see cross sections in Figures 11 to 16) showed that the invert of Duchess Gully is below the observed groundwater levels at all times. This infers that groundwater flow is towards Duchess Gully, which acts as a groundwater drain to the site. Duchess Gully was therefore simulated in the groundwater model using a MODFLOW 'Drain' boundary. This boundary calculates flow into the drain as a function of the head difference between the drain invert and the groundwater level in adjacent cells. The drain nodes do not simulate recharge (i.e. flow towards the aquifer), but this is not considered necessary as the net flow (in a steady state simulation) is toward the drain. Elevation data of the drain invert was not of high resolution, and interpretation was required to select an appropriate drain elevation. Groundwater levels at GW2, which were the lowest on site, could only be replicated if a high conductivity lens in the area was assumed. To model this, drain nodes were extended to cover the region of GW2, simulating efficient drainage from this location towards Duchess Gully. These low groundwater levels are expected to be due to the gravelly lenses encountered in this bore at an elevation approximately equal to the invert of Duchess Gully.

Infiltration of effluent from the Bonny Hills STP was simulated using constant head cells at the locations of the existing infiltration basins. The elevation of the constant head was set at the water levels in the infiltration pond as reported in AWACS (1996): 6.3 m AHD and 5.5 m AHD for EP3 and EP4 respectively.

The wetlands were simulated as MODFLOW Lakes with controlled water levels. The existing lake was set at 3.4 m AHD, and the proposed lake at 3.0 m AHD. These levels were below the adjacent groundwater levels, indicating flow into the lake.

5. SIMULATION OF EXISTING CONDITIONS

5.1 Steady State Approximations

For the purposes of this study, groundwater levels recorded on October 2009 were assumed to be representative of annual average levels and levels recorded in August 2009 were representative of annual average high groundwater (November 2009 levels were considered to be more extreme high levels). Of the available data, none were believed to be representative of annual average low groundwater levels.

Further groundwater monitoring is being undertaken at this site, and once sufficient records are available, these annual average median, low and high groundwater levels can be reviewed.

Steady state models were established to represent each of these assumed “annual average” high, median and low groundwater levels. For the high and median levels, model parameters of recharge and hydraulic conductivity were adjusted to replicated groundwater levels recorded in August and October 2009 respectively. To simulate low groundwater levels, the recharge was simply factored down. The low groundwater simulation is therefore uncalibrated. A summary of the recharge values adopted for each simulation is given in Table 13. Recharge broadly corresponded with the geologic ‘zones’. Note that the value of recharge adopted is representative of net recharge after losses to evapotranspiration.

Table 13
Values of Recharge Adopted in Steady State Models

Zone	Geologic Unit	Recharge (mm/d)		
		Annual Average Low	Annual Average	Annual Average High
1	Sand Dunes	2	3.5	5
2	Silty Sand	0.1	0.3	0.6
3	Residual Clay	3×10^{-7}	4.5×10^{-7}	6×10^{-6}
4	All Other Clays	1×10^{-7}	1×10^{-7}	4×10^{-7}

5.1.1 Calibration

The steady state models were capable of an adequate representation of the measured groundwater levels. Statistical details describing the model calibration are summarised in Table 14.

Table 14
Calibration Statistics

Calibration Statistics	**Simulation of Annual Average (October 2009) Groundwater Levels**	**Simulation of Average Annual High (August 2009) Groundwater Levels**
Residual Mean	-0.02	0.2
Residual Standard deviation	0.32	0.34
Absolute Residual Mean	0.24	0.12
Observed Range in Head	3.61	3.51

Note that if "Residual Standard Deviation" is less than 10% of the "range observed", the calibration is considered to be good.

In Figure 24, the observed groundwater levels in August and October 2009 are compared to simulated levels. With four exceptions, the model replicated observed levels to within +/- 0.25 metres.

Levels within the dune formations (GW1 and GW2) were less successfully modelled, being generally +/- 0.6 m. This is because the representation of geology in this region is simplistic. The orientation and depth of a confining coffee rock layer (as identified in AWACS 1996, and during drilling for this study) in this vicinity is only approximated in the 2 layer groundwater model. In addition, a lens of smooth and large river gravel was identified in GW2, which is believed to explain the low observed groundwater levels at depth in this location. Visual inspections at the site also confirmed water at the surface (~ RL 4 to 5 m AHD) in this location, which is predicted accurately by the model. The measured levels in GW2 are therefore indicative of free falling vertical flow, which is not simulated fully in the model.

Levels in LC11/1 and GW7a were also not simulated as successfully – being generally 0.5 to 1 m out, respectively. These bores are adjacent to the drain, and the numerical model, with a 10 m grid, does not accurately simulate the seepage face of groundwater to the drain in this vicinity. The levels may also be affected by coffee rock layers which are only approximated in the model.

The net flow rate from the STP infiltration galleries into the aquifer was reported by the model as approximately 0.3 to 0.5 ML/day, which is commensurate with the known operation of these basins. The net flow rate into Duchess Gully is approximately 8 L/s, which is considered to be a sensible value.

5.1.2 Results

The results for the steady state simulations for average, low and high groundwater levels are shown in Figures 21, 22 and 23 respectively. These figures show contours of groundwater elevations, superimposed on the site aerial photograph and surface topography. Note that elevated portions of the site were simulated as drying out, and a saturated groundwater table, according to the model, only occurs in the lower lying land. This is considered to be a sensible representation.

In the western portion of the site, groundwater flow is dominated by the existing wetland, with water level contours (and hence the flow direction) falling gradually towards the wetland. East of the existing wetland, groundwater flows towards Duchess Gully and out of the model.

In the vicinity of the proposed wetland, groundwater levels are slightly mounded, with flow diverging towards the existing wetland in the south, and Duchess Gully in the north and west.

A distinctive groundwater mound is found in the vicinity of the STP, with a high gradient towards the ocean to its east and Duchess Gully to its west, and towards GW2, the lowest groundwater levels on site were recorded.

In the north east corner of the site, groundwater level contours were simulated to be generally parallel to the coast, indicating flow towards the ocean from the elevated topography adjacent to the coast in this location.

The differences between low, medium and high rainfall simulations are reflected by generally lowered levels, but the flow patterns remain consistent. The levels at the STP remain relatively unaffected, being dominated by the infiltration system in this region.

5.2 Transient – Verification by Replication of Monitoring Period

A verification of the steady state models was undertaken in 'transient' mode. This was done by simulating the observed decline in groundwater levels between the period of 29th August 2009 to 10th October 2009.

The groundwater model was run in steady state to simulate August 2009 levels, and then an additional 'transient' modelling period of 42 days duration was run. For this period, recharge was set to zero, and evapotranspiration of 5 mm / day was applied (with extinction depth of 3 metres) across the whole model domain. The predicted decline in groundwater over this period was compared to observed groundwater levels.

In general terms, groundwater records from within the silty sand aquifer (within the vicinity of the proposed wetland) were simulated reasonably well. Results from selected bores are shown in Figure 25.

In the western region of the model, the simulated rate of drainage rate was too low. This may reflect the assumption of a no-flow boundary at the base of the model or the presence of un-modelled (and un-investigated) flow paths toward existing lake.

In the dune sand region (east of Duchess Gully) the simulated drainage rate of 0.7 m head in 42 days was higher than the observed rate of approximately 0.3 m head. Water levels at this location are controlled by the STP operation, making transient simulation difficult unless STP operational details are applied. As stated, the representation of geology in this region is also an approximation.

6. SIMULATION OF PROPOSED DEVELOPMENTS

The post-development condition was simulated in the groundwater model by setting cells within the perimeter of the proposed wetland to have a constant head of 3.0 m AHD. This simple representation was found to be appropriate for simulation of the proposed wetland. This is because the proposed wetland, with weir level at RL 3.0 m AHD is below the level of the adjacent groundwater bodies, and will experience a relatively constant inflow of groundwater. The weir level in the wetland is therefore considered to be a good representation of water levels in the wetland for a steady state simulation. The apparent constancy of water levels in the existing wetland is considered to be an example. Surface water assessments undertaken by Cardno (2008) also showed that the wetland level is expected to be regularly maintained from surface water inflows alone.

The results for the steady state simulations for post development conditions for the cases of average, low and high groundwater levels are shown in Figures 26, 27 and 28 respectively.

The drawdown in groundwater levels between the pre-and post- development condition was assessed as the differential in groundwater heads between the two scenarios. The drawdown for the average groundwater level case is shown in Figure 29.

According to the groundwater model, the drawdown in this region is associated with a net steady-state groundwater seepage discharge of 40 m^3/day into the proposed wetland.

The post-development conditions represented in the model did not include any alterations to recharge as a consequence of development, and did not include the fill placed within the residential regions. This is discussed in Section 7.

7. DISCUSSION OF IMPACTS

7.1 Drawdown

The establishment of the proposed wetland with water level at RL 3.0 m AHD is seen to result in drawdown of the saturated groundwater level (water table) across the site. The maximum drawdown in the order of 0.8 metres occurs in the vicinity of the proposed wetland, and the magnitude of drawdown diminishes with distance away from the wetland. The drawdown is confined primarily to the silty sand aquifer. The location of Duchess Gully is observed to be an effective barrier, with nil or negligible (generally less than 0.01 m) of drawdown occurring in regions to the east of Duchess Gully.

7.2 Identified Protection Areas

Two key regions have been identified in previous studies as having ecological significant features that should be protected from any impacts due to changes to groundwater conditions.

Firstly, a strip of littoral rainforest is found at the north eastern perimeter of the site, parallel to the ocean. The modelling predicts drawdowns of less than 0.01 m in this region. In addition, inspections in the vicinity of GW2 (between the proposed wetland and the littoral rainforest) indicated a strongly vertical flow field, approaching a free falling condition. In such a condition, the level of perched water (as observed at the surface) cannot be impacted by reductions in piezometric head at depth. Based on the available information, it is WRL's opinion that the groundwater systems adjacent to these littoral rainforests will not be impacted by the establishment of the proposed wetland.

A second region that has been identified is a small portion of land surrounding BH3, adjacent to the existing wetland. This region has been identified as a potential habitat for a species of frog with 'marshy' damp conditions found at the surface.

The saturated groundwater table in this location reflects the level of the adjacent lake, being approximately 1.6 m below ground. A borehole in this region showed a thick deposit of high plasticity clays extending from the surface. The 'marshy' conditions at the surface are thus believed to be perched, and are separate from the saturated water table. The numerical groundwater model predicts drawdown in the saturated water table in this region of approximately 0.1 m. This drawdown is not expected to impact on the moist 'marshy' nature of the surface soil conditions in this location.

7.3 Impacts to Aquifer Water Quality

In a letter from the Department of Water and Energy (DWE) to the Department of Planning regarding this development (21st May 2009), concerns were raised that the proposed wetland may lead to contamination of groundwater by infiltration of surface water from the proposed wetland. Based on the measured groundwater levels and groundwater modelling, it is WRL's view that little surface water will be directed to the aquifer from the proposed wetland. Flow is likely to be primarily in the opposite direction (i.e. groundwater seepage into the pond). Based on the available water quality data, it is anticipated the wetland will not introduce to the aquifer water that is of comparatively lesser quality.

7.4 Acid Sulfate Soils

ASS have been identified on this site. Many of the existing higher risk ASS deposits will remain below the water table following development. Such ASS deposits do not present a potential risk. However, two (related) ASS risks have been identified on the site.

Firstly, water quality data from bores adjacent to the proposed wetland, as presented in this report, indicate ASS risks and instances of poor quality low pH groundwater. Results from the groundwater model indicate development of a slight gradient of groundwater flow toward the wetland following its construction. As such, consideration must be given to the impacts of seepage of ASS affected groundwater on water quality in the proposed wetland.

Secondly, from examination of the available ASS data, there is a region of shallow ASS deposits to the North West of the proposed wetland. The groundwater model indicates that this region may be subject to some drawdown, indicating that the risk of further oxidation of these ASS deposits should also be considered. While it is understood that the management of ASS is not considered to be problematic (this area will be covered in fill), there is a risk that such oxidation would exacerbate groundwater conditions, and therefore contribute to potential water quality issues in the proposed wetland. A region where more than 0.1 m drawdown, as predicted by the model, corresponds with these materials has been mapped and is shown in Figure 30. The same details are reproduced in Figure 31, but showing the proposed layout of fill.

These risks have been given detailed consideration for this report and are discussed below.

The existing wetland is considered to be a robust test case for future water quality in the proposed wetland. The existing wetland is likely to be subject to the same proportions of inward seepage of ASS affected groundwater, and may have previously caused drawdown and some oxidation of ASS on site. Nonetheless, there is no current indication of the development of ASS conditions in the existing wetland (see water quality results presented in Tables 8 and 9). This is a positive indication for water quality in the proposed wetland, and is expected to indicate that dilution and buffering of ASS affected groundwater seepage by the inflow of surface water is sufficient to maintain healthy conditions.

A simple water quality model (PHREEQC) was undertaken to examine the potential development of acidic conditions in the wetland. For this model, quantities and characteristics of two different water types (representing surface water and ASS affected groundwater) were 'combined' and, under the assumption of complete mixing, the resulting quality was predicted.

For this model, conservative (i.e. high) estimations of groundwater inflow discharge with poor quality characteristics was used. As estimated inflow rate of 80 m^3/day (~1 L/s) of groundwater seepage was assumed. This is representative of twice the net seepage inflow under steady state conditions predicted by the model, or the maximum seepage from the identified potential ASS affected zone during lower lake levels and higher recharge (estimated by application of Dupuit's equation). The groundwater was assumed to have the characteristics outlined in Table 15:

Table 15
Groundwater Characteristics used in PHREEQC

Groundwater Quality Condition		Water Quality Indicators							
		Na	K	Ca	Mg	Cl	SO_4	HCO_3	pH
1.	Currently Observed Conditions	46.6	3.9	7.3	7.8	64.8	27.2	45	5.89
2.	For Assumed pH= 5.2							10	5.2
3.	For Assumed pH= 4.5							4	4.5
4.	For Assumed pH= 4.0							1	4.0

*Note: All values are averaged from bores within and adjacent to the proposed wetland.

Note that the adopted values for Major Ions, pH and Bicarbonate (HCO_3) for Case 1 are based on average values recorded at bores within and adjacent to the proposed wetland. For Cases 2 to 4, the Major Ions remained the same, but increasingly lower pH values were assumed and Bicarbonate values were adjusted to maintain a compatible ionic balance with the assumed pH.

For the characterisation of surface water quality, the average values of the recent measurements (as per Table 9) were used to represent surface water characteristics in PHREEQC.

For surface water quantity, Cardno (2008) stated that an average annual runoff of 240 mm from an effective catchment area of 354 ha was expected to be delivered to the existing wetland (Table 18, Cardno 2008). This is indicative of an annual inflow of 850 ML/a, or daily average of 2300 m^3/day (~27 L/s). For the PHREEQC model, three cases of surface water flow were assumed, representing increasingly conservative (i.e. low) estimations of inflow of 1750 m^3/day (~20 L/s), 720 m^3/day (~8 L/s) and 320 m^3/day (~4 L/s). In the PHREEQC model, where complete mixing was assumed, these represent cases of volumetric ratio of surface water to groundwater (%) of 95.6:4.4, 90:10 and 80:20 respectively.

In summary, the water quality modelling undertaken in PHREEQC examined 12 scenarios, representing the product of the four cases on groundwater quality (Table 15), and the three cases of surface water inflow. The first scenario represented expected water quality conditions with conservative flow conditions. The remaining scenarios represented increasingly conservative flow and groundwater quality assumptions. The results of predicted pH within the proposed wetland for these 12 scenarios are shown in Table 16.

Table 16
Predicted pH in the Proposed Wetland

Mix Ratio (%)	Predicted pH for Various Groundwater Quality Cases			
	Case 1	Case 2	Case 3	Case 4
95.6/4.4	7.3	7.3	7.2	7.1
90/10	7.2	7.2	7.2	7
80/20	7.2	7.2	7.1	6.8

The results from the PHREEQC modelling suggest that even for conservative assumptions the predicted pH in the proposed wetland will be acceptable.

The assessment of the risk of oxidation of ASS (as shown in Figure 30) and the impacts to the proposed wetland should also consider other processes that may act to reduce the risk further. Firstly, the groundwater levels predicted by the model are considered to be conservative because the net recharge to the clay layer is likely to increase following placement of fill. This was not included in the model as it is difficult to quantify the degree of change.

Secondly, the placement of fill over this region (Figure 31) is likely to limit the exposure of this region of ASS[3]. The establishment of a sandy layer of fill above the high plasticity clays is likely to result in the development of a perched water table within the sands, above the clays, keeping them saturated. Such a perched water table would develop because infiltration to a sandy formation exceeds that of the high plasticity clays. This is a design principle commonly adopted in protection of covered waste sites and is relied upon in high risk applications.

Thirdly, it is well established that developments can lead to increased water levels due to recharge from leaking services, watering of gardens and reduction of evapotranspiration. While it is not good practice to rely on these mechanisms for safety, it is nonetheless likely that recharge to this region will increase, and will contribute to the formation of a perched lens above the ASS clays. The availability of cost effective and high reliability recycled water to this development area (for garden watering) is noted.

Lastly, while the available ASS data does suggest the presence of a shallow ASS lens, the findings regarding the nature of this lens are not uniformly severe. For example, ASS tests on soils from this formation in Bores 107, 108 and 110 indicate "very slight potential, no management required" (Luke and Co., 2007b).

In summary, the risk of development of acidic water quality within the proposed wetland due to seepage of ASS affected groundwater is considered to be low, but cannot be ruled out. The concern is that acid generation would approach a 'tipping point' at which conditions progressively deteriorate. Nonetheless, based on water quality modelling and consideration to the proposed works, it is considered likely that the water quality in the proposed lake with be similar to water quality currently observed in the existing lake, and that buffering and dilution from surface water inflows will be sufficient to maintain near-neutral pH levels. It is recommended that the Groundwater Management Plan (Appendix B) is adopted to monitor groundwater and surface water quality, providing early indications and opportunities for remedial action.

[3] The ASSMP should incorporate actions to ensure that oxidation to these clays does not occur during construction – for example, fill that has ASS characteristics should be treated and, if the fill is placed wet, this will limit exposure of the clays during construction.

8. CONCLUSIONS

WRL has compiled and reviewed the available data characterising the geology and hydrogeology of the proposed development site in Bonny Hills. This includes data recently obtained from a series of groundwater levels and water quality investigations.

An overview of the hydrogeological setting of the site is given, and the local aquifer systems have been characterised. In summary, two key sandy aquifer systems exist, which are effectively separated by a deep creek gully referred to as Duchess Gully. A third saturated clay body is also found in the west of the site.

The sandy aquifer to the west of Duchess Gully is a shallow unconfined system within a limited deposit of silty sands of Aeolian origin. This aquifer lies fully within the property boundary and is bound on its northern, southern and western edges by clays of estuarine, marine and residual origins. Clays to the western region of the site are low lying and generally saturated, and could be considered to be a low yielding poor quality aquifer. To the east of Duchess Gully, a perched freshwater aquifer system is found. This aquifer is of limited extent, being perched above a saline interface of ocean water. The aquifer is compartmentalised, in regions, by a layer of iron indurations (coffee rock).

Water quality data has been used to characterise the existing beneficial usage category of the groundwater in the identified aquifer systems. The water quality in the silty sand aquifer is indicative of acid sulfate soils, and exhibits low pH, and elevated concentrations of iron and aluminium. The water is not suitable for drinking and long term irrigation, but in isolated instances samples from the aquifer fulfil requirements for longer term irrigation and stock watering. Water quality within the saturated clays is similarly poor, and has no identifiable beneficial usage category in terms of the relevant guidelines. Water quality within perched coastal dune aquifers is typically fresh and of high quality. Such water might support littoral rainforests to the north east of the study area. The long term operation of the Bonny Hills STP to the south east of the study area has detrimentally impacted water quality within this aquifer. Within the vicinity of the STP, water may technically be of benefit to short term irrigation and stock watering. However, with respect to risks of contamination, such usages would generally not be recommended.

In a review of the proposed development, DWE were concerned about the presence of broad coastal aquifers of high quality that may be impacted. Site investigations and water quality sampling do not support this view. Rather, such aquifers are of limited extent and poor quality. Where high quality aquifers potentially existed, they have been significantly impacted by current land uses.

WRL modified an existing groundwater model to calibrate it to groundwater level data that has been recently obtained from across the site. This groundwater model was used to examine the impacts to the groundwater systems from establishment of a proposed wetland within the property. Groundwater modelling showed that drawdown to groundwater will occur, as presented in Figure 29. Drawdowns are expected to be confined primarily to the silty sand aquifer that is contained within the site, and will not significantly impact on the identified valued groundwater resource which sustains a littoral rainforest to the north east of the study area. WRL has also reviewed other identified regions where groundwater impacts are of concern, such as a frog habitat adjacent to the existing wetland. It is WRL's opinion that the saturated condition of the clays at the surface in this location will not be affected by the establishment of the proposed wetland.

Acid sulfate soils exist on the site. WRL have considered longer term risks to ASS on the site (risks during the construction phase are understood to be addressed in the ASSMP). In most cases ASS deposits remain below the water table but a risk of drawdown and oxidation of a shallow lens of ASS has been identified. The transport of poor quality groundwater from this region and into the proposed wetland has been considered. Risks to wetland water quality from this process cannot be ruled out, but are considered to be low based on: the nature and extent of ASS deposits; the processes that are likely to limit the risk of oxidation, and; the indications from the existing wetland and a water quality model that dilution and buffering from surface water inflows is sufficient to maintain acceptable water quality. Nonetheless, developments should be accompanied by a robust ASSMP as well as a monitoring and a response plan as set out in Appendix B of this report.

9. REFERENCES

ANZECC /ARMCANZ (2000), Australian Guidelines for Water Quality Monitoring and Reporting.

ANZECC (2000), Australian and New Zealand Guidelines for Fresh and Marine Water Quality. National Water Quality Management Strategy.

ANZECC (1995), Guidelines for Groundwater Protection in Australia, Australian and New Zealand Environment and Conservation Council, September 1995.

AWACS (1996), Lake Cathie Bonny Hills STP Groundwater Investigation 1996.

Cardno (2008), Rainbow Beach Estate, Bonny Hills. Water Engineering and Environmental DGR Assessments. October 2008.

DLWC (1997), The NSW State Groundwater Policy Framework Document. Department of Land and Water Conservation August 1997.

DLWC (1998), The NSW Groundwater Quality Protection Policy. Department of Land and Water Conservation December 1998.

EDAW (2009), Rainbow Beach Open Space / Drainage / Habitat Corridor Landscape Master Plan Concept Report. March 2009.

Holmes & Holmes (1993), Geotechnical Appraisal for Development Options at Lake Cathie for Global Pty Ltd, Holmes & Holmes Pty Ltd, Coffs Harbour Jetty, 23 November 1993.

Holmes & Holmes (1998) Preliminary Acid Sulphate Soil Investigation South of Lake Cathie (Formerly Rainbow Pacific Site), Holmes & Holmes Pty Ltd, Coffs Harbour Jetty, 15 December 1998.

Holmes & Holmes (2003a), Rainbow Beach Groundwater Levels, Holmes & Holmes Pty Ltd, Coffs Harbour Jetty, Fax 30 March 2003.

Holmes & Holmes (2003b), Record of Boreholes, Holmes & Holmes Pty Ltd, Coffs Harbour Jetty, Fax 20 June 2003.

Holmes & Holmes (2003c), Record of Boreholes, Holmes & Holmes Pty Ltd, Coffs Harbour Jetty, Fax 23 June 2003.

Laxton, J and Laxton, E (2009), Quality of Ground Water and Surface Water at Bonny Hills, NSW. November 2009. Report for St Vincents Foundation.

Luke & Company (2007a), Development Report – Earthworks Luke & Co, Port Macquarie, 2007.

Luke & Company (2007b), Development Report – Geotechnical Luke & Co, Port Macquarie, 2007.

Nielsen, P, Davis, G A, Winterbourne, J M and Elias, G (1988), Wave setup and the water table in sandy beaches. Public Works Report T.M 88/1 September 1988.

Public Works (2000), Lake Cathie / Bonny Hills Sewerage Treatment Plant Groundwater Monitoring Plan. NSW Department of Public Works and Services. October 2000.

Turner I L, Coates B P and Acworth R I (1997), Tides, Waves and the Super-elevation of Groundwater at the Coast. Journal of Coastal Research, Vol. 13, No. 1 (Winter, 1997), pp. 46-60 Published by: Coastal Education & Research Foundation, Inc.