EVALUATION OF POTENTIAL ENGINEERING OPTIONS FOR REDUCTION OF NITROGEN INPUTS TO LAKE ROTORUA

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EVALUATION OF POTENTIAL ENGINEERING OPTIONS FOR REDUCTION OF NITROGEN INPUTS TO LAKE ROTORUA

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Project Team:
Jo McQueen-Watton - Report author
William Shaw - Report author, peer review

Prepared for:
Toi Moana
Bay of Plenty Regional Council
P.O. Box 364
Whakatāne

99 SALA STREET, WHAKAREWAREWA, 3010, P.O. BOX 7137, TE NGAE, ROTORUA 3042
Ph 07-343-9017; Fax 07-343-9018, email ecology@wildlands.co.nz, www.wildlands.co.nz

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Reviewed and approved for release by:

W.B. Shaw
Director/Principal Ecologist
Wildland Consultants Ltd

1. INTRODUCTION

Bay of Plenty Regional Council have a sustained programme of nitrogen reduction targets for the Lake Rotorua catchment. This includes requirements for farming activity within the catchment to discharge less than specified discharge limits and for the continuous review and implementation of good management practices. However, 50 t (tonnes) of nitrogen (N) input into Lake Rotorua per year is to be reduced through 'engineering solutions'. Of this 50 t N, existing and currently proposed projects may address 30 to 35 t N. The existing and currently proposed projects are the N-removal plant proposed to be constructed at Tikitere, on the Waiohewa Stream, which should remove 20-25 t N per year, and improved sewage reticulation around the catchment will remove around 10 t N per year. That leaves about 15 to 20 t N per year still to be removed to meet the 50 t N per year target.

Bay of Plenty Regional Council commissioned Wildland Consultants to undertake a review of other engineering solution options potentially available to remove a further 15 to 20 t N per year from Lake Rotorua. The scope of the review is to include both in-lake interventions, such as weed harvesting, chemical applications, flocculates, flow diversion walls, and within-catchment interventions such as constructed wetlands, watercress (*Nasturtium officinale*) beds and anything else that may potentially be available and suitable. The review is to focus on N removal, although where P is also removed, the general efficacy of removal will be noted. The part of the Lake Rotorua catchment that is diverted down the Ōhau Channel will not be considered, as any N reductions here will not be reflected in the N budgets for the Lake.

This report presents the results of this desktop review, and places technologies into a 'rejected' group (with rationales), and a 'potentially feasible' group. Future actions required to implement the potential solutions are then provided.

2. OVERVIEW OF THE LAKE CATCHMENT

2.1 Ecological context

Lake Rotorua is located within the Rotorua Lakes Ecological District, which is part of the Northern Plateau Ecological Region (McEwen 1987). Rotorua Lakes Ecological District comprises the catchments of the Rotorua lakes system, with Lake Rotorua as the main feature. Rotorua Lakes Ecological District is a distinctive volcanic landscape of plateaus, terraces, and rolling hill country that comprise a matrix of farmland, indigenous forest, and exotic plantation forest. Residential settlement is concentrated on lake margins, largely at Rotorua and Ngongotahā. Rural lifestyle properties are common in the Rotorua basin. There are also a number of dairy farms, predominantly on the western side of the catchment. All landforms and mantling tephras within the Lake Rotorua catchment are of volcanic origin (Shaw & Beadel 1998). Various geothermal surface expressions, and related vegetation and habitats, are characteristic features of parts of the catchment.

2.2 Geology

The Rotorua basin was formed approximately 220,000 years ago by volcanic eruptions - centred around Ngongotahā - that created substantial ground collapse and a caldera which was partially infilled to form Lake Rotorua. Fifty to 100 metres of lake sediments now overlie ignimbrite, lava flows, and rhyolite domes. A number of faults are present within the caldera, including Puarenga, Whakarewarewa, Pohaturoa, Roto-a-Tamaheke, and Ngāpuna (Environment Bay of Plenty 2005).

Rotorua Geothermal Field lies at the southern end of the Rotorua caldera and covers 20 km^2 of the geothermally-active Taupō Volcanic Zone. Rotorua Geothermal Field includes *c*.1,550 individual surface features (Cody 2003), with major surface expressions of geothermal activity at Whakarewarewa-Arikikapakapa, Government Gardens-Ngāpuna-Sulphur Bay, and Kuirau Park-Ohinemutu.

2.3 Lake Rotorua

Lake Rotorua is a large (80 km^2 or *c*.8,000 hectares), shallow, polymictic lake. The lake has a wide littoral zone 0.5 to 5.0 metres deep, with most of the lake being between five and 20 metres deep (Irwin 1969); the mean depth is 10 metres (Gibbs *et al*. 2016). Maximum depth is 44 metres, in a deeper section of the lake one kilometre off Motutara Point (Healey in Jolly *et al.* 1975; Irwin 1969), and a trench about 20 metres deep extends northwards from the western side of Mokoia Island and towards the Ōhau channel outlet (Gibbs *et al.* 2016). Lake level is controlled within a 0.8 metre range by a permanent weir placed in the Ōhau Channel, preventing wide fluctuations in lake level.

The lake sits within a circular depression known as the Rotorua caldera. Mokia Island is a rhyolite dome within the central basin of the lake. The lake is typically well mixed, with short periods of defined stratification, which usually don't last longer than one week before convective and wind-driven events remix the lake (Gibbs *et al.* 2016). Many streams, including streams of spring-fed and hydrothermal origins, enter the lake. The main inflowing streams are the Utuhina, Ngongotaha, Waiteti, Awahou, Hamurana, and Puarenga. Several of these are spring-fed, at least in part. Puarenga Stream, which flows into Sulphur Bay at the southern end of the lake, is influenced considerably by hydrothermal waters from the Whakarewarewa thermal area, as is the Waiohewa Stream, which receives geothermal water from Tikitere thermal area. The main outflow from the lake is the Ōhau Channel, which flows into nearby Lake Rotoiti and then into the Kaituna River (See Figure 1). The Ōhau Channel wall diverts most of the outflow directly to the Kaituna River.

The lake and its surface catchment cover an area of 502 km^2 (50,200 ha) and the contributing groundwater catchment is approximately 537.1 km^2 (White *et al.* 2014).

The lake was classed as eutrophic until 2007, when a period of sustained alum dosing of the Utuhina and Puarenga Streams was undertaken, starting in 2006. The lake has numerous naturally P-rich streams, and a legacy of phosphorus in the bottom sediments which has occurred from land clearance activity in the catchment and

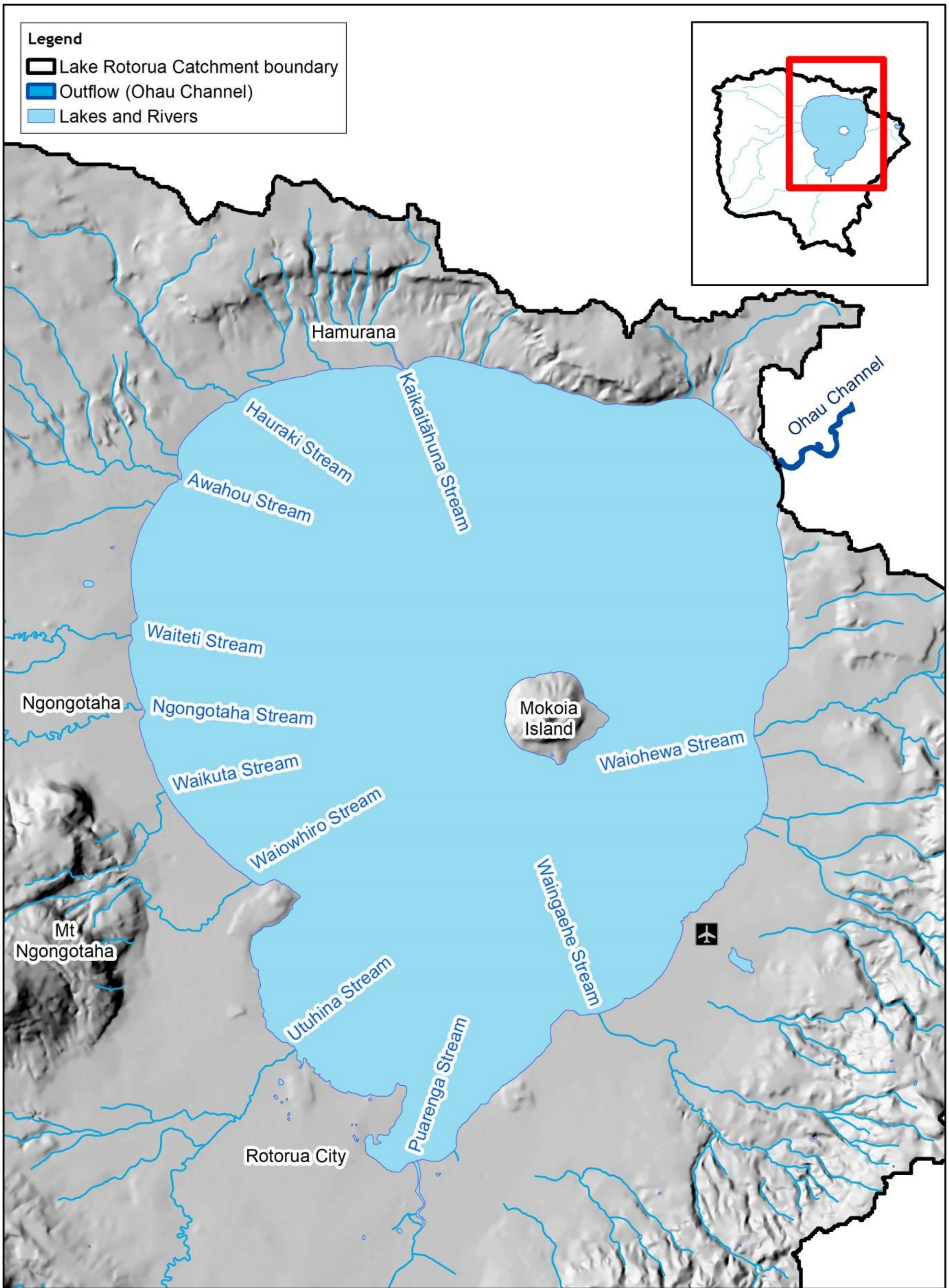

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Figure 1. Lake Rotorua Waterways

0 2.5 5 km

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historical disposal of sewage waste water from the city of Rotorua. Waste water inputs ceased in 1991, but the expected improvement in water quality has been slow, and there are still frequent cyanobacterial blooms and bottom-water deoxygentation events. Lake Rotorua has remained in a stable condition long-term, as indicated by LakeSPI monitoring, with lake condition being ranked as moderate (Burton and Clayton 2014; Scholes and Hamill 2016).

Eighteen species of submerged aquatic macrophytes have been recorded in the lake (Clayton *et al.* 1990). Emergent vegetation is rare, and occupies only about one percent of the total shoreline. Indigenous aquatic macrophyte species are relatively rare in comparison with exotic species. Of the exotic species, *Egeria densa* is the most common, followed by *Elodea canadensis* and *Lagarosiphon major* (Clayton *et al.* 1990). The lake has a large wind-exposed shallow littoral zone subject to considerable wave action, which has the effect of reducing silt build up and helps prevent large surface-reaching weed beds forming around much of the lake margin (Burton and Clayton 2014).

2.4 Sub-catchments

As mentioned above, Lake Rotorua is fed by numerous waterways: Waiohewa and Waingaehe Streams on the eastern side of the lake, Puarenga and Utuhina Streams at the southern end of the lake, Waiowhiro, Waikuta, Tupapakurua, Waitete, Awahou, Hauraki, and Kaikaitahuna (Hamurana) Streams on the western side of the lake.

The Waiohewa Stream catchment - which includes the Ohuanui and Wairewarewa tributaries - is relatively large (within the context of Lake Rotorua), and flows into the eastern side of Lake Rotorua at Te Ngae. The Wairewarewa tributary is only about one kilometre long, and includes a small wetland (Lake Maui), draining farmland on easy rolling country. The Ohuanui Stream is longer (*c.*3.5 kilometres) and includes four or more tributaries. It also drains low to rolling hill country, mostly in farmland, although the headwaters include indigenous forest in the vicinity of Whakapoungakau (758 metres). Due to inputs from the Tikitere Geothermal Field, the Waiohewa Stream is very acidic (about pH 2.9) with an average temperature of 28°C, and has a very high sediment load, also of geothermal origins.

Nitrogen loads and concentrations under base flow conditions for major sub-catchments to Lake Rotorua are shown in Table 1 below (adapted from Rutherford and Timpany 2008). These loads could have been underestimated by up to 50 percent due to the effects of storm events (Scholes 2013), and show an increasing trend over time (Scholes 2013).

Table 1: Nitrogen loads and concentrations under base flow conditions for major inflowing sub-catchments to Lake Rotorua (adapted from Rutherford and Timpany 2008). (NO_3 loads have been adapted from Hamilton *et al.* 2012).

Catchment	Total Flow (L/s)	Baseflow (L/s)	Total Baseflow N (t/year)	NO_3
Awahou	1,594	1,468	59.8	67.7
Hamurana	2,495	2,468	58.9	56.3
Puarenga	1,711	1,099	47.0	106.3
Waiteti	1,156	788	34.1	54.7
Utuhina	1,845	1,162	33.7	61.2
Ngongotaha	1,734	963	31.6	66.3
Waiohewa	319	207	19.1	51.3
Waingaehe	227	209	10.1	12.4
Waiowhiro	358	255	8.61	16.0

3. KEY FACTORS AFFECTING NITROGEN REMOVAL

There are several factors that affect potential nitrogen removal rates and these have been considered within the various technology options examined.

Firstly, nitrogen removal ability is based on the **concentration** of nitrogen in water. While Lake Rotorua and streams entering the lake have low concentrations of nitrogen, they may high total baseflow N loads ($t\ y^{-1}$) (Table 1), due to high flow volumes. Most technologies have an optimal nitrogen concentration at which they perform best. When the nitrogen concentration in the water is too low, many technologies either do not work, or work sub-optimally. Many denitrification technologies have been designed to clean-up waste water with very high N concentrations.

Secondly, nitrogen removal ability is often affected by **water temperature**, particularly with bacteria being part of the denitrification process. Many streams entering Lake Rotorua are very cold, and many technologies will therefore either not work, or will only work sub-optimally at the natural stream temperature. Water temperature often varies with season, meaning that, for many technologies, there will be a seasonal component to their denitrification potential.

Thirdly, nitrogen is present in the lake in a number of **forms**: dissolved inorganic nitrogen (DIN), which includes nitrates (NO_3), nitrites (NO_2), and ammonium (NH_4), dissolved organic nitrogen (DON), and particulate nitrogen (PN), which sum to make total nitrogen (TN). Of these forms, most technologies focus on DIN, which is biologically available for plant (macrophyte and phytoplankton) growth. Note that DIN in the water column becomes PN when assimilated into phytoplankton tissue so there may not be a change in TN concentration following a treatment that reduces DIN.

Different technologies are often specific to the form of nitrogen, particularly as nitrates and nitrites are negatively charged, while ammonium is positively charged. Many chemical treatments rely on the positive or negative charges to attract the nitrogen and bind it to a compound, thereby making it unavailable for plant growth.

4. ASSESSMENT OF POTENTIAL TECHNOLOGIES

Existing Information and Initial Evaluation

A literature review was undertaken to compile information on all feasible nitrogen removal technologies.

All known potential options were considered, and results were set out in a matrix to provide a framework for initial analysis of the technologies proposed, to be discussed at an expert workshop (see below). The aim of this stage was to narrow the options to those that are potentially feasible. Therefore, if a show-stopper was immediately evident, that technology would be rejected and no further analysis of the option would be undertaken.

Basic analysis of the feasibility of each option was undertaken. Other factors considered included how much N will be removed (and type of N), scale-up likely to be required, a ballpark indication of costs, and other considerations such as flow-on ecological (and political and cultural) consequences that should be considered. Technologies were identified at this preliminary stage as one of the following: 'rejected', or 'potentially feasible'.

Workshop

The above analysis was discussed at an expert workshop, held at in Rotorua at the Bay of Plenty Regional Council Office on 16 May 2017. Attendees included:

- Jo McQueen-Watton and William Shaw - Wildland Consultants
- Alastair McCormick and Andy Bruere - BOPRC
- Max Gibbs - NIWA
- John McIntosh - Consultant
- Keith Hamill - Consultant

Each technology was discussed in some detail, and additional technologies were added, based on expert knowledge. During this discussion and evaluation, some technologies were moved from feasible to rejected, and vice versa.

Matrix

Twenty technological options were assessed in the matrix that was developed (some of these were separate technologies that were lumped together on final analysis). Of these, nine showed potential as possibly feasible options requiring further analysis. A brief summary of each technology is provided here on the basis that the report reader is somewhat familiar with the different technical options proposed. References for further reading are provided where possible.

Cost indications for the rejected technologies have been provided from referenced work, and no attempt has been made to standardise these costs. For the feasible technologies, costs have been provided in units of cost per kg of N removed as a standard comparable unit. However, it should be noted that most of these costs are derived from referenced work and are indicative only.

A prioritised list of actions to achieve the 20 t N removal target is provided.

5. REJECTED TECHNOLOGIES

5.1 Overview

The following technologies were assessed for potential feasibility, but have been rejected as being unfeasible for various reasons, as addressed below. Brief discussion is provided for each of them but they are then not considered further in this evaluation:

- Nanobubbles.
- Flocculent application.
- Aeration-driven destratification.
- Lake bottom oxygenation.
- Wave barriers.
- Dredging.
- Grass carp.
- Hamurana diversion wall.
- Wave barrier at Waiohewa.
- Floating wetlands.
- Removal of sewage from the catchment.

Rationales for rejection of these options are presented below.

5.2 Nanobubbles

Potential N Removal: Not yet quantified.

Nanobubbles are nanoscopic gaseous (typically air) cavities in aqueous solutions that have the ability to change the normal characteristics of water. Ordinary bubbles have a diameter which range from 1 µm and larger. These quickly rise to the surface of a liquid and collapse. Nanobubbles which are <100 nm in diameter will drift randomly due to what is termed Brownian Motion and can remain in liquids for an extended period of time (http://www.nanobubbles.com/nanobubbles-2/what-are-nanobubbles/#.WSZBvWiGOUk). The product that produces the nanobubbles is a mixture of chitosan and local soil in which nanobubbles of oxygen have been incorporated (Gibbs 2015). The product works to floc the fine suspended particulate matter from the water column and cap the sediment with the nanobubble-treated local soil, which prevents the release of dissolved reactive phosphorus from the sediment (Gibbs 2015).

NIWA and the University of Waikato are currently researching this technology, funded by Bay of Plenty Regional Council. Preliminary findings from NIWA (Max Gibbs, NIWA, pers. comm.) are:

- The technology is patented and has only been produced in China to date. The shelf-life of the product is only three days, i.e. it must be manufactured and put into a lake within three days. Unless the product is able to be produced in New Zealand, it will never become a feasible technology on this basis alone.
- The product looks like a modified zeolite, and is required to be spread over the lake bed sediments in a layer three centimetres thick and spreading to this thickness is unlikely to be technically feasible or cost-effective. See Section 5.3 below for discussion of the feasibility of spreading products onto the lake bed sediments as a much thinner layer.
- There is no indication of how long the technology would continue to work in the lake, assuming that the three centimetre thick layer can be achieved.
- No toxicology studies have been undertaken and, as the product is still a secret, New Zealand researchers still have no idea what is in it and therefore the safety of the product cannot even begin to be assessed.
- The timeframe for the product to actually be an option for Rotorua could be decades, if it is proven to be safe, able to be spread properly, and a resource consent is able to be obtained.

Given the above, this technology is simply too early in the development phase to be a serious contender as a solution for nitrogen removal for Lake Rotorua.

<u>References and Further Reading</u>

Max Gibbs, NIWA, pers. comm.

Agarwal, A. Ng, W.J. and Liu Y. 2011. Principle and applications of microbubble and nanobubble technology for water treatment. *Chemosphere 84*: 1175-1180.

5.3 Flocculent application

Potential N Removal: Various rates, depending on product used. Most are made to remove phosphorus and therefore only remove positively charged ammonium ions.

Various flocculents are available on the market, including various versions of Zeolite (modified Zeolite, Z2G1, Aqual-P), Allophane, Alum, Bentonite, Steel slag, Phoslock, and limestone. Most of these target phosphorus removal, and only a few will improve nitrogen levels in the water (see Table 2, adapted from Miller 2005). These work by ‘capping’ the sediment with a layer of material to which mainly phosphorus ions bind, thus preventing release of phosphorus from the sediment layers. A layer of around two millimetres of Z2G1 can block the release of phosphorus from the sediment (Gibbs and Ozkundakei 2010). Accurate application of the capping material on the lake bed is very important (Gibbs and Ozkundakei 2010).

Table 2: Various mineral and non-mineral flocculent materials and the major nutrient ions affected (adapted from Miller 2005).

Material	Major nutrient ions affected
Allophane	NH_4^+, NO_3^-, PO_4^{2-}
Bentonite	PO_4^{2-}
Charcoal (activated)	Organically bound N and P
Chitin	NH_4^+
Pumice	NO_3^-, PO_4^{2-}
Steel slag	PO_4^{2-}
Wood wastes	NH_4^+, NO_3^-,
Wool	?
Zeolite	NH_4^+, NO_3^-, PO_4^{2-}

Because most flocculents do not remove significant amounts of nitrogen from the system, most can be discounted as a potential solution for nitrogen removal for Lake Rotorua. Some may even temporarily increase nitrogen in the water column, as they may adversely affect the denitrification microbial community in some situations (Gibbs and Ozkundakei 2010). However, for those that do remove some N, the show-stopper problems for them are:

- The frequent mixing of Lake Rotorua. Gibbs *et al.* (2016) found that the lake only stratifies for about one week per year, and the waters are frequently mixed with the sediment layers, meaning that any sediment capping will probably be resuspended into the water column frequently. This would have the effect of making the lake turbid, potentially change the toxicology of the products, and redistribute the sediment cap, meaning that it will no longer be evenly spread over the lake bed, and thus may not be as effective.

- Any sediment cap is likely to be quickly buried in Lake Rotorua conditions. Lake Rotorua sediments accumulate at a rate of about one centimetre per year (Hamilton *et al.* 2007). Hamilton *et al.* (2012) predicted that any sediment cap would be effective for a maximum of four years.

- A small lake - Lake Okaro, 20 hectares - has been dosed with flocculent at a cost of $225,000, including product and application. Extrapolated to Lake Rotorua, the cost would be in the order of $89 million.

- Two streams flowing into Lake Rotorua are being Alum-dosed, and this has resulted in a significant improvement in water quality. The mechanism driving this improvement is not fully understood and further study is required. It is possible that the lake currents have resulted in the Alum being moved some distance from the stream mouth, and thus the dosing effect is being seen over a large area already (Gibbs 2015); the volume applied has been equivalent to the amount required to block all P release from the lake sediment (Gibbs 2015).

Given the high cost of flocculent application, and the high chance that it simply won't work (as it will be mixed continuously), flocculents have been rejected from further analysis.

Allophanic clay is a further type of flocculent that could be a better option, as only a one centimetre thick layer is required on the bottom of the lake. Trials have shown that it binds N and P and cleared the water column. Zooplankton present in the water-column remained unaffected by this treatment in laboratory trials. However, the only New Zealand sources of allphanic clay (in Taranaki) have been found to have steadily increasing levels of phosphorus (due to fertiliser use on the land above), and thus there may not be a suitable source of clay in New Zealand. There is also the potential to actually bring more phosphorus into the lake than will be removed. The same issues as outlined above for other flocculents also apply to allophanic clay, particularly cost. This option was therefore also rejected from further analysis.

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5.4 Aeration-driven destratification

Potential N Removal: Unknown, as the mechanism is enhancement of denitrification.

Mixing of the lake water to prevent stratification. When stratification occurs, the lake bottom becomes anoxic, and phosphorus in particular is released from the sediments. The internal regeneration of phosphorus from the sediments during stratification events when hypolimnetic anoxia occurs is estimated at 24 tonnes (Hamilton *et al.* 2003; cited in Miller 2007). The following matters would need to be taken into account:

- An aeration trial was undertaken on Lake Rotoehu (790 hectares), but was not found to be particularly efficient. The mixers only managed to make a difference on the scale of 100s of metres (McBride *et al.* 2015). To be effective on Lake Rotorua, an enormous number of mixers (pumps) would be required to mix the 25 km^2 area of lake that stratifies.

- The cost-benefit of this method does not stack up at $524,000 for mixing only about 200 m^2 of Lake Rotoehu, which means that the cost for Lake Rotorua would be in the order of $65 million.

- The number of pumps needed, maintenance, running costs, noise, effects on wildlife and people mean that this option is not feasible.

- Lake Rotorua does not stratify for very long each season (only about one week); therefore the effect on water quality improvement is likely to be minimal.

This option has been rejected from further analysis on the basis of cost, minimal water quality improvement, and the scale of infrastructure required.

<u>References and Further Reading</u>

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5.5 Lake bottom oxygenation

Potential N Removal: Unknown, as the mechanism is enhancement of denitrification.

Similar to the aeration-driven destratification, but pure oxygen is pumped to the bottom of the lake, to oxygenate the very bottom sediment layer and allow denitrification to occur. When the bottom waters have oxygen, release of nutrients, particularly phosphorus, from the sediments is prevented. In Virginia, USA, a water reservoir has been successfully deoxygenated by bubbling liquid oxygen through an irrigation hose held just above the bottom sediments with a series of floats (Gerling *et al.* 2014). The following matters also need to be taken into account:

- Such a system could be put in place on Lake Rotorua but could only operate when stratification occurs.
- Liquid oxygen is expensive at about $700 per tonne plus the storage and handling facilities for liquid oxygen on site as well as the special pumps and distribution pipes that would be required. Costs could exceed $200,000 just to set up the shore station. There would be noise associated with running pumps, which would affect where these were able to be placed.
- In shallow lakes, there is a risk that this treatment can lead to higher turbidity.
- Effects on nitrogen in Lake Rotorua are likely to be minor, as this technology will mainly affect the release of phosphorus from sediments. It could enhance nitrification and therefore denitrification for the few weeks of stratification each year. However, given the short time that the lake is stratified, this technology is likely to have little impact on overall water quality.
- The cost of this option is not known, but could be expected to be very costly given the need for pumps and oxygen.
- It is an unproven technology, with just one successful experiment to date.

References and Further Reading

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5.6 Wave barriers

Potential N Removal: Not quantifiable

Some kind of structure is placed in the lake to prevent wave action and create a calm area of water. This creates the opposite conditions required for aeration, as addressed above. The purpose of a wave barrier would be to prevent bottom sediment mixing, which may stop release of some N and P from sediment by disturbance of pore water. The following should be taken into account:

- This technology is not going to remove any N from the lake on its own, but would provide conditions that could enhance denitrification.
- It would prevent some additional release of N and P from the sediment layers if barriers were put in the correct place on the lake, e.g. the lake front area. Social implications of putting a structure in this area are probably large. This would only prevent sediment mixing in northerly winds, and may have large consequences on whole lake mixing, which has been shown by Gibbs *et al.* 2016 to encompass the whole lake.

This option has been rejected from further analysis on the basis that it will not removal additional N from the lake (as per the scope of this report). However, it could possibly be part of a solution, in conjunction with other technologies. See Section 6.1 below.

References and Further Reading

Gibbs M., Abell J., and Hamilton D. 2016: Wind forced circulation and sediment disturbance in a temperate lake. *New Zealand Journal of Marine and Freshwater Research*: 1175-8805

5.7 Dredging

Potential N Removal: Unknown.

Removal of the bottom sediments of the lake, with the aim of removing a source of N and P. An in-depth study on dredging options for Lake Rotorua was undertaken by Miller (2007). Dredging has been undertaken on some very small lakes, such as the 0.63 hectare Oranga Lake in the University of Waikato campus, and has been successful at improving water quality, and can be assumed to remove large quantities of N and P from the lake system. To be successful, the entire sediment cover would need to be removed, otherwise the same issues with release of N and P from the sediments would continue to occur. The following should be taken into account:

- The sediment layer on the bottom of Lake Rotorua is at least three metres deep (Hamilton *et al.* 2007).

- Removal of any sediment would have unknown consequences on the nutrient balance of the lake.

- To remove an area of sediments 30 km^2 to a depth of 10 cm, would result in a total wet volume of three million m^3.

- A large pumping infrastructure would be required to get the wet sediments from the lake to a suitable location onshore.

- Wet sediments would probably need to be dried somewhere to make it feasible to undertake further transport. A location where this could be done without affecting the lake would need to be found. Dewatering technologies could be employed to dry the sludge more quickly, but these all require additional infrastructure and land space.

- A large area of land would be required for disposal of the sediments; perhaps infilling of an open cast mine in the Waikato. However, the sediment material is very fine, and likely to liquefy in seismic events.

- The sediments will contain a number of contaminants, including arsenic and mercury from the geothermal influences that affect Lake Rotorua. PCPs and associated dioxins, used in timber treatment, are also present in lake sediments (Miller 2007). These are likely to limit the usefulness of the sediments for other land uses.

- To dredge 0.5 metres of sediment from all parts of Rotorua deeper than 10 metres, would take four years, operating 24 hours per day, six days per week.

- Methane and hydrogen sulphide gases in sediments are other hazards, and would potentially contaminate the water column.

- Fish and invertebrate life, particularly benthic fauna such as koura and kākahi within the lake bed, and aquatic plant species (both indigenous and introduced) would all be adversely affected by dredging.

- Effects on the water column could be minimal if dredging is undertaken correctly, but an inefficient operator or gear failure could see the sediments dispersed into the lake, which would have adverse consequences for water quality.

- A rough cost estimate by Miller (2007) to dredge part of Lake Rotorua (43.7 km^2) came to $84 - $252 million, with disposal costs being additional (assuming that a culturally and environmentally acceptable disposal site could be found).

- Obtaining a resource consent to undertake such works is likely to be difficult.

Based on the many issues outlined above and the exceedingly high cost to undertake this, this technology has been rejected from further analysis.

References and Further Reading

Miller N. 2007: Summary report on possible dredging of lakes in the Rotorua District. *Unpublished Report*. Prepared for Environment Bay of Plenty by Analytical and Environmental Consultants.

Hamilton D., Pearson L., Hendy C., Burger D., McCarthy M., and Healey T. 2007: Historical and contemporary perspectives on the sediments of Lake Rotorua. *GSNZ Newsletter 143*: 7-13.

5.8 Grass carp

Potential N Removal: Nil. Grass carp (*Ctenopharyngodon idella*) simply recycle the fixed N in plant leaf matter back into the water column as bioavailable N which is useable by phytoplankton for growth.

Introduction of grass carp, a fish species that eats lake weed in large quantities. By eating the lake weeds, they can remove nutrients from the system, provided that the grass carp themselves are harvested from the system so that a proportion of nutrients actually leaves the lake system. The following should be taken into account:

- The amount of N removal is likely to be extremely low as only that retained in the body mass of the grass carp will be removed from the system. Most nutrients will just be recycled within the lake. Grass carp are unlikely to get large enough to meaningfully harvest, thus removal of N will be minimal.
- The use of grass carp would preclude the use of some more viable options, such as weed harvesting (see Section 6.2 below).
- A permit is required under the Conservation Act 1987 to allow the release of grass carp. The chances of making a good case to gain a permit are not high.
- Effects on water quality are likely to be minimal. Turbidity may even increase as grass carp will disturb the lake bed.
- Once released, another exotic species has entered the system, with no natural competitors. The population would require ongoing management. There is ongoing potential for unexpected events to occur.

Based on the very low to zero potential to remove N from the system, this technology has been rejected from further analysis.

References and Further Reading

Hofstra D.E. 2014: Grass carp effectiveness and effects. Stage 2: Knowledge review *NIWA Client Report No. HAM2014-060*. Prepared for the Department of Conservation.

5.9 Hamurana diversion wall (with and without gates)

Potential Tones of N Removal: 54.6 t N per year, and any further increases in load from the Hamurana Stream which is predicted to double over the next 50 years.

A proposed wall to divert the waters from the Hamurana Stream down the Ōhau Channel through the use of a diversion wall, similar to the Ōhau Channel wall in Lake Rotoiti. The wall would be 6-6.5 kilometres long and 30-50 metres offshore.

- A full diversion wall would affect trout fishing opportunities at the Hamurana Stream mouth, although gates could be installed in sections of the wall which could be opened to allow for trout fishing opportunities during the summer months.
- A concern raised during preliminary investigations into this technology, was the effect on the lake bed of not receiving the cold water plume from the Hamurana Stream during the summer months. However, dye tracer studies showed that the plume did not affect the thermocline or biogeochemistry below the thermocline (Gibbs *et al.* 2007).
- Nutrient load modelling (Hamilton *et al.* 2012) found that the proposed diversion would not improve water quality as expected, based on water quality alone.
- It is very likely that most of the Hamurana Stream water is actually moving fairly quickly down the Ōhau Channel, based on current knowledge of lake water mixing (Gibbs *et al.* 2016), and a wall will therefore have little impact on lake water quality.
- Obtaining resource consent for a large wall is likely to be problematic, based on cultural sensitivity, aesthetics and impeding trout fishing from the Hamurana Stream.
- BOPRC and ratepayers have another large infrastructure asset requiring ongoing maintenance and replacement over time.
- The cost of construction is estimated to be in the order of $12 million.

Based on the very high cost and considerable uncertainty as to whether such a structure would actually make a discernable difference to lake water quality, this technology has been rejected from further analysis.

<u>References and Further Reading</u>

Anonymous Undated: Proposed Hamurana Stream Diversion. *Unpublished file note*. BOPRC?

Gibbs M., Abell J., and Hamilton D. 2016: Wind forced circulation and sediment disturbance in a temperate lake. *New Zealand Journal of Marine and Freshwater Research*. 1175-8805.

Gibbs M., Bowman E., and Nagels J. 2007: Hamurana Stream water movement in Lake Rotorua. *NIWA Client Report HAM2007-031*. Prepared for Bay of Plenty Regional Council.

Hamilton D.P., Ozkundakci D., McBride C.G., Wei Y., Liancong L., Silvester W., and White P. 2012: Predicting the effects of nutrient loads, management regimes and climate change on water quality of Lake Rotorua. *ERI Report 005.* Prepared for Bay of PLenty Regional Council.

Rowe D., Gibbs M., Bowman E., and Lodge S. 2005: The Hamurana Stream in Lake Rotorua: some potential effects of its diversion on the trout fishery and on summer nutrient dynamics. *NIWA Client Report HAM2005-025*. Prepared for Bay of Plenty Regional Council.

5.10 Wave barrier at Waiohewa

While the Waiohewa Stream was not included in the scope of this study, due to installation of the denitrification plant there, the installation of a wave barrier along this reach of lake edge was discussed as a potentially more effective and feasible option than the Hamurana Wall discussed above. Concrete motorway dividers could sit on the lake bed about 200 metres offshore, for a distance of about 3.8 kilometres (these may not be visible from the surface, so they would pose a potential navigational hazard on the lake) to prevent wave action hitting the shore, forcing water along to the Ōhau Channel. A structure here would not have the issues of cold water inputs that the proposed Hamurana Wall poses. However, many of the same issues would be faced around consenting: public perception, recreational use of the land by landowners along the 3.8 kilometre stretch, and movement of the issue downstream. If the denitrification plant at Tikitere works as planned, N inputs from the Waiohewa Stream will be minimal, and the wave barrier technology would not be required. If the denitrification does not achieve the expected outcomes, re-examination of this technology may be worthwhile.

5.11 Floating wetlands

Potential Tonnes Nitrogen Removal: 0.46 - 0.76 t nitrogen per hectare per year.

Artificial wetlands constructed on floating beds that are anchored to the lake bed. Of all the wetland technologies, floating wetlands potentially have the highest nitrogen removal rates, being up to four times more effective than a terrestrial wetland in reducing nutrient levels in water bodies (McIntosh 2011), but only if the plant biomass is harvested. The following matters should be taken into account:

- Floating wetlands are very expensive to construct, although they do not require the purchase or lease of land.
- While they can theoretically remove high amounts of N, this is based on trials where water flowed through the wetland. Placement of these wetlands in a stream may therefore achieve similar results. When placed in a lake, however, replenishment of the water beneath the wetland will rely on lake currents, which will be much slower, and therefore N uptake may be limited. Therefore they may have only a minor effect on nutrients in the lake (Gibbs 2015).

- They can have an additional benefit of acting as a wave barrier to reduce re-suspension of sediment in shallow margins of the lake (McIntosh 2011).

- It will be very difficult to actually measure the uptake of N in an in-lake wetland.

- While the theoretical uptake of N is quite high, this is based on high N concentration in the water, whereas the concentration of N in Lake Rotorua is actually very low. Hamill *et al.* (2010) report that the nutrient extraction in Lake Rotorua is expected to be five times less than that recorded in trials due to the low concentration of N in the lake water compared to the stream water trials.

- The $1 million wetland installed in Lake Rotorua broke up in the first real wind event it was exposed to, adding significant cost to an already expensive undertaking. Vandalism has also resulted in damage (a boat is thought to have deliberately rammed into part of it).

- Weeds (particularly willows) are currently invading the existing wetland, and if not controlled, could eventually lead to the collapse of the wetland through increased weight.

- Long-term ongoing maintenance of floating wetland structures is required to remove weeds and periodically remove accumulated biomass. Harvesting is essential.

- Over 28 hectares (or up to 44 hectares) of floating wetland would need to be installed in Lake Rotorua to meet the nitrogen target. Finding suitable areas where there is enough current to allow N uptake to occur, without the wetlands being overly exposed to wave action and extreme wind events, while also being socially acceptable (not blocking boat ramp use for example), is highly unlikely.

- The current trial wetland is 0.4 hectares, therefore massive scale up would be required to reach 28 hectares.

- The lifespan of the wetland is currently not known but could be short as climate change produces more short duration severe weather events.

- Lake birds may be either positively or negatively affected by floating wetland structures as many birds may use them as additional roost habitat.

- Placement along the lake edge near the airport should not be considered, due to the risk of birds roosting on the wetland and then flying across the airport runway to Lake Rotokawa, and vice versa (Wildland Consultants 2013).

- Construction cost is high at $1 million for 0.4 hectares, i.e. $2.5 million per hectare or $70 million for 28 hectares. Ongoing maintenance costs are also high, but have not been quantified.

Based on the high cost and issues experienced with the installed floating wetland to date, unquantifiable but probably relatively low N uptake in-lake, and the sheer scale required to meet the N targets, this technology has been rejected from future analysis. However, it should be noted that if there were other reasons for installing further floating wetlands in the lake, there is nothing essentially ‘wrong’ with the technology that would prevent installation of future wetlands in suitable places, and they could remove a significant amount of N from the lake. For example, a floating wetland could be associated with a tourism destination and include boardwalk structures and interpretation panels. Such a wetland would still provide some contribution to water quality improvements.

References and Further Reading

McIntosh J. 2011: An assessment of effectiveness of a floating wetland. *Unpublished Report*. Prepared for Bay of Plenty Regional Council.

Hamill K., MacGibbon R., and Turner J. 2010: Wetland feasibility for nutrient reduction to Lake Rotorua. *Opus International Consultants Ltd Client Report*. Prepared for Bay of Plenty Regional Council. 82 pp.

Sukias J.P.S., Yates C.R., and Tanner C.C. 2010: Assessment of floating treatment wetlands for remediation of eutrophic lake waters - Maero Stream (Lake Rotoehu). *NIWA Client Report.* Prepared for Environment Bay of Plenty.

Tanner C.C., Sukias J., Park J., Yates C., and Headley T. 2011: Floating Treatment Wetlands: a New Tool For Nutrient Management in Lakes and Waterways. *Unpublished paper*. NIWA.

Tanner, C.C., Sukias, J.P.S., Yates, C.R., Bruere, A., McIntosh, J., Cave, S., Uytendaal, A. (2011). Nutrient removal from agriculturally-impacted streams using floating treatment wetlands. Oral presentation at 15th IWA International Conference on Diffuse Pollution and Eutrophication, Rotorua, New Zealand. 19-23 Sept. 2011.

Wildland Consultants 2013: Lake Rotorua floating wetland – assessment of potential avifauna interactions with Rotorua International Airport. *Wildland Consultants Ltd Contract Report No. 3270*. Prepared for Rotorua District Council. 12pp.

5.12 Removal of sewage from the catchment

Approximately 30 tonnes of N is budgeted to enter the lake through the Rotorua wastewater treatment plant. If another option could be found, then this would mean the additional 20 t would not need to be removed from the system. A body of work has been undertaken on options to remove treated wastewater from the catchment by Rotorua Lakes Council, including diversion straight into the upper Kaituna River. While ecologically and technically feasible, and probably not that costly (in relative terms) this option is not culturally or politically tenable to those in the receiving environment and thus is unlikely to be a serious option in the foreseeable future.

Further Reading and References

http://www.rotorualakescouncil.nz/our-council/consultation-and-public-notices/ Documents/Water percent20Consultation percent20Booklet percent20web.pdf

6. POTENTIALLY FEASIBLE TECHNOLOGIES

6.1 Overview

While there are clear-cut reason(s) for rejection of the above technologies, the following technologies may be feasible under the right conditions:

- Denitrification plant (c.f. Tikitere)
- Lake weed harvesting.
- Natural wetlands.
- Constructed wetlands (with surface flow).
- Denitrification beds/carbon walls.
- Watercress beds.
- Seepage wetlands and grass hedges.
- PAM blocks.
- Removal of N-fixing plant species from the catchment.
- Other considerations.

These options are all discussed further below.

6.2 Denitrification plant (c.f. Tikitere)

Potential N Removal: 25 t N per year.

A denitrification plant is proposed to be constructed on the Waiohewa Stream, at Tikitere. This will treat water with high N from geothermal sources through a series of zeolite beds, before returning the treated water back into the stream. This technology relies on the removal of ammonium-N.

This technology can be rejected from application on other streams in the Rotorua catchment simply because no other streams entering Lake Rotorua have high loadings of ammonium-N, necessary for capture by the zeolite beds. However, if other streams were found to have high loadings of ammonium-N, then this a potentially feasible option.

References and Further Reading

Bouskova A. 2010: Pilot-scale trial for the removal of nitrogen from geothermal water using Lentikats Biotechnology - Final report.

Bruere A. and Sumeran N. 2016: Tikitere nitrogen removal update. *Report to: Rotorua Te Arawa Lakes Programme Steering Group*. *Objective ID: A2293360*. Bay of Plenty Regional Council.

Wildland Consultants 2014: Ecological assessment of a proposed full scale denitrification plant at Tikitere, Rotorua. *Wildland Consultants Ltd Contract Report No. 3432*. Prepared for Bay of Plenty Regional Council. 31 pp.

Woolhouse A. 2013: Assessment of the efficiency of natural zeolite to remove ammonium-N from a high ammonium geothermal stream at Tikitere, Lake Rotorua. Version 1.2 amendments 31 July 2013. *Environmental Management and Training Services Ltd Client Report*. Prepared for Bay of Plenty Regional Council.

6.3 Lake weed harvesting

*Potential Tonnes Nitrogen Remova*l: 0.0012 - 0.0014 t N per t weed harvested.

Approximately 15,400 tonnes of lake weed - being a mixture of all macrophyte plants growing in the lake - would need to be removed from Lake Rotorua to achieve the 20 t target. Lake Rotorua does not contain this volume of lake weed, however, so achieving the 20 t target through this technology alone is not feasible. However, removal of lake weed does remove N from the system, especially if the lake weed is taken out of the catchment. Therefore, even small harvests of lake weed will make a small contribution to overall N targets and there are often other compelling reasons to harvest lakeweed (such as aesthetics).

Extent and volumes of weed in Lake Rotorua vary from year to year and can be almost nothing in some years, to greater than 400 hectares in others (Gibbs 2015). There is often about 150 hectares of weed bed around Kawaha Point, but this is not consistent (Gibbs 2015). Lake weed is still sprayed in the lake front area on a regular basis (Gibbs 2015). This practice could cease and the weed harvested instead as this will remove N from the system (whereas herbicide spraying results in the dead matter and therefore nutrients staying within the lake system). There is a risk that any weed beds allowed to grow would be uprooted in storms and deposited onshore, as has occurred on many occasions. If this occurs, pick up from the shore would still achieve N removal outcomes, provided the weed is taken out of the catchment for composting.

Lake weed has been harvested regularly on other lakes within the Rotorua area, and there is therefore good information on efficiencies and costs of harvest. It is a relatively cheap solution, particularly as there are a number of lakes that harvesting occurs on, achieving scale of operation. Estimated cost is around $41.50 per kg of N removed (Mallinson 2016a and 2016b). The annual cost to remove 20 t of N, if this were possible, is around $830,000. It currently takes about 4.2 hours to remove 1 t of weed (Mallinson 2016c).

Wet weed will require disposal, which will incur additional cost. Additionally, the wet weed may be contaminated with heavy metals, which may limit disposal options.

An option that should be examined in more detail to help increase the amount of N removed through this method is the set-up of specific areas of the lake for weed harvest. This could involve the use of wave barriers to create an environment where weed growth is optimal, from which the weed is then harvested whenever it reaches sufficient size. The size of the harvest area could be specifically designed to be optimised for the harvester with regards to pass length and load size. Ideally it would also be placed where trucks can easily access the area for efficient removal of the weed. It is unlikely that the full 20 t of N removal would ever be achieved by this technology option alone, but it could be worth consideration as part of a suite of options to achieve the 20 t target.

References and Further Reading

Gibbs M. 2015: Assessing lake actions, risks and other actions. *NIWA Client Report No. NIWA2015-102*. Prepared for Bay of Plenty Regional Council.

Mallinson R. 2016a: 2016 Lakeweed harvesting Lake Rotoiti. *Unpublished Internal File Note*. Bay of Plenty Regional Council.

Mallinson R. 2016b: Hornwort harvesting Lake Rotoehu 2016. *Unpublished Internal File Note*. Bay of Plenty Regional Council.

Mallinson R. 2016c: 2014 Hornwort harvesting Lake Rotoehu 2014. *Unpublished Internal File Note*. Bay of Plenty Regional Council.

McRae J. 2014: Hornwort weed business case study. *Deloitte Client Report*. Prepared for Bay of Plenty Regional Council.

6.4 Natural wetlands: protection, maintenance and enhancement

Potential tonnes N removal: Protection and enhancement required. Natural wetlands currently remove 98 percent dissolved inorganic N input from local groundwater inflows. If land development removes or bypasses these natural wetlands, the N load on the lake from this source will increase.

Gibbs and Lusby (1996) found that lake edge wetlands, even in relatively poor condition, removed up to 98 percent of the dissolved inorganic nitrogen from groundwater moving into/through that wetland. However, where the wetlands have been hydrologically altered through drainage or infilling, or vegetation has been cleared, there is little or no nitrogen removal and the dissolved inorganic nitrogen in the groundwater is transported by the groundwater directly into the lake. Some types of infilling do allow localised zones of denitrification to occur, meaning that if done correctly, accessways, or similar could still be constructed through wetlands without losing wetland functionality.

These lake edge wetlands clearly play a substantial and very important role in the control of nitrogen inputs into the lake, as well as also removing phosphorus and bacteria. Importantly, there was no indication of a seasonal pattern to the removal of N; and even grey willow wetlands with little indigenous plant component are effective at N removal.

Case studies were undertaken by Gibbs and Lusby (1996) as part of the study above. The Te Ngae kahikatea stand, at the northern end of the airport, was found to be removing almost 98 percent of the dissolved inorganic N in the groundwater. Importantly, there was an indication that some anaerobic processes played a part in the removal of nitrates from groundwater.

At Hannahs Bay (note that this case study was undertaken prior to significant wetland rehabilitation efforts at that site), the willow-dominated wetland was found to remove

98 percent of the dissolved inorganic-N entering the wetland. However, water in an open drain within the wetland was virtually unchanged as it reached the lake, meaning that it had no interaction with the wetland processes, and thus no N removal. Other open drains within the area had around 50 percent removal, attributed to uptake by beds of watercress and musk (*Mimulus moschatus*) growing along the sides of the drains.

At Hinemoa Point, the wetland there also removed more than 98 percent of the dissolved inorganic-N. At the end of Owhata Road, a very narrow wetland strip of less than 10 metres only removed about 16 percent of the source-dissolved inorganic-N, indicating that contact time in the wetland is important. Because of the narrowness of the wetland, and the presence of upwelling springs very close to shore, the groundwater did not pass though much wetland before entering the lake. However, it should be noted that even a 16 percent reduction in dissolved inorganic-N was a good contribution given the high concentrations present there.

Lake edge wetlands are a 'last resort' before water enters the lake, and can remove significant concentrations of dissolved inorganic-N from groundwater. This means that even wetlands with no obvious overland flow are performing a very important function in the improvement of lake water quality. On this basis, all lake edge wetlands should be formally protected from clearance and drainage, and enhanced where possible. This is a particularly high priority. During this analysis, we became aware that at least one wetland site (probably consisting of grey willow with low biodiversity values) has been recently cleared within the last year. We also know of other losses within the last 5-10 years.

Natural wetlands will already be functioning to remove N from the lake, and thus improvements to the total lake N budget may not be as high as 20 t per year. However, given they are already included in the lake N budget, it is essential that they are all protected from drainage and infilling. This includes what could be regarded as 'scrappy' wet areas full of grey willow as there is an opportunity to restore these areas to better quality wetlands that will make a considerably difference to nitrogen budgets. Many of these areas will fall outside of current protection rules which focus on the biodiversity aspects of wetlands. Protection rules may need to change urgently, to ensure that potential nitrogen removal aspects of all wetlands and wet land (i.e. poorly-drained low-lying land) are considered in order to ensure that these areas do not succumb to land development pressures.

Restoration of existing natural wetlands will be significantly cheaper than constructing wetlands and is the obvious starting point in achieving N targets. Restoration will also achieve other significant biodiversity values for the Region. Wherever possible, natural wetlands should be increased in size through rehabilitation of hydrology. Drains should be redirected through wetlands with the use of bunds, as the research summarised above showed that water in drains was not affected by wetland processes and therefore N was not removed.

The estimated cost to protect the existing wetlands is only $14 per kg N removed (Hamill *et al.* 2010). Appendix 1 shows the location of current natural wetlands identified in the Rotorua catchment. There are 18 lake margin wetlands, ranging in size from 0.01-38.4 hectares, with a total area of 417 hectares (Wildland Consultants

2004). Of these, 12 hectares of natural wetlands have the potential for restoration, which includes drainage correction and weed control (Hamill *et al.* 2010). Restoration of these wetlands alone has been estimated to cost in the order of $2.5 million, and could lead to an estimated additional removal of 0.34 t N per year, comprising 1.7 percent of the 20 t N target. This would also result in other benefits. This works out to be $60 per kg N removed (Hamill *et al.* 2010), which includes potential land lease costs. It should be noted, however, that of the current lake margin wetlands, only four have any legal protection status (Hannahs Bay, Rotorua Lakes Council reserve; Sulphur Bay, Rotorua Lakes Council reserve; Ngapuna, Ngā Whenua Rahui kawenata, Lake Rotorua Marginal Strip, Department of Conservation).

References and Further Reading

Gibbs M.M. and Lusby F.E. 1996: Lake edge wetlands: their environmental significance to the Rotorua Lakes. *NIWA Consultancy Report BPR005/2*. Prepared for Environment Bay of Plenty.

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Wildland Consultants 2004: Digital mapping of freshwater wetlands in the Bay of Plenty Region - based on the freshwater wetlands database and the Regional Digital Aerial Mosiac (RDAM) (desktop study). *Wildland Consultants Ltd Contract Report No. 941*. Prepared for Bay of Plenty Regional Council. 26 pp.

6.5 Constructed wetlands

Potential Tonnes N Removal: 53.3 t N/year if 145 hectares of wetland is constructed (Hamill *et al.* 2010)

Constructed wetlands are an artificial wetland created for the purpose of treating water, using the natural functions of wetland vegetation, soil, and organisms to treat water. Similar to the carbon wall technology described below, it is the organic layer (carbon) that is used by microbes to undertake denitrification of the nitrates in the water. On this basis, N-removal in constructed wetlands can be enhanced through the addition of carbon, in the form of wood chips or similar, during construction. The key advantages of constructed wetlands are (adapted from Hamill *et al.* 2010):

- Able to remove a significant proportion of a catchment’s nitrogen and phosphorus load, especially nitrogen.
- Can remove up to 45 percent or more of the total nitrogen load.
- There a number of sites suitable for the construction of wetlands around the edge of Lake Rotorua where N-removal will make a significant quantifiable contribution to lake N budgets.
- They have low maintenance requirements.
- Can be used to successfully remove nutrients in the subsurface water.
- Provide other biodiversity values.

Constructed wetlands have been used throughout the world to treat water, and are generally quite successful, although there are also equally numerous case studies where they have been found to be ineffective. A trial wetland was installed at Lake Okaro, which is removing 42 percent of the targeted total inflow N. Results were higher in the first year, but additional catchment changes have also occurred, resulting in lower wetland performance (Hudsen and Nagels 2011). This removal rate is not as effective as a natural wetland, where 98 percent removal rates have been found (Gibbs and Lusby 1996), but removal rates may change as the wetland matures and a deeper organic layer is built up. Alternatively, hydrology may need to be re-examined periodically as it is possible that much water is either bypassing the wetland or passing through with insufficient residence time. As with the denitrification technologies, concentration of nitrates in the source water is an important factor in denitrification rates. Flow rates through the wetland are also an important consideration, and in flood events much water may bypass a wetland. Some ongoing maintenance of constructed wetlands is required, particularly weed control and ensuring that water flows are maintained correctly. The Lake Okaro wetland has suffered from lack of maintenance, and maintenance costs should be included in any consideration of this technology.

Hamill (2010) estimated the cost of this technology at $79 per kg N removed to establish the wetlands, assuming leasing of land and an average wetland size of three hectares. Actual costs will depend on the complexity of design work needed to alter the hydrology, land costs, and construction cost, including planting. In some cases, this cost could be reduced considerably if a slightly different approach to be taken to constructing wetlands. Wildlands has used lower cost approaches successfully in a number of places, such as Norske Skog, Kawerau. This involves undertaking the earthworks component and only planting a minimal number of plants in the first year on the basis that once water is present, many wetland plants will self-establish reasonably quickly, thus reducing planting costs (which is often the highest proportion of the cost of establishment).

Construction of 145 hectares of wetland within the Rotorua catchment would remove up to 53.3 t N per year, significantly exceeding the 20 t target. Creation of 145 hectares of constructed wetland requires at least 145 hectares of suitable land to be available and, if possible, the land needs to have an overland water source for this technology to remove the predicted N rates, or to intercept subsurface groundwater flows or an underground spring. Hamill *et al.* (2010) found 181 hectares of land area potentially available and undertook a further study on a potential constructed wetland on the Bonnington property, at the end of Parawai Road (Hamill and Worth 2011). Two concept designs have been developed to divert a portion of the Waiowhiro Stream into the property, with one wetland being 12.1 hectares in size and treating 39 percent of the stream base flow, with storm events controlled by a flood detention basin. Another option would create a 15.2 hectares wetland and treat 90 percent of the flow with storm events controlled by a flood detention basis. The second option may not provide for enough fish passage, and thus the first option treating only 30 percent of the stream flow is likely to be favoured. Cost of construction for option one was estimated to range from $1,357,000 to $2,757,000, or $55.1/kg of nitrogen removed. The second option was estimated to range from $1,564,000 to $3,172,000, or $47.9/kg of nitrogen removed. These costs assume free use of the land and no ongoing maintenance. Planting costs estimates range from $45,000 to $90,000 assuming that 75 percent of the area is planted. Because this proposed wetland is immediately adjacent to a natural wetland, we suggest that it would only be necessary to plant about 50 percent of the area. Maintenance costs are likely to be in the order of $40,000 per year, and would need to include removal of sediment, weed control, and infill planting if required.

Locations potentially suitable for constructed wetlands are shown in Appendix 2. Given the findings that natural wetlands remove a significant amount of dissolved inorganic-N from groundwater, without surface flow, constructed wetlands in the Lake Rotorua context should not be confined to areas with surface flow, but should also include areas where underground springs, upwellings, or swampy wet ground are present. In other words, any damp depression or flattish land close to the lake margin could be considered to comprise a potential candidate for a constructed wetland. All 'wet' areas around the lake margin should therefore be protected immediately from clearance or other forms of loss as we are rapidly losing opportunities to implement these sustainable technologies. Many of the wet areas are proposed as constructed wetlands, and the cheapest way to construct wetlands will be as a continuation of natural wetlands, as planting requirements will be minimal.

References and Further Reading

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Hamill K., MacGibbon R., and Turner J. 2010: Wetland feasibility for nutrient reduction to Lake Rotorua. *Opus International Consultants Ltd Client Report*. Prepared for Bay of Plenty Regional Council. 82 pp.

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Ozkundakci D., Hamilton D.P., and Scholes P. 2010: Effect of intensive catchment and in-lake restoration procedures on phosphorus concentrations in a eutrophic lake. *Ecological Engineering 36*: 396-405.

6.6 Denitrification beds/carbon walls

Potential Tonnes N Removal: 3-5 g of N per day from one m^3 of wood chip.

Denitrification beds and carbon walls are essentially a large container or a trench filled with a high carbon substrate (such as wood chip), through which water passes and a natural microbial denitrification process occurs, converting nitrate to nitrogen gas. They can be placed to intercept ground water (carbon walls) or within a stream or a drain. The key limitation of this technology is that it only removes nitrate-N.

They are also temperature-dependent, relying on natural microbial process and they are concentration-dependent, and the size of the wood chip (or other carbon substrate) is also important. On the positive side, the technology is very simple to implement, once exact placement is known, and relatively cheap to install and maintain.

In order to remove 20 t of N from Lake Rotorua, approximately four million cubic meters of wood chip would be required at a cost of some $160 million for the wood chip alone (L. Schipper, University of Waikato, pers. comm.). Clearly, it is not feasible to find a place(s) where four million cubic metres of wood chip could be placed around Lake Rotorua that would have water flow through it. Therefore, there is no way that this technology alone will remove the targeted 20 t of N from Lake Rotorua. However, this technology could provide a contribution to the target, and would be a simple and cost-effective solution in various places through the catchment. The technology has been trialed in a stream entering Lake Rotoehu, where it was found that the stream water was too cold for it to work effectively. Most streams entering Lake Rotorua are also cold, and most have insufficient nitrate concentration for the technology to work effectively.

We propose that this technology could be applied in a few key places around Lake Rotorua where groundwater springs upwell near the lake edge, often with fairly high nitrate loads, and good flows. Because there is no surface flow, there is little opportunity for wetland vegetation to remove N from these springs. The key advantage is that, once installed, the surface land use(s) can be retained.

Key places that should be investigated further are (see Appendix 3):

- Hinemoa Point springs upwelling (where the wetland was not that effective at N removal in the case study undertaken by Gibbs and Lusby (1996).
- Koutu spring (identified by Max Gibbs, NIWA, pers. comm.).
- Potentially a site at the discharge from the trout hatchery, before water enters the Ngongotaha Stream[1].

Further investigation into the practicality of installing carbon walls in these locations (and other potential locations within the catchment) is required, including a more detailed cost analysis. Potential N removal from the lake through installation of a small number of carbon walls is difficult to quantify, and should form part of further investigation.

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6.7 Watercress beds

Potential Tonnes N Removal: Theoretically up to 5.98 t N/ha/year at high flow rates (Woolhouse 2016); but the reality is likely to be less than this when implemented on a large scale.

Watercress is a ‘luxury’ feeder meaning that it takes up more nutrients than it requires for growth. It is therefore capable of removing large amounts of N from the system, by accumulating excess N and that then being harvested. Watercress is found naturally in many streams and drains, and there is a potential end use as a food product or stock feed.

A trial was undertaken on the Waingaehe Stream by Sukias *et al.* (2009) to evaluate potential N removal from the stream. Two flow rates were trialed (high - 2.4 hours for water to pass through the growing beds and low - 24 hours). To achieve removal of the full 13.6 t N from the Waingaehe Stream, between 2.3 hectares and 14 hectares of watercress beds would be required, subject to the flow rates used (Woolhouse 2016). This assumes that nutrient uptake remains constant as nutrients are stripped (unlikely), and that there is no seasonal variation in uptake rates (which there will be). The trial size was only 0.02 percent of the scale required, so limitations could well be found during scale-up implementation.

Approximately 16 hectares of land is still available in the lower reaches of the Waingaehe Stream that could possibly be converted into watercress beds (not considering flood protection implications; c.f. Freeman and West 2008).

To be feasible, this technology would need to consider the implications of diverting entire streams through watercress beds (or, recover less nitrogen, but divert only part of streams to leave in-stream values intact, particularly for trout spawning). Issues to consider in the implementation of this technology include:

- Ongoing operation of the watercress beds; whether this undertaken commercially or not, water flow needs to be maintained and the watercress harvested to maximise N uptake.
- Watercress growth is seasonal, and there is an assumption that nutrient uptake remains constant as nutrients are stripped, which is unlikely. Therefore N removal rates are therefore likely to have been overestimated.
- Watercress also readily absorbs arsenic and mercury, which are both toxic to humans and stock. High levels of these metals will prevent the watercress being on-sold, and thus commercial operation may not be viable. Plants can replace up to 30 percent of their P with arsenic, making that material toxic to animals.
- Costs include implementation, but also ongoing maintenance and harvesting requirements. Costs can be assumed to be the same as constructed wetlands as it will involve earthworks and planting.
- Further investigation would be required to determine who would undertake the ongoing maintenance and harvesting. If a commercial provider is used, there is a risk that being driven by commercial markets will detract from the N-removal purpose.
- Cost of implementation is similar to that for a constructed wetland (see above), but there will be ongoing costs associated with this technology. Wetlands also provide additional biodiversity benefits that would not be provided by watercress farming alone.
- Watercress farming would require surface flows, rather than subsurface flows which can be ‘exploited’ for N removal using natural wetlands, constructed wetlands, and carbon walls.

Further scale-up trials and investigation into this technology are warranted, given its potential to remove large amounts of N. There are a number of potential locations for the creation of watercress beds in the catchment. These are all at the same locations as constructed wetlands and thus there would need to be a trade-off between the best option at each site. Watercress plantings could be easily included in constructed wetlands, relying on local foragers to provide the harvesting component required. Where the object of any riparian strip is nutrient uptake, active management will be required to minimise stream channel shading and allow plants such as watercress to survive (Howard-Williams and Pickmere 2010). When shading occurs, less nutrient uptake occurs over time (Howard-Williams and Pickmere 2010).

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6.8 Seepage wetlands and grass hedges

Potential Tonnes N Removal: around 2.3 t/year but very uncertain. Grass hedges could remove significant amounts of N in high rainfall events.

Seepages: enhancing existing and creating new

Seepage wetlands occur around seeps and springs, and in reality are often no more than very wet pasture. Around seven hectares of seepages have been identified by Hamill *et al.* (2010), but the condition of these is unknown. There could easily be more or less, as they are very small areas, not readily visible on aerial photography. Fenced seepages will already be acting to remove N from the system. Fencing, some minimal planting and drainage correction if required (particularly of bunds to allow sediments to settle) is estimated to cost in the order of $20 per kg N removed (Hamill *et al.* 2010). This means that this is a very cost-effective option at the landscape scale. At the individual property scale, it will require landowner buy-in and may have some impacts on grazing land. On the positive side, these areas may be where stock get stuck, and thus farmers may be quite willing to see these fenced off. Policies and rules should be implemented to encourage farmers to protect and restore seepage wetlands.

More work is required to identify the locations of seepage wetlands within the catchment and to determine associated management requirements.

Grass Hedges

Grass hedges are essentially a farming practice where by temporary fences are erected to create a band of protected managed grass that provides a buffer between possible contamination sources and a water body (Sukias *et al.* 2009). They only function when there is surface runoff during or following a rainfall event, and land can therefore be grazed periodically. Long grass removes N in the surface flows and collects fine sediment, reducing PN and PP[1] inputs into streams. This technology could be combined with the construction of bunds to provide settling of sediments, which removes a large component of PN and PP load. Further benefits could be obtained through the installation of PAM blocks in these areas, installed in covered flumes to prevent stock damage and to channel water flows over them. See the section on PAM blocks below. Grass hedges are new a farming practice which is a simple technological solution, and should be implemented through farmer education and Regional Council land management staff. Further trials are needed to determine how best to use this as a management technique to maximise nutrient uptake.

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[1] Particulate phosphorus

6.9 Anionic PAM blocks

Potential Tonnes N Removal: unknown at this stage. They remove total suspended solids which includes PN and PP.

Anionic Polyacrylamides (PAM) blocks are a well-tested technology that is mostly used in New Zealand during earthwork construction to collect fine sediments e.g., Mackays to Peka Peka Expressway near Wellington (NZTA 2012). They work by binding fine sediments, and thus remove N and P from situations where fine sediment doesn't settle. They work best in conjunction with settling ponds, but require slow flowing water; about 20 l/s has been found to be optimum. They would work well in detention bunds and, for a low cost, could be installed in all detention bunds throughout the catchment to enhance sediment entrapment. They are considered completely safe, and are used throughout the world in drinking water systems. America and China are the largest users worldwide (Gibbs 2015) where anionic PAM is applied to irrigation water for crops to reduce soil erosion and keep soil on the land. It has been used in America since 1995, and a vast body of research has been undertaken on its use and safety (Sojka and Surapaneni undated). Auckland Council has undertaken some studies into the safety of anionic PAM blocks in waterways and has concluded that they are safe to use. The blocks dissolve slowly over time.

Blocks could easily be retrospectively installed throughout a stormwater network to improve water quality entering the lake through this means, only working during rainfall events.

Gibbs (2015) recommended that further investigation was warranted for the use of anionic PAM blocks for managing sediment runoff from farmland. He also noted that it had a potential role as a flocculent in bunds designed to trap sediment on land, accelerating the settling of fine sediment that would otherwise flow into surface streams. The solid block application can be used where there is intermittent flow such as stormwater outfalls or on the inflows to pastoral bunds used for sediment trapping. It can also be applied in liquid form as a replacement for alum, to enhance settling of suspended solids including PN and PP in open water bodies.

Sojka and Lentz (1997) estimated the cost at $US37-$US88 per hectare when applied in irrigation water. The cost of anionic PAM will depend on how it is applied, and in what situation. There is a body of overseas literature on application rates, but some further work is likely to be required for the New Zealand context. The cost is in the order of $AU360 for three kilograms of blocks.

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6.10 Removal of N-fixing plant species from the catchment

Potential Tonnes N Removal: around 38 kg/ha/yr

Nitrogen budgets for the catchment currently include the removal of 30 tonnes of N from gorse removal, based on one study by Magesan and Wang (2008), which showed that on one particular soil type, gorse could be leaching excess N into groundwater. The subsequent policy to remove gorse could be expanded to include numerous other N-fixing plants growing within the catchment, some with greater rates of N-fixation than gorse (McQueen *et al.* 2006), and that many of these grow directly in waterways, wetlands, or in damp areas, where it is absolutely certain that excess N will be entering waterways and/or groundwater systems directly, without any possible recovery through other plant uptake. This was also pointed out by Gibbs (2015).

Alders are significant fixers of nitrogen (McQueen *et al.* 2006), grow close to and within waterways, and have large root systems. Therefore, much of the excess N that they produce is very likely to be contributing to the N-load of the waterways they occur in. Alders occur extensively through the Rotorua catchment, particularly along the Puarenga Stream[1]. Alders are likely to be having a greater impact than gorse in the catchment, due to their preference to grow near waterways, and due to being a long-lasting tree (versus gorse shrubs which are usually eventually replaced with indigenous species within 15-20 years, if left). Other N-fixing species, such as wattles, lupins, and Scotch broom should also be removed from wet areas, and further studies should be undertaken to see what effect these trees are having on groundwater

[1] Note that some of the alders along the Puarenga Stream are an important kawau (shag) nesting colony site. This is a relatively small proportion of the total alder infestation in the catchment.

N levels, including further evaluation of gorse. Further studies should also be undertaken on other commonly planted N-fixing species - such as lucerne and clovers - growing within the catchment as it may be necessary to place restrictions on planting of these where there is a risk that excess N could leach into waterways or groundwater, particularly when planted over shallow groundwater. Lucerne can fix 100 kg N ha^{-1} y^{-1} and leach about 25 kg N ha^{-1} y^{-1} into the groundwater from cut and carry (McLeod 2015). Grazing on-site increases the loss of N to groundwater.

If removal of gorse is predicted to remove 30 tonnes of N from the catchment, then removal of alders and other N-fixing plants in wet locations, could result in the removal of another 30 tonnes or more. A small study on the extent of nitrogen-fixing species in the catchment would be inexpensive and, if the leaching rates from gorse were to be extrapolated in lieu of detailed studies, the actual tonnes of N could be calculated adequately.

On the assumption that there is approximately 100 hectares of alders and wattles within the catchment along waterways, then removal of these would cost in the order of $42,500 (assuming that no traffic management or particularly specialised tree felling skills are required). Ongoing maintenance control would also be required as both species can regenerate prolifically.

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6.11 Other considerations

A number of small scale initiatives and actions, if implemented together, may also contribute to the 20 t N reduction target. These include:

- An in-depth investigation into stormwater inputs into Lake Rotorua, and identification of opportunities to intercept and treat this water before it enters the lake, including a requirement for new development to consider nutrient load, not just water volume, in the design of new stormwater systems. Scholes (2013) notes that stream nutrient loads may be up to 50 percent higher than what is cited, due to fluxes in storm events.

- An investigation into N and P runoff from an urban environment, particularly the home gardens and small lifestyle blocks which are currently exempt from any restrictions around fertiliser use, but from which high runoff directly into the lake may be occurring through the over-use of off-the-shelf fertilisers. Such a study should also examine how restrictions could be placed on the use of these, or whether education alone is sufficient.

- Efforts such as sweeping leaves from streets prior to a predicted rainfall event to reduce the N and particularly the P load carried down stormwater drains with fallen leaves.

- Providing car washing stations throughout the city to prevent public from washing straight into stormwater drains. Runoff from the stations would be on-treated through a series of settling ponds, anionic PAM block baffles, and a constructed wetland. While education campaigns can urge people to wash cars on lawns, many urban properties no longer have sufficient lawn space for car washing.

7. IS THERE A SOLUTION HERE?

This review has evaluated engineering solutions able to potentially remove 15 to 20 tonnes of N from Lake Rotorua. The review has included both in-lake interventions and within catchment interventions. All technologies were robustly debated in an expert workshop, and the arguments for and against each technology have been captured above. It is evident that removal of an additional 15 to 20 tonnes of N from the lake is possible, but potentially costly, subject to the approaches used.

Protection of existing wetlands and 'scrappy' wet areas of naturally-occurring low-lying poorly-drained land has to be the first priority towards achieving the 20 t N targeted reduction. These wetlands, even degraded ones, as Gibbs and Lusby (1996) showed, can remove up to 98 percent of the total N entering the lake through surface and groundwater flows. This N removal will already be captured with lake nutrient budgets, so they must all be absolutely protected from drainage and development, as a first step. During research for this review, we became aware of at least one wetland area that has been drained in the last few years for development, reducing future opportunities for wetland enhancement and construction. Where possible, nutrient uptake of existing wetlands should be enhanced, and enhancement of existing wetlands could increase N uptake for only $14 per kg of N removed. Construction of wetlands as a continuation of natural wetlands and in other wet areas also has the potential to meet the 20 t N target, if enough are constructed and they work as planned. Constructed wetlands could include watercress as part of the planting mix to ensure good N reduction, and this could be harvested as part of regular wetland maintenance. The cost of constructed wetlands is estimated at $79 per kg of N removed.

Quantifying the N difference that enhancement or even construction of wetlands will make will not be simple, and a suite of solutions should be implemented which also includes the construction of denitrification walls in some key sites to intercept groundwater flows, and lake weed harvesting (in years when weed beds are of sufficient extent).

The cost to undertake these options needs further analysis, as there are many assumptions associated with each costing. This means that existing numbers from the literature may not be directly comparable depending on what has and has not been included in the cost. As stated in Section 6.5, most of the cost assumptions around constructed wetlands are based on what it cost to construct the Lake Okaro wetland. Based on Wildlands' experience, there are significantly cheaper ways to construct wetlands, particularly when already adjacent to existing wetlands. Further work into the potential costs for constructed wetlands is therefore warranted. Table 3 shows the cost of the acceptable technologies per kg of N removed. An attempt to provide a cost to implement the technology has also been made, based on published figures.

Table 3: Potential costs to implement technologies likely to be feasible for N removal in the catchment of Lake Rotorua.

Technology	Cost ($) per kg N Removed	Cost ($) to Implement Over Catchment	Reference
Lake weed harvesting	42	To remove 15,400 tonnes of lake weed[1]; $830,000.	Mallinson 2016a and 2016b.
Natural wetlands - protection	14	417 hectares to protect through policy changes and lease arrangements or land purchase. If all land was purchased at a rate of $14,550 per hectare (drystock value), then the cost for complete protection in perpetuity would be $6,067,350.	Hamill *et al.* 2010: Dairy NZ 2015. http://www.rotorualakes.co.nz/vdb/document/ 1353.
Natural wetlands - enhancement	60	12 hectares estimated to be enhanced; $2.5 million (including land lease, so would be less if already purchased).	Hamill *et al.* 2010.
Constructed wetlands	79	145 hectares land area available: $16,261,460 based on Lake Okaro costs[2]; or $2,900,000 based on a much lower cost of $20,000 per hectare.	Hamill *et al.* 2010.
Denitrification walls	22	Costs estimated at US $3,249 to set up; assume tjree walls are constructed; approximate cost of $15,000.	Schipper *et al.* 2010.
Watercress beds	79	Assume same cost as constructed wetlands, but need to consider ongoing operation costs also.	Hamill *et al.* 2010.
PAM blocks	?	Approximately $245,000 (US) to treat a large sediment pond in a construction context, but more research required to	Pitt *et al.* 2007.

[1] Note that Lake Rotorua is unlikely to have this volume of harvestable weed.
[2] These costs also likely to include land leasing.

Technology	Cost ($) per kg N Removed	Cost ($) to Implement Over Catchment	Reference
		determine real costs in the Lake Rotorua scenario.	
Removal of N-fixing plants	11	Approximately $42,500 based on 100 hectares of alder and wattle in wet areas/waterways within the catchment.	Wildland Consultants calculation based on professional weed control charge out rates.

Although the Regional Council has already undertaken an extensive process around Plan Change 10, changing of land use within the catchment has to be considered as a cost-effective way of removing 20 t N. If land was to be purchased for $14,550 per hectare then, for $12 million (the cost of constructing the Ōhau Channel diversion wall), then 824 hectares of key areas could be purchased and planted or managed back to indigenous vegetation. Control of this scale of land area could see drastic changes able to be made to lake nutrient budgets. Buying of catchment land by regional authorities in order to control land management activities for water quality purposes has been undertaken before. New York city has purchased or protected over 53,000 hectares since 1997 under its Land Acquisition Program, after costing treatment options and deciding that land use change was the most cost-effective and most enduring approach.

8. NEXT STEPS

Actions that could potentially lead to 20 t N reduction in Lake Rotorua, as well as removal of phosphorus, in order of relative importance, are:

- Protect all existing wetlands from development and drainage, now. Protection should be formal and in perpetuity. These wetlands are already functioning to remove N from lake nutrient budgets; further reduction of these will increase the amount of N that needs to be removed through 'other' means. Only four lake edge wetlands currently have any legal protection status.

- Protect and/or purchase 'wet' land adjacent to existing wetlands, where wetlands could easily be extended or constructed (shown in Appendix 2). These 'wet' and scrappy areas are likely to be under extreme pressure from development, and the land must be secured in some sort of arrangement with the Regional and/or District Council soon, before these opportunities for constructed wetlands are lost.

- On a case-by-case basis, look at what can be done to enhance N uptake by existing wetlands, including fencing, weed control (particularly alders), blockage or rerouting of drains, construction of stormwater detention bunds.

- On a case-by-case basis, examine what is required, and the cost, of constructing wetlands in key locations. In some very wet areas, only minimal earthworks may be required, making the cost of construction considerably less than has been quoted previously.

- On a case-by-case basis, undertake further feasibility studies into the construction of denitrification walls to intercept key underwater flows into the lake, where wetland construction is not possible.

- Investigate the actual extent of seepage wetlands in the catchment, and whether or not they are already retired from farming. Determine the resources required to fence and plant these areas.

- Investigate the potential for installation of anionic PAM blocks into the Rotorua city storm-water network, and into farm sediment ponds in such a way that they are protected from stock.

- Cease spraying of aquatic weed in Lake Rotorua and plan to harvest it out of the lake when it becomes a nuisance to lake users, or when beds reach sufficient extent to do so.

- Investigate further options for changes in land use within the catchment to reduce the amount of N reaching the lake in the first place. This could include investment of some of the money that would have been spent on high cost technological solutions, such as building of the Hamurana Wall, into key land purchases and wetland enhancement.

9. CONCLUSION

A range of technological options have been examined for removal of an additional 20 tonnes of N from the catchment of Lake Rotorua. All technologies have been discussed in previous reports to Bay of Plenty Regional Council, and for some, quite in-depth analysis has been undertaken on their feasibility. Of the technologies discussed, there is no single solution or silver bullet technology solution available to the Council. The best options still remain to protect and construct wetlands close to the lake edge to mop up the nutrients before they enter the lake. Wetlands may not be a technologically advanced solution, but they offer the best value for money solution, are proven to work, offer a range of other wider benefits, and are a long-term permanent and sustainable solution that does not rely on continuous resource consent requirements. An alternative approach would be to look at changing land use higher in the catchment, through incentives or land purchases, so that the 20 tonnes is removed from the nutrient budgets. Further investigation of this option is required.

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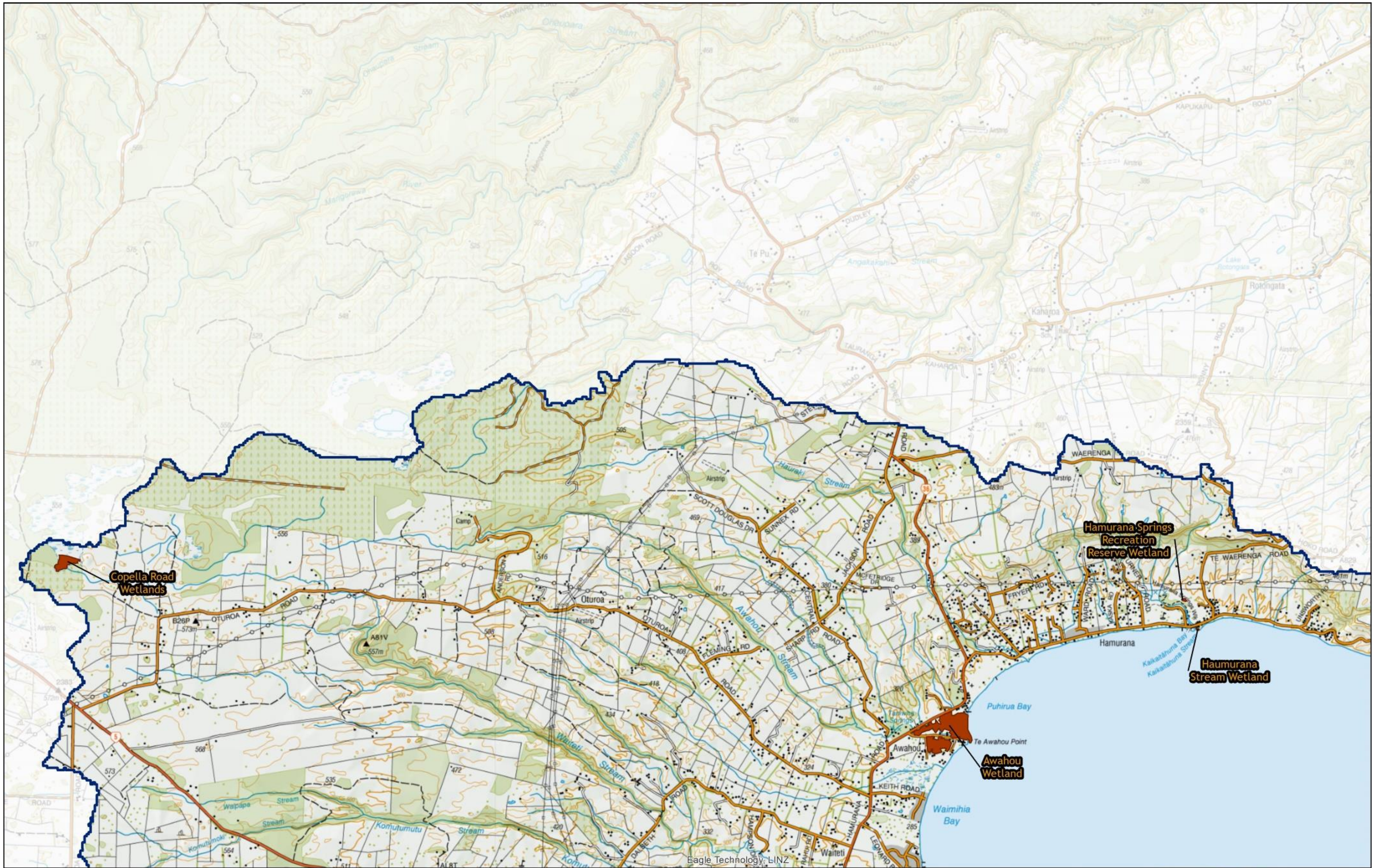
APPENDIX 1

EXISTING WETLANDS
IN CATCHMENT

(as mapped by
Wildlands 2004, 2005a, 2005b)



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Data Acknowledgment
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Client: BOPRC
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Legend
- Current extent of wetland
- Rotorua catchment boundary

Figure 1. Existing wetlands within the Rotorua catchment
Page 1 of 5

0 2.5 5 km

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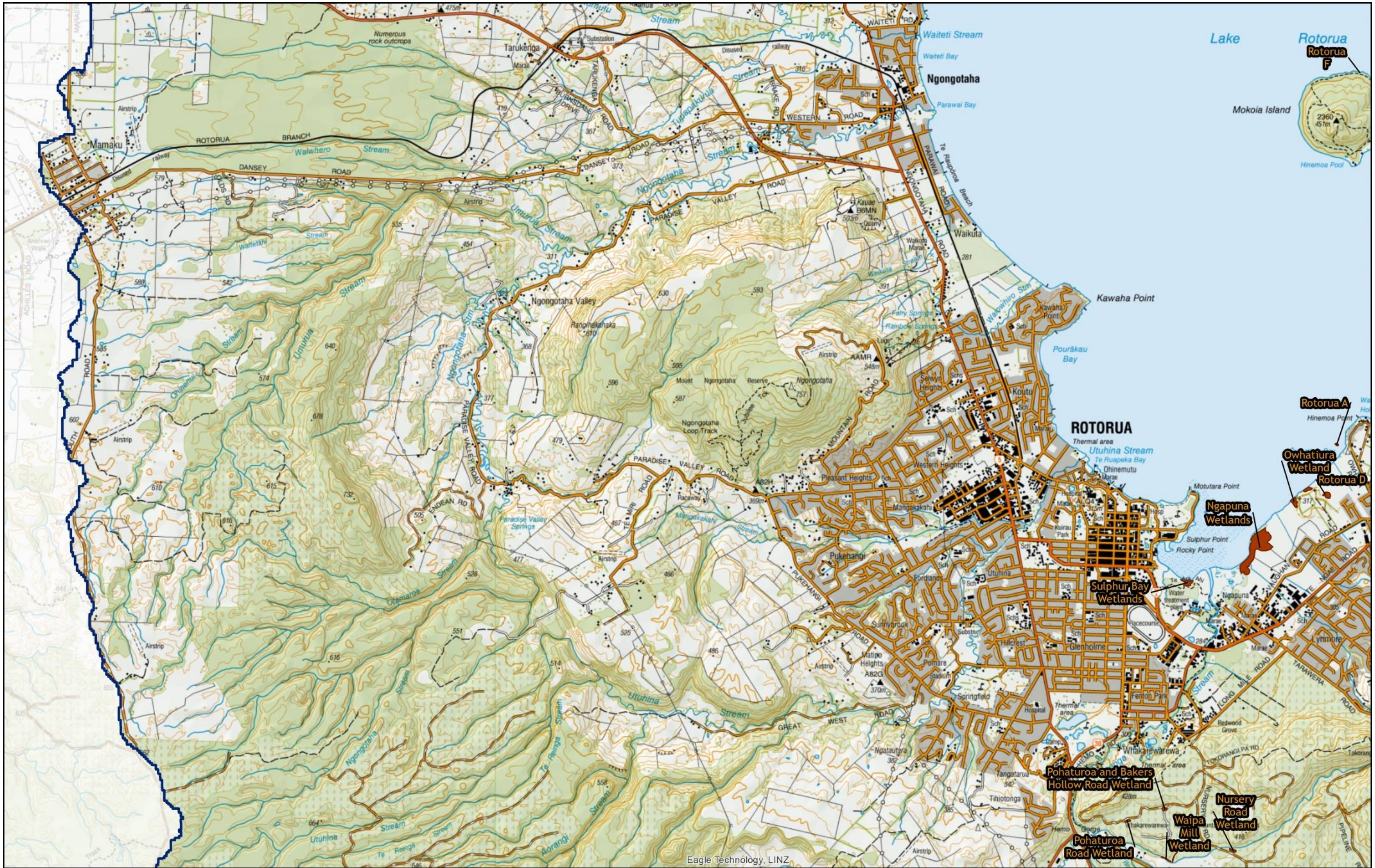
Scale: 1:50,000
Date: 25/07/2017
Cartographer: RPB
Format: A3R



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Legend
Current extent of wetland
Rotorua catchment boundary

Figure 1. Existing wetlands within the Rotorua catchment
Page 2 of 5

0 2.5 5 km

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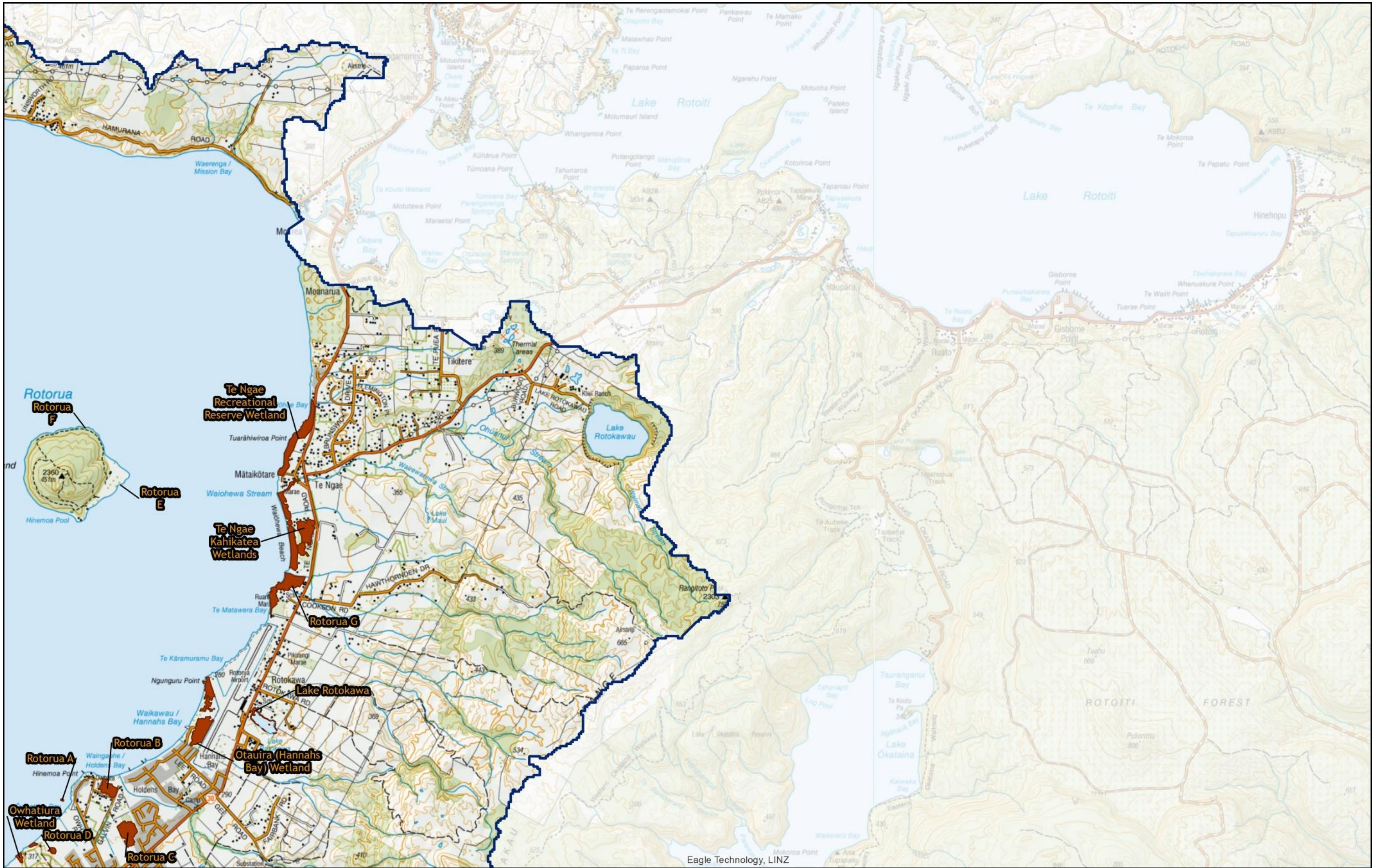
Scale:	1:50,000
Date:	25/07/2017
Cartographer:	RPB
Format:	A3R



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Legend
- Current extent of wetland
- Rotorua catchment boundary

Figure 1. Existing wetlands within the Rotorua catchment
Page 3 of 5

0 2.5 5 km

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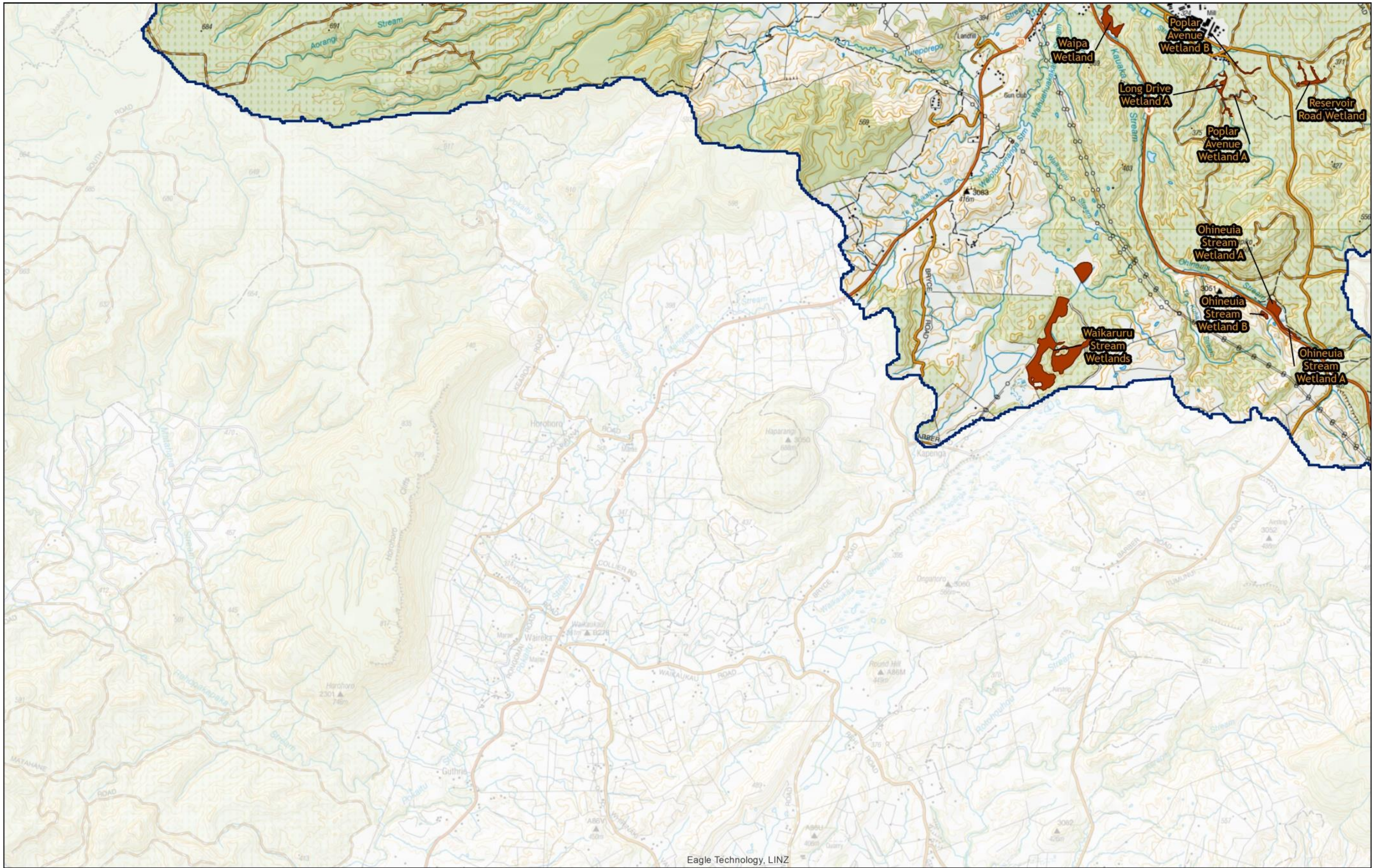
Scale: 1:50,000
Date: 25/07/2017
Cartographer: RPB
Format: A3R



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Legend
Current extent of wetland
Rotorua catchment boundary

Figure 1. Existing wetlands within the Rotorua catchment
Page 4 of 5

0 2.5 5 km

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Scale: 1:50,000
Date: 25/07/2017
Cartographer: RPB
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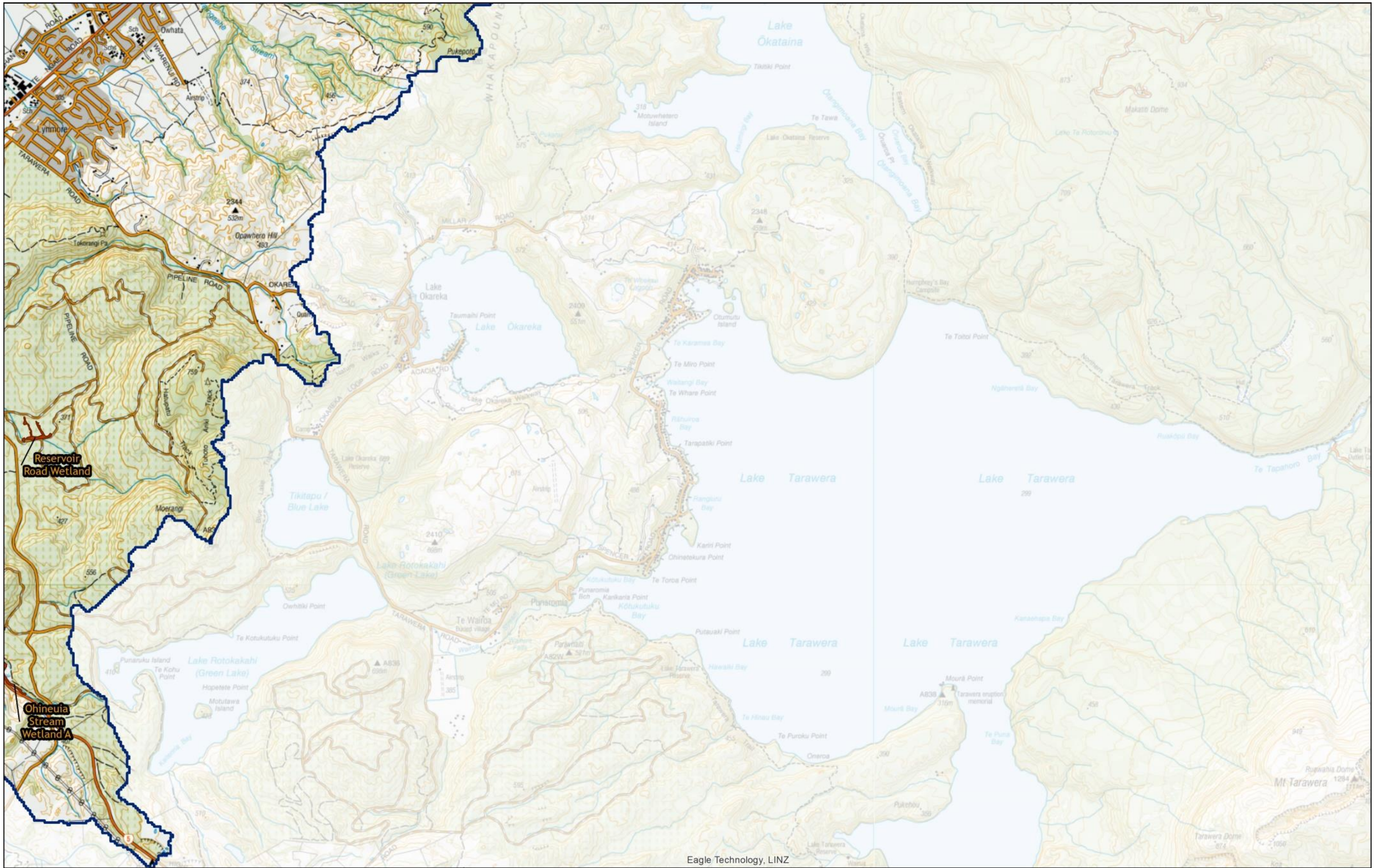

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File: Figure_Existing_wetlands.mxd

Legend
Current extent of wetland
Rotorua catchment boundary

Figure 1. Existing wetlands within the Rotorua catchment
Page 5 of 5

0 2.5 5 km

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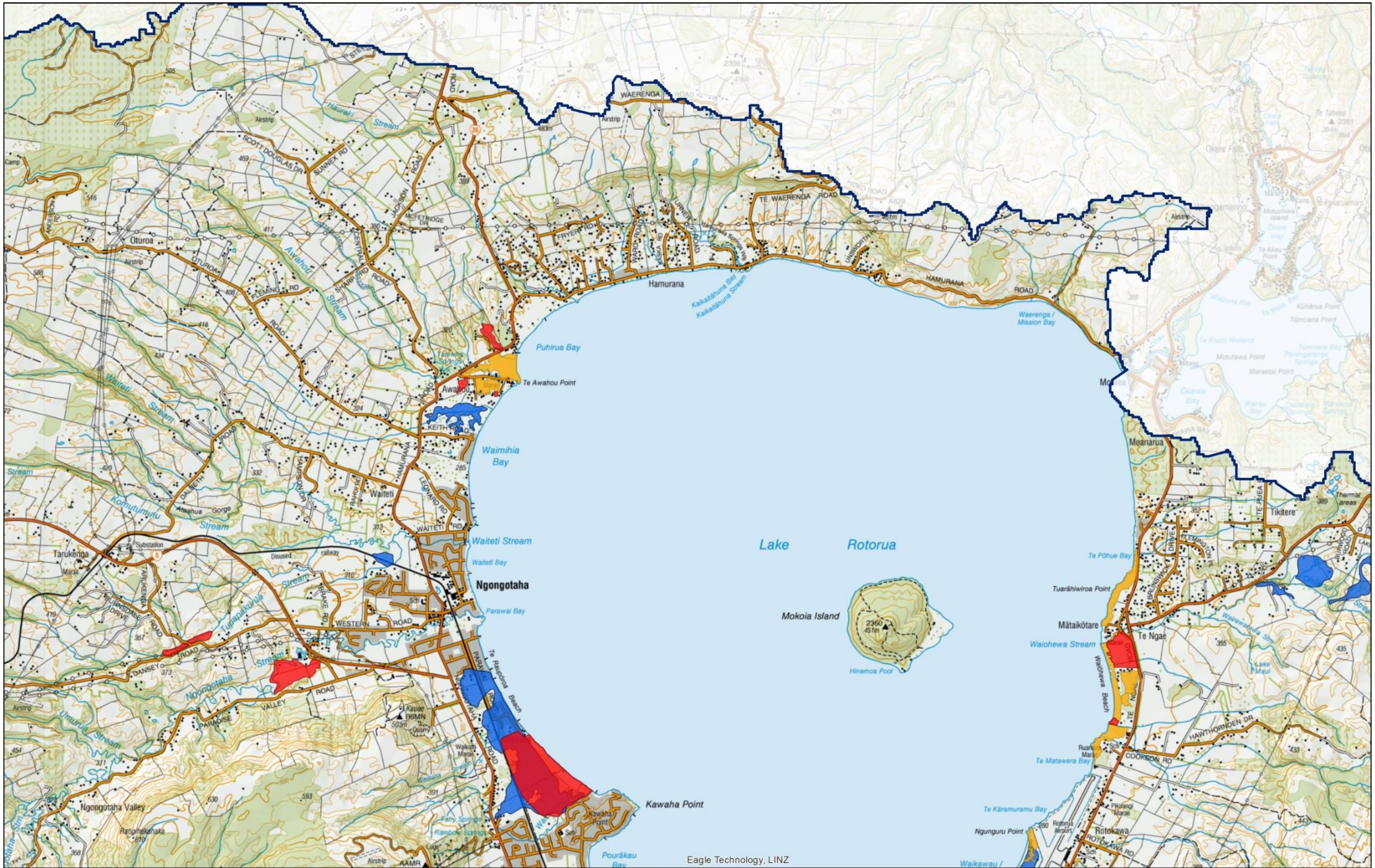
Scale:	1:50,000
Date:	25/07/2017
Cartographer:	RPB
Format:	A3R

APPENDIX 2

POSSIBLE LOCATIONS FOR CONSTRUCTED WETLANDS

(Note that these locations are indicative only and based on a brief mapping exercise by Hamill *et al.* 2010 and the authors own knowledge of the Rotorua catchment; each potential location would require its own case study to ascertain landownership and technical feasibility of wetland construction. Historic wetlands known to Te Arawa is Wildland's own digitisation of the wetland extent as recorded by Don Stafford (Stafford 1994).



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Report: R4181
Client: BOPRC
Ref: 01 1752
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File: Figure_Pot_constructed_wetlands.mxd

Legend
- Rotorua catchment boundary
- Potential constructed wetlands
- Current extent of wetland
- Historic wetlands known to Te Arawa

Figure 2. Potential areas for construction within the Rotorua catchment
Page 1 of 2

0 2.5 5 km

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Scale: 1:50,000
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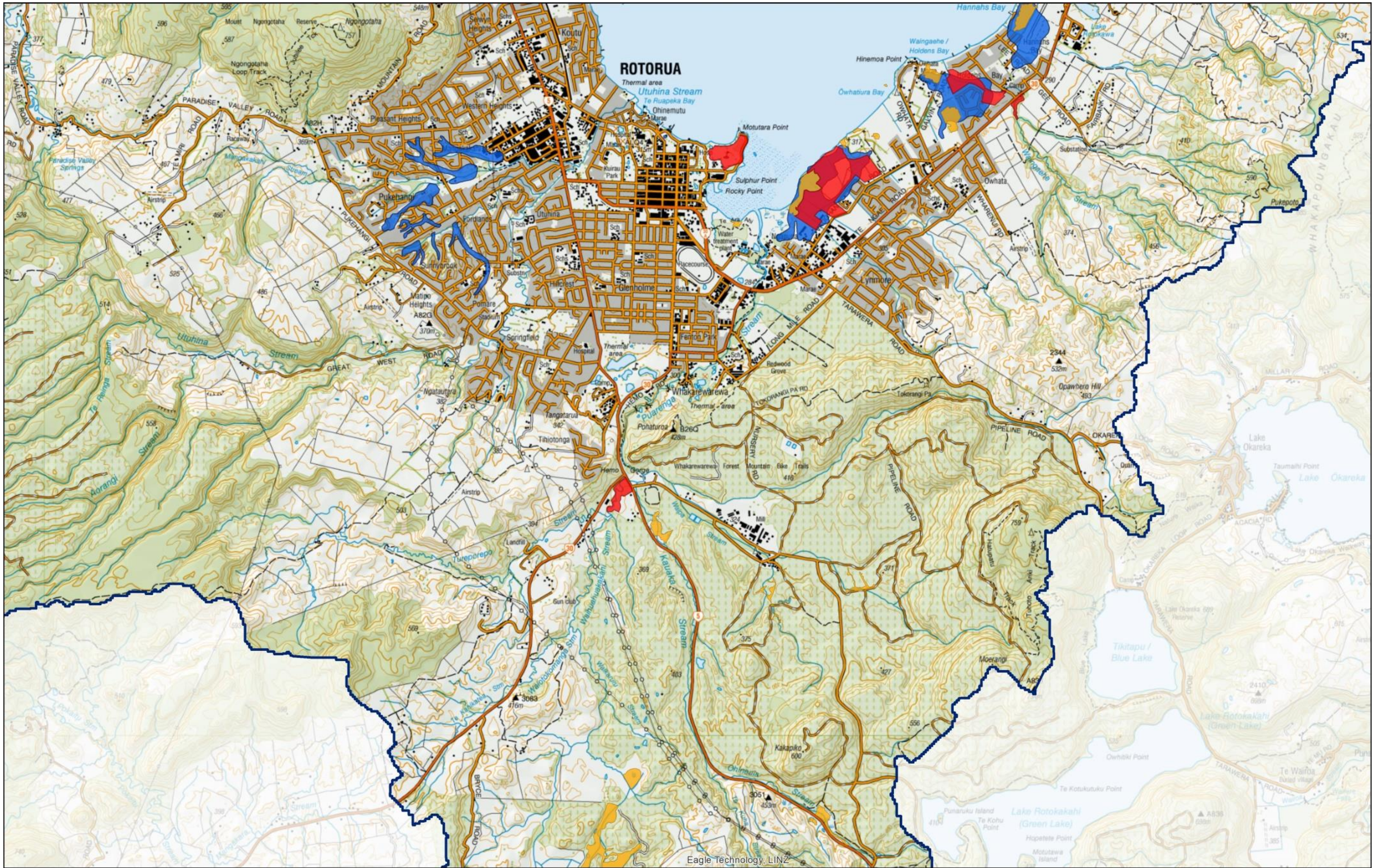
Format: A3R



N	**Data Acknowledgment**	**Legend**
	Map contains data sourced from LINZ Crown Copyright Reserved	Rotorua catchment boundary
	Report: R4181	Potential constructed wetlands
	Client: BOPRC	Current extent of wetland
	Ref: 01 1752	Historic wetlands known to Te Arawa
	Path: E:\gis\LakeRotorua_NitrogenProject\mxd\	
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Figure 2. Potential areas for construction within the Rotorua catchment
Page 2 of 2

0 2.5 5 km

Technology, LINZ

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Scale:	1:50,000
Date:	25/07/2017
Cartographer:	RPB
Format:	A3R

APPENDIX 3

POTENTIAL DENITRIFICATION WALL LOCATIONS TO INTERCEPT UPWELLING SPRINGS ON THE LAKE MARGIN

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Client: BOPRC
Ref: 01 1752
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File: Figure_Denitrificationwall.mxd

Figure 3. Potential location of a denitrification wall

0 500 1,000 m

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