Shoalhaven City Council

West Culburra groundwater assessment

Preliminary report (Stage 1)

HGEO Pty Ltd
Date: 28 June 2017
Project number: J21423
Report: D17262

DOCUMENT REGISTER

Revision	Description	Date	Comments
A	1st Draft	7/6/2017	Draft to SCC
B	Final	28/6/2017	Final as pdf

FILE

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Cover photo: Looking southwest over Lake Wolumboola from the boat ramp on West Crescent.

QUALITY CONTROL

Process	Staff	Signature	Date
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Approved	Stuart Brown		28/6/2017

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

EXECUTIVE SUMMARY

HGEO Pty Ltd was engaged by the Shoalhaven City Council to carry out a groundwater investigation over and area encompassing two proposed developments west of Lake Wollumboola.

The objectives of the investigation are to: 1) develop a conceptual model for the groundwater systems in the area being considered for development to the west of Lake Wollumboola; 2) carry out field investigations to delineate the groundwater catchment for Lake Wollumboola and groundwater flow directions within the area; and 3) characterise baseline groundwater conditions by collecting groundwater quality and level data.

The investigation will be carried out in three stages:

- Stage 1: Review and conceptualisation – including a site inspection and revision of the investigation scope [This report];
- Stage 2: Detailed field investigation – drilling and installation of groundwater monitoring bores and interpretation of groundwater levels and groundwater quality data;
- Stage 3: Ongoing groundwater monitoring

This report presents the findings of the preliminary (Stage 1) investigation, including an updated scope for the Stage 2 investigations. The report outlines the hydrogeological setting and climate, and the results of previous groundwater investigations at the site. A site inspection was carried out between 3 and 5 April 2017 to assess site conditions and access for drilling. The proposed groundwater monitoring network was revised on the basis of those preliminary findings.

The recommended monitoring network comprises 14 locations. Nine (9) of those locations will consist of two nested bores, designed to monitor "deep" groundwater within the Permian siltstone, and "shallow" groundwater within the regolith and/or Quaternary alluvial deposits. A baseline monitoring program will include the installation of 21 automated groundwater level loggers and two level/salinity (EC) loggers to provide continuous high-quality monitoring information. Groundwater samples will be collected quarterly to establish baseline groundwater chemistry and nutrient concentrations.

1. INTRODUCTION

HGEO Pty Ltd (HGEO) was engaged by Shoalhaven City Council (SCC) to carry out a groundwater investigation in a proposed development area west of Lake Wollumboola. A groundwater investigation is required by SCC to inform the preparation of an integrated water cycle assessment required for the Halloran Trust Planning Proposal (Rezoning) which covers 1681.5 ha of land at Culburra Beach, Callala Bay and Currarong.

1.1 Scope of the investigation

The scope of the investigation is defined by the Consultants Brief issued by the SCC, dated 7 November 2016, and the proposal by HGEO that was accepted on 30 March 2017. The investigation focuses on proposed development areas to the west of Culburra Beach, with a particular focus on the area between the Crookhaven River and the north-west shores of Lake Wollumboola. This area includes the proposed golf course development on Long Bow Point (SSD 8406, previously DA11/1728) and the West Culburra Mixed Use Subdivision (Application 09_0088).

The principle objectives of the investigation are to:

- develop a conceptual model for the groundwater systems in the area being considered for development to the west of Lake Wollumboola;
- Carry out field investigations to determine the height(s) of the water table, and delineate the groundwater catchment for Lake Wollumboola and groundwater flow directions within the area;
- characterise baseline groundwater conditions by collecting groundwater quality and level data;
- update the conceptual model and provide recommendations on the assessment of potential impacts from proposed and future developments in the investigation area.

The investigation is divided into three stages:

- Stage 1: Review and conceptualisation – including a site inspection and revision of the detailed investigation scope if necessary;
- Stage 2: Detailed field investigation – drilling and installation of groundwater monitoring bores and interpretation of groundwater levels and groundwater quality data;
- Stage 3: Ongoing groundwater monitoring

This report presents the findings of the preliminary (Stage 1) investigation, including an updated scope for the Stage 2 investigations.

2. BACKGROUND

2.1 Location and topography

The site is located to the west of the township of Culburra Beach on the south coast of NSW, and covers an area between the north-western shores of Lake Wollumboola and the southern shores of the Crookhaven River, incorporating the proposed golf course and mixed use developments (specified in the previous section).

A broad north-east to east trending ridgeline divides the site into northward sloping (towards the river) and southward sloping (toward the Lake) domains. Ground elevations range from 0 to approximately 38 m above Australian Height Datum (or mean sea level; AHD), with generally gentle slopes and rounded hills and ridgelines. The coast fringing the Crookhaven River consists of alternating bays (estuarine mudflats) and headlands, typically with banks up to 5 m high. The western and northern edges of Lake Wollumboola vary between fine sandy beach, estuarine mud and boulder outcrop.

The site is currently dominated by remnant native vegetation (eucalypt forest) and pasture and is predominantly used for grazing. Most areas are accessible by unsealed tracks. The eastern part of the study area overlaps with residential and light industrial properties of Culburra Beach.

2.2 Climate

Daily rainfall and solar exposure are recorded at the Culburra Beach Treatment Plant (within the area of investigation) and the Greenwell Point Bowling Club (~1.5 km to the north). The closest comprehensive weather station is at the Nowra Naval Air Station (~18 km west of the site).

Culburra Beach has a temperate climate with warm summers, cool winters and no distinct dry season (BOM 2005). Mean daily maximum temperatures at Nowra range from 27.6 °C in January to 16.5 °C in July (Figure 1). Rain falls all year round but tends to be higher in the late summer months (February – March).

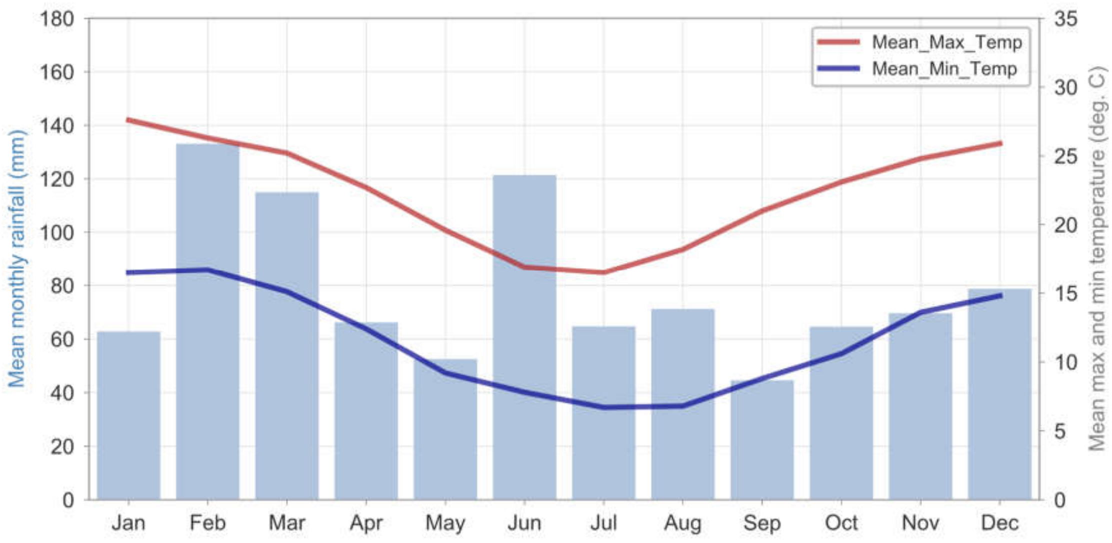

Figure 1. Monthly average rainfall and temperature at Nowra Airport (2001 – 2017)

Mean annual rainfall at Culburra Beach is 1143 mm (2001 – 2017), slightly higher than the mean annual rainfall in Nowra (902 mm). A bar graph of rainfall and Culburra Beach and adjacent coastal weather stations shows that rainfall was generally below average in the years between 2001 and 2009, and generally above average since 2010 (Figure 2). Regional groundwater levels tend to reflect these longer-term trends in excess or deficit rainfall relative to the long-term mean.

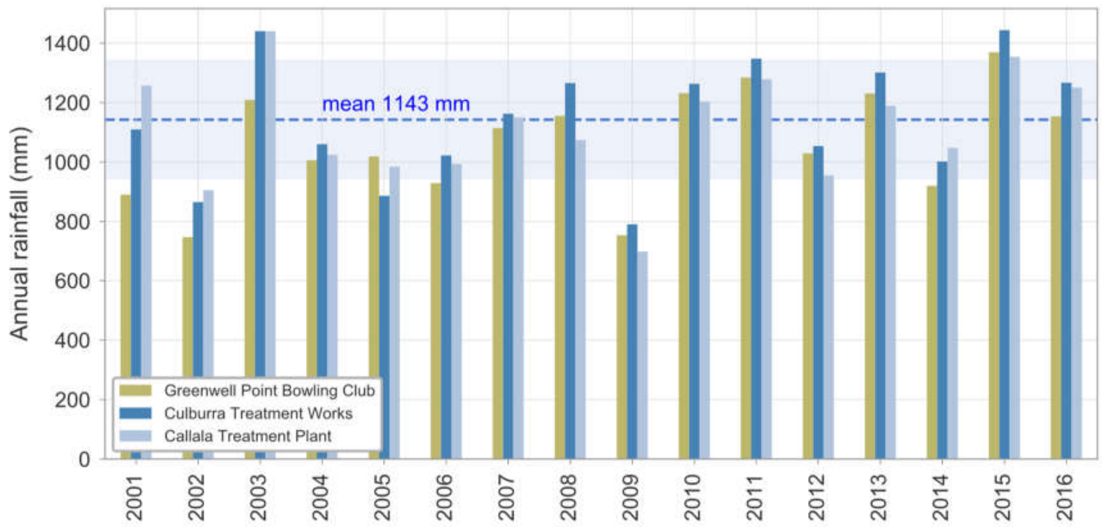

Figure 2. Annual rainfall between 2001 and 2016

2.3 Geology and soils

The site is underlain by the Permian Wandrawandian Siltstone of the lower Shoalhaven Group (Rose 1966). The Permian rocks are overlain by Quaternary alluvium associated with the Shoalhaven and Crookhaven estuary systems (Troedson and Hashimoto 2013), Lake Wollumboola and its tributaries.

The Wandrawandian Siltstone Formation is a mid-grey to blue-grey, fine-grained quartzlithic silty sandstone and siltstone. Scattered pebbles occur throughout decreasing slightly in frequency toward the top of the sequence. Small lenticular bodies of sandstone and claystone occur throughout but the silty texture of the formation is universal. The Permian siltstones are intruded in several locations by igneous dykes (noted in this study). Basement rocks are pervaded by sets of planar fractures (known as joints) which are secondary features associated with deformation and uplift since their deposition.

Quaternary alluvial systems and deposits of the Shoalhaven region are described by Troedson and Hashimoto (2008). The Shoalhaven floodplain is characterised as a broad estuarine-deltaic plain, enclosed seaward by Holocene barrier sands. Estuarine deposits (muds and muddy sands) extend upstream along the Shoalhaven River as far as Nowra.

Lake Wollumboola itself is (morphologically) characterised as a barrier estuary system dominated by an estuarine silt and clay substrate and bounded to the east by barrier dune sands and marine delta deposits. The western bays of Lake Wollumboola are mapped as estuarine channel-bar and beach deposits. These deposits grade upstream into flood-plain alluvial silts and alluvial valley fill.

On the ridges and mid-slopes weathered Permian siltstone is overlain by a regolith (soil profile) between 0.5 and 1.0 m deep comprising weathered and fragmented siltstone and residual clays. Profiles classify as podosols (with a high organic content) to red-brown solodic soils. Sandy horizons and root cavities can impart relatively high permeability to the soil profile relative to the siltstone substrate.

2.4 Hydrology

The site can be divided into northerly draining (towards the Crookhaven River) and southerly draining domains. Because the ridgeline is closer to the Crookhaven River than the Lake, catchment areas in the northern domain are small and drainage is dominantly by broad overland flow with poorly defined channels in valleys. By contrast, the southerly draining domain forms part of the larger Lake Wollumboola catchment comprising several well-defined watercourses.

Lake Wollumboola catchment

In this study, the surface water catchment for lake Wollumboola was defined using a digital elevation model (DEM) generated from Light Detection and Ranging data (LiDAR). The elevation data were processed using standard Geographical Information System (GIS) tools including TauDEM (Tarboton 2015) to determine overland flow directions, streamlines and associated catchments. Catchment boundaries are shown in Figure 3.

The lake is fed by three main watercourses associated with the three western bays, as well as direct runoff via sheet flow and minor creeks around the Lake edge. Some of the watercourses are not formally named, but have been given informal names in this study to aid discussion:

- Northern Creek (after the terminology of Martens (2015))
- Downs Creek (including the tributary named Southern Creek by Martens (2015))
- Coonemia Creek (which includes named tributaries Wollong Creek and Irrayadda Creek)

A minor creek, known locally as Sheep Wash Creek, enters the Lake adjacent to the boat ramp at West Crescent and drains a small low-lying parkland area within the Culburra Beach residential area.

Catchment boundaries become indistinct adjacent to the Lake edge due to the variable lake level and flat gradients and were adjusted to reflect contributions to the major creeks. Lake catchment areas that do not report to the major creeks are divided into domains of direct lake drainage from the headlands and the northern, eastern and southern lake margins.

Table 1 lists sub-catchments and catchment areas that contribute runoff to Lake Wollumboola. The Coonemia Creek sub-catchment is by far the largest, accounting for 70.4% of the total catchment area for the Lake. The Downs Creek sub-catchment accounts for 15.9% of the total catchment, while all other catchments comprise a much smaller proportion of the catchment area (<14% in aggregate). It is clear from these statistics that surface water contributions to the Lake are dominated (86%) by the Coonemia and Downs Creek catchments which are relatively undeveloped bushland.

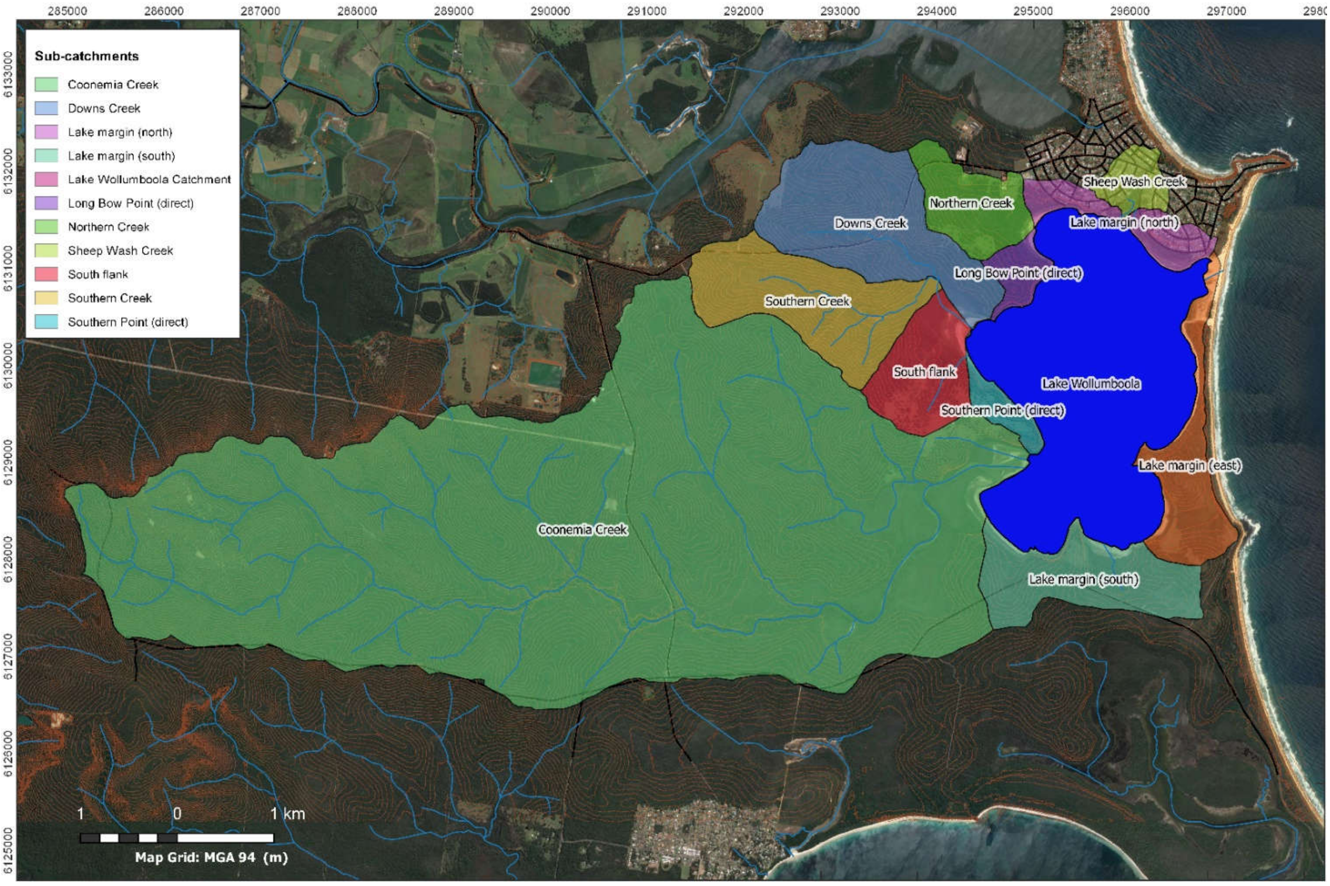

Figure 3. Map showing surface water sub-catchments of Lake Wollumboola

Table 1. Sub-catchment areas contributing to Lake Wollumboola

Sub catchment	Sub-element	Area (km2)		Percentage of L. Wollumboola Catchment	
Northern Creek	Northern Creek	0.92	1.25	2.5	3.4
	Longbow Point direct	0.33		0.9	
Downs Creek	Downs Creek	2.43	5.81	6.7	15.9
	Southern Creek	2.01		5.5	
	south flank	1.08		3.0	
	southern point direct	0.29		0.8	
Coonemia Creek	all tributaries	25.63	25.6	70.4	70.4
Northern lake margin	Sheep Wash Creek	0.39	1.04	1.1	2.9
	direct – other	0.65		1.8	
Eastern lake margin	direct	1.56	1.56	4.3	4.3
Southern lake margin	direct	1.14	1.14	3.1	3.1
TOTAL	excluding the Lake surface	**36.43**		100	
Lake Wollumboola	lake surface area	**5.63**		n/a	

Lake Wollumboola

Lake Wollumboola is an estuary within a remnant valley system with a wave-dominated entrance that is periodically cut off from the sea by coastal barrier sands. Scanes et al. (2013) defined Lake Wollumboola as a unique Back-Dune Lagoon estuary system. Based on statistical analysis of chemical parameters from numerous NSW estuaries, Scanes et al. (2013) concluded that Lake Wollumboola belongs to a distinct sub-type of estuary ("AT") characterised by high concentrations of dissolved organic nitrogen (DON), moderate chlorophyll, high ammonia (NH_4+) and very low phosphate and turbidity.

The lake opens to the ocean with a long-term frequency of 3 to 5 years. Natural opening occurs when lake levels reach approximately 2 – 3 m AHD, depending on the height of the entrance berm at the time of major rainfall events. The lake is artificially opened from time to time by the NSW NPWS to protect low lying property in the Lake catchment when levels reach 2.75m AHD.

Once the sand barrier is breached, the Lake water flows rapidly into the sea and the Lake level drops to near sea level. While open, the Lake is tidally influenced and salinity levels approach that of sea water. The tidal influence extends several km upstream of the Coonemia Creek mouth. When the Lake is closed, the Lake level and salinity vary according to rainfall conditions.

Under high rainfall conditions when surface water runoff exceeds evaporation and seaward seepage through the sand barrier, the Lake level rises above sea level and salinity decreases as low as 5 to 10 g/L (Total Dissolved Solids - TDS). During low rainfall conditions, lake levels are low and the water can become hypersaline (salinity higher than sea water) due to the evaporative concentration of salts. The lake is therefore subject to large contrasts in both level and salinity with an irregular periodicity.

The role of groundwater seepage in the Lake water balance is not well understood, but is of key importance to understanding long term risks to the Lake ecosystems. Scanes et al. (2013) considers groundwater to be a very important factor in relation to water quality based on observations of high tannin (coloured dissolved organic compounds; CDOM), high dissolved organic nitrogen (DON), infrequent surface water drainage to the Lake; and the prevalence of microalgae and *Ruppia* around the margins of the Lake.

A survey of radon (^{222}Rn) and CO_2 concentrations in surface waters carried out by Baiada et al. (2016) provided more definitive evidence for groundwater contributions to the Lake. The study showed elevated concentrations of radon in samples from the western margin of the Lake (and its tributaries) compared with samples from the eastern side of the Lake, interpreted to reflect the input of groundwater to the Lake along its western margin.

2.5 Groundwater

The hydrogeology of the of the Shaolhaven area was assessed by Little and McKibbin (1992) in the context of potential exploitable groundwater resources. Three broad groundwater environments were recognised:

1. Fractured basement rocks of Ordivician and Devonian age (these rocks are not exposed in the study area);
2. Porous sedimentary rocks of Permian age; and
3. Unconsolidated alluvial deposits of Quaternary age. These include alluvial and estuarine deposits and dune sands.

Of these, the most prospective aquifers are within the coarser grained alluvial deposits and dune sands near the coast, with the dune sands along Culburra Beach identified as a potential resource. By contrast, Permian sedimentary rocks are associated with generally low bore yields and variable groundwater quality. Because the study was of regional focus, it does not provide specific groundwater data for this investigation.

More detailed groundwater investigations were carried out by Martens (2014) in support of the proposed West Culburra Mixed Use Subdivision and by Martens (2015) in relation to the proposal golf course development on Long Bow Point.

The 2014 investigation of the West Culburra site (conducted in 2010) consisted of the drilling of 26 boreholes (eight of which were completed as monitoring bores), and the excavation of 16 test pits. At the time of writing, the current status of these monitoring bores was unknown. Permeability testing was carried out at some of the locations and observations made of groundwater level where water was intersected. Three groundwater samples were chemically analysed.

The groundwater investigation in the Martens (2014) report can be summarised as follows:

- The boreholes ranged between approximately 2 m and 7 m depth.
- Most bore logs show a profile consisting of organic silty clay (<0.5 m), overlying residual orange-brown clay (~ 1m), over weathered siltstone.
- Both the clay and the weathered siltstone are of low permeability (hydraulic conductivity ranging between 0.002 and 0.08 m/day), implying that groundwater would move very slowly down-gradient.
- Half (4/8) of the monitoring bores did not intersect permanent groundwater (were dry). The remaining four monitoring bores showed groundwater within 1.5 m of the surface. Three of those 4 monitoring bores were located on the lower slopes towards the Crookhaven River.
- Monitoring bores 1 and 1a provided evidence for groundwater in the siltstone being locally confined beneath the clay.
- Three groundwater samples were highly variable in terms of salinity, ranging from fresh (TDS = 180 mg/L) to brackish / saline (TDS = 13,000 mg/L).

The 2015 groundwater investigation at Long Pow Point (conducted in 2011) consisted of drilling 13 test bores between 0.75 m and 11 m deep, of which ten were converted to monitoring piezometers. A recent site inspection (April 2017) identified four piezometers that appear operational and may be of use in the current investigation.

Groundwater was identified in five of the 10 completed piezometers, and two samples were collected for chemical analysis. The study concluded that:

- The permanent regional groundwater table occurs within the unweathered siltstone rock underlying the site, with groundwater levels ranging between 2.26 m AHD and 7.47 mAHD. Notably groundwater was intersected in only one bore along the ridgeline (BH201) where it was at 8.26 m below ground level.
- Shallow groundwater (< 1 m bgl) was observed within Quaternary alluvium adjacent to the Lake and tributary creeks, although the relationship between these two occurrences is unclear.
- Packer testing determined that the permeability of the unweathered siltstone is 0.002 m/day. This is very low and implies a very slow rate of seepage of surface water (and rain water) into the regional groundwater system.

- The dominant groundwater flow path is likely to be within the regolith (soils and weathered rock). Surface water infiltrating the soil will accumulate on, and flow laterally down-gradient along, the interface between weathered and unweathered rock.
- Seepage calculations based on measured permeability and hydraulic gradients (and Darcy's law of groundwater flow; (Darcy, 1856)) indicate that regional groundwater inputs to the Lake will be in the order of 0.15 ML/year over a lake edge length of 2.4 km (and 2 m deep seepage face). This was considered insignificant (Section 4.7 of the Martens report). Infiltration through the soil profile was calculated at 4 ML/year under pre-development conditions using a program called "ReCycle". These calculations were not verified in this report.
- Groundwater collected from two bores was saline (19,000 µS/cm and 15,000 µS/cm) and moderately acidic (pH 5.6 and 4.8). It is assumed the sampled bores were BH102 and BH104, respectively (both intersect clay and weathered siltstone).

3. SITE OBSERVATIONS

A site inspection was carried out between the 3rd and the 5th of April 2017 with the objectives of assessing:

1. site access for monitoring bore installation,
2. the landscape, geology and hydrogeological environments (to the extent possible without drilling), and
3. surface water quality (where practical).

3.1 Site access

The month prior to the site inspection was unusually wet (291 mm fell in Culburra during the previous month). As a consequence, all tracks were muddy and soft, although still accessible by four-wheel drive in most cases. Most watercourses were flowing and overland (sheet) flow was visible on grassy slopes. The western lake shores and isolated island outcrops were accessed by kayak. Water quality was measured at key locations using a multiparameter water quality probe.

3.2 Geology and soils

Outcrops of Permian siltstone of the lower Shoalhaven Group can be seen along the Lake shore, typically at the headlands. At least two small island outcrops of siltstone were exposed at shallow points in the Lake. Steep embankments around the Lake and the Crookhaven River exposed patchy outcrop of siltstone and yellow to brown soil profiles. At the time of the site visit water could be seen discharging from the shallow soil profile (specifically cracks and root-holes) at a number of locations near the base of embankments, but relatively little (if any) discharge was associated with fractures in the siltstone. It was apparent that during times of high rainfall, groundwater accumulates within the soil profile above the less permeable siltstone substrate. Such accumulations are often referred to as ephemeral perched aquifers and “interflow”.

At least two sets of planar fractures (joints) can be seen in the siltstone where it outcrops at various locations around the Lake. Fractures have a typical spacing of ~10 cm to 1 m. In some cases, thin (mm) zones of alteration along the fractures indicate movement of groundwater through the fracture sets in the past. Due to the very low permeability of the siltstone matrix, it is likely that groundwater movement within the Permian rocks will be dominated by fracture flow, whereas flow through the matrix will be several orders of magnitude slower. Such “dual porosity” is a well-known characteristic of groundwater systems in the Sydney Basin. Fractures and joints tend to close with increasing depth (and lithostatic pressure) such that fracture related permeability generally decreases with depth (Wooley 1982).

The Permian siltstone is intruded by younger igneous rocks. Trachyte dykes (sub-vertical tabular intrusions) more than three metres wide are noted at three locations along the shores of the Crookhaven River and Lake Wollumboola. The margins of igneous intrusions are commonly fractured and can be more permeable than the surrounding host rock (i.e. a focus for groundwater flow). However, the margins of these intrusions are not well exposed around the Lake and therefore their extent and role in groundwater flow in the study area is not clear.

Low-lying areas within the Lake bays are underlain by quaternary alluvium and estuarine deposits. Holes drilled by Martens (2015) indicate that the deposits reach depths of greater than 2 metres; hole BH102 near Northern Creek records weathered siltstone at a depth of 2.7 m. These deposits receive runoff and interflow through the soil profile and are likely saturated for extended periods after rain and when lake levels are high. They are therefore minor aquifers that will fill and store groundwater during periods of high rainfall and lake level, and release that storage back to the Lake when the Lake level drops.

3.3 Water quality

Water quality measurements taken during the site visit in April 2017 are summarised in Table 2. Multiple readings were recorded at each location using a calibrated *InSitu* SmartTroll multiparameter probe and averages are reported for brevity. At several locations on the Lake, readings were taken at various depths between the surface and the Lake bed to assess salinity stratification.

Table 2. Water quality measurements between 3 and 5 April 2017

Water body	Location	Readings	EC (µS/cm)	TDS (mg/L)	pH	ORP (mV)	Temp °C
Lake Woolumboola	Various (average)	47	43934	26360	7.9	71	20.8
Northern Creek	Creek mouth	9	395	237	7.6	116	19.6
	Upstream pond	7	282	169	8.3	142	17.8
Downs Creek	Culburra Rd culvert (east)	4	173	104	6.4	156	19.2
	Culburra Rd culvert (west)	5	142	85	5.8	162	18.8
Coonemia Creek	Coonemia Rd bridge	13	128	77	5.5	174	17.0
	Coonemia Ck Trail / boat ramp	7	4721	2832	7.3	199	18.5

At the time of the site inspection, the Lake was open to the sea. Water salinity as measured at several locations around the western part of the Lake ranged between 22,800 mg/L and 28,100 mg/L equating to approximately 65 % to 80 % of the salinity of sea water. Where depth profiles were measured, water salinity tended to be slightly lower at the Lake surface than the Lake bed (by about 1000 to 2000 mg/L). The lake depth at the measurement points was typically between 0.5 and 1 m. Salinity was distinctly lower near creek mouths where fresh, tannin-rich surface water could be seen mixing with lake water.

Surface water in creeks draining into Lake Wollumboola was fresh (77 – 237 mg/L), and 2 to 3 degrees (Celsius) cooler than the Lake, except in the lower reaches of Coonemia Creek where water was brackish due to a tidal influence. Most surface water was strongly coloured by tannins. The tannin colouration was even noted in residual puddles on grassy tracks. It is worth noting that tannins are typically associated with decaying vegetation (Campbell and Fuchshuber 1995) and are not specific indicators of groundwater discharge.

4. REVISED SCOPE

4.1 Conceptual model

This section briefly outlines a conceptual understanding of the groundwater systems that are relevant to the water balance and water quality of Lake Wollumboola. It will be further updated and developed during stage 2 of the investigation.

Review of available information and site observations suggest there are three main groundwater systems with contrasting groundwater characteristics and behaviours (Figure 4):

1. Permian siltstone of the lower Shoalhaven Group,
2. Quaternary alluvium and estuarine deposits, and
3. Seasonally perched groundwater within the soil profile.

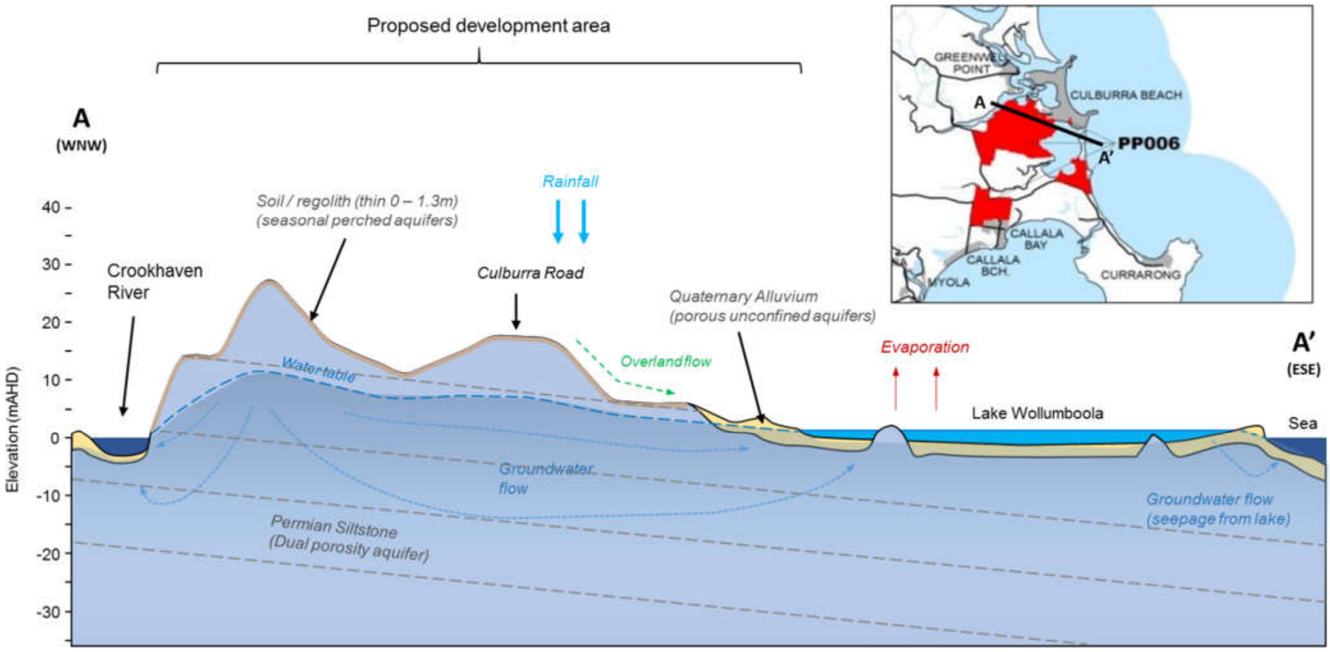

Figure 4. Conceptual hydrogeological cross section

The Permian siltstones form a low-permeability substrate across the investigation area. Testing carried out by Martens (2015) indicate permeabilities of around 2 x 10^{-3} m/day, but experience elsewhere based on hundreds of packer tests in similar rocks of the Southern Coalfield suggests that the permeability of the rock matrix could range to several orders of magnitude lower. At regional scales rock permeability is likely to be more influenced by fracture networks and will be somewhat higher than matrix permeability. Packer tests such as those carried out by Martens (2015) are typically applied to isolated lengths of diamond core hole of 3 m or more, larger than the observed fracture spacing. Therefore, the available packer test measurements may be representative of the fracture permeability of the weathered siltstone, including fractures. Assuming an average permeability of 2 x 10^{-3} m/day and typical hydraulic gradients (10^{-2} to 10^{-3}), groundwater will move very slowly through the matrix (< 1 cm per year) and the flux of groundwater to the Lake via the siltstone is likely to be a very small component of the Lake water budget compared with surface water input.

Quaternary alluvium and estuarine deposits are likely to play a more important role in the Lake water budget. The lake is underlain and fringed by unconsolidated quaternary deposits. The approximate extent of the deposits has been mapped by Troedson and Hashimoto (2013), and can be inferred from the detailed topographical data (LiDAR). The maximum thickness is unknown, but existing information suggests alluvium within the western lake bays may be between 2 and 3 m thick. These deposits are texturally variable, ranging from muds to sands and the permeability of the deposits will be similarly variable, although significantly higher than the siltstone substrate, on average. Reference to standard texts (Fetter 2001) suggests that permeability in these deposits may range from 10^{-2} to 1 m/day for silty sand and fine sand, to 10^{-4} to 10^{-3} m/day for muds and silts. The drainable porosity (also referred to as Specific Yield) is likely to be in the range of 10% to 25%.

Groundwater levels in the Quaternary deposits is likely to vary depending on rainfall and lake levels. During high rainfall and when lake levels are high, the deposits will be recharged and groundwater levels will rise. When the Lake entrance is breached and lake levels fall, a portion of the groundwater stored within the Quaternary deposits will seep back into the Lake. This form of temporary storage is similar conceptually to river-bank storage during flood events. The approximate areas of Quaternary deposits within the three western bays of Lake Wollumboola are 0.29 km^2 (Northern), 0.45 km^2 (Downs) and 1.5 km^2 (Coonemia). For a drop in groundwater level of 1 m, and assuming the hydraulic properties in the previous paragraph, the deposits would yield approximately 60 ML, 90 ML and 300 ML, respectively over the months following a lake level drop of that magnitude. These volumes represent approximately 1 % to 6 % of the estimated volume of the Lake (~ 5 to 10 GL depending on the water level). Volumetrically it is not a major component particularly when the Lake becomes tidal (and therefore regularly flushed), but has the potential to influence water quality near the Lake – sediment interface.

The influence of groundwater discharge from the Quaternary sediments will depend on the groundwater quality within those aquifers. Currently there is little information on groundwater quality. One sample collected by Martens (2015) from hole GMB102 indicates that groundwater quality in the clay deposits of the Northern Bay is brackish to saline (~ 11,400 mg/L). It is expected that the groundwater quality will be highly variable, given that recharge is from a combination of: fresh rainfall and runoff, seepage from the adjacent regolith and siltstone, and from the Lake during high stands.

The third aquifer type is seasonal perched aquifers within the soil profile and weathered rock interface. Soil permeability tests were not presented by Martens (2015), however site observations indicate that the soil permeability can be high relative to the underlying siltstone where there are voids, cracks and roots. During wet periods, perched groundwater has the potential to migrate down-slope and discharge at the Lake edge or to provide lateral recharge to the alluvial aquifers. As with those aquifers, the quality of perched groundwater is not well known but is likely to be variable. The perched groundwater is shallow (< 1 to 2 m) and subject to direct evaporation and evapotranspiration via vegetation. Therefore, perched systems may become rapidly depleted during dry periods. As was concluded by Martens (2015) seepage of rain water through the soil and to the regional water table within the siltstone will be very slow. This is supported by the > 7 m depth to groundwater beneath the ridges.

The concept of groundwater catchment and potential pathways for contaminants will be different for the three different groundwater environments described:

1. Permian siltstone: The catchment boundaries will be controlled by the major regional hydrological boundaries: The lake edge, the Crookhaven River and the sea. The location of the catchment boundary does not necessarily correspond to the topographic catchment and may change very slowly over time (decades) due to changes in sea and lake levels, and

changes in land use. The location of the boundary would need to be defined by drilling and groundwater level observations.

2. Quaternary alluvium: The aquifers are relatively small and restricted to valley bottoms as mapped. These aquifers may be recharged by seepage from perched aquifers, surface runoff and the Lake.
3. Perched groundwater within the soil profile. The soil and weathered zone forms a mantle over the underlying rock. Therefore, the catchment for perched aquifers will be approximately defined by the topographic (surface water) catchments.

Elements of the proposed stage 2 investigations have been adjusted to reflect the evolving understanding of the groundwater systems and to allow more targeted analysis. In particular:

1. A greater emphasis on understanding and monitoring groundwater within the Quaternary alluvial aquifers is recommended. At least two nested bores will be located near the axes of the Northern and Downs Creek alluvium deposits to monitor water levels and quality relative to lake levels. Where possible shallow piezometers should be installed near the Lake edge, within the alluvium to assess groundwater-lake interactions (see locations 13 and 14 below).
2. Other nested bore locations will be altered slightly to allow better access and take into account existing groundwater monitoring assets (as installed by Martens, 2015).

4.2 Revised investigation program

The following sections outline a revised investigation and monitoring program.

Proposed monitoring bores

An updated monitoring network is proposed in Table 3, and shown in Figure 5. The network is modified from the initial proposed network based on the principles described in the previous section.

Table 3. Nominal locations and configurations of nested monitoring bore installations

Location	MGA_mE	MGA_mN	Elevation (mAHD)	Bores	Nominal depth (m)	
					Deep	Shallow
1	293794	6130850	3	2	12	4
2	293372	6131079	21	2	21	6
3	292294	6132421	13	2	15	6
4	292435	6131924	34	1	34	
5	294791	6131616	3	2	15	6
6	293992	6131655	22	1	21	
7	293868	6132215	17	2	21	6
8	293620	6132760	9	2	12	3
9	293546	6131590	7	1	15	
10	294756	6132609	2	2	12	4
11	294699	6132143	11	2	15	4
12	294567	6131777	3	2	15	4
13	294209	6130811	2	1		4
14	294948	6131694	2	1		4
			Total No.	**23**		

Compared with the initial scope, two additional locations are included (13 and 14). These are intended to provide a means for monitoring the groundwater levels and salinity profiles near the Lake – Quaternary sediment interface. The locations cannot be accessed by vehicle and so may need to be installed by hand auger. It is anticipated that these would be no more than 3 to 4 metres deep.

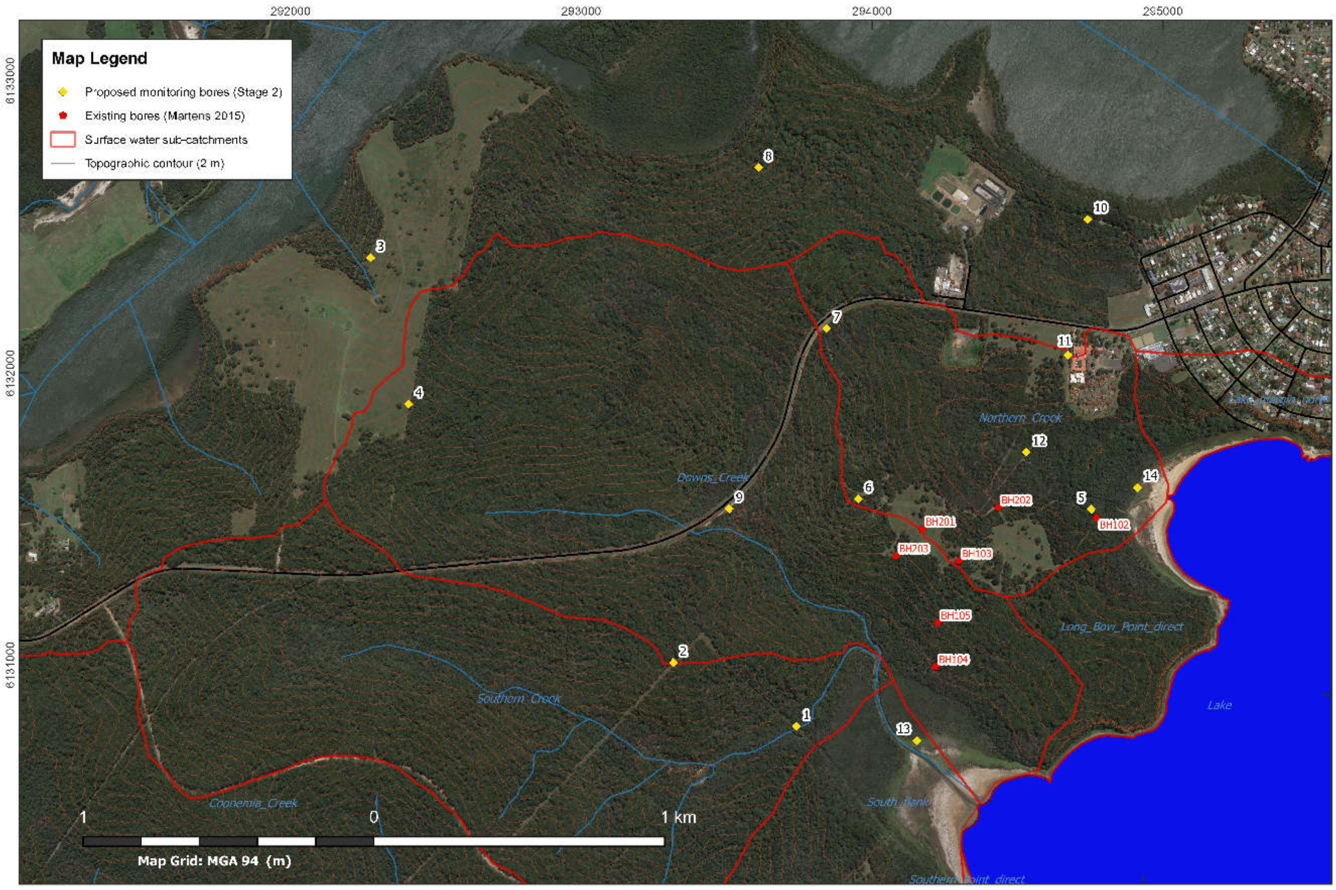

Figure 5. Proposed monitoring bore network

Drilling and installation

Drilling and bore installation will be carried out by Highland Drilling, based near Moss Vale. The drilling will be undertaken with a small track mounted rig to minimise impact.

Monitoring bores will be installed according to the Minimum Construction Requirements for Water Bores in Australia (3rd ed., 2012). Each monitoring bore will be constructed as follows:

- Holes will be drilled to 125 mm or similar diameter to allow for the casing and gravel pack;
- Samples will be collected at 1 m intervals and retained for logging.
- The monitoring bore will be constructed using 50 mm uPVC casing, with 3 m screened sections of slotted uPVC (monitoring zone). The casing collar will nominally be 1 m above the ground surface (or can be made flush with the ground in visually sensitive areas).
- A gravel pack will be installed around the annulus of the screened section to a height of about 2 m above the screen. The remaining annular space will be backfilled or grouted.
- The installation will be completed with a concrete plinth around the monitoring bore at ground level and a lockable steel monument enclosing the exposed PVC casing. The steel monument protects against vandalism and animal damage.
- Each monitoring bore will be *developed* (cleaned out) by air-lifting. Development can take several hours per bore, but is necessary to ensure quality monitoring data.

Drill cuttings and logs

Drilling will be done using a rotary blade bit for the shallow/unconsolidated formations (clays and weathered siltstone), and potentially air/hammer for consolidated formations if encountered. Geological information will be logged by inspection of drill cuttings. An experienced hydrogeologist will be on site to log the geological strata and assess groundwater intersections when they occur (for example noticeable increases in water flow when water bearing fractures are encountered).

It is recommended that one drill hole be cored to a depth of 12 metres to allow assessment of the weathered rock profile. At least three core samples will be taken and sent for core permeability measurements (of the rock matrix). Geological drill logs will be presented in the final assessment report. Cuttings and core will be photographed and representative samples of drill cuttings will be retained for future reference.

Survey

It is important that each monitoring bore is surveyed to sub-cm accuracy to allow absolute groundwater elevations to be compared between locations, and against lake levels. At each bore, the elevation (in m AHD) should be measured at two points:

1. The natural ground elevation immediately next to the bore monument, and
2. The elevation of the PVC collar at the point where manual groundwater level measurements are taken.

A survey will be carried out of each bore location.

4.3 Monitoring

Initial testing and monitoring

Following installation (and development) of the monitoring bores, an initial round of monitoring will comprise the following:

1. Static groundwater levels measured at each bore
2. A groundwater sample will be collected from each bore and submitted for analysis (following appropriate groundwater sampling protocols)
3. An automated groundwater level datalogger will be installed at each location
4. A permeability test will be carried out at each bore location (slug test)

Ongoing monitoring

Ongoing monitoring will be required to assess baseline conditions across site. Baseline conditions include temporal variations in groundwater level (and quality) in response to rainfall-runoff events and changes in lake level. Both the NSW Aquifer Interference Policy (DPI 2012) and the ANZECC guidelines for fresh and marine water quality (ANZECC 2000) recommend a baseline period of two years to capture variations associated with two seasonal cycles. In practice, the baseline period will depend on the characteristics and sensitivity of the groundwater system and the timeframe of the development.

For the purpose of this investigation, it is recommended that ongoing monitoring be carried out using automated dataloggers to allow collection of continuous high-quality data. The monitoring period would be initiated as soon as the first measurements is taken and the first set of dataloggers are deployed.

It is recommended that all monitoring bores (23) are equipped with an automated water level datalogger. Further, it is recommended that two loggers adjacent to the Lake edge (locations 13 and 14) are equipped with loggers that also monitor water electrical conductivity (EC). Water EC is a commonly used proxy for salinity and can be translated into units of Total Dissolved Solids (TDS). The loggers could also be used to measure salinity profiles in those bores each time the loggers are manually downloaded. This would allow the salinity stratification in the quaternary aquifers adjacent to the Lake to be assessed.

The program therefore requires:

- 21 x LT (level and temperature) dataloggers;
- 2 x LTC (level, temperature and conductivity) dataloggers; and
- 1 x Baro logger (monitors barometric pressure which is necessary to correct water level data)

Four LT loggers and one baro logger out of the number listed above will be deployed as soon as possible in existing (Martens, 2015) monitoring bores in order to take advantage of those monitoring assets, and to initiate the baseline period.

Monitoring of lake levels

It is important that the Lake level is monitored at a similar frequency and accuracy as the groundwater network. If there is currently no automated logger in the Lake, it is recommended that either a LT or LTC logger be installed at an appropriate gauge point (in cooperation with OEH). The logger could be telemetered to allow easy access to real-time data.

Water quality parameters

Samples will be collected by a suitably trained person and submitted to an accredited laboratory for analysis on a quarterly basis (or as otherwise agreed). Each sample will be analysed at a NATA accredited laboratory for the following analytes:

- Field parameters (at the time of sampling (EC, pH, ORP and temperature)
- Physical parameters (EC, pH, TDS)
- Major anions and cations (Na, K, Ca, Mg, Cl, SO4, Total Alkalinity)
- Dissolved metals (Al, As, Cd, Cu, Fe, Mn, Ni, Zn, Pb)
- Nutrients (NO2-, NO3-, NH3/NH4, TKN, Total P, Filt. Reactive P)
- Stable isotopes of water ($\delta^{2}H$, $\delta^{18}O$) [for the first sampling round only]

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