City of Bayswater

Maylands Lakes

Management Options Assessment

September 2020

WATER | ENERGY & RESOURCES | ENVIRONMENT | PROPERTY & BUILDINGS | TRANSPORTATION

Executive summary

The City of Bayswater (the 'City') commissioned GHD to undertake an assessment of management options to address water quality issues at the Maylands Lakes, located alongside De Havilland view and Hinkler Loop within the Peninsula estate, Maylands, Western Australia (the 'Site'). The Site comprises three lakes: Lake Brickworks; Lake Bungana; Lake Brearley (the 'Lakes') and their associated catchment area. The Site location is illustrated in **Figure A-1** (Appendix A).

The lakes were formerly utilised as clay pits, providing clay feedstock for the adjacent former Maylands Brickworks. The brickworks was in operation between 1927 and 1984, after which time the pits were allowed to naturally fill with groundwater and stormwater, creating the three lakes present today.

Based on anecdotal evidence from the City and the surrounding community, water quality within the Lakes has been an issue since 2007 when high levels of algae were first noted (Essential Environmental, 2016). Persistent algal growth occurred from the summer of 2014 through 2016, which led to the formation of the community organisation *Friends of Maylands Lakes* to advocate for water quality and amenity improvements at the Lakes.

Several previous environmental investigations have been undertaken, however the monitoring programs were disparate and disjointed, and a quality long-term set of lake environmental data did not exist. Additionally, the processes which govern overall lake health, including hydrology and water quality, were not well understood. In response, the City commissioned GHD to developed and implement a lakes monitoring program between June 2019 and May 2020, the results of which were documented within the companion report to this document, the *Maylands Lakes 2019-2020 monitoring report* (the '*Annual Report'*, GHD 2020).

The *Annual Report* made several key findings, including that the lakes are stratified for a large portion of the year, when they were previously assumed to have been generally well mixed. This stratification was considered to be linked to the cycling of nutrients within the water column and a driving mechanism for growth of nuisance algae and general poor water quality.

The City's priorities and actions are guided by the *Strategic Community Plan 2017-2020* ('the SCP', City of Bayswater 2017). The plan includes as a desired outcome "*Natural environment and biodiversity which are conserved and protected*" with an associated emerging priority of "*Conserving wetlands*". A minor review of the SCP was conducted in 2019 which added the strategy "*N1.1 Conserve, enhance and repair natural and urban areas*" (City of Bayswater 2019).

Based on these broad objectives and an understanding of community expectations based on *Friends of Maylands Lakes* correspondence and information provided by the City, further site-specific management objectives were developed, including that the lakes have an established ecosystem with the function and resilience of that of similar surrounding ecosystems, and that the lakes meet a high level of aesthetic amenity and do not support nuisance populations of algae.

To meet these objectives, a review of a broad range of lake restoration and remediation techniques was undertaken. These techniques were classified into three categories: biological and ecological engineering, physical engineering and chemical applications, and comprised the current known best-practice responses to the identified management concerns.

A summary of common lake ecosystem stressors was presented, and the results of the *Annual Report* were used to characterise the lakes with respect to these stressors.

An assessment of the presented management options was then undertaken, summarising the benefits and disadvantages of each option. The suitability of each option to the lakes system was assessed on the basis of appropriateness to observed lake conditions, demonstrated success in similar circumstances, presumed levels of community acceptance, duration of effectiveness and broad estimates of cost.

Based on the results of the options assessment, the following recommendations were made to the City for immediate action:

- Community consultation: The management objectives developed within this report did not include a program of community consultation. The adopted objectives could be further refined through consultation with the community that they are aligned with the City's SCP priorities within leadership & governance, as well as the natural environment.
- Ongoing monitoring: An ongoing program of water quality and level monitoring was recommended. The program includes a reduced frequency of sampling and analysis (i.e. quarterly instead of monthly), but is recommended to be timed to capture seasonal variability. The program is considered critical in building a longer-term environmental data set from which inter-annual trends in lakes behaviour can be identified, and the success of adopted management actions can be assessed and the management approach refined.
- Lake de-stratification: It was concluded that one of the main mechanisms driving elevated nutrient concentrations with Lake Bungana and Lake Brearley was the cycling of nutrients from the lake sediments into the water column during periods of stratification, and reductive and anoxic conditions at the sediment-lake interface. De-stratification seeks to reduce the release of nutrients from the sediments, which increases under anoxic conditions, by introducing oxygen into the hypolimnion, and circulating water between the epilimnion and hypolimnion. De-stratification may be achieved by mechanical mixing using purpose designed floating impellers.
- Lake modelling: In order to confirm the engineering design of the proposed de-stratification system, creation of a lakes numerical model is recommended. The model should seek to quantify the required mixing volume and frequency, then optimise the number, size and location of the design of the selected mixing equipment to minimise whole of life system costs, as well as provide predictions of efficacy to compare to monitoring data.
- It is recommended that the modelling is undertaken using the hydrodynamic numerical model DYRESM and the ecological model CAEDYM. An indicative cost for this work is approximately $25,000 with an approximate two month period of development and delivery.

Optional management responses could form part of a long term lake management strategy if the recommended strategies do not meet the City's objectives and they have not already been implemented. Optional management responses include:

- Dredging and phosphorus de-activation: Within the monitoring period, the City undertook dredging within Lake Bungana and applied a phosphorus de-activation product within Brickworks Lake, Lake Bungana and Lake Brearley for the purposes of reducing reactive phosphorus availability within the lakes. It is difficult to assess the effectiveness of the measures with a short monitoring period following their implementation, however it was concluded within the *Annual Report* that the measures appeared to have little measureable impact on the availability of phosphorus within the water column and high levels of algae growth were observed in both Lake Bungana and Lake Brearley in August 2020, only seven months after dredging and treatment. It is recommended that these management options are not pursued until after the recommended de-stratification actions have been undertaken and assessed for effectiveness.

- Other management measures: The City and the *Friends of Maylands Lakes* have undertaken several management actions which are recommended to be continued, including the implementation of floating treatment wetlands and revegetation of the lakes' riparian zones, regular maintenance and removal of excess algae from the wetlands and riparian zones, reduction in fertiliser applications in the lake catchment and community education and engagement programs.

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Abbreviations

Abbreviation	Description
AHD	Australian Height Datum
ALS	Australian Laboratory Services
ANZECC	Australian and New Zealand Environment and Conservation Council
ARMCANZ	Agriculture and Resource Management Council of Australia and New Zealand
AS	Australian Standards
ASC	Assessment of Site Contamination
ASLP	Australian Standard Leaching Procedure
bgl	below ground level
BG	Lake Bungana
BL	Lake Brearley
BW	Lake Brickworks
CoC	Chain of custody
COPC	Chemicals of potential concern
CT	Contaminant threshold
DER	Department of Environmental Regulation
DO	Dissolved oxygen
DoH	Department of Health
DoW	Department of Water
DWER	Department of Water and Environmental Regulation
EC	Electrical conductivity
EPA	Environmental protection agency
LIDAR	Light detection and ranging
LOR	Limit of reporting
MGA	Map Grid Australia
MW	Monitoring well
NATA	National Association of Testing Authorities
NEPC	National Environment Protection Council
NEPM	National Environmental Protection Measure
NPUG	Non-potable use (groundwater)
NTU	Nephelometric turbidity units
PASS	Potentially acid sulfate soils
POS	Public open space
PVC	Polyvinyl chloride
ORP	Oxidation-reduction potential
QA/QC	Quality assurance/quality control
SAQP	Sampling, analysis and quality plan
SCP	Strategic Community Plan
SPC	Specific conductivity
SRN	Sample receipt notice
TDS	Total dissolved solids
TKN	Total Kjeldahl nitrogen
TN	Total nitrogen
ToC	Top of casing
TOC	Total organic carbon
TP	Total phosphorus
TPTC	Total potentially toxic cynophites

Abbreviation	Description
TSS	Total suspended solids
WQIP	Water quality improvement plan

1. Introduction

The City of Bayswater (the 'City') commissioned GHD to undertake an assessment of management options to address water quality issues at the Maylands Lakes, located alongside De Havilland view and Hinkler Loop within the Peninsula estate, Maylands, Western Australia (the 'Site'). The Site comprises three lakes: Lake Brickworks; Lake Bungana; Lake Brearley (the 'Lakes') and their associated catchment area. The Site location is illustrated in **Figure A-1** (Appendix A).

Water quality issues at the Lakes have led to the occurrence of persistent algal blooms. However, the processes which govern overall lake health, such as hydrology and water quality, have are not well understood. The City has acknowledged that future management of the Lakes, including treatment and remediation efforts, are dependent on a comprehensive understanding of the local hydrology of the three-lake system. The monitoring of the Lakes aims to provide the City with information to inform management decisions through a better understanding how the Lakes function, specifically in terms of key lake processes: water balance, nutrient balance, internal nutrient cycling, lake interconnectivity and resultant water quality in the lake system.

1.1 Objectives and purpose

The objectives of this report are to define management objectives for the Lakes, assess management options and provide recommendations to achieve these objectives.

The City's overall objective with respect to these works is to achieve a sustainable improvement in water quality, amenity and environmental values of the Maylands Lakes.

1.2 Scope

The scope of works undertaken included:

- A review of previous investigations undertaken at the Lakes and the 12-month monitoring program undertaken recently by GHD (2020a)
- Establish management objectives for the Lakes and set criteria for assessing progress to these objectives
- A literature review of relevant legislation, guidelines and research publications
- Characterisation of the Lakes with respect to the identified guidelines and criteria
- Identification and assessment of management options
- Recommendations for management actions

1.3 Limitations

This report: has been prepared by GHD for City of Bayswater and may only be used and relied on by City of Bayswater for the purpose agreed between GHD and the City of Bayswater as set out in Section 1.1 of this report.

GHD otherwise disclaims responsibility to any person other than City of Bayswater arising in connection with this report. GHD also excludes implied warranties and conditions, to the extent legally permissible.

The services undertaken by GHD in connection with preparing this report were limited to those specifically detailed in the report and are subject to the scope limitations set out in the report.

The opinions, conclusions and any recommendations in this report are based on conditions encountered and information reviewed at the date of preparation of the report. GHD has no responsibility or obligation to update this report to account for events or changes occurring subsequent to the date that the report was prepared.

The opinions, conclusions and any recommendations in this report are based on assumptions made by GHD described in this report. GHD disclaims liability arising from any of the assumptions being incorrect.

GHD has prepared this report on the basis of information provided by City of Bayswater and others who provided information to GHD (including Government authorities)], which GHD has not independently verified or checked beyond the agreed scope of work. GHD does not accept liability in connection with such unverified information, including errors and omissions in the report which were caused by errors or omissions in that information.

The opinions, conclusions and any recommendations in this report are based on information obtained from, and testing undertaken at or in connection with, specific sample points. Site conditions at other parts of the site may be different from the site conditions found at the specific sample points.

Investigations undertaken in respect of this report are constrained by the particular site conditions, such as the location of buildings, services and vegetation. As a result, not all relevant site features and conditions may have been identified in this report.

Site conditions (including the presence of hazardous substances and/or site contamination) may change after the date of this Report. GHD does not accept responsibility arising from, or in connection with, any change to the site conditions. GHD is also not responsible for updating this report if the site conditions change.

2. Background

2.1 Site history

Surrounding Lake Bungana, Lake Brearley and Lake Brickworks is the Maylands Peninsula Estate, which primarily consists of residential properties and public open space. The Maylands Peninsula Golf Course and Maylands Police Complex are located immediately to the west of the Lakes, with residential properties located along a significant portion of the southern and eastern Lakes boundary.

Historically, Lake Brearley and Lake Bungana were the site of clay pits used to provide clay for Maylands Brickworks, which is located directly west of Lake Brickworks. Maylands Brickworks was in operation from 1927 to 1984 and is now a registered heritage site (Essential Environmental, 2016). A kiln and stack at the brickworks complex sustained significant damage during the 1986 Meckering earthquake and were subsequently demolished, along with other old structures onsite. During the demolition process, construction and demolition waste was dumped in the clay pits, along with other inert waste (Essential Environmental, 2016).

The clay pits were decommissioned in approximately 1986 and then allowed to naturally fill allowing the formation of the actual water bodies of the Lakes. The former clay pits were classified as modified wetlands by the Environmental Protection Agency (EPA), whereby the existing wetland function of the Lakes was to be retained (Essential Environmental, 2016). The Lakes are not classified as geomorphic wetlands by the Department of Parks and Wildlife.

Based on anecdotal evidence from the City and the surrounding community, water quality within the Lakes has been an issue since 2007 when algal blooms were first noted (Essential Environmental, 2016). Persistent blooms have occurred from the summer of 2014 through 2016, which led to the formation of the community organisation *Friends of Maylands Lakes* (FOML) to advocate for water quality and amenity improvements at the Lakes.

2.2 Strategic context

The City's priorities and actions are guided by the *Strategic Community Plan 2017-2020* (City of Bayswater 2017). The plan includes as a desired outcome "*Natural environment and biodiversity which are conserved and protected*" with an associated emerging priority of "*Conserving wetlands*". A minor review of the plan was conducted in 2019 which added the strategy "*N1.1 Conserve, enhance and repair natural and urban areas*" (City of Bayswater 2019).

2.3 Investigation history

The Site has been subject to several previous environmental investigations, including the following:

- JDA 1996, Pt Lot 508, Cnr Peninsula Road and Swan Bank Road, Maylands – hydrological investigation, Ref No. J257e. Prepared for City of Stirling (not available for review)
- JDA 2001, Peninsula Estate, Maylands Water Quality Information, facsimile to the City of Bayswater 12 June 2001 (not available for review)
- JDA 2003, Peninsula Estate Maylands Annual Groundwater Monitoring Report (July 2002 to June 2003) WRC Groundwater Licence 00095073 (not available for review)
- Essential Environmental (2016) Lake Bungana, Lake Brearley & Brickworks Lake, Maylands Stage 2 Management options report, September 2016, Perth, Western Australia

- GHD (2018a) City of Bayswater, Maylands sediment investigation, Sampling Analysis plan, August 2018
- GHD (2018b) City of Bayswater, Maylands lakes, Sediment Assessment, October 2018
- GHD (2020b) Maylands Lakes 2019-2020 Monitoring Report, September

The results of the investigations and consequences for management of the Lakes are discussed in Section 5.

Lake Bathymetry survey results are included in Appendix B.

3. Management objectives and criteria

3.1 Management objectives

The City's priorities and actions are guided by the *Strategic Community Plan 2017-2020* (City of Bayswater 2017). The plan includes as a desired outcome "*Natural environment and biodiversity which are conserved and protected*" with an associated emerging priority of "*Conserving wetlands*". A minor review of the plan was conducted in 2019 which added the strategy "*N1.1 Conserve, enhance and repair natural and urban areas*" (City of Bayswater 2019).

More detailed and site-specific management objectives have been established for the purposes of indicating what Lakes management practices need to achieve. The objectives, if met, should provide that the site is suitable for the specified uses and provide adequate protection of environment values.

The management objectives are set out in Table 3-1.

Table 3-1. Management aspects and objectives

Management aspects	Management objectives
Social and recreation	Actively engaged and consulted key stakeholders that have agreement on Site use Lakes water quality is not a risk to passive recreational use, including direct-contact activities Lakes do not support nuisance populations e.g. midges Aesthetics meet stakeholder expectations
Physical stability	Safe and stable landforms
Water and drainage	Water quality suitable for long-term irrigation is maintained within Brickworks Lake Maintain engineering function of upstream stormwater drainage systems Lakes are flood-path conscious
Flora and vegetation	Lakes and landscapes that are comparable to reference vegetation communities established through leading practice restoration techniques and within the constraints of the environment set by the former land uses Prevent the introduction, spread and impact of weeds that threaten the health and sustainability of the surrounding environment Biodiversity values are protected
Ecosystem function and sustainability	Algae blooms are prevented or minimised The Lakes are non-polluting and have water quality compatible with surrounding environmental values The established ecosystem has function and resilience indicative of target ecosystem

3.2 Investigation and management framework

The following legislation and guidelines provide the framework for investigation and management of the Lakes:

- Australian and New Zealand Environment and Conservation Council (ANZECC) & Agriculture and Resource Management Council of Australia and New Zealand (ARMCANZ) (2000) *Australian and New Zealand Guidelines for Fresh and Marine Water Quality*
- *Contaminated Sites Act 2003* and *Contaminated Sites Regulations 2006*

- Cooperative Research Centre for Contamination Assessment and Remediation of the Environment (2009) *National Remediation Framework*
- Department of Water and Environmental Regulation (2014) *Assessment and Management of Contaminated Site, Contaminated sites guidelines, Department of Environmental Regulation*
- National Environment Protection Council (NEPC) (2013) *National Environment Protection (Assessment of Site Contamination) Measure 2013 (No.1)* (the 'ASC NEPM')
- National Health and Medical Research Council (NHMRC) (2008) *Guidelines for managing risks in recreational water.*
- Swan River Trust (2009) *Swan Canning Water Quality Improvement Plan*
- World Health Organisation (WHO) (1999) *Toxic Cyanobacteria in Water A Guide to their Public Health Consequences, Monitoring, and Management*

3.3 Management criteria

Based on the management objectives set out in Table 3-1, water quality criteria have been selected from published guidelines (above) for the purposes of establishing criteria against which to determine whether particular management options are viable.

The criteria are adopted as indicators against which to assess management actions and are not considered remedial or management end-points.

The following management criteria have been selected for the assessment:

Table 3-2. Management criteria

Document and author	Criteria	Purpose
ANZECC & ARMCANZ (2000) *Australia and New Zealand guidelines for fresh and marine water quality*	Slightly to moderately disturbed systems	Environmental health
NHMRC (2008) *Guidelines for managing risks in recreational water*	Health	Human health during recreational use
Swan River Trust (2009) *Swan Canning Water Quality Improvement Plan*	Short term and long-term targets	Environmental health
DOH (2011) *Guideline for the Non-potable Uses of Recycled Water in Western Australia*	Non-potable uses of recycled water	Human health during recreational use

Further water quality criteria and parameters for assessing and classifying lake ecosystem functions are discussed in Section 4.6.

4. Literature review

4.1 Lake ecosystem stresses

Lakes, both natural and artificial, may suffer from stresses which produce negative outcomes for lake water quality and ecosystem health. The loss of environmental values is often associated with impacts to human health, amenity and use of the waterbodies.

Lake water quality stresses can be generally classified within five categories: eutrophication, saprobisation & microbial infection, acidification, salinisation and contamination (Klapper 2003). Common causes and consequences for these stresses are summarised below in Table 4-1.

Based on investigations conducted to date, is considered that the most significant stresses on the Lakes are eutrophication, saprobisation and microbial infection, discussed further below. Discussion of observed Lakes water quality and ecosystem health is included in Section 5.

Table 4-1. Lake stress contributing factors and consequences

Lake ecosystem stresses	Significant contributing factors	Consequences for the ecosystem
Eutrophication	Nutrient load from point sources Nutrient load from diffuse sources	Unwanted high plant growth, algae blooms, fish kills (very numerous)
Saprobisation & microbial infection	BOD-load from anthropogenic sources (sewage), natural sources (e.g.humic matter from rewetting of bogs), or autochthonous biomass	Oxygen depletion, fish kills
Acidification	Acid rain with SO_2 and NO_x Geogenic sulfur acidification from pyrite oxidation	Low pH, metal load, absence of hydrogen carbonate, low species diversity (soft water lakes in the primary rocks, mining lakes)
Salinisation	Transpiration losses by irrigation Transpiration losses by big surface connections to salt layers Mobilisation of salinity in unsaturated soil profile	Decreased size of lake Decrease of the throughflow Meromixis in mining lakes
Contamination	Hazardous substances: industrial wastes; nitrate or pesticides from agriculture	Oxygen depletion, insufficient self-purification

Source: Adapted from Klapper 2003

4.2 Eutrophication

Eutrophication can be generally characterised as the inorganic nutrient enrichment of natural waters, leading to an increased production of algae and macrophytes. The term is generally associated with human activities, where the artificial introduction of nutrients which promote plant growth (such as phosphorus and nitrogen, commonly via the application of fertilisers within lake catchments) lead to changes in the ecological community and cascading deterioration of water quality.

Eutrophication may also occur through natural maturation processes within a lake, as increasing sediment thickness as a lake matures can lead to increased nutrient loads within the lake ecosystem. Surrounding nutrient-enriched soils may also contribute to natural eutrophication.

Consequences of eutrophication include increased plant growth and shifts in phytoplankton to bloom-forming species that are often toxic. This in turn may result in a considerable reduction in dissolved oxygen, decreases in water transparency, issues with taste and odour, and fauna deaths (Carpenter et al. 1999).

The source of nutrients contributing to eutrophication are generally characterised as either point source and due to a single or number of single on- or off-site sources, or nonpoint such as the stormwater runoff from an urban environment. Non-point sources are more difficult to manage for, due to the increased difficulty in affecting changes to distributed and numerous sources.

Lakes are generally classified according to four eutrophic states: oligotrophic, mesotrophic, eutrophic or hypereutrophic. These lake trophic states correspond to gradual increases in lake productivity from oligotrophic to eutrophic. Oligotrophic lakes generally contain low levels of nutrients and are biologically unproductive. Mesotrophic lakes are at an intermediate state of nutrient availability and biological productivity, and eutrophic lakes are generally nutrient-rich and highly productive. Hypereutrophic lakes are the extreme conditions of the eutrophic state (Lewtas et al 2015).

The growth rate of algal biomass is dependent on the concentration of the limiting nutrient in the lake's photic zone, and therefore appropriate investigation and analysis can determine the feasibility of management options regarding nutrient load and cycling in reducing eutrophication symptoms. Phosphorus is usually the most important limiting nutrient, however forms of nitrogen such as nitrates are known to be limiting in some ecosystems (Bajkiewicz-Grabowska 2011).

Remediation of eutrophic lakes should generally begin with the reduction of nutrient inputs from the surrounding environment, lest the effects of remedial management actions be short-lived due to re-loading of nutrients via these sources.

Although addition of nutrients to a lake may lead to immediate increases in the symptoms of eutrophication, the effects of decreasing the rate of nutrient addition to a system may not lead to an immediate reduction in symptoms as internal lake processes may cycle nutrients from lake sediments into the water column. In some cases, eutrophication cannot be reversed by decreasing nutrient inputs alone and additional management actions are required in order to decreases nutrient cycling, accelerate sedimentation and/or increase the nutrient output of the system (GWP 2015).

Sediment volume and characteristic play a large role in the eutrophic state of a lake. Their ability to retain and cycle nutrients is dependant on their physiochecmical characteristics as well as the oxidation-reduction conditions at the interface between sediments and the water column.

4.3 Saprobisation and microbial infection

Saprobisation describes the extreme eutrophication of a lake, characterised by a disturbed and unstable ecosystem which develops extreme fluctuations in water quality and experiences noxious algal and bacterial blooms, among other symptoms of eutrophication as detailed above. Saprobisation is a state that results from excessive inflow and accumulation of nutrient and organic substances, leading to widespread anoxia, and it shows as an overwhelming presence of polysaprobic organisms (fungi, microorganisms, bacteria).

Artificial systems such as aquaculture or wastewater treatment ponds are examples of saprobisation, however natural lakes with high and uncontrolled nutrient and organic inputs may also be characterised in this way.

4.4 Acidification

The dominant mechanism for acidification of soil and water within the Swan Coastal Plains is through acid generation by Acid Sulfate Soils (ASS), which refers to soils and sediments containing iron sulfide minerals such as pyrite (FeS_2) and iron monosulfide (FeS). These minerals are the natural by-product of microbiological activity in coastal, estuarine and freshwater soils and sediments. Key components of ASS include soluble sulfate concentrations, organic matter (e.g. decaying vegetation), and a source of iron.

The Swan Coastal Plain is an alluvial and Aeolian plain largely formed of Quaternary sand and sand-limestone dunes. The Plain has minimal surface drainage features due to the high permeability of these sediments. Fresh surface water bodies within the Plain are generally wetlands within inter-dunal depressions, which are expressions of the unconfined superficial aquifer. Although the sulfate in these systems is likely to have been derived from marine salts in the landscape, the distribution of ASS is governed by groundwater flow patterns and biological processes at the water table (Appleyard et al. 2004).

ASS remain benign when in an anoxic state, however when disturbed and exposed to oxygen have the potential to cause significant environmental damage, leading to consequences such as fish kills and loss of biodiversity in wetlands and waterways; contamination of groundwater resources by acid, arsenic, heavy metals and other contaminants; loss of agricultural productivity; and corrosion of concrete and steel infrastructure by acidic soil and water (DER 2015).

The rate at which acidity is generated from exposed acid sulfate soils depends on the characteristics of the sulfide minerals (such as grain size), the type of sediment containing the sulfide minerals (e.g. sand or clay), and the sediment moisture content (i.e. ease of oxygen access). Acidification will occur when the buffering capacity of the soils or sediments is insufficient to compensate for the acids produced during iron-sulphide oxidation.

Acidity may be generated within a lake, or transported to a lake via surface or groundwater flows. Significant ASS accumulations are known to occur in some inland waterways in association with eutrophication issues (for example, the Avon River) (Shand & Degens 2008).

The fate of acidity generated within lake soils and sediments or transported to lake waters can be affected by the following processes (DEH 2009):

- Neutralisation of acidity by carbonate minerals within lake soils and sediments;
- Neutralisation of acidity by aluminium silicate minerals (e.g. clays) within lake soils and sediments;
- Re-precipitation of sulphides within the saturated zone of lake soils and sediments in the presence of organic carbon and iron (likely to occur when pH remains above 4.5);
- Microbial re-precipitation of sulphides within lake soils and sediments in the presence of some alkalinity, organic carbon and iron; and
- Neutralisation by soluble bicarbonate alkalinity within lake waters.

There are a number of risks associated with acidification by ASS, including most significantly (EPHC & NRMCC 2011):

- Acidification: Generation of acid via a series of complex oxidation reactions when ASS is exposed to oxygen. If the amount of acidity produced by this oxidation process is greater than the system's ability to absorb that acidity (the acid neutralising capacity) the pH of the system falls.
- Deoxygenation: Some ecosystems containing ASS have high capacity to neutralise acid and may not acidify. However, ASS oxidation consumes oxygen and can deoxygenate the water resulting in extreme anoxia events that lead to mortality of aquatic organisms (e.g. fish kills). Deoxygenation is most likely to occur if monosulfidic materials (formerly monosulfidic black oozes), are physically disturbed and distributed throughout a water column.
- Release of metals and metalloids: Oxidation of sulfidic materials may lead to heavy metals (such as cadmium and lead) and metalloids (such as arsenic) becoming more available in the environment. Once freely available in the environment they can be directly incorporated

into living tissue and potentially enter the food chain. Dissolved aluminium, the most common and harmful metal released is toxic to many aquatic plants and fish (ANZECC and ARMCANZ 2000). It can be released from clays that are broken down under acidic conditions. Metal flocculants may also form, which can be fatal or cause injury to organisms with gills.

Acidification may also lead to damage to infrastructure, such as concrete and steel drainage features, and have social impacts including loss of amenity by degradation of environmental values and for example generation of odours.

4.5 Contamination

Contamination can be present in the soil, groundwater or surface water of a site. It may be present in the solid, liquid or gaseous phases (e.g. soil or groundwater contamination giving rise to contaminant vapours in soil pore spaces).

Some naturally occurring substances can present a risk of harm when they are disturbed and can therefore be considered contaminants, for example naturally occurring acid sulfate soils (ASS), radioactive minerals, asbestos and metals and metalloids in mineralised areas.

Human activities can also discharge contaminants which have a polluting effect on a site and can present a risk to human and/or environmental health.

The legislative framework for the definition and management of contaminated sites is Western Australia includes the *Contaminated Sites Act 2003* and associated regulations, the revised national site assessment framework provided in the *National Environment Protection (Assessment of Site Contamination) Measure 1999* (NEPM) and the Department of Water and Environmental Regulation's *Assessment and management of contaminated sites – Contaminated sites guidelines* (DER 2014).

4.6 Lake characterisation framework

To effectively assess the suitability of management practices, the analysis of a waterbody's limnological and morphological parameters is necessary. The sections below discuss parameters for the assessment and classification of lake stresses.

4.6.1 Eutrophication

Table 4-2 lists parameters which are useful in determining the trophic state of a lake (adapted from Ryding & Rast 1989). The parameters set out the basis for investigation of a eutrophic status of a lake ecosystem.

Table 4-2. Criteria for assessing eutrophication status

Conditions	Parameter	Unit
Morphometric conditions	Lake surface area	km^2
	Lake volume (average condition) [2]	$10^6\ m^3$
	Mean and maximum depth	m
	Location of inflow and outflow	-
Hydrodynamic conditions	Volume of total inflow (including ground water) and outflow for different months	m^3/day
	Theoretical mean residence time (renewal time, retention time)	y
	Thermal stratification (vertical profiles along longitudinal axis, including the deepest point)	-
	Flow-through conditions (surface overflow or deep release, and possibility of bypass flow)	-

In-lake nutrient conditions	Dissolved reactive phosphorus; total dissolved phosphorus; and total phosphorus	µg P/L
	Nitrate nitrogen; nitrite nitrogen; ammonia nitrogen; and total nitrogen	mg N/L
	Silicate (if diatoms constitute a large proportion of phytoplankton population)	mg SiO_2/L
In-lake eutrophication response parameters	Chlorophyll-α	mg/L
	Transparency (Secchi depth)	m
	Hypolimnetic oxygen depletion rate (during periods of thermal stratification)	g O_2/d
	Primary production	g C/m^3 d g C/m^2 d
Diurnal variation in dissolved oxygen [3]		mg/L
Major taxonomic groups and dominant species of phytoplankton, zooplankton and bottom fauna		
Extent of attached algal and macrophyte growth in littoral zone		

Source: Ryding & Rast (1989)

The eutrophic status of a lake can generally be related to three parameters: concentrations of chlorophyll-α, an analogue for lake productivity; concentration of Total Phosphorus, commonly considered to be the most important growth-limiting nutrient; and the depth to which a Secchi disc is visible within the water column, an assessment of water turbidity.

Typical values associated with each eutrophic state are detailed in Table 4-3 below. Further parameters and values for distinguishing between oligotrophic eutrophic lakes are detailed in Table 4-4 below.

Table 4-3. OECD boundary values for open trophic classification system

Parameter		Oligotrophic	Mesotrophic	Eutrophic	Hypertrophic
		Annual mean values			
Total phosphorus [µg/L]	x	8	26.7	84.4	
	x ± 1 SD	4.9 – 13.3	14.5 – 49	48 – 189	
	x ± 2 SD	2.9 – 22.1	7.9 – 90.8	18.8 – 424	
	Range	3 – 17.7	10.9 – 95.6	16.2 – 386	750 – 1,200
	n	21	19	71	2
Total nitrogen [µg/L]	x	661	753	1,875	
	x ± 1 SD	371 – 1,180	485 – 1,170	861 – 4,081	
	x ± 2 SD	208 – 2,103	313 – 1,816	395 – 8,913	
	Range	307 – 1,630	361 – 1,387	393 – 6,100	
	n	11	8	37	
Chlorophyll-α [µg/L]	x	1.7	4.7	14.3	
	x ± 1 SD	0.8 – 3.4	3 – 7.4	6.7 – 31	
	x ± 2 SD	0.4 – 7.1	1.9 – 11.6	3.1 – 66	
	Range	0.3 – 4.5	3 – 11	2.7 – 78	100 – 150
	n	22	16	70	2
Chlorophyll-α peak value [µg/L]	x	4.2	16.1	42.6	
	x ± 1 SD	2.6 – 7.6	8.9 – 29	16.9 – 107	
	x ± 2 SD	1.5 – 13	4.9 – 52.5	6.7 – 270	
	Range	1.3 – 10.6	4.9 – 49.5	9.5 – 275	
	n	16	12	46	
Secchi depth [m]	x	9.9	4.2	2.45	
	x ± 1 SD	5.9 – 16.5	2.4 – 7.4	1.5 – 4.0	
	x ± 2 SD	3.6 – 27.5	1.4 – 13	0.9 – 6.7	
	Range	5.4 – 28.3	1.5 – 8.1	0.8 – 7.0	0.4 – 0.5

	n	13	20	70	
The geometric means (after being transformed to base 10 logarithms) were calculated after removing values which were greater than or less than two times the standard deviation in the first calculation *x* = geometric mean; SD = standard deviation					

Source: *Organisation for Economic Co-operation and Development (1982)*

Table 4-4. Parameters for determination of the trophic state of a lake

Parameter	Oligotrophic	Eutrophic
Occurrence of algal bloom	Rare	Frequent
Frequency of green and blue-green algae	Low	High
Daily migration of algae	Considerable	Limited
Characteristic algal groups	*Bacillariophyceae* *Pinnularia, Cymbella* *Chlorophyceae* *Chrysophyceae* *Synura, Chromulina*	Cyanophyceae *Microcystis, Nostoc*
Characteristic zooplankton groups	Represented by small size species: Cladocerans (*Bosmina*) Copepods	Represented by large size species: *Daphnia* (decreases in hypereutrophic)
Density of plankton	Low	High
Characteristics of fish	Finer variety of fish	Coarse fish
Depth	Deep	Shallow
Summer oxygen in hypolimnion	Present	Absent
Algae	High species diversity with low density and productivity often dominated by Chlorophyceae.	Low species diversity with high density and the productivity often dominated by Cyanophyceae.
Blooms	Rare	Frequent
Plant nutrient flux	Low	High
Animal production	Low	High
Fish	Finer variety of flux (e.g. carps)	Coarse fish (e.g. air breathers)

Source: *Ghosh & Mondal (2012)*

The responses of biological and physiochemical parameters to increased eutrophication are summarised in Table 4-5 below (adapted from OECD 1982).

Table 4-5. Trophic criteria and responses to increased eutrophication

Physical	Chemical	Biological
Transparency [D] Suspended solids [I]	Nutrient concentration [I] Chlorophyll-α [I] Electrical conductance [I] Dissolved solids I Hypolimnetic oxygen deficit [I] Epilimnetic oxygen supersaturation [I]	Algal bloom frequency [I] Algal species diversity [D] Phytoplankton biomass [I] Littoral vegetation [I] Zooplankton [I] Fish [I] Bottom fauna [I] Bottom fauna diversity [D] Primary production [I]
1. (**I**) signifies the value of the parameter generally increases with the degree of eutrophication; (**D**) signifies the value generally decreases with the degree of eutrophication. **2.** The biological criteria have important qualitative (e.g., species) changes as well as quantitative (e.g., biomass) changes, as the degree of eutrophication increases.		

3. Aquatic plants in the shallow, near-shore area may decrease in the presence of a high density of phytoplankton.
4. Fish may be decreased in numbers and species in bottom waters (hypolimnion) beyond a certain degree of eutrophication, as a result of hypolimnetic oxygen depletion.
5. Bottom fauna may be decreased in numbers and species in high concentration of hydrogen sulfide (H_2S), methane (CH_4) or carbon dioxide (CO_2), or low concentrations of oxygen (O_2) in hypolimnetic waters.

Source: *Organisation for Economic Co-operation and Development (1982)*

4.6.2 Acidification

ASS, including sediments considered acid forming, are generally considered not to pose a risk of acidification while saturated. Lake sediments are therefore generally not at risk of acidification via ASS mechanisms unless exposed to oxygen either by dredging or receding lake water levels.

Parameters and guidelines for the characterisation of ASS sediments are provided by the WA Department of Water and Environment Regulation, as summarised Table 4-6. pH_F refers to field soil pH, and pH_{Fox} is used as an indication of the presence of stored potential acidity.

Table 4-6. Acid Sulfate Soils indicators

pH_F	pH_{Fox}	Result	Comment
3.5	3.3	AASS present	Oxidation has occurred and sulfuric acid has formed in the past. This soil may not have much more potential to oxidise further as the pHF and pHFOX are similar.
3.7	1.4	AASS present; PASS— strong indication	Oxidation has occurred in the past. This soil has the potential to oxidise further indicated by the strong reaction, appreciable pH unit difference (pHFOX is significantly lower than the pHF) and the very low final pHFOX.
6.5	2.1 (*1.9)	No AASS; PASS— strong indication	This soil is not yet oxidised but has the ability to produce sulfuric acid if exposed. Little buffering capacity in the soil. Laboratory analysis using SPOCAS could confirm this.
8.5	3.0 (*3.2)	No AASS; PASS—likely	The initial pH may be reflecting a strong seawater influence (pH 8.2) or some form of dissolved carbonates. The large ΔpH indicates a strong likelihood of PASS even though the pHFOX is borderline. Here, the ΔpH and the reaction gives strength to the argument. Laboratory analysis using SPOCAS and reacted calcium (CaA) could confirm this.
8.0	2.0 (*6.0)	No AASS; PASS— strong indication; Considerable buffering capacity	The initial alkaline pHF indicates a seawater influence. The initial large decrease in pH indicates the soil is likely to contain sulfides. The pH measured after 20 minutes may indicate a large % of shell dissolving into solution as the acid contacts it (a small amount of HCl added to a sample of soil could confirm its presence). Laboratory analysis using SPOCAS and CaA could confirm this (see Ahern & McElnea (1999)).
5.5	5.4 (*5.3)	No AASS; PASS— unlikely	The strong reaction is probably due to the presence of manganese in the soil sample.
5.5	3.8 (*3.5)	No AASS; PASS— possible	The strength of the reaction indicates possible organic matter. There may be some sulfides present also. Laboratory analysis using the SCR could confirm this.

* pH_{FOX} after 20 minutes (or overnight)
PASS – Potential Acid Sulfate Soils
AASS – Actual Acid Sulfate Soils

Source: *Department of Water and Environment Regulation (2015)*

4.6.3 Contamination

The National Environment Protection Council's (NEPC) *National Environment Protection (Assessment of Site Contamination) Measure 2013 (No.1)* (2013) provides the framework for the investigation and characterisation of site contamination in Australia, with further guidance provided within the Department of Water and Environmental Regulation (WA) contaminated sites guideline series.

Within the *Annual Report*, a series of assessment criteria were adopted for the purposes of providing preliminary, high-level characterisation of the contamination status of the lakes against established guidelines. These are summarised below in Table 4-7.

Table 4-7. Contamination criteria

Document and author	Criteria	Purpose
ANZECC & ARMCANZ (2000) *Australia and New Zealand guidelines for fresh and marine water quality*	Slightly to moderately disturbed systems	Environmental health
NHMRC (2008) *Guidelines for managing risks in recreational water*	Health	Human health during recreational use
DOH (2011) *Guideline for the Non-potable Uses of Recycled Water in Western Australia*	Non-potable uses of recycled water	Human health during recreational use

4.7 Management options

A broad range of restoration and remediation techniques have been developed and implemented to manage lake stresses. These techniques can generally be classified into three categories: biological and ecological engineering, physical engineering and chemical applications, as discussed below.

The most common and successful techniques within these categories are discussed below. Further discussion of the techniques is contained in Section 6, including a summary of their benefits and disadvantages and an assessment of their suitability to Lakes conditions (Table 6-1).

4.7.1 Biological and ecological engineering

Revegetation

Vegetation on the fringes of a lake actively contributes to nutrient reduction in overland stormwater flows to the lake by plant assimilation and by altering the underlying physical and chemical conditions of riparian soils and groundwater (O'Toole et al. 2013). Nitrogen is primarily removed through microbial denitrification and to a lesser extent plant uptake, while phosphorus is primarily removed from surface flows through soil sorption and to a lesser extent plant assimilation (Brian et al. 2004).

There are limited opportunities for further revegetation at the lakes due to the location of residential development and bricked lake walls around the eastern portions of Lakes Bungana and Brearley.

Biomanipulation

Biomanipulation is the manipulation of the biological components of an ecosystem and their habitats in order to facilitate changes which are beneficial to the ecosystem health. The size of algal populations is influenced their growth rate and immigration, and losses due to flushing, settling and grazing. Increases in grazing activities are therefore linked to decreases in phytoplankton populations at similar nutrient levels, and grazer populations are often controlled by fish populations.

Biomanipulation is most often focussed around managing fish species to minimise the presence of zoo- and benthivore fish and promoting populations of piscivorous fish (which primarily eat fish). This occurs through fish removal and stocking, and/or the fostering of lake environments which promote planktivorous over piscivorous fish.

The practice of biomanipulation has been broadly implemented and reviewed (e.g. Søndergaard et al. 2007), and it is generally recognised that the practice can result in a broad range of outcomes. Effecting long-lasting changes within a lake using biomanipulation is very difficult.

Floating treatment wetlands

Wetlands rely upon natural processes to mechanically and biologically filter water as it passes slowly through shallow areas of dense aquatic vegetation, and through permeable bottom soils. The primary mechanisms for nutrient removal are microbial transformation and uptake; macrophyte assimilation, absorption into organic and inorganic substrate materials; and volatilisation (Stewart et al 2008).

Nutrient loads within a lake may be controlled by replicating these natural processes within artificially introduced floating treatment wetlands. A floating platform is provided for macrophyte and microbial growth, from which the macrophyte roots are able to extend into the water column and uptake nutrients hydroponically. While the mechanisms relating to nutrient removal may be complex, the most significant factor in their success is their size.

Long-term success of floating wetlands relies upon upkeep of the wetlands, including macrophyte removal as discussed below.

Removal of macrophytes

During period of growth, rooted macrophytes act as a net sink for nutrients, extracting them from sediments and the water column. However as macrophyte populations mature and cycle through senescence they may return nutrients to a system. Internal nutrient loading from macrophyte senescence in many eutrophic lakes may be greater than external loading, particularly as external loading is reduced.

Macrophyte removal can be a successful management strategy within lakes which contain a large macrophyte biomass and which have conditions which encourage macrophyte growth following removal. Macrophyte removal is an on-going management strategy which requires frequent re-implementation.

4.7.2 Physical engineering

Dilution and flushing

Dilution and flushing act to improve water quality by decreasing the availability of nutrients (i.e. dilution) and increasing the rate of water exchange (flushing). Both mechanisms may reduce algal growth by limiting access to nutrients. Adding a quantity of water with lower nutrient concentrations than the receiving body reduces overall nutrient concentrations, and increasing the rate of outfall causes nutrient and algal biomass losses.

Dilution and flushing are most effective where there is access to a large quantity of low-nutrient water. The amount of water needed to achieve a given reduction in inflow concentration is a function of the concentration difference between the normal inflow and dilution-water source.

Hypolimnetic withdrawal

Within stratified lakes, phosphorus, ferrous iron (Fe(II)) and ammonia often accumulate in hypolimnetic (i.e. denser, bottom) waters as a result of the reduction-oxiodisation cycling of iron and phosphorus under anoxic conditions and decomposition of settling organic matter (Klapper 2003).

Hypolimnetic withdrawal describes the removal of the nutrient-rich water from the lower layer of a stratified lake. The may occur via pumping, although this is typically prohibitively expensive in all but the smallest lakes. Generally, hypolimnetic withdrawal is achieved through the setting of a lake's outfall intake at the level of the hypolimnion, i.e. submerged and close to the lake bottom.

Stratification should be maintained during the withdrawal in order to maximise the nutrient load within the discharged waters and minimise mixing of the hypolimnion into the less nutrient rich waters above. The potential impacts associated with the disposal of low oxygen/high nutrient water must be considered as part of any implementation of this strategy.

Hypolimnetic aeration and oxygenation

The loss of dissolved oxygen (anoxia) within the lower (hypolimnetic) waters of a stratified lake is generally one of the first indicators of eutrophication. This occurs when the respiration of organic matter within sediments and the hypolimnia is sufficient to exhaust dissolved oxygen before mixing can occur through more oxygen rich near-surface waters. Anoxia accelerates internal recycling of nutrients, mobilises undesirable metals from sediments, and introduces changes in the distribution of fish and other biota (Lewtas et al 2015).

Hypolimnetic aeration is generally undertaken by injecting pure oxygen or air in fine bubbles to the hypolimnion so that oxygen dissolves without disturbing stratification (Moore et al 2015). This is undertaken with the objectives of reducing sediment to water cycling of phosphorus and metals by establishing undesirable conditions for this to occur at the sediment-water interface and creating increased habitat and food supply for cold water fish.

Artificial circulation

Lakes get much of their oxygen from the atmosphere through diffusion. Thermal stratification acts to reduce mobilisation of dissolved oxygen from a lake surface to deeper waters. Artificial circulation aims to improve water quality by increasing oxygenation of the entire water column resulting in the oxidation of undesired substances (e.g. increasing sedimentation of phosphorus) and providing an increased habitat for aerobic species.

Artificial circulation is generally achieved through the use of air injector (diffusion) systems (similar to hypolimnetic as discussed above) or by upward pumping of the hypolimnia to mix it with near surface waters or downward pumping of surface waters into the hyplimnia.

Internal loading and the total phosphorus load may decrease in shallow, stratified lakes following circulation; however, circulation may increase the availability of phosphorus within the photic zone for algal growth. Circulation improves dissolved oxygen and reduces iron and manganese, as well as causes light to limit algal growth in environments where nutrients are uncontrollable and neutralize the factors favouring the dominance of blue-green algae (Lewtas et al 2015).

Dredging and removal of sediment

Lake sediments often act as a sink for nutrients, as nutrients contained within lake inflow undertake sedimentation, resulting in lower concentrations of nutrients within lake outfalls, resulting in the loading of lake sediments with nutrients. Under certain conditions, generally indicated by anoxia, nutrients may be cycled from the sediments back in to the water column, contributing to eutrophication and promoting algal growth. The removal of lake sediments aims to reduce this effect by removing a source for water column nutrients.

There are two common mechanisms used for the removal of sediments: draining of the lake and sediment removal by dryland earthmoving equipment and dredging.

Sediment removal is considered a short-term or temporary management option only, as it does not address nutrient loading from sources external to the lake. Dredging was completed at Lake Bungana in late 2019.

4.7.3 Chemical application

Phosphorus inactivation

A large body of research has been dedicated to the management of phosphorus within lake ecosystems, due to the commonly held belief that within freshwater lakes, phosphorus is most likely to be the limiting nutrient in algal growth.

Phosphorus inactivation aims to improve water quality by introducing adsorbates such as aluminium, iron, calcium and lanthanum, which bind with phosphorus in the water column resulting in sedimentation of the nutrient.

Phoslock™ is a phosphorus inactivation product which has historically been applied to the Maylands Lakes, most recently in January 2020.

Sediment oxidation

Sediment oxidation aims to oxidise the top of a lake sediment profile in order to control the cycling of phosphorous and nitrogen from sediments into the water column.

Nitrate, iron and calcium carbonate are injected into lake sediments. Nitrate acts as an alternate electron acceptor to oxygen, preventing the development of ferrous iron and subsequent phosphorous release.

Algicides

Algicide directly addresses the symptoms of eutrophication by killing algal biomass. There are a wide variety of commercial products available targeted at various algal populations, including those based on the application of copper sulfate, silver nitrate, potassium permanganate and sodium hypochlorite.

Algicides are rarely used in natural lakes due to their toxicity to non-target biota and potential impacts on human health. The effects of algicides are generally short-lived as they do not address the underlying causes of algal outbreaks and will be naturally diluted or consumed over time. In addition, some algicides may accumulate within the lake ecosystem and sediments, causing long-term impacts which may be difficult to address.

5. Lakes characterisation

5.1 2019-2020 monitoring program

A twelve month investigation of water quality within the Lakes was undertaken between July 2019 and June 2020. The investigation included the following:

- A groundwater investigation comprising installation of three new groundwater monitoring wells (one adjacent each lake), continuous monitoring of groundwater levels at each well with a logging pressure transducer, and four groundwater monitoring events for field parameters, nutrients, physical parameters, major ions, chlorophyll-α and total organic carbon.
- Installation of a floating platform of monitoring equipment at Lake Bungana and Lake Brearley including two floating buoys each fitted with two telemetry enabled multi-parameter sondes (measuring temperature, specific conductivity, turbidity and dissolved oxygen) installed at near-surface and near bottom depths, three gauge plates and three telemetry-enabled water level loggers.
- Completion of twelve monthly monitoring events, of which four included an extended suite:
  - Monthly: field parameters, nutrients, physical parameters, major ions, chlorophyll-α and total organic carbon, plus depth profiles for physical parameters
  - Extended: The above plus major ions and total algae count

The results of the investigation are reported within the *Maylands Lakes 2019-2020 Monitoring Report* (GHD 2020) and summarised in the sections below.

5.2 Eutrophic status

Table 5-1 below summarises the results of the monitoring program (GHD 2020) with respect to the lake characterisation parameters total phosphorus, total nitrogen, chlorophyll-α and secchi depth.

Based on the results and the boundary values for assessing the trophic status of a lake presented in Table 4-3, the Lakes may be classified as eutrophic.

Mean total phosphorus values at all Lakes were within the OECD observed ranges for a eutrophic lake, with results from depth at Lakes Bungana and Brearley particularly elevated. Mean total nitrogen values at Lakes Bungana and Brearley were significantly elevated, exceeding mean values for a eutrophic lake, and increasing with depth. Brickworks Lake was closer to a mesotrophic classification with respect to total nitrogen.

Mean secchi depths were extremely shallow; approximately 0.53 m at Lake Bungana and 0.31 m at Lake Brearley, compared to the mean OECD value for a eutrophic lake of 2.45 m.

Brickworks Lakes generally exhibited better physical water quality results compared to Lakes Bungana or Brearley, in particular with respect to total nitrogen, however could also be classified as eutrophic.

Table 5-1. Observed values for lake characterisation criteria

Parameter		Lake Bungana				Lake Brearley				Brickworks Lake
		BG1 bottom	BG1 surface	BG2 bottom	BG2 surface	BL1 bottom	BL1 surface	BL2 bottom	BL2 surface	BW1 surface
		Value (July 2019 – June 2020)								
Total phosphorus [µg/L]	Mean	103	24	38	26	106	61	54	55	58
	Minimum	<10	<10	<10	<10	30	<10	<10	<10	<10
	Maximum	810	50	60	60	280	140	130	120	140
	n	12	12	12	12	12	12	12	12	4
Reactive Phosphorus as P [µg/L]	Mean	<10	<10	<10	<10	30	<10	<10	<10	<10
	Minimum	<10	<10	<10	<10	<10	<10	<10	<10	<10
	Maximum	<10	<10	<10	<10	120	<10	<10	<10	<10
	n	12	12	12	12	12	12	12	12	12
Total nitrogen [µg/L]	Mean	2,617	1,538	2,933	1,458	6,567	2,492	2,775	2,800	600
	Minimum	1,500	100	1,600	800	1,900	1,600	1,500	1,800	400
	Maximum	5,100	2,700	7,000	2,100	24,000	3,800	5,200	4,900	900
	n	12	16	12	12	12	12	12	12	4
Chlorophyll-α [µg/L]	Mean	75	49	82	47	55	58	64	59	48
	Minimum	17	10	36	11	10	25	41	39	22
	Maximum	168	115	126	113	111	101	110	105	108
	n	11	15	11	11	11	11	11	11	4
Secchi depth [m]	Mean	0.53		0.55		0.31		0.31		-
	Minimum	0.23		0.23		0.23		0.23		-
	Maximum	1.03		1.33		0.53		0.4		-
	n	10		10		10		10		-

Note: For the purposes of calculating means, results reported as below laboratory limits of detection were assigned the limit of detection value

5.3 Stratification

A significant new finding of the 2019-2020 monitoring program is that Lakes Bungana and Brearley were stratified for a large part of the year, where previously they were presumed to be vertically well mixed.

The stratification is most evident within the vertical profiling and within differences between temperature and dissolved oxygen levels measured at ‘deep’ and ‘shallow’ logging instruments, as described within the *Annual Report*.

Across the monitoring period, occasional de-stratification was observed to be induced by two mechanisms: when ambient air temperatures dropped, cooling surface water temperatures to a similar level to deeper waters; and by significant rainfall & wind events. The brief de-stratification events were generally followed by the rapid de-oxygenation of the hypolimnion over subsequent days, indicating significant biological activity at depth.

Stratification creates a thermal and density structure in the water column characterised by well mixed surface layer, the epilimnion, and a deeper hypolimnion, separated by a sharp density gradient referred to as a metalimnion. The metalimnion prevents mixing between the surface layer and the hypolimnion, often leading to a hypoxic or anoxic hypolimnion due to exhaustion of dissolved oxygen by chemical reduction processes and biological respiration (e.g. decomposition of organic matter), which is unable to be replenished by more oxygen-rich surface waters.

Anoxic conditions within the hypolimnion have a secondary effect of the release of nutrients previously bound in lake sediment. This may contribute to problematic algal growth, and common contaminants such as hydrogen sulphide (an indicator of odorous, reduced sulphide gases) and various metals. Stratification within the lakes system is therefore an important mechanism for consideration when developing management responses to water quality, amenity and algal growth.

Stratification is generally not observed within similarly located natural wetlands in the Swan Coastal Plain, as these lakes are generally not deep enough to allow thermal stratification to occur. It is considered that the unusual depth of Lake Bungana and Lake Brearley pose relatively unique management challenges within the area.

Stratification is commonly observed within the Swan-Canning Estuary, linked to salt-water intrusion from its connection to the Indian Ocean, in the lower estuary, and inflow of fresh stormwater run-off in the upper estuary. Periodically, hypoxic or anoxic conditions development within the bottom waters, generally within the upper estuary.

5.4 Acidification

The laboratory measured pH of Lake Bungana and Lake Brearley varied between 7.65 and 9.03 over the June 2019 through May 2020 monitoring period of the *Annual Report*, indicating the lake waters are slightly to moderately alkaline.

Total alkalinity results varied between 191 and 334 mg/L as $CaCO_3$ within Lake Bungana and between 342 and 653 mg/L as $CaCO_3$ within Lake Brearley, indicating moderate buffering capacity within the lakes.

The *Maylands Lakes sediment assessment* report (GHD 2018b) found that seven out of eight sediment samples taken from Lake Bungana and Lake Brearley analysed for ASS parameters exceeded the WA DER (2015) guideline for net acidity without acid neutralising capacity guideline of 18 mole H^+/t.

Some of these samples were reported to have elevated results for net acidity without ANC, particularly locations BG5, BG6, BG8, BL2, BL6 and BL7 (ranging from 79 mole H^+/t to 3,580 mole H^+/t). Accordingly, the liming rate reported for these samples range from 6 kg $CaCO_3$/t to 269 kg $CaCO_3$/t. However, the potassium chloride pH (pHKCl) for the samples exceeding the WA DER (2015) guideline (18 mole H+/t) for net acidity without ANC< range from 7 to 9. These results indicate the presence of potential acid sulfate soils (PASS) in these locations.

Based on these results, it is considered that the risk of acidification of the lakes is low and does not require active management. The buffered condition of the lake waters means that any additional oxygenation of the hypolimnion is unlikely to result in any significant change in the lake pH.

5.5 Contamination

It is noted that a site contamination assessment was not the purpose of the monitoring program, and therefore contaminant types common within POS water bodies and sediments, such as metals and pesticides, were not included within the analysis suites.

Total Phosphorus and Total Nitrogen concentrations with Lake Bungana and Lake Brearly recorded many exceedances of the adopted *Swan Canning Water Quality Improvement Plan - Interim targets,* both short- and long-term, indicating that discharge of water from the lakes poses a risk to the environmental health of the Swan River.

Ammonia as N concentrations recorded some exceedences of the adopted assessment criteria for slightly to moderately disturbed ecosystems (ANZECC & ARMCANZ 2000).

Turbidity and pH levels in Lake Bungana and Lake Brearley regularly exceeded the adopted *Guidelines for the Non-potable Uses of Recycled Water in WA – medium and high exposure risk* (DoH 2009), indicating the lake waters were a risk to human health, in these regards.

No exceedances of the *Guidelines for managing risks in recreational water* (NHMRC 2008) were recorded, although it is noted that the only parameter from the monitoring suite for which these guidelines provide an assessment criteria is sulfate.

6. Options assessment

Table 6-1 presents the results of an assessment of the management options presented in Section 4.7.

The suitability of each option to the lakes system is assessed on the basis of appropriateness to observed lake conditions, demonstrated success in similar circumstances, presumed levels of community acceptance, duration of effectiveness and broad estimates of cost.

Table 6-1. Management options benefits, disadvantages and costs (colour scale: orange = likely not suitable, yellow = potentially suitable, green = preferred)

Management option	Benefits	Disadvantages	Suitability
Bio-manipulation	Improvements in water quality including decreased turbidity, decreased chlorophyll-α, increased transparency, decreased nutrient concentrations Comparatively inexpensive No significant infrastructure required Does not require the introduction of potentially toxic chemicals Piscivorous fish are more likely to have appeal to recreational fishers	Enormous variability in success. Multiple restocking events might be necessary Changes in fish populations are difficult to maintain Changes to fish populations introduce difficult to predict changes in nutrient transport Piscivores more likely to disturb / re-suspend sediments, recirculating nutrients Planktivores may immigrate from surrounding systems Not all algae common to eutrophic lakes are edible (e.g. cyanobacteria)	The size and make-up of fish populations within the lakes are not well understood. Community expectations around fish populations are also not understood. The literature review indicated that bio-manipulation is most effective in shallow (<3 m) lakes, and lakes with Total Phosphorus values <100 µg/L, neither of which apply to Lakes Bungana or Brearley. Additionally, due to the eutrophic state and high turbidity of the lakes, current lake conditions may be hostile to desirable fish populations. Due to these factors, combined with the uncertain outcomes, bio-manipulation is not considered a suitable management option.
Floating treatment wetlands	Comparatively inexpensive Reduces redox potential and anoxic conditions at the installed depths May be combined with systematic macrophyte removal to extend longevity of remedial effect Provides visual amenity when well managed Provides fauna habitats Reduces biogas emissions Reduces nuisance insect population Little to no adverse effects on lake quality s	Potential effects on nitrogen:phosphorous ratio, with effects on cyanobacterial growth May restrict access or reduce available area for recreational use Fauna attracted to the vegetation may increase lake nutrient loading Potential for inducing anoxic conditions if high lake surface coverage is achieved	Floating treatment wetlands are currently employed within the lakes. Due to their relatively recent introduction and the lack of inter-annual monitoring, it is difficult to measure their effect on nutrient concentrations within the lakes. However, their growth and subsequent pruning / macrophyte removal confirms that the wetlands are removing nutrients from the lakes system. FTWs are a relatively low-cost management response which provide potential long-term nutrient reduction (with ongoing maintenance) with short-term improvements in lake amenity and fauna habitat. For these reasons they are considered suitable for ongoing use. Their effectiveness in nutrient removal may be further assessed with longer-term monitoring of lake nutrient concentrations, a more detailed lake nutrient balance, and detailed record keeping regarding the species, volume and time of vegetation removed from the platforms.
Removal of macrophytes	Removes nutrients from both sediments and the water column Increases lake aesthetic and recreational values	Large and prolonged effects on biota, including direct and indirect removal of fish, invertebrates and other species Loss of habitat for grazers Potential loss of recreational value fish from the littoral zone Decreases competition for nutrients within the water column and may therefore promote algal growth Requires a large volume of macrophytes to be removed in order to effect changes in lake nutrient loads (i.e. potentially inefficient)	Problem or nuisance levels of macrophyte growth were not observed during the 2019-2020 monitoring period, and anecdotally have not been reported in recent years. The macrophyte biomass within the lakes is therefore insufficient to feasibly undertake macrophyte removal, outside of the maintenance of the FTWs.
Hypolimnetic withdrawal	Comparatively low capital and operational costs Long term effectiveness when implemented successfully May increase hypolimnetic dissolved oxygen concentrations, which may improve fauna habitat Reduces accessibility of cyanobacteria to Fe(II), now thought to be a precursor to the development of blue-green algal blooms.	Potential to contaminate receiving water body (likely Swan River), discharge volumes too great to economically send to sewer Strong stratification (and maintenance of stratification through treatment) typically required to be effective which is not present at the lakes. Difficult to implement for Bungana.	There is evidence of the effectiveness of hypolimnetic withdrawal in a number of cases; and successful implementation of this method is restricted to deeper, stratified lakes with considerable internal loading or phosphorus release from sediments at the bottom of the lake, which match conditions found within Lakes Bungana and Brearley. However, the periodic natural de-stratification of Lakes Bungana and Brearley mean the method may not be employed year-round. In addition, the method requires removal of a significant volume of water to be effective, which in dryer months could result in unsatisfactorily low water levels within the lakes. While there is currently a limited, high-level overflow from Lake Brearley to the Swan River, there is a risk that approval may not be granted by the relevant authorities to artificially pump and discharge significant volumes of nutrient-rich waters from the lower levels of Lakes Bungana and Brearley to the Swan River, due to nutrient concentrations exceeding Swan River Trust guideline values. Hypolimnetic withdrawal is therefore not considered a suitable management method.
Dilution and flushing	Low cost, if low-nutrient water is available in a large quantity Relatively low cost if water is available in high quantity Immediate effect on nutrient concentrations, along with long-term reduction in nutrient loads with ongoing dilution Moderate success even if only moderate-to high-nutrient water is available through reduction in retention times	May introduce undesirable flora/fauna if water is introduced from outside the lakes regular catchment Potential impacts on the waterbody from which water is taken Undesirable taxa may be introduced when sourcing water from outside catchment Potential for impacts on source water body	Stormwater from the surrounding catchment is considered to be a nutrient source for the lakes, and diversion of further stormwater is therefore not considered likely to dilute nutrient concentrations. Approximately 15 kL of groundwater per year already is pumped into Brickworks Lake from a nearby groundwater bore, close to its licensed capacity. Water quality within the bore is unknown, but presumed to contain have lower nutrient concentrations than the lakes and may be a key reason for improved water quality conditions in Brickworks lake.

Management option	Benefits	Disadvantages	Suitability
			While groundwater pumping into Brickworks Lake may continue as required for irrigation purposes, dilution and flushing is not considered a suitable management option due to the scale of water required to achieve the desired results and the lack of a suitable nearby source.
Hypolimnetic aeration and oxygenation	Decrease in internal loading of nutrients and contaminants Anoxic hypolimnia can switch to an oxic state while maintaining epilimnia environment Aeration may improve habitat quality for fish, even if improvements in epilimnetic water quality are not achieved	Interactions between iron and phosphorous primarily affect only the short-term cycling of phosphorous, and do not result in the permanent storage of phosphorous in lake sediment. Some variability in outcomes for phosphorous concentrations Lakes where internal P recycling is driven by processes unrelated to Fe-P interactions may not show any positive effects on nutrient loading Potential to increase eddy diffusion of nutrients into the epilimnion, even though stratification is maintained Slow circulation conditions and destratification may introduce toxic chemicals into the epilimnion	While the lakes are not continuously stratified with respect to temperature, dissolved oxygen concentrations near the bottoms of Lakes Bungana and Brearley are generally near zero year-round. While hypoliomnitic aeration is often undertaken with the intent of preserving thermal stratification, modifications may be made (i.e. increasing airflow rates) to drive de-stratification. It's considered that aeration of the hypolimnetic layer may be a suitable management option for Lakes Bungana and Brearley pending design and costing of an effective system.
Artificial circulation (destratification)	Increased circulation usually results in the complexation and precipitation of iron and manganese, reducing trace elements and phosphorus internal loading, and therefore algal biomass. Circulation can reduce phytoplankton biomass by increased depth of mixing of plankton cells and increased light limitations If sediments are distributed by mixing, algal biomass may also decrease due to decreased light availability	If circulation increases the suspension of particulate material, associated phosphorous may mineralize and become available to phytoplankton Mixing of sediment may increase inorganic turbidity Overall lake temperatures typically increase following treatment	While artificial circulation may have a short to medium term effect of increasing the availability of phosphorous in the photic zone through upward mixing of higher nutrient hypolimnetic waters, the longer term effect is to reduce cycling from the sediments in to water column, thereby reducing nutrient availability for algal growth. When maintained for a sustained period (months) artificial circulation disrupts the lifecycles of some problematic algae species, including blue-green algae, and can promote the establishment of a more diverse and ecologically healthy lake algae population. Artificial circulation is considered a suitable management strategy, pending design and costing of an effective system.
Sediment oxidation	Although greater in cost, treatment is an effective alternative to aluminium to inactivate sediment phosphorus Chemicals added are found in high concentrations naturally in unpolluted sediments Toxicity to animals is perceived as a lesser issue than for other phosphorus inactivation methods Potentially more permanent than aluminium due to direct injection into the sediment column	Expected to succeed only if internal loading of phosphorus is controlled by iron redox reaction. Limited documented successful applications	Due to the limited documentation of successful applications and greater cost than other management options, sediment oxidation is not considered suitable.
Dredging and removal of sediment	Bulk removal of nutrients/contaminants from lake sediments decreases availability for re-circulation into the water column	Effects are short-term only without an associated reduction in lakes nutrient inputs Nutrient release from disturbed sediments and porewaters Potential release of toxic substances associated with fine particulars Temporary resuspension of sediments on aquatic organisms including clogging filtering apparatus of benthos and zooplankton, and reduction of light Many fish species cannot tolerate high sediment load	Dredging of Lake Bungana occurred in late 2019, with insufficient monitoring to date to confirm its effectiveness in reducing algal activity or altering the lakes eutrophic status, however recent (August 2020) algal blooms in both Lake Bungana and Lake Brearley indicate that dredging alone is unlikely to achieve the City's objectives. Dredging is considered a relatively expensive management option for short-term impacts, when not accompanied by a reduction in nutrient loading to the system, especially for relatively deep lakes such as Bungana and Brearley, with only comparatively thin layers of nutrient rich sediment. As nutrient loading is unable to be reduced, dredging would be required on an ongoing basis to continue to remove bulk nutrients from the lakes system. The observed lake characteristics indicate that dredging is a suitable option for reducing overall nutrients within the lake system, but it is considered that more cost effective and longer term management options are available.
Phosphorus inactivation (Phoslock™)	Proven effective control, non-toxic under a wide range of environmental conditions Effective under a wide range of pH values and alkalinities Does not affect pH levels following treatment	Potential toxicity of Lanthanum Long-term negative ecological impacts not well understood Ineffective in the presence of high dissolved organic carbon Maximum efficiency in phosphorus binding within reviewed literature was between pH 5 and 7, with marked decreases in effectiveness above pH 9. Application is not recommended during algal blooms due to associated high pH and low availability of reactive phosphorus Not recommended for use in saline (>15 ppt) environments due to release of lanthanum	Phosphorus inactivation longevity does not typically exceed 15 years and depends on phosphate release rates and application dose. The monitoring program indicated that the January 2020 application had negligible effect on phosphorus concentration in the water column for the period March-May 2020, and the efficacy of its application within Lake Bungana is unclear. On-going re-application would be required without further controls on the input of nutrients to the lake system and the prevention of nutrient cycling from lake sediments.

Management option	Benefits	Disadvantages	Suitability
Algicide	Very effective in the short-term as a treatment for algal blooms	Ineffective for long-term treatment Potential human health problems Mortality of toxic algae from copper sulfate may result in the release of cellular toxins such as microcystin Resistance may develop in target algae Dissolved oxygen depletion can occur when large volumes of dead algal cells decompose Reduce potential binding capacity of lake sediment. Negatively impacts aquatic communities. Copper stress impairs food-web functions. Accelerated phosphorus recycling from lake bed. Copper accumulation in the sediment. Disappearance of macrophytes. Reductions in benthic macroinvertebrates.	Algicide is not considered a suitable short term or long term management option due to its short-term effectiveness, relatively high cost and associated risks, as listed.

7. Recommendations

7.1 Community consultation

The City's objectives for management of the lakes have been inferred from its Strategic Community Plan. The SCP provides high-level strategic goals for management of the natural environment and public open space, however does not provide specific objectives for the management of the lakes.

Site-specific management objectives were drafted within Section 3.1 of this report to provide a basis for evaluating lakes management options. These objectives were drafted based on the appreciation for the site developed within the *Annual Report* and community feedback presented within FOML newsletters.

It is considered that the management objectives may be further refined through a process of community consultation. Further development of the management objectives would facilitate the selection of management options.

The community consultation may address community expectations and aspirations including:

- Amenity and aesthetic values
- Beneficial uses e.g. fishing, swimming
- Lake embankment and fringe landscaping preferences
- Tolerances for percentage cover by floating treatment wetlands
- Connectivity and continuity with the Swan River foreshore

7.2 Recommended immediate management responses

7.2.1 Ongoing monitoring

It is recommended that the current remote-monitored telemetry instruments are continued to be utilised for at least the expected life of the instruments as the capital expenditure on the instrumentation has already occurred, the operational costs of the remote monitoring telemetry system are low and the ability of the system to directly monitor the effectiveness of management interventions systems such as destratification.

As discussed within the *Annual Report*, the water level monitoring devices with Lake Brearley and Lake Bungana experienced reasonably significant instrument drift over the monitoring period. This should be rectified as soon as possible by more firmly fixing them to the monitoring platforms.

It is recommended that the monthly monitoring rounds undertaken as part of the *Annual Report* are discontinued. However, it is recommended that the quarterly monitoring rounds undertaken as part of the *Annual Report* are continued, regardless of the other management actions undertaken.

The quarterly rounds will provide a data with which to assess the effectiveness of lakes management actions. Additionally, long-term monitoring will facilitate identification of inter-annual trends in lake behaviour, and a more detailed understanding of lake responses to inputs and ambient conditions.

The proposed monitoring suite is detailed in Table 7-1 below. In order to capture seasonal highs and lows, it is recommended that monitoring in undertaken in March, June, September and December.

Table 7-1. Proposed quarterly monitoring program

Location	Analyte	Limit of reporting
BG1b, BG2, BL1b, BL2	pH	0.01 pH
	Electrical conductivity	1 µS/cm
	Total dissolved solids	10 mg/L
	Total suspended solids	1 mg/L
	Turbidity	0.1 NTU
	Total organic carbon	1 mg/L
	Total nitrogen, total kjeldahl nitrogen, organic nitrogen, nitrate, nitrite and ammonia as N	0.1 mg/L
	Total phosphorus	0.01 mg/L
	Total phosphate	0.01 mg/L
	Reactive phosphorus	0.001 mg/L (reduced from 0.01 mg/L)
	Calcium, chloride, magnesium, potassium, sodium, sulfate	1 mg/L
	Total anions, total cations, ionic balance	0.01 meq/L
	Chlorophyll α	1 mg/m^3
	Total algae count ('shallow' sample depths only)	5 cells/mL

A high-level cost estimate for the implementation of the above annual monitoring program is $60,000 per year, for collection, laboratory analysis and reporting.

In addition to the remote monitoring and laboratory analytical suite, it is recommended that the lakes continue to be visually monitored by the community and Council staff for amenity issues and removal of excess algae and vegetative matter continue as required. The following data should collected by the City on an on-going basis:

- A log of all management actions undertaken e.g. changes to operation of the aerators; lake embankment plantings; alterations to pumping regimes
- A log of the amount of vegetation removed from the floating treatment wetlands
- A log of anecdotal reports from community members or City officers reporting algae blooms or other amenity impacts (e.g. midges, odour)
- Monthly groundwater pumping volumes in to Brickworks Lake (it is understood this is already recorded)
- Monthly irrigation abstraction from Brickworks Lake
- Details on the type, quantity and frequency of fertiliser applications on POS within the lakes catchment

7.2.2 Lake de-stratification via artificial mixing

As identified within the *Annual Report*, stratification of the lakes and the presence of an anoxic hypolimnion is considered that currently, the most dominant mechanism controlling nutrient concentrations within the water column. It is therefore considered that management options addressing de-stratification are given priority.

With reference to the management options assessed within Section 6, artificial de-stratification seeks to aerate/oxygenate the hypolimnion by increasing lake circulation and preventing the formation of strata in the water column. Artificial de-stratification is most commonly achieved by one of two methods: air injection and mechanical mixing.

Air injection is generally undertaken using a diffusion system comprising an air compressor attached to a number of lines of perforated pipe laid across the lake bed. Pumping air through these pipes both directly oxygenates the hypolimnion and has an artificial circulation effect as rising air bubbles pull water from the hypolimnion upwards into the epiliminon. At high enough pumping rates this may achieve full mixing (ie. de-stratification) of the lake, however the process is relatively energy intensive and hence has a high power consumption cost. The system also requires a compressor to be located nearby which will would housing for weather protection and noise attenuation as it will need to operate 24 hours per day.

Mechanical mixing in stratified lakes is generally achieved through the use of a floating mechanical axial flow pump (or impeller) set within the epilimnion, close to the water surface. The pump is used to circulate warmer, oxygen rich water from the epilimnion down into into the hypolimnion. The pump may be attached to a vertical 'draft tube' to target a particular depth within the hypolimnion. Again, at high enough pumping rates breakdown of the lake stratification may be achieved as a circulation pattern is established within the lake.

There are many examples of the use of both air injection and mechanical mixing in wastewater and reservoir management industries. The Swan River Trust has also previously undertaken artificial oxygenation and de-stratification trials using air injection within portions of the upper Swan River estuary (Tweedley & Hallett, 2014). Mechanical mixing is also commonly in use. WEARS Australia (https://www.wears.com.au/) have developed a range of Australian manufactured floating impellers specifically designed to mix and de-stratify deep reservoirs and lakes such as Lake Brearley and Lake Bungana.

The recommended method of de-stratification within Lake Bungana and Lake Brearley is mechanical mixing. Mechanical mixing is preferred over air injection in this instance, as while both may achieve oxygenation of the hypolimnion and de-stratification, mechanical mixing is less energy intensive.

It is considered that this has an additional effect beyond de-stratification of disrupting populations of problem algae by circulating them from the near-surface photic where they collect into the deeper, turbid lake waters where they are unable to photosynthesise.

It is considered that the life-cycle costs of mechanical mixing and air injection are similar enough that costs are not a consideration when selecting between the two.

A high-level estimate of the whole of life costs of the installation of an appropriate mechanical mixer within each of Lake Bungana and Lake Brearley is presented below in Table 7-2.

Table 7-2. Indicative whole of life costs for mechanical mixers[1]

Item	Indicative cost estimate assuming design life of 20 years
Two mechanical mixers (one per lake)	$250,000
Installation, provision of power cables (16A, 240v supply)	$25,000
Annual maintenance	$$120,000 ($6,000/year)
Estimated annual operating cost (two mixers)	$80,000 ($4,000/year)
Whole of life cost (20 years)	*$$475,000* *($12,000 per year per lake)*

[1] Costing based on indicative pricing from WEARS Australia. Actual pricing and quotations have not been sought at this time and would depend on final design and product selection.

7.2.3 Lake modelling

In order to confirm the engineering design of the proposed de-stratification system, creation of a lakes numerical model is recommended.

The model should take as inputs the surveyed lake bathymetry and the current understanding of the lakes water balance as presented within the *Annual Report*. The model should seek to quantify the required mixing volume, frequency and target water quality conditions, then optimise the type, number, size and location of the mixers minimise whole of life costs, i.e. capital and operational costs, as well as provide predictions of efficacy to compare to monitoring data.

It is recommended that the modelling is undertaken using the hydrodynamic numerical model DYRESM and the ecological model CAEDYM. An indicative cost for this work is approximately $25,000 with an approximate two month period of development and delivery.

7.2.4 Floating treatment wetlands

It is recommended that the current program of installation and maintenance of floating treatment wetlands is continued. These can be progressed as funds permit on the grounds that they are unlikely to be adversely affecting water quality or amenity and could ultimately provide a key pillar of a sustainable lake management solution.

The monitoring data collected to date does not allow for calculation of the quantity of nutrients removed by the installed FTWs, however FTWs have been well demonstrated within reviewed literature to effectively remove nutrients from the water column. Their effectiveness in nutrient removal may be further assessed with longer-term monitoring of lake nutrient concentrations, a more detailed lake nutrient balance, and detailed record keeping regarding the species, volume and time of vegetation removed from the platforms.

The presence of floating vegetation is understood to be generally well received by community members, however further community consultation may be appropriate to guide the maximum acceptable coverage of the lakes system by FTWs.

7.3 Optional future management responses

Optional management responses could form part of a long term lake management strategy if the recommended strategies do not meet the City’s objectives.

7.3.1 Dredging

It is understood that the 2019 dredging program within Lake Bungana was undertaken at a cost of approximately $400,000, with a total approximate cost of $1,000,000 should both Lakes Bungana and Brearley ultimately be dredged. It is difficult to quantify the success of the dredging with a relatively short (i.e. approximately 6 month) monitoring period since its implementation, however an algal bloom has occured in August 2020 in both Brearlety and Bungana suggesting it has not had any immediate impact in preventing Algal blooms..

While the effectiveness of dredging in managing algae blooms is not currently proven, the frequency of dredging required to achieve this outcome is also poorly understood. As nutrients continue to be added to the lakes through stormwater and groundwater inflows, and the deposition of fauna faeces, on-going dredging would eventually be required.

Dredging on a 5 yearly basis would give a 20 year cost (i.e. similar to the whole of life cost of the recommended mechanical mixing infrastructure) of circa $2,000,000 or $50,000/lake per year.

It is therefore recommended that further dredging is not conducted until there is better evidence of efficacy and need.

7.3.2 Phosphorus de-activation

Based on the results of the monitoring program detailed within the *Annual Report*, it is difficult to discern the effect of the application of Phoslock in January 2020. Reactive phosphorus concentrations were below laboratory limits of detection at all monitoring locations except BL1b (Lake Brearley) across the period. Total phosphorus concentrations were generally lower in February 2020 compared to January 2020, except for a large spike at BL1b (Lake Brearley) within the deep sample. Total phosphorus concentrations then returned to previously observed levels for the remainder of the monitoring period, March-May 2020.

It is difficult to quantify the amount of phosphorus removed from the water column by the application of Phoslock, and based on the monitoring program any effect appears short-lived, on an approximate one month scale. An algal bloom in both treated lakes in August 2020, 7 months after treatment, confirms that phosphorus de-activation alone does not achieve the City's goals even in the short term.

It is therefore recommended that Phoslock application is discontinued. It may be re-assessed as a management option pending the results of the recommended management and monitoring actions.

Any further applications of Phoslock should be accompanied by a monitoring program assessing the presence of lanthanum in the water column. Lanthanum is the key component within Phoslock, and excess free lanthanum within the water column (generally observed to occur when applied in low alkalinity lakes, which these lakes are not) has potential negative ecotoxicological effects.

7.3.3 Other management practices

A suite of other ancillary management practices, many of which have been previously proposed, are recommended for implementation or continuation. These are discussed below.

Revegetation

A recommendation of the *Lake Bungana, Lake Brearley & Brickworks Lake, Maylands – Stage 2* report (Essential Environmental 2016) was the revegetation of areas of the lakes' embankments and riparian zones.

Significant progress has been made in this regard by the City and the Friends of Maylands Lakes, with several co-ordinated vegetation planting events.

It is recommended that this practice continue, along with the previously recommended maintenance program of six-monthly inspections and removal of dying or excessively bulky vegetation.

Records of the date, type and volume of vegetation removed should be kept to aid analysis of the effectiveness of management measures.

Public open space fertiliser application

Excess fertiliser applications may enter the lakes through stormwater run-off and infiltration subsequently transported by groundwater.

Application of fertilisers within the areas surrounding the lakes should be minimised or ceased, where feasible.

Community engagement and education

It is understood that the City is currently undertaking community engagement processes regarding behaviours that may positively effect the health of the lakes systems. These include:

- Regular maintenance of rooftops and gutters to remove leaf litter and other organic matter which may enter the lakes via the piped urban stormwater drainage network
- Minimisation of the application of fertiliser on private lots, which may enter the lakes through stormwater run-off via the piped urban stormwater drainage network and stormwater infiltration subsequently transported by groundwater
- Discouraging the dumping of pet fish or aquatic fauna, rubbish or organic wastes into the stormwater network or directly into the lakes

These measures should continue to be implemented.

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Appendices

Appendix A – Figures

Paper Size ISO A3

0 50 100 150 200

Metres

Map Projection: Transverse Mercator
Horizontal Datum: GDA 1994
Grid: GDA 1994 MGA Zone 50

N

GHD

City of Bayswater
Maylands Lakes Monitoring

Site Location

Project No. **38418**
Revision No. **B**
Date **22 Aug 2019**

FIGURE A1

G:\61\38418\GIS\Maps\MXD\6138418_001_SiteLocation_RevB.mxd
Print date: 22 Aug 2019 - 09:06

Data source: Landgate: Roads - 20190128, Railway - 20190304, Suburbs, Imagery - 20190426 (accessed: 20190820); GA: NatMap Geodata Topo 250k Series 3. Created by: cgverzosa

Appendix B – Lake bathymetry

Elevation Scale

RL	Colour
<= -5.5	
-5.5 - -5.0	
-5.0 - -4.5	
-4.5 - -4.0	
-4.0 - -3.5	
-3.5 - -3.0	
-3.0 - -2.5	
-2.5 - -2.0	
-2.0 - -1.5	
-1.5 - -1.0	
-1.0 - -0.5	
-0.5 - 0.0	
0.0 - 0.5	
0.5 - 1.0	
1.0 - 1.5	
>= 1.5	

RM SURVEYS
LICENSED SURVEYORS

PHONE: 08 9457 7900 EMAIL: INFO@RMSURVEYS.COM.AU WEBSITE: RMSURVEYS.COM.AU

SCALE 1:1250
ALL DISTANCES IN METRES

Surveyor	BT	Vertical Datum	AHD
Survey Date	03/07/18	Horizontal Datum	PCG94

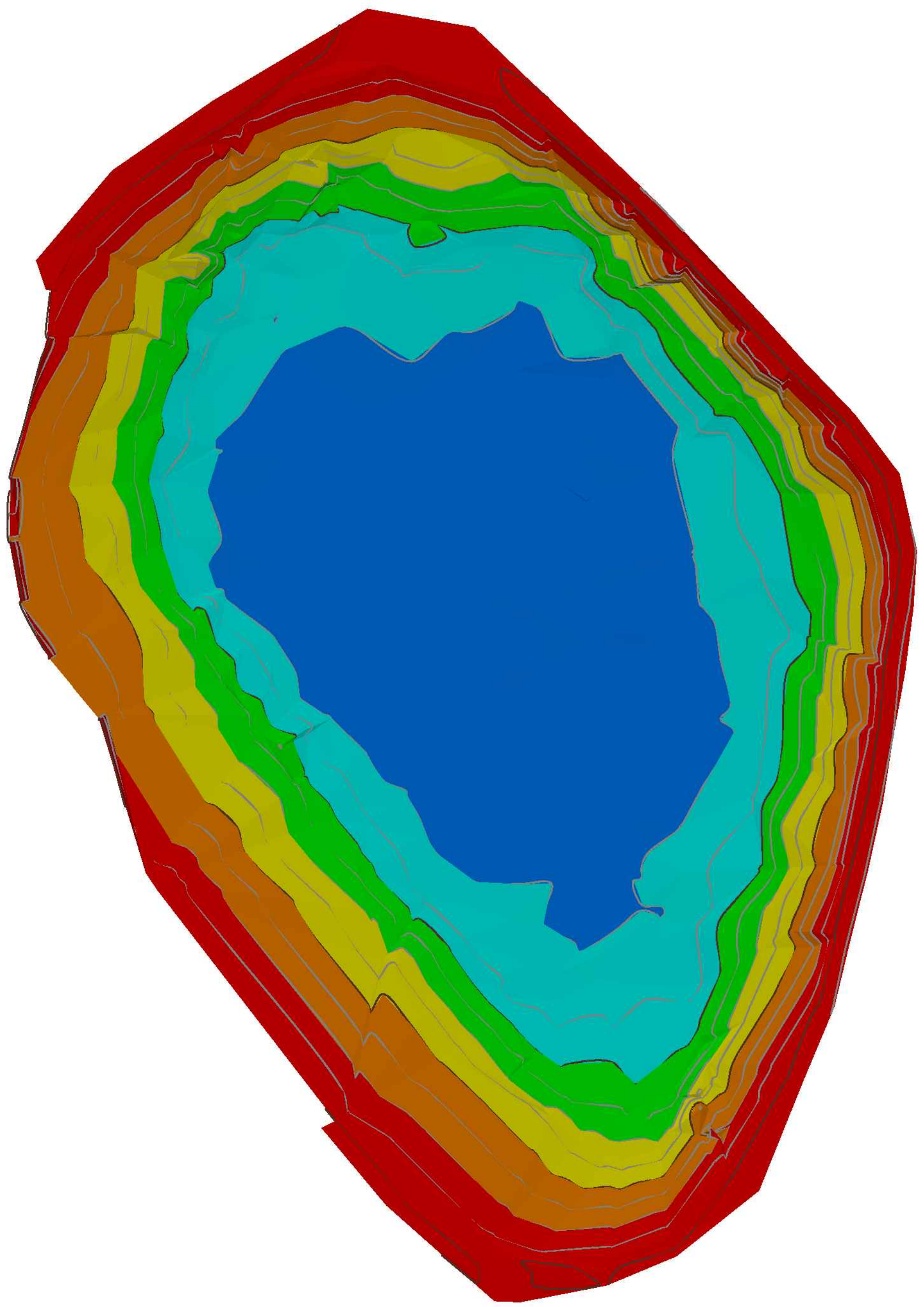
PAPER SIZE A1

Client
Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
1	Amend text.	AC	BT	BT	18/07/18
0	Initial Issue	AC	BT	BT	09/07/18

BATHYMETRIC SURVEY
Lake Brickworks, Bungana & Brearley
Maylands WA

Job No.	Drawing No.	Revision
URB-MAY	URB-MAY-01	1

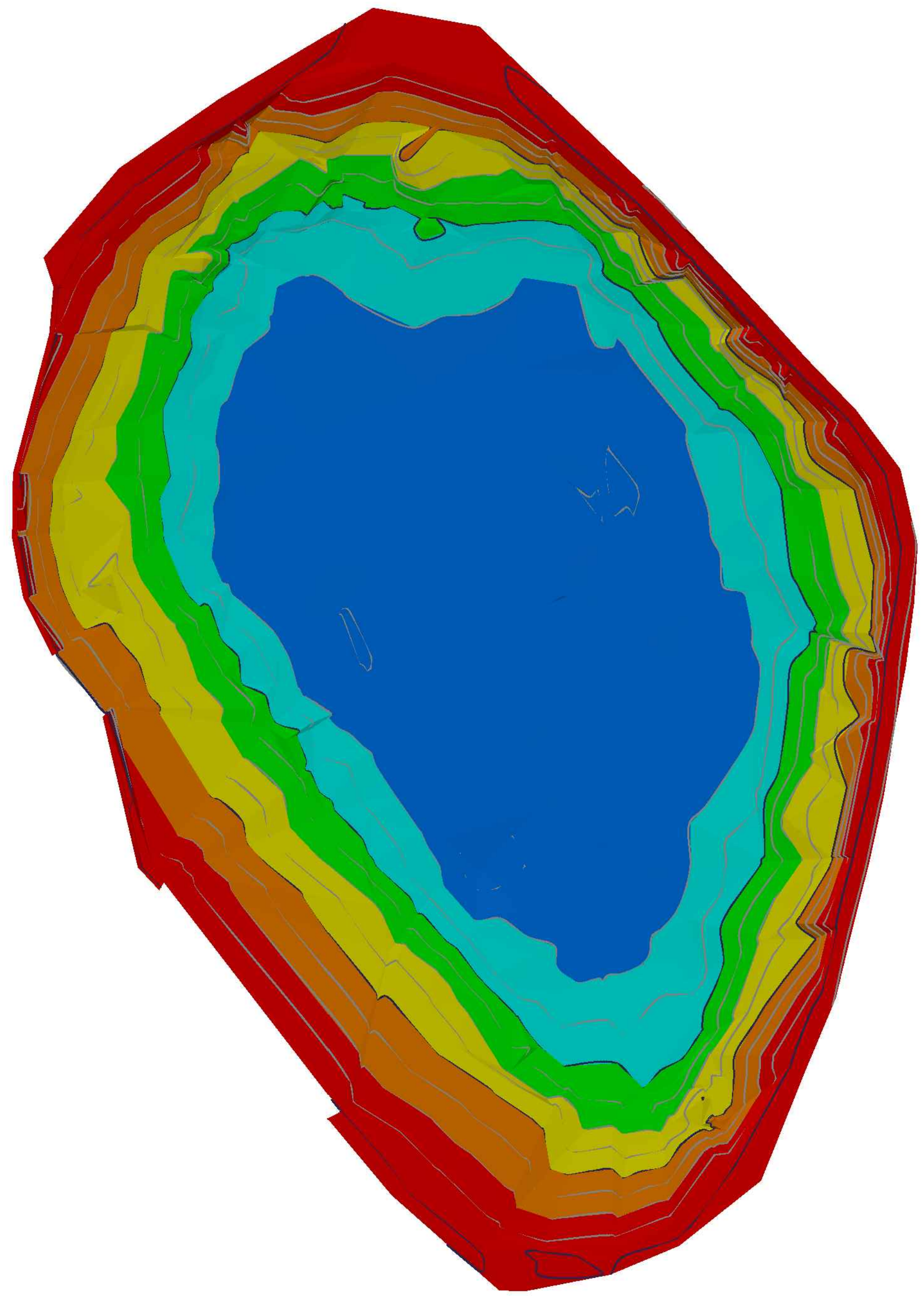


Soft Bottom

Elevation Scale

RL	Colour
<= -2.5	
-2.5 - -2.0	
-2.0 - -1.5	
-1.5 - -1.0	
-1.0 - -0.5	
-0.5 - 0.0	
>= 0.0	

Note: Height datum,
water level = 0.00m



Hard Bottom

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LICENSED SURVEYORS

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0 10 20 30 40
SCALE 1:500
ALL DISTANCES IN METRES

Surveyor	BT	Vertical Datum	LOCAL
Survey Date	09/07/18	Horizontal Datum	PCG94

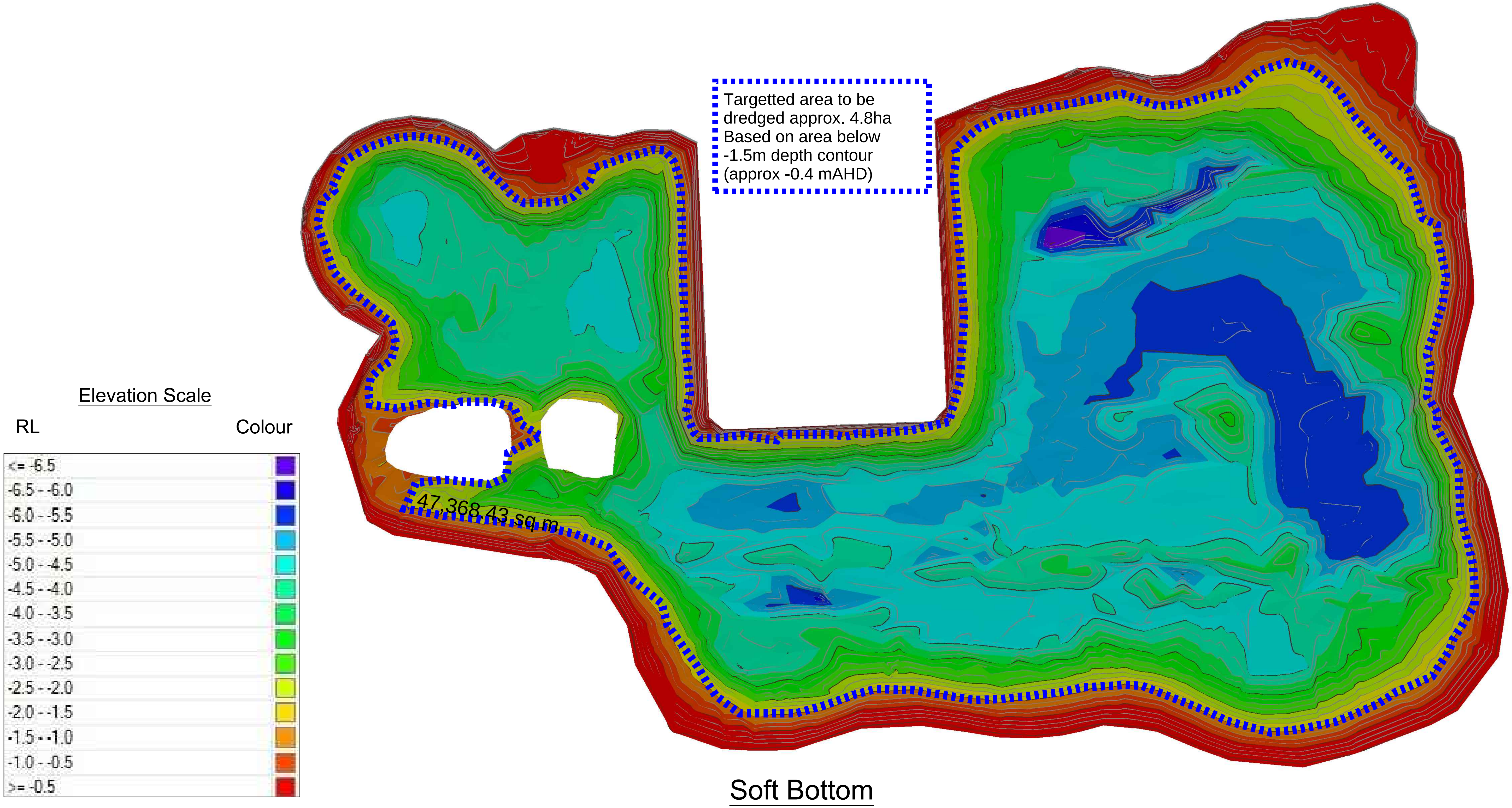
PAPER SIZE A3

Client
Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
0	Initial Issue	AC	BT	BT	19/07/18

BATHYMETRIC SURVEY
Lake Brickworks
Maylands, WA

Job No.	Drawing No.	Revision
URB-MAY	URB-MAY-02	0



Soft Bottom

Note: Height datum,
water level = 0.00m

RM SURVEYS
LICENSED SURVEYORS

PHONE: 08 9457 7900
EMAIL: INFO@RMSURVEYS.COM.AU
WEBSITE: RMSURVEYS.COM.AU

SCALE 1:1250
ALL DISTANCES IN METRES

Surveyor	BT	Vertical Datum	LOCAL
Survey Date	09/07/18	Horizontal Datum	PCG94

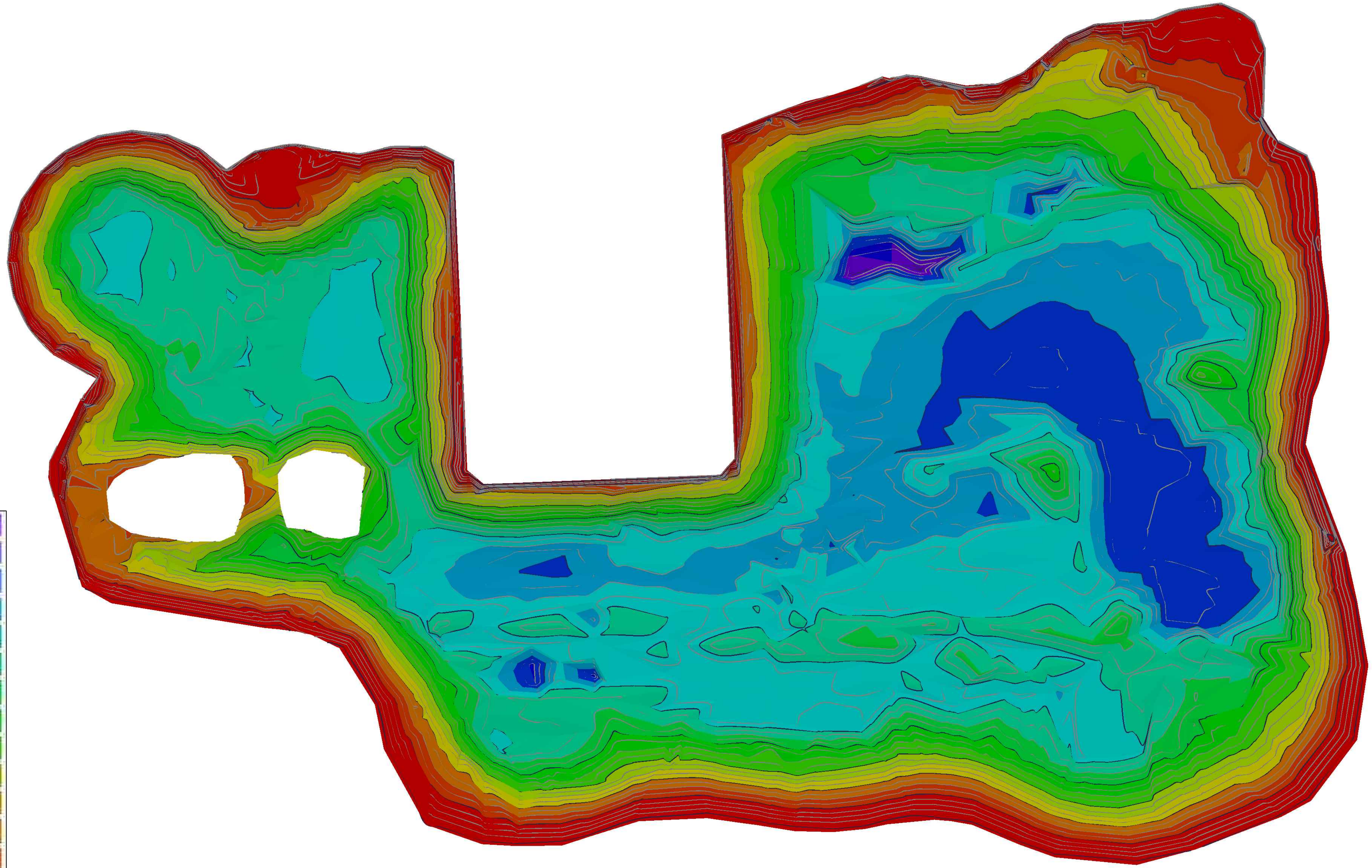
PAPER SIZE A3

Client
Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
0	Initial Issue	AC	BT	BT	19/07/18

BATHYMETRIC SURVEY
Lake Bungana
Maylands, WA

Job No.	Drawing No.	Revision
URB-MAY	URB-MAY-03	0



Hard Bottom

Elevation Scale

RL	Colour
<= -6.5	
-6.5 - -6.0	
-6.0 - -5.5	
-5.5 - -5.0	
-5.0 - -4.5	
-4.5 - -4.0	
-4.0 - -3.5	
-3.5 - -3.0	
-3.0 - -2.5	
-2.5 - -2.0	
-2.0 - -1.5	
-1.5 - -1.0	
-1.0 - -0.5	
>= -0.5	

Note: Height datum,
water level = 0.00m

RM SURVEYS
LICENSED SURVEYORS

PHONE: 08 9457 7900 EMAIL: INFO@RMSURVEYS.COM.AU WEBSITE: RMSURVEYS.COM.AU

0 10 20 30 40 50 60 70 80 90 100
SCALE 1:1250
ALL DISTANCES IN METRES

Surveyor	BT	Vertical Datum	LOCAL
Survey Date	09/07/18	Horizontal Datum	PCG94

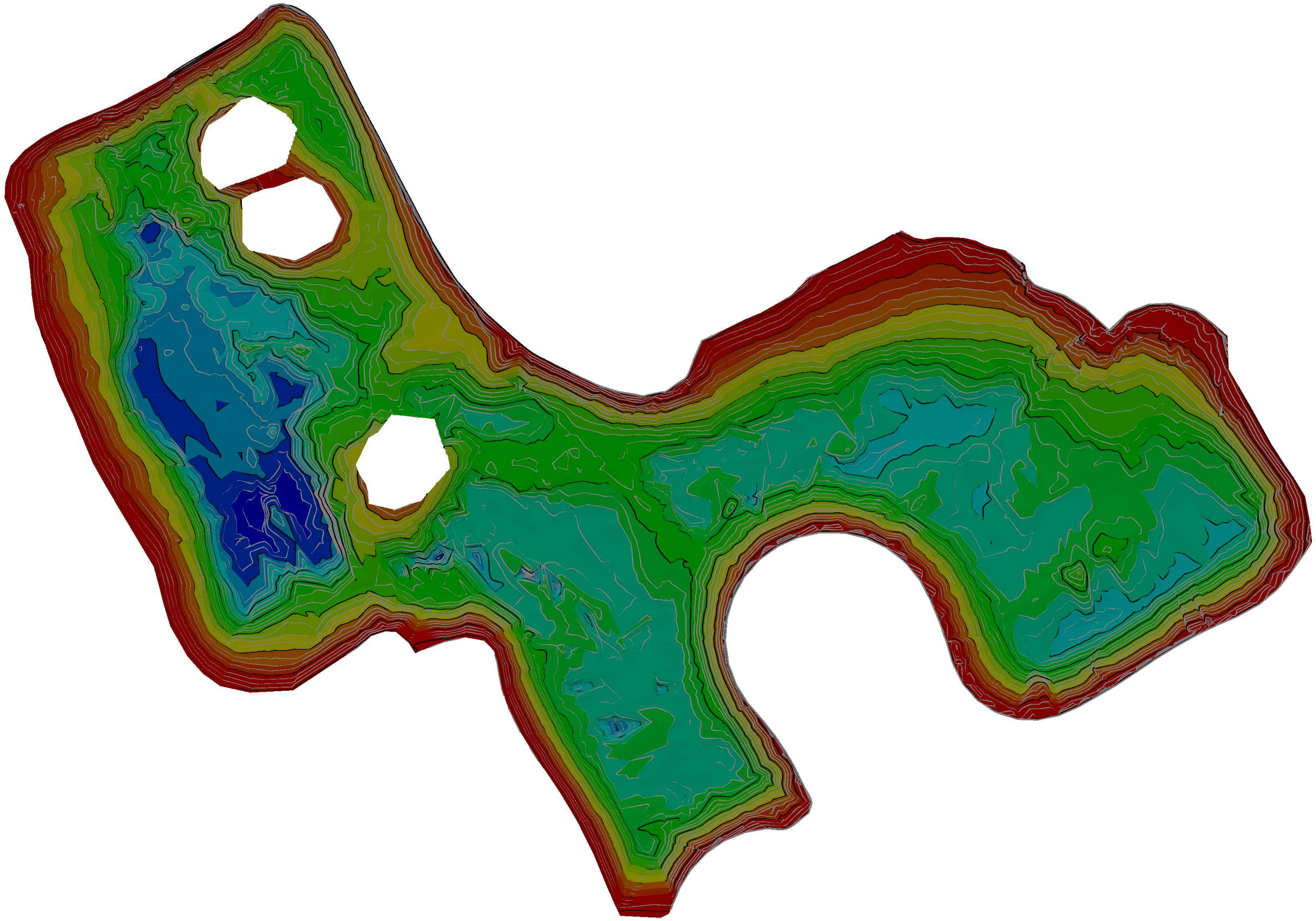
PAPER SIZE A3

Client
Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
0	Initial Issue	AC	BT	BT	19/07/18

BATHYMETRIC SURVEY
Lake Bungana
Maylands, WA

Job No.	Drawing No.	Revision
URB-MAY	URB-MAY-04	0



Elevation Scale

RL	Colour
<= -6.5	
-6.5 - -6.0	
-6.0 - -5.5	
-5.5 - -5.0	
-5.0 - -4.5	
-4.5 - -4.0	
-4.0 - -3.5	
-3.5 - -3.0	
-3.0 - -2.5	
-2.5 - -2.0	
-2.0 - -1.5	
-1.5 - -1.0	
-1.0 - -0.5	
>= -0.5	

Note: Height datum, water level = 0.00m

Soft Bottom

RM SURVEYS
LICENSED SURVEYORS

PHONE: 08 9457 7900 EMAIL: INFO@RMSURVEYS.COM.AU WEBSITE: RMSURVEYS.COM.AU

0 20 40 60 80 100 120 140 160
SCALE 1:2000
ALL DISTANCES IN METRES

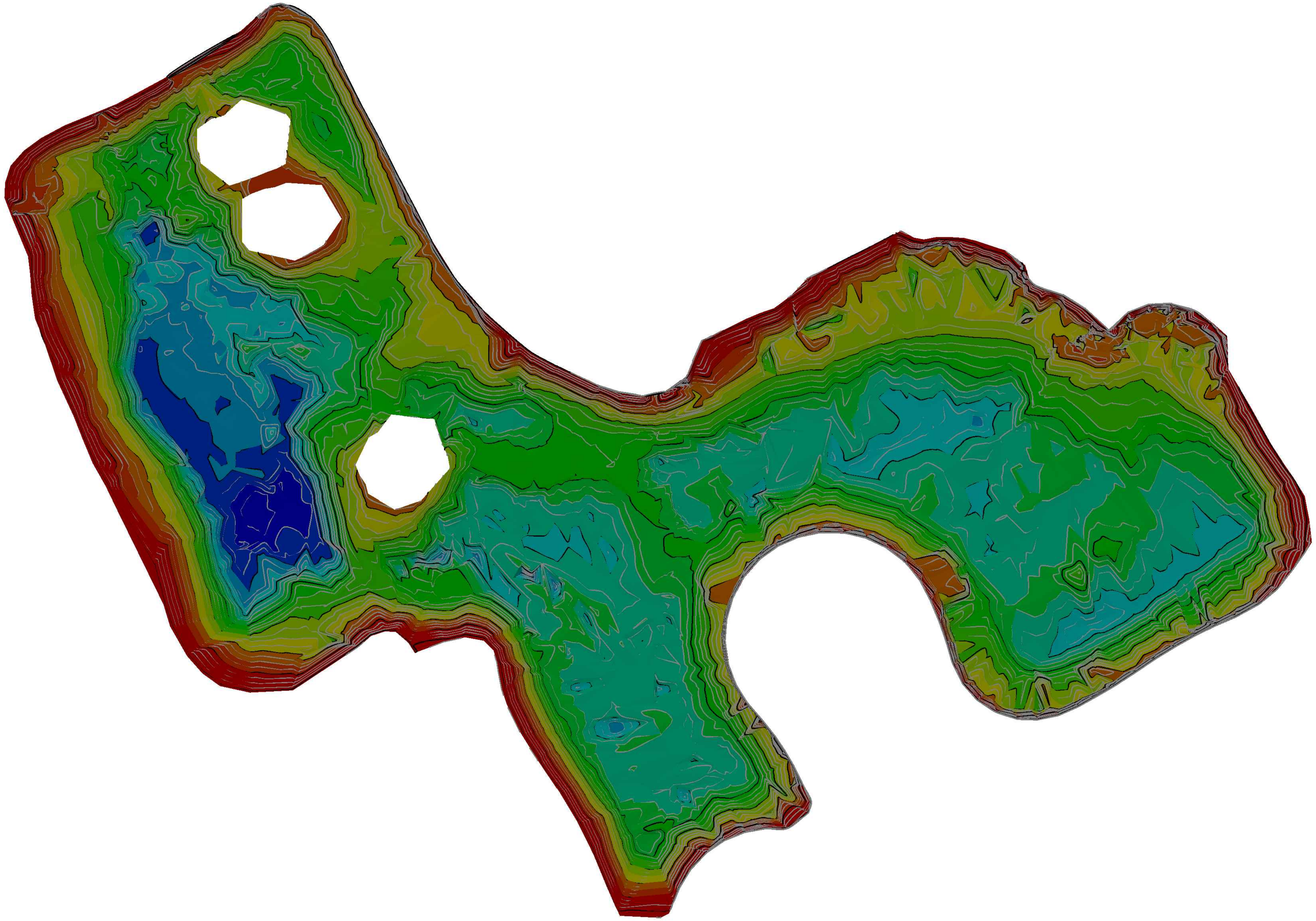
Surveyor BT
Survey Date 09/07/18
Vertical Datum LOCAL
Horizontal Datum PCG94
PAPER SIZE A3

Client
Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
0	Initial Issue	AC	BT	BT	19/07/18

BATHYMETRIC SURVEY
Lake Brearley
Maylands, WA

Job No. URB-MAY
Drawing No. URB-MAY-05
Revision 0



Elevation Scale

RL	Colour
<= -6.5	
-6.5 - -6.0	
-6.0 - -5.5	
-5.5 - -5.0	
-5.0 - -4.5	
-4.5 - -4.0	
-4.0 - -3.5	
-3.5 - -3.0	
-3.0 - -2.5	
-2.5 - -2.0	
-2.0 - -1.5	
-1.5 - -1.0	
-1.0 - -0.5	
>= -0.5	

Note: Height datum,
water level = 0.00m

Hard Bottom

RM SURVEYS
LICENSED SURVEYORS
PHONE: 08 9457 7900
EMAIL: INFO@RMSURVEYS.COM.AU
WEBSITE: RMSURVEYS.COM.AU

0 20 40 60 80 100 120 140 160
SCALE 1:2000
ALL DISTANCES IN METRES

Surveyor: BT
Survey Date: 09/07/18
Vertical Datum: LOCAL
Horizontal Datum: PCG94

PAPER SIZE A3

Client: Urbaqua Ltd

Rev	Description	Drawn	Chkd	Appvd	Date
0	Initial Issue	AC	BT	BT	19/07/18

BATHYMETRIC SURVEY
Lake Brearley
Maylands, WA

Job No.: URB-MAY
Drawing No.: URB-MAY-06
Revision: 0

GHD

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Document Status

Revision	Author	Reviewer		Approved for Issue		
		Name	Signature	Name	Signature	Date
A	A Wallace	C Gwynne		C Gwynne		31/08/2020
0	A Wallace	C Gwynne		C Gwynne		25/09/2020

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