Wetland Feasibility for Nutrient Reduction to Lake Rotorua

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Prepared for
Bay of Plenty Regional Council

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Executive Summary

The Proposed Lakes Rotorua and Rotoiti Action Plan sets a target to remove nitrogen (N) loads to lake Rotorua by 311 tonnes/yr and to reduce phosphorus (P) loads by 35 tonnes/yr. Nutrient reduction targets required from agricultural land are 230 tonnes N/yr and 10 tonnes P/yr.

Establishing wetlands for nutrient removal is one intervention being considered for reducing N and P loads from surrounding land uses to achieve these targets. This report presents the results of a feasibility study to assess the cost-effectiveness of different types of wetlands and potential for a package of wetlands to remove nutrients entering Lake Rotorua.

The effectiveness of different types of wetlands to achieve long-term sustainable nutrient removal was assessed based on results reported in literature and using a tanks-in-series kinetic model. The key criteria for effective nutrient removal using wetlands were identified, these include:

- High hydraulic loading (e.g. >30 m/yr)
- High concentration of incoming nutrients (e.g. nitrate N >1.5 mg/l)
- Warm incoming water temperature (e.g. warmer water improved denitrification)
- High hydraulic efficiency (e.g. minimal short circuiting or bypass flow) (aspect ratio of 4:1 – 6:1)
- High proportion of vegetation cover
- Settlement ponds for pre-treatment
- Stable base flow to minimise need to bypass storm events
- Natural / seepage wetlands present in the landscape
- Existing natural seepage wetlands compromised, but able to be remediated (e.g. removing drainage, reinstating vegetation removal)
- Suitable land available and accessible for maintenance
- Value for nutrient attenuation > value of partial drainage
- Willingness of landowners to use land for treatment wetlands.

The preferred location of treatment wetlands in the Rotorua catchment was identified mapping current concentrations in different sub-catchments, mapping existing wetlands and identifying possible locations for constructed wetlands through discussions with Bay of Plenty Regional Council (BOPRC) land management staff. This identified 417 ha of natural wetlands, 181 ha potentially available for constructing treatment wetlands, 12 ha of natural wetland area that could be restored for nutrient attenuation and 7.2 ha available for restoring seepage wetlands for nutrient attenuation.

The effectiveness of different wetland types for sustainable removal of nitrogen was, in order of effectiveness:

floating wetlands > constructed wetlands > seepage > natural wetlands.

The order is slightly different for long term sustainable phosphorus removal with natural wetlands outperforming seepage wetlands. The average removal rates are shown in the table below.

Effectiveness of different wetland types (average removal)

Average treatment performance	constructed wetland	Natural SF wetland	Seepage wetland	Floating wetland
TN (kg/ha)	368	289	323	714
TP (kg/ha)	11	10	2	13

Protecting existing wetlands from drainage and degradation was identified as the most cost-effective policy option. The cost-effectiveness of different wetland types for sustainable removal of nitrogen removal was, from cheapest to most expensive:

seepage < natural surface flow wetlands < constructed wetlands < floating wetlands.

For phosphorus removal, seepage wetlands drop two places and were more expensive per kilogram removed than constructed wetlands. The average cost-effectiveness is shown in the Table below.

Cost-effectiveness of different wetland types. Average and (inter-decile range)

Wetland type	constructed wetlands	Restoring Natural SF wetlands	Restoring Seepage wetlands	Floating wetlands	Protecting natural wetlands
cost effectiveness TN ($/kg)	$79 (64-97)	$60 (47-85)	$20 (14-29)	$437 (330-570)	$14 (11-18)
cost effectiveness TP ($/kg)	$2,548 (1650-4600)	$1,714 (1110-3190)	$2,739 (1600-4720)	$24,271 (17000-35900)	$431 (260-870)
cost effectiveness TN & TP ($/kg)	$76 (63-94)	$58 (45-82)	$20 (14-28)	$429 (330-560)	$13 (10-18)

Three wetland packages were developed for removal of nitrogen. These were:

- An ‘optimal’ $1 million package (maximising the area of wetland types that provide the most cost effective nitrogen treatment to the extent to which suitable sites exist);
- A ‘practical’ $1 million package (reducing the area of wetland types that have low certainty about availability of suitable sites); and
- A ‘maximum’ package which estimates the cost and nutrient load reduction if all suitable sites in the catchment were used.

It should be noted while wetlands are low maintenance systems, they still require some maintenance and renewal. Our whole-of-life costs have accounted for ongoing maintenance, renewal and lease costs, thus for any wetland package some money (about 20 - 25%) should be put aside to cover these future costs.

The results of each package are shown in the table below:

Nutrient reduction from $1 million wetland packages in Rotorua catchment

$1 million wetland packages for nutrient reduction ($0.963M NPV)	Total Nitrogen (tonnes/yr)	Total Phosphorus (tonnes/yr)	Make up of package (as % of area)
Practical package	1.26 (1.1 - 1.5)	0.033 (0.022 - 0.047)	54% (2.1ha) constructed, 22% (0.8ha) natural SF, 24% (0.9ha) seepage
Optimal package	2.00 (1.6 - 2.5)	0.042 (0.025 - 0.061)	50% (3.4ha) natural SF, 50% (3.4ha) seepage

This project identified the cost-effectiveness of different types of wetlands at removing nutrients from entering Lake Rotorua. Two $1 million wetland packages were developed. An 'optimum' package consisting of 50% seepage wetlands and 50% natural SF wetlands (by area) was estimated to remove 2.16 tonnes N/yr (+/- 22%) and 0.038 tonnes P/yr (+/- 43%) for every $1 million invested (as Net Present Value (NPV)). .

A 'practical' package consisting of 55% constructed, 22% natural SF and 24% seepage wetlands (by area) was estimated to remove 1.34 tonnes N/yr (+/- 16%) and 0.033 tonnes P/yr (+/-38%) for every $1 million invested. We calculated the budgeted target for removing N by the Lake Taupo Protection Project to use as a rough comparison, this is about 1.6 tonnes N/yr per $1 million, which is comparable to the wetland packages.

We identified areas in the Rotorua catchment that might be suitable for treatment wetlands. A scenario that utilises all identified wetland sites across the landscape (a 'maximum' package) would cost $54.4 million and remove about 59.1 tonnes N/yr (+/- 15%), corresponding to about 26% of the nitrogen reduction target sought from the catchment. The actual amount of land available for creation of treatment wetlands needs field validation, but our analysis has shown that wetlands can be a realistic option within a package of interventions to reduce nitrogen and phosphorus loads to Lake Rotorua.

Wetlands are not the whole solution to reducing nutrient loads to Lake Rotorua but they should certainly be considered as part of the solution. Furthermore, consideration could be given to investing more than the $1 million currently allocated. In addition to nutrient attenuation, this could provide benefits for biodiversity, cultural values and recreation that have not been considered in this analysis.

Treatment wetlands could most efficiently be created in the landscape by providing incentives for landowners to reduce nutrient loads. The uptake of using treatment wetland will depend to a large extent on the policy framework, for example if reverse auctions are used they would need to allow the sale of many small packages of nutrient credits and not be limited to just larger packages.

A number of recommendations are made for further work to improve understanding of using wetlands to reduce the nutrient load to Lake Rotorua.

1 Introduction

1.1 Background

Lake Rotorua is under pressure from development and land-use changes that have contributed to reducing lake quality to its current 'eutrophic' state and recent algae blooms. Catchment land use activities are a major source of nitrogen and phosphorus to the lake which enter the lake via streams, springs and groundwater.

Bay of Plenty Regional Council (BOPRC) has developed 'Action Plans' for some of 12 of the Rotorua lakes that describe interventions that should be taken to reduce nutrient inputs to the lakes in order to meet nutrient goals and improve lake water quality. The Proposed Lakes Rotorua and Rotoiti Action Plan sets a target to remove nitrogen (N) loads to Lake Rotorua by 311 tonnes/yr and to reduce phosphorus (P) loads by 35 tonnes/yr. Nutrient reduction targets required from agricultural land are 230 tonnes nitrogen/yr

Establishing wetlands for nutrient treatment is one intervention being considered for reducing nitrogen and phosphorus entering Lake Rotorua from the catchment. Bay of Plenty Regional Council (BOPRC) commissioned Opus International Consultants and Scion to investigate the feasibility and cost-effectiveness of establishing wetlands to reduce nutrient loads entering Lake Rotorua. The purpose of the study was to provide high level assessment to allow decision makers to compare the cost-effectiveness of different types of wetlands and the use of wetlands generally with alternative interventions (e.g. nutrient trading) to reduce nutrient loads to Lake Rotorua.

The key outcomes specified in the project brief were to:

- Develop a set of criteria for identifying and assessing the effectiveness of wetlands for removing nutrient (nitrogen and phosphorus);
- Assess the potential nitrogen and phosphorus reductions and costs for a range of wetland types;
- Develop a package of potential areas of wetlands that are likely to deliver the most effective nutrient removal within the budget of $1 million dollars spread equally over two years (2012/13 to 2013/14);
- Assess the viability of implementing a package of wetlands for reducing nutrient loads to Lake Rotorua using the assessment template provided by BOPRC.

The intervention assessment framework provided by BOPRC consisted of the following criteria:

- Description of intervention (e.g. wetland type or package);
- Situation characteristics (what problem is being managed);
- Characteristics of intervention (what impact will it have and how widely can it be used);
- Other factors to consider.

This project provides a method and estimates for comparing the potential of different types of wetlands to remove nutrients in terms of dollars per kilogram per hectare of wetland per year and to estimate how many kilograms of nitrogen and phosphorus can be removed using a package of wetlands costing one million dollars. The project does not attempt to estimate the total amount of nutrients removed by wetlands in the Lake Rotorua catchment which would require a comprehensive understanding of wetland coverage and condition.

The project was intentionally restricted in scope to the use of wetlands for removal of nitrogen and phosphorus. Wetlands have many other functional benefits (e.g. providing values for biodiversity, aesthetic, recreation, water storage and flood attenuation) that are not part of our analysis. Similarly, we have not accounted for potential negative aspects of wetland creation such as the potential emission of greenhouse gases (e.g. CO_2, CH_4, N_2O), although for well managed wetlands greenhouse gas emissions are generally low (Kadlec and Wallace 2009).

1.2 Types of wetlands

There are three basic types of wetland treatment systems: a) natural wetlands, b) constructed surface flow (SF) wetlands and c) constructed sub-surface flow wetlands. Constructed wetlands replicate and optimise the treatment conditions found in natural wetlands, but unlike natural wetlands they take time to mature to maximum performance levels[1]. Treatment efficiency is enhanced by optimising dispersion, flow paths, water depths, residence times and vegetation characteristics. Cost-effectiveness can be improved by utilising natural features of the landscape; these are sometimes called ‘facilitated wetlands’.

Wetlands can be applied at a range of spatial scales (from a small wetland treating a tile drain to a large wetland at the base of a catchment) and there are a range of variations on the basic wetland treatment systems. McKergow *et al* (2007) identified several types of wetlands considered to be most applicable for cost-effective treatment of diffuse agricultural flows. These were: natural seepage wetlands, constructed wetlands managing surface water, constructed wetlands managing subsurface water, floating wetlands and harvested aquatic plant systems. A number of systems to potentially enhance nutrient attenuation were also noted including: denitrification walls, wood chip filters, and adding reactive materials to wetlands (e.g. sawdust as a carbon source or alum to immobilise phosphorus).

In this project we assessed the following types of wetlands:

- Constructed surface flow wetlands (constructed wetlands with a significant surface water influence from streams). These can be a range of sizes from large constructed wetlands (e.g. Lake Okaro wetland) to small paddock scale wetlands to treat flows from tile drains.
- Natural surface flow (SF) wetlands (natural wetlands with a significant surface water influence from streams).
- Seepage wetlands and lake fringe seepage wetlands. These are typically small (<1 ha) wetlands associated with groundwater seeps and springs that can occur

[1] The experience from Lake Okaro suggest this can take several years.

anywhere in the catchment. Lake fringe seepage wetlands were identified by Gibbs and Lusby (1996) as acting as a last line of protection against pollution for the Rotorua lakes. Seepage wetlands are often drained and degraded so have potential to restore for improving nutrient attenuation.

- Constructed floating wetlands. The use of floating wetlands to remove nutrients is a new technology but trials at Lake Rotoehu have shown promise (Sukias 2010).

We have not included in our assessment constructed subsurface flow wetlands because there are very few examples of these being used to treat diffuse source pollution from agricultural land. Design guidelines have been developed for constructing wetlands for treatment of tile drainage (Tanner *et al*. 2010); these are constructed surface flow wetlands treating water from subsurface flow.

In some cases there are no clear boundaries between one wetland type and another. For example, some 'constructed surface flow wetlands' may be on the lake edge and merge with lake fringe seepage wetlands. Enhancing existing wetlands on the lake edge could include either seepage wetlands or lowland natural wetlands.

1.3 Structure of document

In order to keep this document concise detailed discussion about wetland processes for sustainable, long term nutrient removal and description of assumptions used in the cost-effectiveness model are described respectively in Appendix 1 and Appendix 2.

Chapter 2 describes the general approach used in assessing cost-effectiveness of different wetland types and in developing a package of wetlands for nutrient removal.

Chapter 3 describes the factors controlling the effectiveness of nutrient removal by wetlands. Further information on wetland processes is described in Appendix 1.

Chapter 4 describes the sources of nutrients and location of wetlands in the Lake Rotorua catchment.

Chapter 5 assesses different wetland types for removing nutrients to Lake Rotorua using the BOPRC template.

Chapter 6 compares the different wetland types.

Chapter 7 discusses potential wetland packages to reduce nutrients to Lake Rotorua; and

Chapter 8 draws broad conclusions based in previous discussion.

2 Approach to assessing wetland nutrient attenuation

2.1 Assessing wetland effectiveness

The effectiveness of wetlands to reduce nutrient loads from the Rotorua catchment was assessed in this report against three general criteria. These were:

1. Cost-effectiveness - $ cost per kg of nutrient removed.
2. Overall nutrient reduction potential - ability to reduce a high percentage of catchment load.
3. Ease of use - installation, operation and maintenance.

These criteria are consistent with a system developed by McKergow *et al*. (2007) to compare the potential of different tools to remove pollutants from diffuse pollution. The criteria were used to assess the effectiveness of each wetland option using a framework provided by BOPRC.

2.2 General method

The cost-effectiveness of wetlands at removing nitrogen and phosphorus was assessed for each wetland type. The nutrient removal effectiveness and total costs of each wetland type was estimated based on values in the literature, established models and experience. The model inputs were adjusted to reflect typical temperatures and nutrient concentrations found in the Lake Rotorua catchment. The effectiveness of different wetlands in removing nutrients is discussed in Section 3 and Appendix 1 and 2.

The range of uncertainty around removal rates and costs was estimated as well as the most likely (median) values. The software package @RISK was used to estimate the uncertainty around removal rates and costs by using the range of estimates (i.e. a pert distribution was fitted to minimum, maximum and median values for removal rates, and a triangular distribution fitted for costs).

All costs were expressed as net present value (NPV) using a real discount rate of 8 percent and annualised over 50 years. This period incorporated initial construction and acquisition costs, and annual maintenance. It recognised the longevity of wetlands and incorporated a price for future wetland rejuvenation to maintain ongoing treatment performance. Land was assumed to be leased for constructed wetlands, natural surface flow wetlands and seepage wetlands, but there was assumed to be no cost of land purchase for the establishment of floating wetlands. The cost of wetland establishment, maintenance and rejuvenation can vary considerably from one wetland type. The method and assumptions are further described in Appendix 1.

For treatment wetlands to be successfully used on a catchment scale there must be sufficient land available for their construction and in an area where there is sufficient nutrient load to be treated. Overall nutrient reduction potential was assessed by identifying the amount of land (near a stream, seep or spring point) potentially available for establishing wetlands in the Lake Rotorua catchment. The major nutrient loads to the lake were identified, known wetlands were mapped and key stakeholders were engaged using a workshop to identify the best locations for different wetland options. This workshop included input from relevant regional council land management and liaison staff. The workshop identified potential locations for different wetland types that could be realistically considered.

It is important to consider the practicalities of implementing and operating any intervention to reduce nutrient loads. These practicalities are discussed in each intervention template.

The wetlands that provided the most cost-effective treatment of nitrogen were combined as a package of wetlands for the Lake Rotorua catchment to provide nutrient treatment. This package had three components:

- An 'optimal' $1 million package[2] (maximising the area of wetland types that provide the most cost effective nitrogen treatment to the extent to which suitable sites exist);
- A 'practical' $1 million package (reducing the area of wetland types that have low certainty about availability of suitable sites); and
- A 'maximum' package which estimated the cost and nutrient load reduction if all suitable sites in the catchment were used.

We estimated the total N and P reductions as a result of these wetland packages and assessed the overall effectiveness of wetlands using the BOPRC effectiveness template.

[2] Spread equally over two years (2012/13 to 2013/14) as requested by BOPRC.

3 Factors controlling effectiveness of nutrient wetlands

There are several processes by which nutrients are processed within a wetland but only a few of these result in long term, sustainable removal. Denitrification (or other degassing), particulate settling and accretion of sediments are the only long term, sustainable processes for nutrient removal. Other processes such as sorption are reversible, and most nutrients taken up by wetland plants are eventually cycled back into the system. Wetland processes controlling the sustainable removal of nitrogen and phosphorus are discussed in Appendix 1.

The key feature of sustainable nutrient removal by wetlands is a trade-off between removal efficiency and load reduction. The actual mass of nitrogen removed increases with loading, thus increasing the hydraulic loading results in more kilograms of nitrogen (N) removed, but this is at the expense of less percentage reduction in concentration; this is illustrated in Figure 3.1.

There is a direct linear correlation between load reduction and nitrate concentration of the incoming water – the higher the concentration of nitrate the more that will be removed. The line representing 2 mg/l concentration is about the same as average catchment nitrate used in this report (i.e. 1.9 mg/l by 2030), 1 mg/l is at the lower end of stream water concentrations found in the Rotorua catchment. See Appendix1 for further discussion.

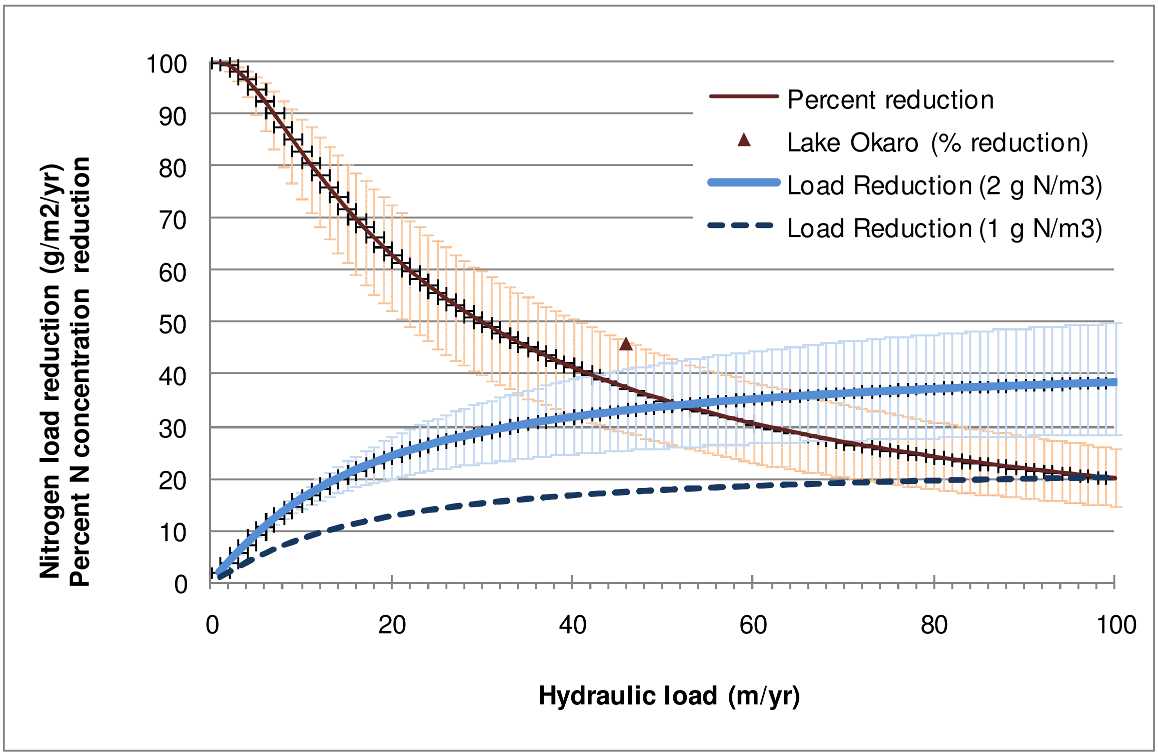


Figure 3.1: Estimated nitrogen reduction with increasing hydraulic load for surface flow wetlands in Rotorua catchment. Error bars are +/- three standard errors plus uncertainty around global warming. Parameters: Ci=2 mg/l, $k_{15.5}$ = 23 m/yr, N = 3.5. (1 g/m^2/yr = 10 kg/ha/yr)

3.1 Criteria for optimising nutrient removal by wetlands

Table 3.1 lists criteria for establishing wetlands in the landscape for effective nutrient removal. All wetlands have potential to attenuate nitrogen or phosphorus, but this can be optimised by giving attention to appropriate design, appropriate placement in the landscape, and appropriate management. The table shows the relevance of each of the criteria to different wetland types. When it comes to constructing any particular wetland, specific design criteria should be applied, particularly to ensure appropriate sizing for the hydraulic load.

Table 3.1: Criteria for effective nutrient removal by treatment wetlands (Y= relevant, '-' = not relevant to wetland type)

Criteria	Constructed	Natural SF	Seepage	Floating	Comment
Treatment Performance Factors					
High hydraulic loading (e.g. >30 m/yr)	Y	Y	Y	Y	Removal rates increase with hydraulic loading (although % removal decreases). Investigation is needed to understand how to maintain a high hydraulic load to a floating wetland in a lake environment.
High concentration of incoming nutrients (e.g. nitrate N >1.5 mg/l)	Y	Y	Y	Y	Removal rates directly correspond to incoming concentrations. Wetlands deriving their nutrients from lake water (e.g. floating wetlands, some lake edge wetlands) will have low removal rates due to low lake water nutrient concentrations (e.g. Lake Rotorua TN = 0.45mg/l compared to 1.9 mg/l from incoming water).
Speciation of incoming nutrients (nitrogen as nitrate, phosphorus as inorganic particulate P)	Y	Y	Y	Y	N removal rates tend to be higher for nitrate nitrogen. Wetlands are more effective as filtering TP when it is in the form of inorganic particulate phosphorus.
Warm incoming water temperature	Y	Y	-	Y	Denitrification rates increase with temperature up to ~60^{o}C. Higher removal rates could be expected if

Criteria	Constructed	Natural SF	Seepage	Floating	Comment
					constructed wetlands receive water warmed by geothermal activity.
High hydraulic efficiency (e.g. minimal short circuiting or bypass flow) (aspect ratio of 4:1 – 6:1)	Y	Y	Y	Y	Draining a wetland or seep will allow nutrient loads to bypass any treatment. Trials of floating wetlands suggest high hydraulic efficiency.
High proportion of vegetation cover	Y	Y	Y	Y	Vegetation is important for improving hydraulic efficiency, filtering and providing a source of carbon for denitrification.
Settlement ponds for pre-treatment	Y	Y	-	-	Settlement ponds prior to the wetland itself can improve sediment retention and possibly phosphorus retention where particulate P is a significant component of the P load.
Landscape Factors					
Stable base flow to minimise need to bypass storm events	Y	Y	Y	-	A stable base flow can be improved by control structures in the catchment.
Natural / seepage wetlands present in the landscape	-	Y	Y	-	Existing natural wetlands are already removing nutrients. This function needs to be protected.
Existing natural seepage wetlands compromised, but able to be remediated (e.g. removing drainage, reinstating vegetation removal).	-	Y	Y	-	The potential to increase nutrient attenuation of natural wetlands depends a lot on the practicality of reversing degradation.
Suitable land available and accessible for maintenance.	Y	Y	Y	-	E.g. low lying areas, naturally prone to inundation and with sufficient hydraulic head between input and outlet.
Value for nutrient attenuation > value of partial drainage.	-	Y	Y	-	Draining a wetland conflicts with nutrient removal but consideration does need to be given to drainage needs of neighbouring land.

Criteria	Constructed	Natural SF	Seepage	Floating	Comment
Willingness of landowners to use land	Y	Y	Y	-	Constructing or restoring treatment wetlands relies on land owners having the right incentives and motivation.

The effectiveness of many wetlands at attenuating nutrients can be significantly enhanced by ongoing management; for example, by removing sediments from sediment traps, or periodic grazing by sheep of seepage wetlands in the summer.

Using natural features of the landscape improves the cost-effectiveness of constructing wetlands (i.e. facilitated wetlands) by utilising existing hydrology, landform and soils. In some cases natural seepage areas historically contained wetlands and restoring these by changing drainage, fencing and planting can improve the ability for nutrient attenuation.

Nutrient attenuation by wetlands is generally better when the inflowing water has higher nutrient concentrations, increasing the cost-effectiveness of establishing wetlands in these areas. Wetland P removal will be better in catchments with higher concentrations of particulate phosphorus, while wetland N removal will be better in catchments with high N concentrations.

Having land available and access for maintenance are obviously critical for establishing a wetland and ensuring the ongoing effectiveness. In practice this will depend on landowner willingness to volunteer, lease or sell their land. It costs money to create wetlands for nutrient control.

3.2 Balancing nutrient removal with other values

Wetlands provide many ecological, aesthetic and hydraulic values but if wetlands are to be optimised for attenuating nutrients they require specific design and management which may compromise other values. Although it may be possible to establish wetlands for nutrient treatment it may not always be desirable.

The main conflicts relate to alternative uses for flood control, wildlife and biodiversity values. Wetlands are often used for flood control and attenuation of peak flows. While adding wetlands to the landscape will add to the peak flood storage, the utilisation of a treatment wetland for peak flood storage may impair its treatment potential (e.g. causing scouring of deposited material in the wetland). Conversely, natural wetlands are often compromised by drainage, and reversing this drainage could cause flooding of upstream properties.

Treatment wetlands will create wildlife habitat; but optimising wildlife habitat may conflict with design goals. For example, habitat for wildfowl is often improved by having areas of open water, however open water can reduce carbon supply and the availability of microbial sites for denitrification. Similarly grazing by wildfowl could reduce the cover of submerged vegetation. Treatment wetlands need to be managed for nutrient removal first and any additional benefits second.

Studies have found different vegetation resulting in different nitrate removal rates (e.g. *Potamageton* sp. were found to be more effective than *Glyceria*, and *Phragmites* stands to be better than open water (Weisner 1997 in Kadlec and Wallace 2009). However, there is no strong evidence that plants that degrade the biodiversity value of a wetland will degrade its nutrient treatment ability. Restoring a degraded wetland by plant pest control will not necessarily improve its ability for nutrient treatment. In contrast, draining a wetland or allowing incoming water to bypass the wetland will always reduce its treatment.

Changing the hydrology or nutrient loads to wetlands can significantly change the character of the wetland, altering the plant species and fauna. Accelerated eutrophication of wetlands can result in the development of filamentous epiphytes on aquatic plants, loss of native macrophytes and sometimes the loss of all macrophytes (Howard-Williams 1985). Similarly, changing the hydrology of a geothermal wetland could have major implications for it character. Care is needed when adding additional nutrient load to a wetland that would not have occurred naturally.

In many cases improving nutrient attenuation will be complementary to biodiversity values. This will particularly be the case when addressing drainage issues to prevent bypass flow and improve nutrient treatment. Also adding a constructed wetland to the front end of an existing natural wetland can improve overall treatment and provide a buffer to the existing wetland.

4 Source of nutrients and location of wetlands in Lake Rotorua catchment

4.1 Introduction

This section broadly discusses the sources of nutrients to Lake Rotorua, and the location of current wetlands with potential for treatment in the catchment. This information is used to estimate the potential loads of nitrogen and phosphorus that wetlands could remove and to broadly identify potential wetland sites in the Lake Rotorua catchment.

4.2 Sources of nutrients to Lake Rotorua

The total nitrogen and phosphorus loads to Lake Rotorua is about 783.1 tonnes/yr and 39.8 tonnes/yr respectively. In addition to this are lake bed sediment releases of about 360 tonnes N and 36 tonnes P that can be recycled into the water column from the lake bed up to 10 times per year. The Lakes Rotorua and Rotoiti Action Plan set targets of reducing nitrogen loads by 2017 by 250 tonnes/yr and reducing phosphorus loads from the catchment by 10 tonnes/yr (plus 25 tonnes/yr reduction from in-lake recycling) (Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust 2007).

The nutrient losses from the various sources in the Lake Rotorua catchment have been estimated in Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust (2007). The catchment land uses contributing most to nitrogen loss are: Pasture (72%), urban (6.4%), geothermal (5.4%) and native forest (5.4%). The catchment land uses contributing most to phosphorus loss are: Pasture (42%), urban (9.6%), geothermal (3.5%) and native forest (3.3%). The pasture land uses with the highest nitrogen loss coefficients are dairy (50 kg/ha/yr), beef (35 kg/ha/yr) and sheep/beef (18 kg/ha/yr). After weighting the coefficients according to the area of each landuse in the Rotorua catchment the average nitrogen loss coefficient is 28 kg/ha/yr and the average phosphorus loss coefficient is 0.8 kg/ha/yr. Since wetlands take land out of production, these weighted average loss coefficients were added to the estimate of nutrient attenuation by constructed wetlands – accounting for this reduction in leaching increases overall wetland nutrient attenuation by about 10 %.

About 75% of groundwater derived nitrate enters the lakes for nine major streams, about 20% from the lake bed and about 5% from the lakeside springs and minor streams (Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust 2007).

The average nutrient loads and concentrations for the major catchments entering Lake Rotorua are summarised in Table 4.1. Figure 4.1 shows the Lake Rotorua sub-catchments and indicates those with 'high potential for phosphorus removal' and 'high potential for nitrogen removal'. Long term phosphorus removal associated with sediment deposition is much more effective at removing particulate phosphorus (e.g. P bound to sediments) rather than dissolved phosphorus. Thus catchments with 'high potential for phosphorus removal' were defined as those with relatively higher concentrations (>0.02 mg/l) of particular phosphorus[3].

[3] Particulate P was defined as total phosphorus minus dissolved reactive phosphorus (DRP).

Long term nitrogen removal by denitrification is much more effective when there is a higher nitrate concentration in the incoming water. Thus catchments with 'high potential for nitrogen removal' were defined as those with relatively higher concentrations (> 1 mg/l) of dissolved inorganic nitrogen (DIN) - the vast majority of which is in the form of nitrate. Waiohewa Stream is an exception, its strong geothermal influence warms the water but also results in most of its DIN being in the form of total ammonia, which needs to oxidised prior to denitrification. Warmer water can substantially increase the rate of nitrogen removal in wetland systems, but this is somewhat balanced by wetlands having lower removal rates for total ammonia compared to nitrate (Kadlec and Wallace 2009). A denitrification plant is currently planned for the Waiohewa Stream and the effect of this will need to be considered before any wetland is constructed near the stream.

Table 4.1 shows average loads and concentrations under base flow conditions because we have assumed the wetlands will be designed to have bypass flows during flood conditions. In the Waiohewa Stream the concentration of dissolved inorganic nitrogen (DIN) increases slightly with flow, so there may be potential to improve the capacity for wetland nitrate removal by designing a batch flow treatment system.

The load of nitrogen entering Lake Rotorua is predicted to increase over the next 250 years as old groundwater slowly travels to the lake. The increase in N load to Lake Rotorua over time is shown in Table 6 of Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust (2007). If maintained wetlands can attenuate nitrogen in perpetuity but for the purpose of this analysis we have annualised costs over 50 years. We have estimated average nitrate concentrations for each catchment in 2030 (i.e. halfway through the annualised period) and used this in our modelling. The concentrations in 2030 were estimated by using two thirds of the fractional increase between 2005 and 2055 (i.e. a non-linear increase)[4].

We have assumed that work to construct wetlands for nitrogen attenuation will focus on catchments identified in Table 4.1 as having 'high potential for nitrogen removal'. Thus we have used the average nitrate concentration from these catchments in our calculations, i.e. 1.93 mg/l. While wetlands are better at removing nitrogen than phosphorus, but they can be designed to improve phosphorus retention and we assume this will occur primarily in catchments with high concentrations of particulate phosphorus i.e. an average TP concentration of 0.081 mg/l.

[4] Concentration 2030 = concentration 2005 x (0.67 x fractional increase (2005-2055) x concentration 2005)

Table 4.1: Nutrient loads and concentrations under base flow conditions for major sub-catchments to Lake Rotorua (adapted from Rutherford and Timpany 2008)

Catchmment	Total Flow (L/s)	Baseflow (L/s)	% baseflow	baseflow TN (t/yr)	baseflow TP (t/yr)	baseflow TN (g/m3)	baseflow TP (g/m3)	baseflow DIN (g/m3)	baseflow DIN 2030 (g/m3)	baseflow PP (g/m3)	% TP as DRP	% TN as DIN	High potential P removal	High potential N removal
Hamurana	2495	2468	99%	58.9	6.57	0.76	0.084	0.70	1.04	0	100%	92%		
Awahou	1594	1468	92%	59.8	3.24	1.29	0.070	1.21	1.61	0	100%	94%		Y
Waiteti	1156	788	68%	34.1	1.14	1.37	0.046	1.29	1.52	0.010	79%	94%		Y
Ngongotaha	1734	963	56%	31.6	1.96	1.04	0.065	0.82	0.84	0.028	57%	79%	Y*	
Waiowhiro	358	255	71%	8.61	0.42	1.07	0.052	0.95	1.10	0.006	88%	88%		Y
Utuhina	1845	1162	63%	33.7	2.63	0.92	0.072	0.73	0.85	0.028	61%	79%	Y*	
Puarenga	1711	1099	64%	47	2.36	1.36	0.068	1.19	1.38	0.025	64%	88%	Y	Y
Waingaehe	227	209	92%	10.1	0.88	1.53	0.134	1.38	2.77	0.035	74%	90%	Y	Y
Waiohewa	319	207	65%	19.1	0.43	2.93	0.066	2.63	3.18	0.032	51%	90%	Y	Y
Minor streams				14	0.8									
Lakeside springs				13	0.3									
Total	11439	8619		329.91	20.73									
Average		958	0.74	33.66	2.18	1.36	0.073	1.21	1.59	0.018	75%			
Average for areas of 'high potential N /P removal'							**0.081**	1.44	**1.93**					

Notes:

* = could be limted by the amount of area in the lower catchment available for constructed wetlands.

Waiohewa Stream is geothermally influenced, has warm water and high proportion of DIN as NH4_N. A denitrification plant is planned for the stream.

Puarenga Stream is currently being alumm dosed to treat phosphorus.

Baseflow DIN for 2030 was calculated using two thirds the % increase of loading 2005-2055 (data from Table 6 of EBOP, RDC & Te Arawa Lakes Trust 2007).

Sources: Rutherford and Timpany (2008), EBOP, RDC & Te Arawa Lakes Trust (2007).

4.3 Location of natural wetlands and potential areas for new wetlands

Figure 4.2 shows the location of existing wetlands in the Rotorua catchment, the location of low lying areas near the lake, and specific areas identified as having potential for constructed wetlands or seepage wetlands.

The natural wetlands were identified using layers from the BOPRC GIS database. Most of the wetlands around the lake edge are considered to be regionally or nationally significant wetlands (Taylor and Beadle 2005). Regionally and nationally significant wetlands in the Rotorua catchment are listed in Table 4.2. There are 18 lake margin wetlands ranging in size from 0.01 ha (minimum mapping size) to 38.4 ha (Taylor 2005), these all form part of the Lake Rotorua wetland complex and are classified as nationally significant.

Table 4.2: Regionally and nationally significant wetlands in the Rotorua catchment (from Taylor and Beadle 2005).

Type	Significance	site	grid reference
Lake margin	National	Lake Rotorua, including marginal wetlands 16 on lake edge plus two on Mokoia Island.	-
	Regionally	Copella Road Wetland, Mamaku	U15 798 484, U15 792 483, U15 791 479, U15 787 474, U15 805 491
	Regionally	Te Ngae Kahikatea Stand, Rotorua	U15 019 407

Geothermal	National	Whakarewarewa (includes Kereru Geyser (S28), Puapua Geyser (S81), Te Horu Cauldron Hot Pool (S76), Parekohoru (S284), Korotiotio (S283), Roto-a-Tamaheke Hot Springs (S337), Ororea Group of Springs (S352), Ngararatuatara Boiling Mud, Papakura Geyser (S28), Waikite Geyser (S126), Ngamokaiakoko (Frog Pond), Prince of Wales Feathers Geyser, (S72), Pohutu Geyser (S75), Waikorohihi Geyser (S77), Mahanga Geyser (S78))	U16 95-32-
Geothermal	National	Sulphur Bay	U16 960349
Geothermal	National	Ngapuna 5940	U16 968348
Geothermal	National	Rachel Spring, Rotorua Government Gardens	U16 955355
Geothermal	National	Kuirau Park (including Kuirau Lake)	U16 944362
Geothermal	Regional	Soccer Park	U16 341964
Geothermal	Regional	Redwood Grove Pool	U16 967329
Geothermal	Regional	Ohinemutu	U16 948366
Geothermal	Regional	Arikikapakapa	U16 945327
Geothermal	Regional	Government Gardens	U16 96-34-
Geothermal	Regional	Tangatarua	U16 942327
Geothermal	Regional	Malfroy Geyser	U16 956355

Note: * With the exception of Sulphur Bay and Ngapuna, geothermal wetlands are not shown on maps for this project.

Areas with potential for establishing constructed wetlands or restoring seepage wetlands were identified in a workshop by BOPRC field staff. Detailed maps and aerial photographs of the catchment were discussed and areas with potential were drawn onto aerial photos which already showed the location of existing water bodies and wetlands. Identification of seepage wetlands initially focused around catchments with a high groundwater component to the flow (i.e. >70% as base flow, sub-catchments Hamurana, Awahou, Waingaehe, and Waiowhiro), but soon broadened to the whole catchment.

This desk top exercise provides a starting point for selecting areas for wetland construction but it does not capture all potential areas. In particular areas with potential to restore as seepage wetlands will be under-estimated because these areas are small, widely dispersed and when drained are often difficult to distinguish from a 'damp area' in a paddock. Conversely, it is important to note that there has been no discussion with landowners and that identifying areas for potential wetlands does not imply they will actually be constructed.

4.3.1 Key sites identified for creating / restoring wetlands to remove nutrients

Areas that have potential for constructing wetlands for nutrient removal are scattered around the Lake Rotorua catchment, with almost all sub-catchments having sites available for potential wetland construction. We discuss these below on a catchment by catchment basis, travelling anti-clockwise around the lake. Reference should be made to Figures 4.1 and 4.2.

The total area of natural wetlands and potential areas for constructed wetland is shown in Table 4.3. The maximum treatment area available with these areas is assumed to be 80% of the total area – allowing land for infrastructure.

Table 4.4 lists natural wetlands that may have potential to reduce channelization and bypass flow so as to improve nutrient attenuation. Very rough estimates are made of the area of these wetlands that may be restored being effective for nutrient attenuation. These are desk top estimates for the purpose of estimating the potential of this approach on a catchment wide basis. Fieldwork is needed to confirm these estimates.

Table 4.3: Total area of natural wetlands and constructed wetland.

Catchment	Area in natural wetland (ha)	Potential constructed wetland (ha)
Awahou	92.7	
Awahou Point area	7.9	2.4
Hamurana area	4.3	1.4
Ngongotaha	7.4	15.6
Pohue Bay area	18.6	
Puarenga	60.2	13.8
Rotokawa area (could treat water from Waiohewa)	69.3	11.4
Rotorua city area	1.7	
Utuhina		12.5
Waimehia area (could treat water from Awahou)	17.4	7.5
Waingaehe	3.1	13.0
Waiohewa	4.1	5.9
Waiowhiro area	41.8	25.9
Waitawa area (could treat water from Utuhina)	18.9	50.2
Waiteti	69.9	21.8
Total wetland area	**417**	**181**
Total wetland treatment area		**145**

Assume wetland treatment area = 80% of total area.

Table 4.4: Natural wetlands with possible potential to restore for nutrient attenuation

Wetland	Area (ha)	Additional possible treatment area (ha)
Awahou Wetland	22.8	4.0
Waiowhiro Flat Wetland (Parawai Road Swamp)	38.4	8.0
Total	**72.4**	12

Hamurana

The Hamurana area has a small (1 ha) parcel of land near Wilson's Bay that may offer potential for a small constructed wetland. There may also be potential to extend the extent of the existing Hamurana Road wetland and wetlands at Hamurana Springs Recreation Reserve.

There are a large number of seeps and springs in the Hamurana catchment. Many of these feed existing ponds and wetlands. The potential to fence the head of these seeps is limited by steep terrain.

The Hamurana catchment is not identified as a high priority for nitrogen removal because nitrogen concentrations are currently relatively low. However the nitrogen load (and hence concentration) is predicted to rise by 150% over the next 50 years. There is a proposal, in the Proposed Rotorua and Rotoiti Action Plan, to divert the Hamurana Stream to the Ohau Channel. If this goes ahead there would be little benefit from treating the Hamurana Stream water through a wetland.

Hauraki

No areas were specifically identified with high potential for creating wetlands in the Hauraki catchment.

Awahou and Awahou Point area

There may be some potential to construct a wetland on opposite side of the road to Awahau wetland. The Awahou Stream is channelized through most of the Awahou wetland so there is potential to increase nutrient attenuation in the existing Awahou wetland by doing physical works to increase residence time and loading. An initial estimate is that this would equate to about 4 ha of additional wetland being used for treatment of Awahou Stream base flow. Consideration could also be given to diverting part of the Awahou Stream to wetlands in the Waimehia catchment.

The Awahou Stream is a good fishery and particular care would be needed to ensure this was not compromised. There may be potential for detention dams in the dry washes near the top of the catchment. These would moderate flows as well as retaining sediments and associated phosphorus.

There are a large number of natural wetlands in the upper catchment (i.e. upper Waiteti Stream wetland and Copella Road wetlands) and these may be associated with seepage areas that could be improved for nutrient attenuation.

Waimehia

The Mangorewa/Kaharoa Z Block wetland is currently in a degraded state and channelized through the upper and lower sections of the wetland so there is potential to undertake physical works to improve the retention time in the wetland and improve nutrient attenuation. An initial estimate is that this would equate to about 2 ha of additional wetland being used for treatment. There is also potential to expand the current wetland extent on low lying areas.

The Waimehia catchment is relatively small (about 778 ha) and has intermittent stream flow not well suited for wetland treatment. However it may be possible to transfer some of the flow from the adjacent Awahou catchment into this area for treatment.

Waiteti

Several low lying areas were identified as having potential for wetland creation near the Tupapkurua Stream and lower Waiteti Steam. Areas of springs and potential seepage wetlands were identified in the mid reaches of the Tupapkurua Stream.

There are a large number of natural wetlands in the upper catchment (i.e. Copella Road wetlands, Oturoa Road junction wetland, and Oturoa wetland), these may be associated with seepage areas that could be improved for nutrient attenuation.

Ngongotaha

There were few areas identified in the Ngongotaha catchment as having potential for constructing wetlands for nutrient attenuation. Most opportunity exists around expanding existing wetlands (e.g. Paradise Valley Road wetlands) or restoring seepage wetlands near the stream in the vicinity of Riddell Wetlands.

Much of the upper catchment is in forest and this is reflected in relatively low concentrations of nitrogen in the stream compared to other sub-catchments – reducing the relative potential of wetlands in this catchment to remove nitrogen load.

Waiowhiro

Several areas were identified in the Waiowhiro catchment that have potential for wetland construction. In particular there is potential to expand the Waiowhiro Flat wetland (Parawai Road Swamp) on flat land to the south to treat water from the Waiowhiro Stream (flow of about 320 l/s).

A spring enters the Waikuta Stream just east of the main road offering potential for a seepage wetland in this area. Consideration could also be given to directing the Waikuta Stream through the existing Waiowhiro Flat wetland to improve retention times and increase the overall load being treated. An initial estimate is that this would equate to about 8 ha of easily accessible wetland being available for additional treatment.

The Waikutu Stream and Waiwhiro Stream are spawning streams and the trout hatchery is on the Waiwhiro Stream, thus in constructing any wetlands it would be important to ensure fish passage is maintained.

Utuhina

There were few areas identified in the Utuhina catchment as having potential for constructing wetlands for nutrient attenuation. However the catchment has been neglected by programmes undertaking riparian retirement so there remains good potential for undertaking land management work in general.

Much of the upper catchment is in forest and this is reflected in relatively low concentrations of nitrogen in the stream compared to other sub-catchments – reducing the relative potential of wetlands in this catchment to remove nitrogen load.

Rotorua City catchment area

No areas were identified for wetland creation in the Rotorua City catchment area. Existing wetlands in Sulphur Bay are geothermal and would be at risk of being degraded if managed for nutrient attenuation purposes. Note that the Rotorua City boundaries extend well beyond the Rotorua City hydrological catchment.

Puarenga

Only one area was identified in the Puarenga catchment as having potential for constructing wetlands for nutrient attenuation. This is in the mid-catchment and some further investigation would be needed to determine if nutrient concentrations in this part of the stream would justify creating a wetland. Phosphorus loads in the Puarenga Stream are currently treated with a P locking plant and the marginal benefits /effects would need to be considered before any wetland is constructed for the stream.

Waitawa area

A substantial area of land was identified as having potential for wetland creation in the Waitawa area in association with the Ngapuna wetlands on the lakeward side of Vaughn Road. The estimated total flow from this catchment [5] is 280 l/s, this would require about 17 ha of wetland to treat the base flow (assumed base flow of 220 l/s and a hydraulic loading to the wetland of 40 m/yr), which is less than the area identified as potentially available for wetland construction.

It may be possible to treat base flow from the adjacent Puarenga Stream using potential wetland areas currently in the Waitawa area.

The Rotorua Eastern Arterial is crossing near this area. Some of the area identified as having potential for wetlands are low lying paddock, south-west of Ngapuna wetlands, acquired by the NZ Transport Agency as part of the Rotorua Eastern Arterial project. This offers a real opportunity to create wetlands that could be used for treatment of both road run-off and stream water while achieving efficiency through cost sharing.

Gibbs and Lusby (1996) identified two lake edge seepage wetlands in the Waitawa catchment. Hinemoa Point seepage wetland had about 98% removal rate (but no estimate of loading rate given). Owhata Road seepage wetland achieved about 16% reduction in incoming nitrate but high estimated loading rates (>150 m/yr) and incoming nitrate concentrations of 4 mg/l would result in high absolute removal (estimate by us to be about 85-90 $g/m^2/yr$).

Restoration work has recently been done on the Otauira (Hannah's Bay) wetland to improve biodiversity and recreational values (Peters and Clarkson 2010). The restoration

[5] Using a catchment area of 10.71 km^2 and a run-off estimate of 0.825 m/yr from the Regional Environment Classification.

work did not focus on nutrient treatment but in the future this type of work could be used to cost-effectively develop nutrient treatment wetlands.

Waiangaehe

About 10 ha of riparian land was identified as having potential for wetland creation along the lower section of the Waiangaehe Stream. Base flow nitrate concentrations are reasonably high (1.4 mg/l) in the stream which increases the potential for nitrogen attenuation. This area of wetland (10 ha) has potential to treat about two thirds of the baseflow (two thirds of 209 l/s) from Waiangaehe Stream (assuming a hydraulic loading rate of 44 m/yr).

Rotokawa area

Several areas were identified in the Rotokawa area with potential for seepage wetlands including sections adjacent to Lake Rotokawa. The natural lake edge wetlands are fed by springs and seeps. Gibbs and Lusby (1996) found Holden's Bay wetland removed about 50% of incoming nitrate (2.3 mg/l), and Hannahs Bay (Otauira) wetland to remove about 98% of incoming nitrate (2.9 mg/l, no estimate of loading rate). A drain through Hannahs Bay (Otauira) wetland results in much of the incoming water not being treated and there is potential to create about 1 to 2 ha of additional treatment area by avoiding this bypass flow.

Part of the Te Ngae Kahikatea wetland near the 3D Maze was estimated by Gibbs and Lusby (1996) to remove 98% of incoming nitrate (2.3 mg/l), but the estimated loading rates were very low (<1 m/yr).

There is 10-11 ha landward of the Te Ngae Kahikatea wetland that may have potential for a constructed wetland. This has most potential to treat water from the adjacent Waiohewa Stream and runoff from the Te Ngae Nursery.

Waiohewa

A 10 to 11 ha parcel of land (discussed above) was identified near the outlet of the Waiohewa Stream that offers potential for wetland construction. The Waiohewa Stream has a geothermal influence, thus has warmer water, increasing potential for nitrogen attenuation. The nitrate concentration in the stream is 1.3 mg/l so has reasonable potential for nitrogen removal. A denitrification plant is currently planned for the Waiohewa Stream and the effect of this will need to be considered before any wetland is constructed for the stream.

A number of areas were identified in the catchment with potential for seepage wetlands.

Pohue Bay area

No areas were specifically identified with high potential for creating wetlands in the Hauraki catchment. The nitrogen load from this catchment is relatively small.

4.4 Estimated total area with potential for establishing constructed wetlands or restoring seepage wetlands

Using the approach described above we estimate that the Lake Rotorua catchment has:

- 417 hectares of existing wetlands.
- ~12 hectares of the existing wetlands (above) where residence time / loading could be increased (i.e. in the current Awahou wetland, Waiowhiro Flat wetland).
- 181 hectares with high potential for establishing constructed wetlands. This corresponds to about 145 ha of wetland treatment area (assuming about 20% of the land is used for berms, bunds, structures etc.).
- ~7.25 hectares available for restoring seepage wetlands (assuming 0.25 ha in each of 28 areas).

The calculation of area with potential for constructed wetlands does not include natural wetlands although in many cases they were adjacent. The calculation of area available for seepage wetlands assumes an aggregate of 0.25 ha of seepage wetland in each of the 29 areas identified in the workshop. There is considerable uncertainty around the estimate for seepage wetlands that can only be improved by undertaking fieldwork to identify existing seepage wetlands and, more importantly, degraded seepage wetlands because these have most potential for restoration for nutrient attenuation.

Figure 4.1: Lake Rotorua sub-catchments (indicating those with 'high potential for phosphorus removal' and 'high potential for nitrogen removal').

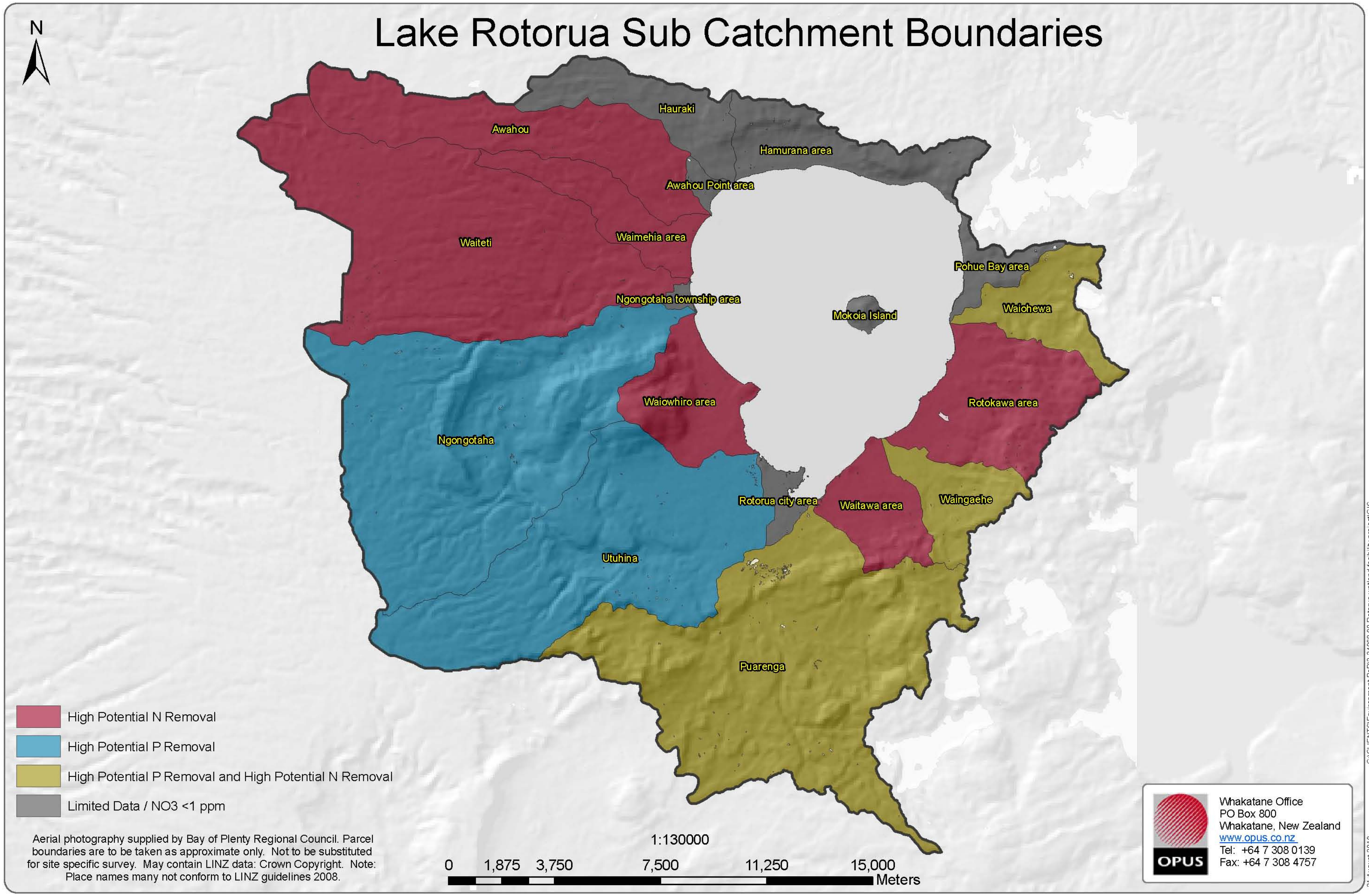
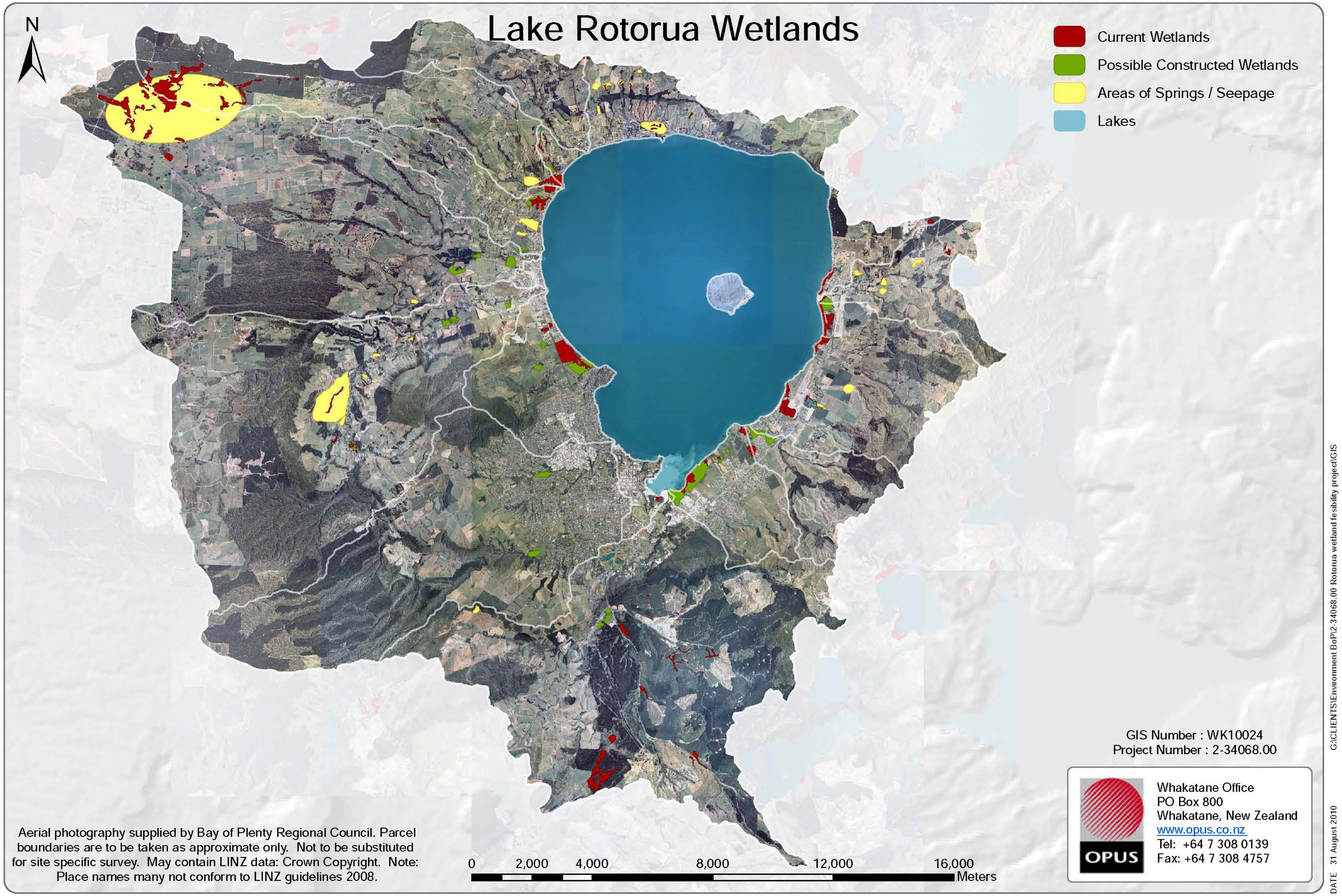


Figure 4.2: Location of existing wetlands and areas with potential for wetland construction in Lake Rotorua catchment.



5 Assessment of wetland types for removing nutrients using BOPRC template

5.1 Introduction

This section provides a generic assessment of each wetland type using the assessment template provided by BOPRC; i.e.

- Constructed wetlands
- Natural Surface Flow Wetlands
- Seepage Wetlands
- Floating Wetlands
- A $1 million Wetland Package

This is primarily a qualitative assessment except where estimates of nutrient reductions and cost-effectiveness have been made. A relative comparison of each wetland type and their cost-effectiveness at removing nutrients is made in the following chapter.

Cost-effective assessment should be interpreted with caution. This was based on published literature and established models, but in some cases there is very limited published literature available on reductions and costs. This provides a high level, generic assessment and it should be noted that the actual cost-effectiveness of different options will vary with market conditions (e.g. land prices) and heterogeneity within the landscape.

The assessments of effectiveness are based on the additional nutrient reductions that could be achieved by establishing, modifying or restoring a wetland. In many cases the absolute nutrient reductions of wetlands in the catchment will be much more, because existing wetlands are already performing an ecological service of removing nutrients. In these situations a policy of avoiding drainage or degradation of existing wetlands is most cost-effective.

Wetland types were given a relative ranking of 'high', 'medium' or 'low' for each effectiveness criteria, i.e. cost-effectiveness, overall nutrient reduction potential, and ease of use. Because these rankings are relative to different wetlands they will need to be revised if being compared with other interventions. In general, all wetlands are expected to have low effectiveness for removing phosphorus compared to many alternative interventions (e.g. riparian protection, or alum dosing).

5.2 Constructed surface flow wetlands

Intervention Description: Constructed surface flow wetlands	
Description	Constructed surface flow wetlands are man-made wetland systems built in the lower reaches of stream catchments for the purpose of extracting nutrient loads from drainage waters from agricultural areas. They are designed and constructed in a way that recreates the hydrology and biological processes, involving wetland vegetation, soils, and their associated microbial assemblages, that occur in natural wetland systems to remove, store and adsorb a significant portion of the nutrient load in the receiving waters. Phosphorus treatment in constructed wetlands is achieved by sedimentation (settling of P-enriched topsoil), adsorption to wetland sediments and plant uptake. Nitrogen treatment is achieved by plant uptake and denitrification (conversion of nitrate to gaseous nitrogen) (Hudson et al. 2009). Nutrient treatment efficiency in constructed wetlands is enhanced by optimizing dispersion, flow paths, water depths, residence times and vegetation characteristics (McKergow et al. 2007). Extraction of 50 to 60% nitrate and TN generally occurs when the size of the constructed wetland is between 2 and 3% of the catchment from which they receive drainage waters (McKergow at al. 2007). Wetlands smaller than this (1% of catchment area) will be less effective at reducing the nitrogen load (30%), while larger wetlands (5% of the catchment area) can achieve 70% removal but the cost per kg of N extracted will be higher. The medium to long term ability of constructed wetlands to remove phosphorus is less than for nitrogen because wetlands have finite P storage and adsorption capacity. Constructed wetland systems that have ponds or similar containment areas where P-enriched sediment can settle and be removed by excavation have the greatest long term value for P extraction. Constructed wetlands are often designed to treat stream base flow and have a bypass channel for flood flows. Minimizing the amount of water that needs to be bypassed will allow more water to be passed through the wetland for treatment. This can be done by installing retention structures further up the catchment.

Situational Characteristics	
Suits what Problem	• Constructed surface flow wetlands have been demonstrated to have the capacity to process diffuse pollution from agricultural land use. • They are most effective at removing nitrogen and are likely to continue to do so for several decades if well maintained. • Constructed surface wetlands are also able to store phosphorus especially in particulate form, but the capacity of the wetland to do this can be expected to fall after the first few years unless the accumulated P-enriched sediment can be excavated from the wetland system or retention ponds.
Effectiveness Factor	**Criteria** — **Nitrogen** — **Phosphorus** 1. Cost-effectiveness ($/kg N removed) — HIGH — LOW-MEDIUM 2. Nutrient reduction potential: — HIGH — LOW 3. Ease of use: installation — MEDIUM maintenance — MEDIUM - HIGH
Strengths / benefits	• Able to remove a significant proportion of a catchment's nitrogen and phosphorus load, especially nitrogen. • There are likely to be suitable sites for the construction of wetlands in the lower reaches of most of the catchments feeding into Lake Rotorua. • Low maintenance requirements, i.e. weed control, occasional supplementary planting, and regular (perhaps 2 yearly) excavation of sediment from the sediment detention area at the upstream end of the wetland. • Can be used with successfully to remove nutrients transported in subsurface drainage (mole, tile and pipe drainage). • Constructed wetlands can provide valuable habitat for plants and animals and an attractive site for passive recreation (although management for biodiversity and recreation should not be allowed to compromise the nutrient treatment performance of the wetland). • There is considerable seasonal variation in treatment performance. This can be a significant advantage by reducing the concentration of dissolved nutrients during the summer when most required by algae.
Limitations / disadvantages	• Constructed wetlands require a large initial investment to establish. • Land for constructed wetlands will need to be purchased or leased, and takes land out of production. • Because these wetlands are large, must be built on relatively flat land, and are most efficient when located in the lower portions of the

	catchment. Suitable locations may not always be available. • There is uncertainty about the functional lifespan of constructed wetlands. • Constructing wetlands requires the good will of landowners to donate, lease or sell their land, (we have assumed a lease arrangement).
Intervention Characteristics	
Impact and Reach	**Impact**: Nitrogen: HIGH Phosphorus: MEDIUM Well established and managed constructed wetlands can remove or retain a significant proportion of the nitrogen (45% or more) and moderate phosphorus loads (20%) passing through them. P retention in constructed wetlands may potentially be enhanced by the addition of a range of P-sorbing materials, including allophanic clays, lime, alum, smelter slag, and some volcanic tephras (Ballantine and Tanner 2010). These substances are currently under assessment in a variety of laboratory and field research trials. **Reach** HIGH Single constructed wetlands located appropriately in the lower reaches of catchments, can intercept a high proportion of the drainage water and remove a sizeable proportion of the nitrogen and phosphorus loads generated in the catchment. About 145 ha of Lake Rotorua catchment were estimated to have potential for constructed wetlands. Constructing wetlands over this area would achieve on average about 53.3 tonnes/yr of nitrogen and 1.4 tonnes/yr of P at a cost of $51.3 million. This is about 23% and 16% of the respective nitrogen and phosphorus reduction target for the catchment. The willingness of land owners to lease of volunteer their land is unknown.
Efficiency (cost-effectiveness in $/kg nutrient removed)	<table><tr><td></td><td>**Nitrogen**</td><td>**Phosphorus**</td></tr><tr><td>Establishing a constructed wetland</td><td>$79 /kg N</td><td>$2,548 /kg P</td></tr></table>
Other factors to consider	
Evidence / Assumptions	The evidence and assumptions made in determining the ratings in the sections above have been generated from the following references: Ballantine and Tanner (2010); Hudson et al. (2009); Kadlec (2005a); Kadlec (2005b); Kadlec and Wallace (2009); Knox et al. (2008); McKergow et al. (2007); Sukias and Tanner (2004); Tanner (2003); Tanner and Kloosterman (2007); Tanner et al. (2005a); Tanner et al.

	(2005b); Tanner et al. (2006); Tanner et al. (2007). The assumptions for cost-effectiveness analysis are described in Appendix 2. Some of the key assumptions are: • Real discount rate of 8%; • Costs include acquisition (design, construction, planting etc), maintenance, and wetland renewal every 25 years. Total costs were annualised over a 50 year life span; • Cost for constructed wetlands were based on costs for Lake Okaro wetland after adjusting for inflation; • The cost per hectare of constructing a wetland reduces with wetland size. We have assumed an average constructed wetland size of 3 ha; • Future constructed wetlands will have a similar design to that used for Lake Okaro (see Appendix 1 and 2); • Land is leased.
Current Deployment	In 2004 there were over 80 constructed wetland systems are in operation for the purpose of secondary or tertiary treatment of wastewaters (Sukias and Tanner 2004), and more have been built since then. The majority of these systems are likely to have been built for the treatment of human wastewaters, however, an increasing number are being built to process agricultural drainage waters. While there is considerable variation in nutrient removal performance between constructed wetlands and from season to season most are effective at removing a significant proportion of the nutrient load contained in the receiving waters. Lake Okaro is the most relevant example of a constructed wetland for this project and to date it appears to be performing close to the predicted levels of nutrient extraction (47% extraction of TN load received, 50% extraction of TP load received). However a large portion of the nutrient load bypasses the wetland during floods.
Interventions indicators	Assessing the effectiveness of constructed wetlands at attenuating nitrogen entering Lake Rotorua would require: 1. Monitoring the flow and nutrient concentrations entering and exiting these wetlands, 2. Monitoring the percentage of catchment generated drainage flow that flows down the bypass channel and misses the wetland.
Overall impact and value for money	Constructed wetlands are very effective tools for the removal of nitrogen and moderately effective tools for the removal of phosphorus from agricultural drainage waters provided they can be built on suitable sites in the lower reaches of catchments where all or most of the catchment drainage can be channelled through them.

	Compared to other wetland types, investment in constructed wetlands is the most practical and certain wetland option for reducing nutrient loads where: • Nitrogen and particulate phosphorus loads are high; • There are suitable locations in the lower reaches of catchments to construct a wetland close to the main river draining the catchment; • Land can be purchased or long-term access rights procured; • Sediment can be removed in pre-treatment.

5.3 Natural surface flow wetlands

Intervention Description: Natural surface flow wetlands	
Description	Natural wetlands that receive most of their water supply from surface drainage rather than springs are generally located on river and lake floodplains. They can be fed by stream flow, flood overflow from streams, and shallow subsurface flow, or all three. Healthy natural wetlands can be important removers of nitrogen and provide variable storage of phosphorus. However, the majority of lowland / floodplain wetlands have been heavily modified and are likely to be less effective at nutrient removal than healthy wetlands. Remnant wetlands that retain some connection to stream flow, or could be reconnected to streams without great cost, do have the potential to be restored to increase their nutrient removal functions (McKergow *et al.* 2007). Fencing to exclude livestock, correction of artificial surface and sub-surface drainage to improve water spread and retention time, and the re-establishment of indigenous wetland vegetation are restoration activities that will need to be undertaken to varying degrees depending on the state of each remnant wetland.

Situational Characteristics	
Suits what Problem	• Natural surface flow wetlands have been demonstrated to have the capacity to process diffuse pollution from agricultural land use. • They are most effective at removing nitrogen and are likely to continue to do so for several decades if water dispersal, water retention time and vegetation are appropriately restored and well maintained. • Natural wetlands have only a limited long term capacity to store phosphorus (mostly in particulate form). Phosphorus removal capacity may be enhanced by the installation of settling ponds up-catchment from the wetland.
Effectiveness Factor	**Criteria** — **Nitrogen** — **Phosphorus** 1. Cost effectiveness ($/kg N removed) — HIGH — MEDIUM – LOW 2. Nutrient reduction potential: — MEDIUM – HIGH — MEDIUM – LOW 3. Ease of use: installation — MEDIUM – HIGH maintenance — LOW
Strengths / benefits	• Natural wetlands that can be restored for nutrient removal typically remove nitrogen almost as efficiently as a mature constructed wetland, and some perform better. • The cost to correct drainage and restore the wetland vegetation in moderately altered wetlands is likely to be less than the cost of establishing a new constructed wetland. • The restoration of altered natural wetlands will also enhance the biodiversity value of those wetlands. • Once restored, the maintenance requirements of natural wetlands are likely to be low, and consist mostly of weed control.
Limitations / disadvantages	• Installing sediment ponds is needed to optimise removal of particulate phosphorus. • The land on which the wetlands are located will need to be purchased, leased or covenanted, and access rights secured, to ensure they are managed in a way that optimises nutrient removal. • There is considerable uncertainty about the effectiveness around restoring natural wetlands (especially to re-establish their water holding capacity), and there is uncertainty around the amount of natural wetland in the catchment that would be suitable for restoration..

<table>
<tr><th colspan="4">Intervention Characteristics</th></tr>
<tr><td rowspan="1">Impact and Reach</td><td colspan="3">Impact:

Nitrogen: MEDIUM - HIGH

Phosphorus: MEDIUM - LOW

Natural wetlands have the potential to perform as well as constructed wetlands for the extraction of nitrogen, however, their catchment-wide average performance is likely to be a little less due to the natural variability in water dispersion and retention.

Natural wetlands exhibit considerable variation in their nitrogen removal capacity. A major reason for this can be because of natural variability in drainage, water dispersion and development of channels that bypass the wetland treatment.

Reach MEDIUM - HIGH

Not all catchments will have existing natural wetlands that can be restored or that are in suitable locations to intercept a significant proportion of the catchment drainage waters.

The best nutrient removal return is likely to be obtained by restoring moderately altered wetlands where drainage can be corrected without huge cost and where a significant proportion of the existing wetland vegetation is appropriate and does need to be replaced. Very heavily modified wetlands (especially those that have been well drained may not be able to be restored to a functional state; the installation of constructed wetlands on such sites may be worth considering.

We have roughly estimated that there are 12 hectares of natural SF wetlands in the Lake Rotorua catchment with potential for restoration. This would remove, on average 3470 kg/yr and 121 kg/yr of N and P respectively at a cost of $2,551,000; i.e. 1.5% of the N reduction target.</td></tr>
<tr><td rowspan="2">Efficiency (cost effectiveness in $/kg nutrient removed)</td><td></td><td>Nitrogen</td><td>Phosphorus</td></tr>
<tr><td>Restored natural wetland</td><td>$60 /kg N</td><td>$1,714 /kg P</td></tr>
<tr><th colspan="4">Other factors to consider</th></tr>
<tr><td>Evidence / Assumptions</td><td colspan="3">The evidence and assumptions made in determining the ratings in the sections above have been generated from the following references:

Blahnik and Day (2000); Burns and Nguyen (2002); Cooper and Knight 1990); Kadlec and Knight (1996); McKergow et al. (2007).</td></tr>
</table>

	In addition to assumptions for constructed wetlands, we have assumed: • Natural wetland nutrient removal rates per hectare are slightly lower (k_{20}=29 m/yr) than for constructed wetlands because of limited ability to control the water depth throughout the wetland. • The cost of restoring nutrient attenuation in a natural wetland will be the same as the cost of rejuvenating a constructed wetland (i.e. half the per hectare construction cost). This cost consists largely of corrective drainage and revegetation, and includes an additional allocation per wetland associated with the procurement of consents. • Land will be leased at median rate for 'sheep and beef'.
Current Deployment	Natural wetlands exist throughout the landscape, mostly in modified form. Research from around the world has shown that healthy wetlands serve as very effective buffers to environmental extremes, including being a sponge, store and "factory" for the storage and removal of nutrients from feeding waters. The least modified natural existing wetlands in the Lake Rotorua catchment will already be removing significant amounts of nitrogen and phosphorus. They should be protected against risk of modification so that they can continue to treat nutrient laden waters generated from the surrounding catchment. This may require that they are purchased or leased from the current land owner so that they can be appropriately managed.
Interventions indicators	Assessing the effectiveness of natural wetlands at attenuating nitrogen entering Lake Rotorua would require monitoring the flow and nutrient concentrations entering and exiting the wetlands.
Overall impact and value for money	Natural wetlands can be very effective tools for the removal of nitrogen and moderately effective tools for the removal of phosphorus from agricultural drainage waters if they can be restored to optimise water retention and dispersion and establish a healthy cover of appropriate wetland rush, sedge and reed species. Those wetlands that do not require large scale drainage correction are of the greatest value because there is a greater likelihood that full nutrient removal functionality can be restored and the cost of restoration will be lower. There are an estimated 417 ha of existing wetlands in the Lake Rotorua catchment. We conservatively estimated 12 ha could practically be restored for nutrient treatment however, field evaluation of these wetlands would be necessary to determine which could be restored to improve their nutrient treatment functionality.

5.4 Seepage wetlands

Intervention Description: Seepage wetlands	
Description	Natural seepage wetlands occur where shallow subsurface or groundwater flow re-emerges through springs or seeps. They generally occur at the head of streams, the toe of hills, and along the margins of streams and lakes (called lake fringe wetlands). The size of each natural seepage wetland depends on the topography of the land; the greater the area of level or gently sloping land immediately below the spring the bigger the wetland is likely to be, however, they are usually smaller than lowland and floodplain wetlands, typically up to about 0.5 ha. Some remain permanently wet while others can be dry for prolonged periods, especially in summer. Small seepage wetlands are often omitted from regional wetland inventories although they may represent a large part of headwater catchments (McKergow, *et al* 2007). Seepage wetlands with the most potential for modification to achieve additional nitrogen extraction are ones with significant, year-round spring flows and which are currently compromised by drainage and grazing.
Situational Characteristics	
Suits what Problem	• Seepage wetlands have the capacity to process diffuse pollution from agricultural land use. • They are most effective at removing nitrogen. Well positioned and maintained seepage wetlands are especially efficient at removing nitrate nitrogen by the process of denitrification. They can remove up to 95% of nitrate from water derived from pastoral farm land. The vast majority of nitrogen entering seeps from groundwater is in the form of nitrate, so nitrate removal corresponds to total nitrogen removal. Seepage wetlands are not, generally, effective at removing phosphorus. This is because seepage wetlands are usually too small to store, sorb or utilise (through plant uptake) more than small quantities of phosphorus. Unlike for nitrogen, there is no wetland process to convert phosphorus to a gaseous form.

Effectiveness Factor	Criteria
	Nitrogen **Phosphorus** 1. Cost-effectiveness ($ /kg N removed) HIGH LOW 2. Nutrient reduction potential: MEDIUM LOW 3. Ease of use: installation HIGH maintenance HIGH
Strengths / benefits	• Seepage wetlands often have high percentage removal rates for nitrate. Nitrate removal of 75% or better has been recorded in several studies of seepage wetland performance. Burns and Nguyen (2002). Found a small wetland (less than 350 square metres) removed over 90% of the nitrate in the emerging spring water. • Seepage wetlands are more efficient at nitrate removal than other surface wetland systems because the spring water emerges through the wetland soils, thus increasing the contact between water and organic soil particles and therefore increasing the effectiveness of the denitrification process that converts nitrate to gaseous nitrogen. • Seepage wetlands associated with springs and seeps are widespread throughout the Lake Rotorua catchment. • The costs associated with restoring seepage wetlands to improve performance are likely to be reasonably low. Most will require fencing from livestock, some drainage correction (e.g. filling in surface drains to prolong water residence time) and the planting of some rushes and sedges to improve performance. • The maintenance requirements of seepage wetlands are likely to be low; probably consisting of annual weed control only.
Limitations / disadvantages	• The mass removal of nitrate by seepage wetlands is often limited by small hydraulic loading rates. • While the fencing and enhancement of seepage wetlands is likely to be inexpensive for each wetland, their small size and scattered distribution will increase the cost of monitoring and servicing. • It is not practical to purchase land for seepage wetlands and leasing may also prove impractical because of their small size. • Access to seepage wetlands for their enhancement and maintenance will be at the discretion of the landowner. Consequently, the availability of seepage wetlands for enhancement is difficult to determine. Formal access agreements will need to be established with each landowner to ensure on-going monitoring and maintenance can occur. • Some seepage wetlands in the catchment occur at the base of very

	steep slopes; for practical construction reasons fencing to exclude livestock may have to occur at the top of ridges which will increase the land area retired from grazing. This, in turn, will increase the planting and maintenance requirements and costs. • Seepage wetlands have limited value in catchments where phosphorus management is important. • There is no information available to establish how effectively existing seepage wetlands in the Lake Rotorua catchment are performing and so there is a degree of uncertainty as to how much improvement in performance will be achieved by fencing and drainage enhancement. • The number and condition of manageable seepage wetlands in the Lake Rotorua catchment is uncertain and so the additional nutrient removal that may occur as a result of wetland enhancement (fencing, drainage correction and planting) is uncertain.
Intervention Characteristics	
Impact and Reach	**Impact**: Nitrogen: HIGH Phosphorus: LOW The protection and enhancement of the larger and high water volume seepage wetlands will reduce the nitrogen load reaching Lake Rotorua. **Reach** LOW Seepage wetlands are highly effective in terms of percentage removal of nitrogen but the absolute amounts removed is limited by the number of seepage wetlands in the catchment, the limited amount of water they intercept and the number in a degraded state that can be enhanced. Seepage wetlands only intercept the waters generated by the springs feeding them plus some surface runoff from the immediate vicinity. Furthermore, the scattered distribution of seeps means a large number of seepage wetlands are needed to intercept a significant proportion of the nitrogen loads entering Lake Rotorua. We have roughly estimated that there are 7.2 hectares of seepage wetlands in the Lake Rotorua catchment with potential for restoration. This would remove, on average 2344 kg/yr and 17 kg/yr of N and P respectively at a cost of $581,400; i.e. ~1% of the N reduction target. While restoring seepage wetlands would have minor impact on a whole catchment scale, they would have a large impact on a farm scale and be cost-effective. This suggests policies should be implemented to encourage

	farmers to protect and restore seepage wetlands.
Efficiency (cost-effectiveness in $/kg nutrients removed)	**Nitrogen** / **Phosphorus** Restoring a degraded seepage wetland: $20 /kg N / $2,739 /kg P
Other factors to consider	
Research requirements	Little research work has focused on how much the N extraction capacity of seepage wetlands can be increased by the enhancement of these wetlands (by fencing, drainage correction and planting). Data generated from research in a Lake Taupo sub-catchment suggests that organic N and total N exports from seepage wetlands are 5-10 times higher when stock are grazing the wetland compared to base flow conditions without grazing (McKergow *et al* 2007). Seepage wetlands are most cost-effective wetland type, but also the wetland type with least knowledge about its occurrence in the landscape. More work is needed to determine the amount of degraded seepage wetlands in the Lake Rotorua catchment.
Evidence / Assumptions	The evidence and assumptions made in determining the ratings in the sections above have been generated from the following references: Burns and Nguyen (2002), Cooper (1990), McKergow *et al*. (2007), Nguyen *et al*. (1999), Nguyen *et al.* (2002), Rutherford and Nguyen (2004), Zaman *et al* (2008). Assumptions are described in Appendix 2. Key assumptions are: • Nutrient removal rates per hectare will be the same as for constructed wetlands after fencing and removing artificial drainage; • We have assumed a seepage wetland size of 0.25 ha for calculating cost-effectiveness. • These estimates assume that the wetland was previously not performing any N removal function and account for nitrogen reduction achieved by doing these works in seepage wetlands. • These estimates do not include provision for any benefits that are being accrued by currently protected and functional wetlands that have not been drained or degraded.

Current Deployment	Seepage wetlands have not been specifically targeted for fencing and enhancement for the purposes of nutrient management, either in the Lake Rotorua catchment or in other parts of New Zealand. This is despite the abundance of good research that confirms the high nitrogen removal capacity of well maintained seepage wetlands. However, springs and seeps that occur close to streams have been included within retired riparian margins at several locations throughout the wider Lake Rotorua catchment, and larger wetland systems that are fed by springs and seeps have also been fenced at several locations.
Interventions indicators	Assessing the effectiveness of seepage wetlands at attenuating nitrogen entering Lake Rotorua would require: 1. Mapping the current extent, location and condition of seepage wetlands in the catchment. 2. Monitoring the flow and nutrient concentrations entering and leaving these wetlands, 3. Monitoring the impact of improvements in terms of fencing and restricting drainage of seepage areas.
Overall impact and value for money	Seepage wetlands are estimated to have moderate overall impact for removing nitrogen from entering Lake Rotorua and very little impact at removing phosphorus. While very effective at a local scale, their overall effectiveness is limited by the nutrient load that can be put through them. Seepage wetlands can only be located where there are groundwater seeps and springs. The scattered distribution of seeps and springs reduces the cost-effectiveness of seepage wetlands because of the need to fence a large number of small areas. The most cost-effective way of using seepage wetlands is to protect existing seeps from being drained or degraded in the first place. Consideration should be given to policies to encourage this (e.g. education, incentives or regulation). It is our recommendation that investment in the enhancement of seepage wetlands for nutrient management is most appropriate in catchments where : • Spring water contributes a high percentage (>80%) of the catchment discharge; • There are several manageable seepage wetlands within the catchment; • Nitrogen loads are high; and • There is no obvious location / opportunity for a constructed wetland to be installed, or for an existing wetland to be extended or restored in the lower catchment.

5.5 Floating wetlands

Intervention Description: Floating treatment wetlands	
Description	Floating treatment wetlands (FTW's) are a relatively new, experimental technology for the treatment of nutrients in nutrient-rich waste and drainage waters. They consist of buoyant mats that are mass planted with emergent wetland plants (usually reeds or rushes), and are anchored on the surface of treatment ponds or nutrient rich lakes. The plant roots grow through the mats and down into the water column forming large, dense mats. Floating wetlands are generally used where the plant root systems cannot reach the sediment; as a consequence they develop larger roots systems than normal to take all of their nutrient requirements from the water column. Biofilms develop over the extensive root surface area and serve to increase organic matter breakdown, nutrient adsorption and trapping of fine particulates (James Sukias, 2010). The shade provided by the plant mats reduces algal growth and results in increased settling of suspended solids onto the pond/lake bottom. Localised anaerobic zones are created beneath the floating mats where the process of denitrification is favoured.
Situational Characteristics	
Suits what Problem	• Floating treatment wetlands have the potential to assist in the extraction of nitrogen and phosphorus from areas of ponded water such as wastewater treatment ponds and nutrient-contaminated lakes. • While the technology is very much at an experimental stage, initial trial results suggest they are very effective at removing nitrogen and moderately effective at removing phosphorus. • FTW's are not suitable for use in shallow streams or on wetlands where there is no pooled water.
Effectiveness Factor	**Criteria** — **Nitrogen** — **Phosphorus** 1. Cost-effectiveness ($ /kg N removed) — LOW — VERY LOW 2. Nutrient reduction potential: — HIGH — LOW 3. Ease of use: installation — UNKNOWN maintenance — UNKNOWN

Strengths/benefits	• Floating treatment wetlands do not require the purchase, lease or donation of land to be utilised. • Initial research suggests floating treatment wetlands can remove twice as much nitrogen as constructed wetlands with the same nutrient load. • The plant material growing on the wetlands can be mechanically harvested (Terry Wearmouth, pers comm.) to increase plant vigour and nutrient uptake. • Floating wetlands may provide additional wildlife habitat (especially for waterfowl), although this may lead to problems with plant damage and additional manure loads generated by the birds.
Limitations / disadvantages	• At this stage, this technology is unproven in terms of nutrient extraction performance on open lake conditions. Extraction rates in Lake Rotorua are expected to be 5 times less than those recorded in trials due to the low concentration of nitrogen in lake water compared to stream water used in the trials. • There is no definitive information available on the establishment and on-going maintenance costs and so estimates of cost-effectiveness are approximate. • There is some doubt about winter nutrient extraction performance and plant survival, especially in areas prone to frosts. • While the installation of these systems on small, accessible wastewater ponds appears to be straight forward it is not known how easy the system will be to establish on open lakes nor what the on-going maintenance costs will be in exposed lake conditions. • There is no available information to suggest how long each floating wetland will perform before the plant material or floating mat needs to be replaced.
Intervention Characteristics	
Impact and Reach	**Impact**: Nitrogen: HIGH on streams, LOW on lake Phosphorus: MEDIUM on streams Preliminary trial results obtained from trials undertaken in small, man-made, experimental baths have produced nitrogen extraction results that match or exceed those achieved in surface flow wetlands : 45% extraction of TN after 4 days water retention (extraction of 234 mg/m^2/day and 77% after 10 days (155 mg/m^2/day) (Sukias 2010). However, no research has been undertaken to determine if such performance will be achieved on

	open lakes. The same experimental trial has produced 20% TP extraction after 4 days 3.1 mg/m^2/day and 23% after 10 days (1.4 mg/m^2/day). **Reach** LOW near streams, HIGH on lake The reach of this technology is likely to be limited by the availability of sites to locate floating wetlands. The removal of nitrogen by treatment wetlands is directly proportional to the nitrogen concentration of incoming water. Thus, floating wetlands will be more effective if treating incoming stream water (e.g. diverting water through a floating wetland) rather than treating lake water directly. One advantage of treating lake water directly is the large amount of lake area that could potentially be covered by floating wetlands (about 8000 ha for the whole lake). Although, in practice the availability of sites will need to be balanced against the other lake uses.
Efficiency (cost-effectiveness in $/kg nutrient removed)	**Nitrogen** / **Phosphorus** Floating treatment wetland: $437 /kg N; $24,271 /kg P The cost-effectiveness calculations are derived from very broad estimates of likely installation and maintenance costs that have yet to be tested in open lake conditions.
Other factors to consider	
Evidence / Assumptions	The information used in this section has been derived from preliminary trial data from NIWA (Sukias 2010) and information supplied by Kauri Park Nurseries who are developing this technology commercially. The floating wetlands cost up to $400 /m^2 to establish with plants and maintain for the first year (Terry Wearmouth, Kauri Park Nurseries, pers comm). These costs could reduce if applied on a large scale, but this is very uncertain. We have assumed a median cost of $280/m^2 for this study. Assumptions used for the cost-effectiveness analysis are described in Appendix 1 and 2. e.g. we assume floating wetlands will be treating stream water with a high concentration of N.
Current Deployment	Floating treatment wetlands are being trialled on wastewater treatment ponds at several locations in New Zealand and in experimental tanks near Lake Rotoehu and Rotoiti.
Interventions indicators	As research trials advance the knowledge of this technology assessment of its usefulness for nutrient management in the Lake Rotorua catchment

	will require information on the following: • Nitrogen and phosphorus extraction performance over several months and years on the lake. • Cost and ease of installation and maintenance. • Impact on lake users and the impact of people and wildlife on the floating wetlands.
Overall impact and value for money	There is insufficient knowledge of the performance of floating treatment wetlands to make an evaluation of value for money at this stage; however, the technology does show potential. The effectiveness of treating water in the lake itself is likely to be poor due to relatively low nutrient concentrations in lake water. However, this system could be deployed as an instream or offline wetland to treat stream water.

5.6 Summary of a $1 million wetland package

Intervention Description: A $1 million package of constructed, natural SF and seepage wetlands.	
Description	Constructed wetlands and rejuvenated natural wetlands (seepage and lowland) are one of a range of management options available to assist in the reduction of nitrogen and phosphorus entering Lake Rotorua. While there are a range of wetland types (which are discussed above) all wetlands function by utilizing natural biological and chemical processes to remove nitrogen and phosphorus from catchment drainage waters. Three packages were developed: • An 'optimal' $1 million package (about equal area of natural SF and seepage wetlands - the most cost-effective wetland types); • A 'practical' $1 million package (which includes about 2 ha constructed wetland to improve certainty about immediate application); and • A 'maximum' package which estimates the cost and nutrient load reduction assuming a scenario where all suitable sites in the catchment were used.
Situational Characteristics	
Suits what Problem	Wetlands can be installed and/or managed to extract both nitrogen and phosphorus from catchment drainage waters in a significant way by installing or rejuvenating the appropriate wetland type or types to match

	the predominant nutrient problem in each catchment feeding Lake Rotorua. Wetlands are better at treating nitrogen rather than phosphorus, nevertheless surface flow wetlands (constructed and natural) and floating wetlands can remove a significant amount of phosphorus. Sediment retention structures can improve this function. The rejuvenation of seepage wetlands and lowland wetlands is the most cost-effecting was to manage nitrogen if they exist in sufficient frequency and area and supported by constructed wetlands if necessary.
Effectiveness Factor	**Criteria** **Nitrogen** **Phosphorus** 1. Cost-effectiveness ($/kg N removed) HIGH LOW 2. Nutrient reduction potential: HIGH LOW - MED (across the catchment) 3. Ease of use: Installation MEDIUM - HIGH Maintenance MEDIUM - HIGH **Notes**: Wetlands are a cost-effective, efficient and relatively easy to use tool for the reduction of nitrogen entering Lake Rotorua provided land can be made available for their construction in each feeder catchment. Wetlands alone are a less cost-effective and efficient option for the management of phosphorus entering Lake Rotorua.
Strengths / benefits	• Once installed or rejuvenated, well maintained wetlands are a relatively low energy, low cost, long life tool for nutrient removal. • The maintenance requirements for all wetland types (with the possible exception of floating wetlands) are generally low. • All wetlands are likely to have a positive impact on the environment, providing suitable habitat for indigenous plant and animal life. In addition wetlands often have high cultural and recreational values. • Within the Lake Rotorua catchment there would appear to be sufficient areas of land with restorable wetlands and land suitable for the construction of wetlands to enable wetlands to significantly reduce the nutrient load entering the lake (up to 26% of the Lake Rotorua TN catchment target and between 18% of the TP target - see Chapter 7). Whether this would actually be achieved depends on many other factors including land owner willingness

	• There is considerable seasonal variation in treatment performance. This can be a significant advantage by reducing the concentration of dissolved nutrients during the summer when most required by algae in the lake.
Limitations / disadvantages	• Land with suitable wetlands or sites where constructed wetlands could be built will need to be purchased or leased, or for seepage wetlands volunteered, and access procured. Resistance from landowners to make their wetlands and wetland sites available will reduce the effectiveness of this tool in the catchment. • The rejuvenation of natural wetlands and the construction of new wetlands will require a substantial investment of capital to significantly reduce Lake Rotorua's nutrient load. • We do not know what the functional lifespan of a wetland will be before its nutrient removal capacity diminishes.
Intervention Characteristics	
Impact and Reach	**Impact**: Nitrogen: HIGH Phosphorus: LOW- MEDIUM Seepage, restored natural lowland, and constructed wetlands all have a high capacity to remove nitrogen from receiving waters, but only a medium to medium –low ability to extract phosphorus over the medium to long term. **Reach** HIGH Wetland reach is high wherever wetlands are located or can be constructed in the lower catchment to intercept all or most of the catchment drainage. There would appear to be suitable land for wetlands in most Lake Rotorua feeder catchments to achieve this. As with all interventions, the reach would be very limited if expenditure is limited to only $1 million.
Efficiency (cost-effectiveness)	**Nitrogen** / **Phosphorus** Optimum $1 M Package[6]: 2,000 kg/yr / 42 kg/yr Practical $ 1M Package: 1,258 kg/yr / 33 kg/yr

[6] This assume $1 million provided over two years with equates to $0.963 million as Net Present Value (NPV).

Other factors to consider	
Utilisation	The following strategy could be adopted to optimise the use of wetlands for nutrient extraction: o Continue to manage and protect existing healthy wetlands. These wetlands will already be functioning as effective nutrient removers. o Fence and restore seepage wetlands, especially in catchments with high nitrogen loads and many springs and seeps. Because the spring water passes through the wetland organic soil nitrogen extraction efficiency is high in a relatively small area. o Restore those modified natural lowland wetlands that can have their drainage corrected without great cost. o Use constructed wetlands in catchments with few seepage wetlands. If the nutrient extraction potential of floating wetlands can be confirmed they could be utilised in constructed wetlands, settling ponds, streams and on the lake to further increase nutrient extraction.
Current Deployment	Constructed, seepage and rejuvenated natural wetlands are being used successfully for nutrient attenuation in several locations in New Zealand and in a number of countries around the world.
Interventions indicators	Assessment of the effectiveness of all wetland types used to reduce the nutrient load entering Lake Rotorua would require an on-going commitment to monitoring the flow and nutrient concentrations entering and exiting the wetlands.
Overall impact and value for money	A Net Present Value (NPV) $1 million optimum wetland package could remove, on average 2.2 tonnes N/yr and 0.04 tonnes P/yr. There is uncertainty about the availability of natural SF and seepage wetlands, so a practical package was developed. A NPV $1 million practical wetland package could remove, on average 1.3 tonnes N/yr and 0.03 tonnes P/yr. Limiting investment in treatment wetlands to $1 million will limit the reach of this intervention. Assuming a scenario that uses all available wetland sites could potentially reduce the Lake Rotorua annual nitrogen load by 59.1 tonnes (26% of the catchment target) and 1.78 tonnes of the annual phosphorus load (18% of the catchment target), and would cost $54.4 million. In addition to providing nutrient attenuation wetlands offer many other biodiversity, aesthetic and cultural benefits.

6 Comparison of wetland types

6.1 Nutrient removal effectiveness

The effectiveness of different wetland types is compared in Table 6.1. The table shows that in order of effectiveness at removing nitrogen in the Rotorua catchment, better performance is achieved with floating wetlands > constructed wetlands > seepage > natural wetlands. The order is slightly different for long term sustainable phosphorus removal with natural wetlands outperforming seepage wetlands.

It should be noted that these assessments were done on a catchment scale and the effectiveness of any specific wetland will vary between wetlands, between seasons and between years. Particularly important is the hydraulic loading, concentration of nutrients in the inflow water, temperature, hydraulic retention (reduced by bypass flow), and contact between the water and the wetland (influenced by vegetation and water depths). Our assumptions around these variables drives some of the variation in treatment effectiveness. For example, constructed wetlands and natural wetlands were assumed to have a hydraulic loading ranging from 35-55 m/yr, whereas the range extended lower for seepage wetland (15-55 m/yr) reflecting low loading rates (and high % extraction) observed in the literature. The range was assumed wider for floating wetlands (25-90 m/yr) because of uncertainty about how floating wetlands will be deployed in this context.

Natural wetlands had worse treatment performance than constructed wetlands in part because of the often poorer performance in less controlled wetlands (e.g. more variation in water depth, less control over bypass flow) and in part because it does not have the added benefit of removing the nutrient load of the previous land use on that piece of land (i.e. 28 kg N/ha/yr for nitrogen and 0.8 kg P/ha/yr for phosphorus). This improved treatment performance by about 10%.

There will be specific wetlands that will exceed our assumptions, and even within the constraints of our assumptions there is considerable variability. However, when multiple wetlands used in a package over a catchment scale the variability tends towards the average.

The performance of 'natural SF wetlands' and 'seepage wetlands' refers to the restoration of these wetlands to effective systems for nutrient attenuation. We have assumed that prior to restoration these systems will have negligible nutrient attenuation (i.e. nutrient removal potential bypassed by drainage). In reality there will be a gradient of performance in different parts of a wetland and larger wetlands only some parts will be drained or degraded so as to have negligible nutrient attenuation performance. The cost-effectiveness estimates only refer to these sections of the wetland.

Table 6.1: Effectiveness of different wetland types (average removal)

Average treatment performance	constructed wetland	Natural SF wetland	Seepage wetland	Floating wetland
TN (kg/ha)	368	289	323	714
TP (kg/ha)	11	10	2	13

6.2 Cost effectiveness

The cost-effectiveness of wetlands is shown in Table 6.2, Figure 6.1 and Figure 6.2. Incorporating the cost of construction, maintenance and renewal of wetlands substantially changes the order of treatment performance. The order of nitrogen treatment performance in terms of cost-effectiveness is, from cheapest to most expensive: protecting existing natural wetlands from drainage < seepage < natural surface flow wetlands > constructed wetlands < floating wetlands. For phosphorus removal, seepage wetlands drop two places and are more expensive per kilogram removed than constructed wetlands.

Protecting natural existing wetlands from drainage is by far the most cost-effective way to control nutrient loads to Lake Rotorua. While protecting existing wetlands is not an active intervention, this needs to be considered a part of the overall strategy to reduce nutrient loads to Lake Rotorua. The price includes the cost of leasing and maintaining natural wetland areas, but not any fencing or work to improve treatment performance.

For most wetland treatment options the variability around cost effectiveness is driven by the potential of wetlands to reduce nutrient loads. However, for floating wetlands the uncertainty around the average figures is due to uncertainties in price.

Table 6.2 shows the uncertainty surrounding our estimates. There is considerable variability in removal rates and cost-efficiency for any one wetland. However, as more wetlands are constructed in the landscape the tendency will be for the overall removal rates to more towards the mean values.

Part of the difference in estimates between natural surface flow (SF) wetlands and seepage wetlands may be due to the different methods used to estimate costs. Bottom-up cost estimates were done for seepage wetlands, while top-down cost estimates were done for natural SF wetlands (i.e. based on the renewal cost of a constructed wetland). In reality there is a continuum between seepage wetlands and natural surface flow wetlands and the costs are also likely to be somewhere between the two. The ‘optimum wetland package’ discussed in the next section accounts for this by assuming equal area of seepage and natural SF wetlands.

These estimates are reasonably insensitive to whether land is leased or purchased. If we were to assume that land used for constructed wetlands was purchased at a cost of \$29,000/ha (the median price of dairy land) instead of being leased (NPV \$5,016/ha), the cost-effectiveness of constructed wetlands changes 6% from \$79/kg to \$84/kg removed.

The cost of constructing treatment wetlands reduces with increasing size. We have assumed that constructed wetlands will be 3.0 ha in size. Constructing a 10 ha wetland will be about 70% of the cost of a 3 ha wetland, which improves (reduces) cost-effectiveness by about \$20/kg N (also see graph in Section 9.4.2).

The cost-effectiveness analysis is sensitive to the discount rate used in calculating Net Present Value. We have used a discount rate of 8% and any comparison with other intervention measure should use a consistent discount rate.

Table 6.2: Cost-effectiveness of different wetland types. Average and (inter-decile range[7])

Wetland type	constructed wetlands	Restoring Natural SF wetlands	Restoring Seepage wetlands	Floating wetlands	Protecting natural wetlands
cost effectiveness TN ($/kg)	$79 (64-97)	$60 (47-85)	$20 (14-29)	$437 (330-570)	$14 (11-18)
cost effectiveness TP ($/kg)	$2,548 (1650-4600)	$1,714 (1110-3190)	$2,739 (1600-4720)	$24,271 (17000-35900)	$431 (260-870)
cost effectiveness TN & TP ($/kg)	$76 (63-94)	$58 (45-82)	$20 (14-28)	$429 (330-560)	$13 (10-18)

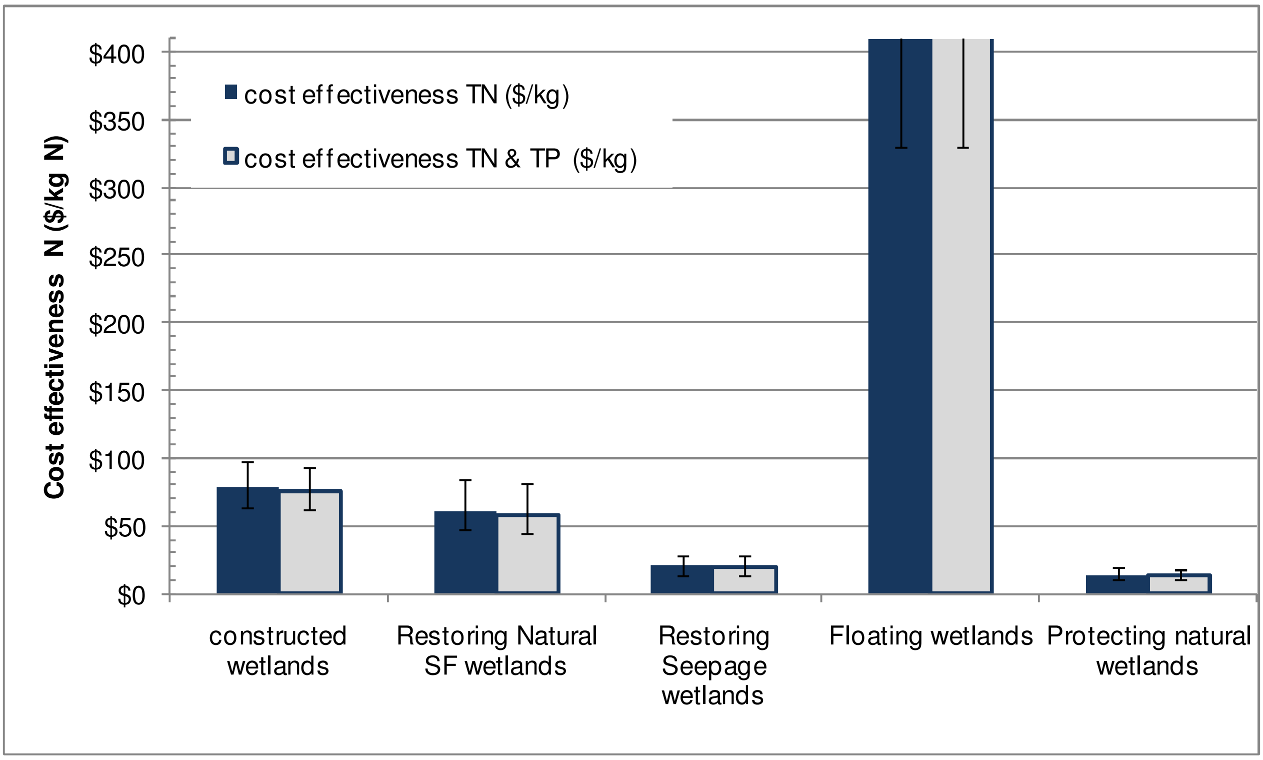


Figure 6.1: Cost-effectiveness of wetland nitrogen removal. Error bars are 5th and 95th percentile values.

[7] The inter-decile range is the range between the 5th percentile and the 95th percentile.

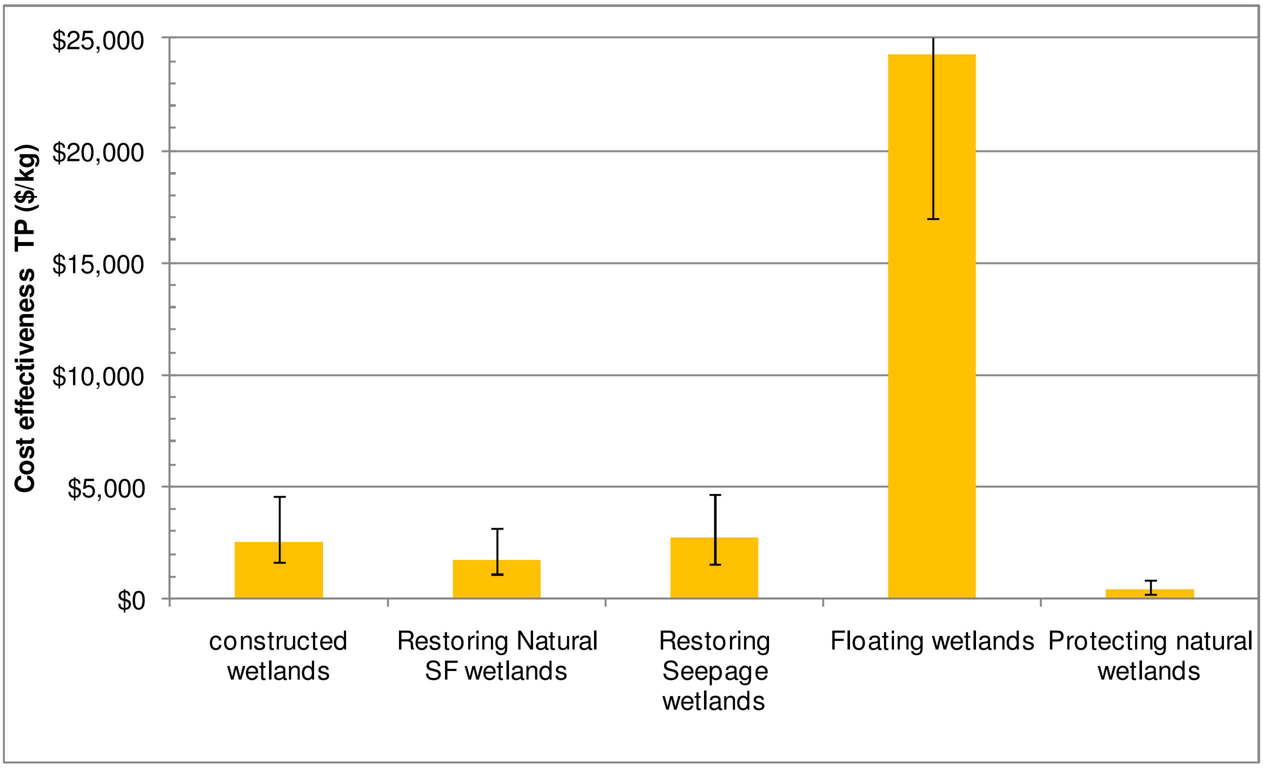


Figure 6.2: Cost-effectiveness of wetland phosphorus removal. Error bars and 5th and 95th percentile values.

6.3 Ease of use

Restoring natural wetlands and restoring seepage wetlands are the most cost-effective wetland options for nutrient attenuation, however they both have considerable uncertainty around the ability to implement these options in the catchment for several reasons. Firstly, our estimates of the amount of wetland that could be restored from a degraded state are approximate and require further confirmation.

Secondly, care would be needed when restoring a natural wetland for purposes of nutrient attenuation that other wetland values are not compromised. We have allowed additional cost for going through a resource consent process, but the outcome of this for any particular wetland is uncertain.

7 Potential of wetland packages to reduce nutrients to Lake Rotorua

7.1 Introduction

BOPRC requested a package of wetland options that provide the most cost-effective use of different wetland types in the landscape. This package was limited to a budget of $1 million dollars spread equally over two years (2012/13 to 2013/14). This equates to $962,960 Net Present Value using a real discount rate of 8%. Three packages were developed:

- An 'optimal' $1 million dollar package[8] (maximising the area of wetland types that provide the most cost effective nitrogen treatment to the extent to which suitable sites exist);
- A 'practical' $1 million dollar package (reducing the area of wetland types that have low certainty about availability of suitable sites); and
- A 'maximum' package which estimates the cost and nutrient load reduction assuming a scenario where all suitable sites in the catchment were used.

The wetland packages were optimised around nitrogen removal because nitrogen reductions dominated over phosphorus reductions in all wetland packages in terms of both mass removal and percentage removal.

It should be noted while wetlands are 'low maintenance systems', they are not 'no maintenance systems'. Our whole-of-life costs have accounted for ongoing maintenance, renewal and lease costs, thus for any wetland package some money will need to be put aside to cover these costs. Our estimates show that for a constructed wetland acquisition costs are about 77% of total costs and ongoing maintenance, renewal and lease costs about 23%. In other words, about 20-25% of a $1 million package should be put aside and invested for ongoing maintenance, renewal and lease costs.

7.2 A $1 million 'practical package' and 'optimal package'

A $1 million ($0.96M NPV) optimum wetland package for nutrient removal was developed by maximising the area of wetland types that provide the most cost effective nitrogen treatment to the extent to which suitable sites exist. In area terms this comprised of an equal area of seepage SF wetlands and seepage wetlands (2.1 ha each). In dollar terms this comprised of two thirds natural SF wetlands ($0.713M) and one third seepage wetlands ($0.25M).

The optimum package would remove, on average 2.0 tonnes N/yr of nitrogen and 0.042 tonnes P/yr of phosphorus. However, there is considerable uncertainty around the practicality of restoring natural and seepage wetlands and the availability of suitable sites, thus we have prepared a 'practical' package of using wetlands for nutrient reduction.

A $1 million ($0.96M NPV) practical package of wetlands was developed for nutrient removal. In area terms this comprised of $0.72M (~2.1 ha) of constructed wetlands, $0.17M (0.8 ha) of natural SF wetlands and $0.07M (0.9 ha) of seepage wetlands. This would

[8] Spread equally over two years (2012/13 to 2013/14) as requested by BOPRC.

remove, on average 1.26 tonnes N/yr of nitrogen and 0.033 tonnes P/yr of phosphorus. This 0.55% of nitrogen catchment target and 0.28% of phosphorus catchment target.

A comparison between a ‘practical package’ to remove nutrients and an ‘optimum package’ to remove nutrients using wetlands is shown in Table 7.1 and Figure 7.1. When expressed in terms of investing $1 million as Net Present Value, the ‘optimum package’ corresponds to 2.16 tonnes N/yr and 0.038 tonnes P/yr for every $1 million invested; and the ‘practical package’ corresponds to 1.34 tonnes N/yr and 0.033 tonnes P/yr for every $1 million invested.

Table 7.1 also shows the 5th and 95th percentile values surrounding the average values. For nitrogen estimates this range represents about +/- 16 percent for the practical package and +/- 22 percent for the optimum package. For phosphorus estimates this range represents about +/- 38 percent for the practical package and +/- 43 percent for the optimum package. The values are sensitive to the mix of wetland types in each package because of the wide range in cost-effectiveness between different wetland types; this is illustrated by the difference between the two packages.

Table 7.1: Nutrients reductions from applying the ‘Optimum Package’ and ‘Practical Package’ to the Rotorua catchment (average with 5th and 95th percentile in brackets).

$1 million wetland packages for nutrient reduction ($0.963M NPV)	Total Nitrogen (tonnes/yr)	Total Phosphorus (tonnes/yr)	Make up of package (as % of area)
Practical package	1.26 (1.1 - 1.5)	0.033 (0.022 - 0.047)	54% (2.1ha) constructed, 22% (0.8ha) natural SF, 24% (0.9ha) seepage
Optimal package	2.00 (1.6 - 2.5)	0.042 (0.025 - 0.061)	50% (3.4ha) natural SF, 50% (3.4ha) seepage

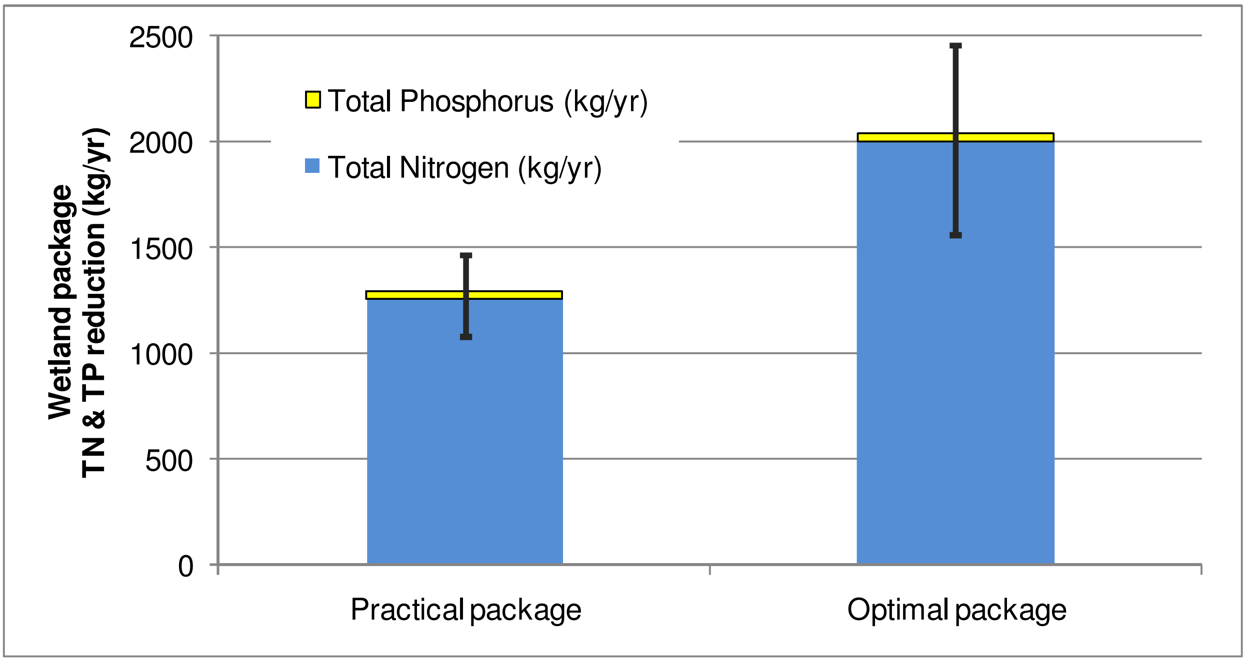


Figure 7.1: Nutrients reductions from applying the 'Optimum Package' and 'Practical Package' to the Rotorua catchment. Error bars represent 5th and 95th percentile values.

7.3 A 'maximum wetland package'

The 'maximum' wetland package estimated the cost and nutrient load reduction if all suitable sites in the catchment were used. This consisted of: 88% (145ha) constructed wetlands, 7% (12 ha) natural wetlands and 4% (7.2 ha) seepage wetlands. The results and inter-decile range of values is shown in Table 7.2.

Applying the 'maximum package' of wetland creation across the Lake Rotorua catchment will remove 59.1 tonnes N/yr (+/- 15%) of nitrogen and 1.8 tonnes P/yr (+/- 40%) of phosphorus. This corresponds to 26% and 18% of the respective N and P reduction targets set for the catchment. Whether this would actually be achieved depends on many other factors including land owner willingness. Also, the actual availability of land should be confirmed with field checks.

McKergow *et al.* (2007) estimated that establishing treatment wetlands in 1% of a catchment area could remove ~30% of the nitrogen load. Applying this rule-of-thumb to the 145 ha of wetland treatment area in the 'maximum package' estimates that 8.3% of the nitrogen load would be removed[9]; this corresponds closely with our estimate for the total catchment load reduction of 7.5%.

The cost of removing 59.1 tonnes N/yr of nitrogen and 1.8 tonnes P/yr of phosphorus using the maximum wetland package would be $54.4 million (+/- 11%). This corresponds to 1.09 tonnes N/yr and 0.033 tonnes P/yr for every $1 million invested.

[9] 145ha = 0.28% of Lake Rotorua catchment area (52347 ha).

Constructed wetlands had less nitrogen removal per dollar compared to natural or seepage wetland options. The higher percentage of constructed wetlands in the 'maximum package' compared to either the 'practical package' or 'optimum package' makes it less cost-effective. In other words, a $1 million package can focus on the most cost-effective wetland options i.e. restoring natural wetlands and restoring seepage wetlands.

Table 7.2: Nutrients reductions from applying the 'maximum package' to the Rotorua catchment (average with 5th and 95th percentile in brackets).

Maximum package catchment reductions	Total	Total nitrogen	Total phosphorus
Cost ($ million)	$54.4 ($48.3 - $60.4)		
Area constructed constructed	145		
Area natural wetland	12		
Area seepage wetland	7.25		
Load reduction (tonnes/year)		59.1 (51 - 68)	1.8 (1.1 - 2.6)
% of Lake Rotorua catchment target		26%	18%
% of total load to Lake Rotorua		8%	0.2%

Maximum package = 88% constructed, 4% seepage & 7% natural SF wetlands (by area).

7.4 A comparison with the Lake Taupo Protection Trust budget

It is useful to compare the cost-effectiveness of using wetlands to remove nutrients with other intervention measures. This is being undertaken in a different project, but in the absence of this analyse we have compared cost-effectiveness with the budget of the Lake Taupo Protection Trust for removing N as a 'touch stone' as to whether the wetland packages are cheap or expensive.

The Lake Taupo Protection Trust was allocated a budget of $72.4 million (excl GST) over 14 year to achieve a nitrogen reduction of 111 tonnes N/yr (20% of the 'manageable load'). This corresponds to about $70.5 million as a NPV in 2010 dollar terms[10]. Thus, to achieve the target within budget requires about 1.57 tonnes N/yr per $1 million.

So far the project appears to be meeting its target within the budget, this is being done largely by purchasing land, imposing a covenant to limit nitrogen loss and reselling the land. Once the land is sold it is typically being planted for production forestry.

Compared to the Lake Taupo Protection Trust budgeted target, the 'maximum wetland package' would remove about 70% of the nitrogen for every dollar spent, so appears to be a more expensive way to remove nitrogen than the approach being taken in the Taupo catchment. The $1 million 'practical wetland package' also appears more expensive, removing 85% of the nitrogen for every dollar spent. However, the 'optimum wetland package' is cheaper, removing 138% of the N for every dollar spent. While comparison is only indicative it does show that wetland packages can be comparable with other alternatives.

[10] Using a real discount rate of 4% to adjust for inflation.

8 Discussion and Conclusions

Wetlands can be an effective part of the solution

This project identified the cost-effectiveness of different types of wetlands at removing nutrients from entering Lake Rotorua. Two $1 million wetland packages were developed. An 'optimum' package consisting of 50% seepage wetlands and 50% natural SF wetlands (by area) was estimated to remove 2.16 tonnes N/yr (+/- 22%) and 0.038 tonnes P/yr (+/- 43%) for every NPV $1 million invested.

A 'practical' package consisting of 55% constructed, 22% natural SF and 24% seepage wetlands (by area) was estimated to remove 1.34 tonnes N/yr (+/- 16%) and 0.033 tonnes P/yr (+/-38%) for every $1 million invested. These are comparable to the budgeted target for removing N by the Lake Taupo Protection Project (~1.6 tonnes N/yr per $1 million).

We identified areas in the Rotorua catchment that might be suitable for treatment wetlands. A scenario that utilises all identified wetland sites across the landscape (a 'maximum' package) would cost $54.4 million and remove about 59.1 tonnes N/yr (+/- 15%), corresponding to about 26% of the nitrogen reduction target sought from the catchment. The actual amount of land available for creation of treatment wetlands needs field validation, but our analysis has shown that wetlands can be a realistic option within a package of interventions to reduce nitrogen and phosphorus loads to Lake Rotorua.

Wetlands are not the whole solution to reducing nutrient loads to Lake Rotorua but they should certainly be considered as part of the solution. Furthermore consideration could be given to investing more than the $1 million currently allocated. This could provide additional benefits for biodiversity, cultural values and recreation that have not been considered in this analysis.

Protection is cheaper than restoration

Our analysis suggests that most cost-effective way to use wetlands to manage the nutrient load to Lake Rotorua is to protect existing natural wetlands and seepage wetlands from drainage. Mechanisms to achieve this should be considered in an overall strategy to reduce nutrients to the lake. Protection, however, will only maintain a status quo; to reduce current loads the most cost-effective approach to using treatment wetlands are (from most to least effective):

- Rejuvenating seepage wetlands (but limited sites are available);
- Rejuvenating natural wetlands (but high uncertainty about the number and suitability of sites available);
- Constructed wetlands;
- Floating wetlands installed in or alongside streams;

- Floating wetlands installed in the lake itself (less effective due to the lower nitrogen concentration in the lake compared to incoming water).

Wetlands are much more effective at reducing nutrient loads when they receive high concentration inputs and when water temperatures are warmer. This suggests that streams with a geothermal water influence (e.g. the Waiohewa Stream) should be a priority of nutrient reduction using wetlands.

The cost per hectare of establishing a treatment wetland reduces with increasing size. Our analysis assumed constructed wetlands would be 3 ha in size, thus creating wetlands greater than 3 ha will make wetland packages more cost-effective.

Nutrient farming

The term nutrient farming has been applied to using wetlands to reduce nutrient loads across the landscape (Kadlec 2005). If this is to occur on a wide scale, the right incentives need to be put in place. Leasing land provides an incentive for landowners to provide land for creating wetlands for nutrient control. Reverse auctions could also provide an incentive to construct treatment wetlands. The Overseer model, increasingly used by farmers and government authorities to produce nutrient budgets, currently allows only crude adjustments for nitrogen removal by wetlands and does not account for additional loading from spring or seepage areas. This reduces the incentive provided to landowners for constructing treatment wetlands. Refinements may be needed to Overseer if there is to be widespread promotion of wetlands as an option for nitrogen treatment. Alternatively, actual nitrogen load reductions could be measured – which would encourage good maintenance.

One advantage of providing incentives for landowners to create treatment wetlands is that it allows the people who have the most knowledge of local conditions, the land owners themselves, to identify suitable areas for wetland that will maximise overall benefits and minimise costs. However, this will only have benefits for the lake if the nutrients removed are not replaced by way of more intensive landuse. There will be no gain for the lake if landowners were to use wetlands to simply offset more intensive land use.

Reverse auctions are one mechanism being considered for buying and removing nutrient credits from the catchment. In order for reverse auctions to realise the potential for establishing treatment wetlands throughout the landscape, they need allow the sale of a large number of small packages of nutrient credits and not be limited to purchasing only large packages.

Seasonal variation in wetland nutrient removal

This analysis has focused on the long-term sustainable removal of nitrogen and phosphorus by wetlands and has ignored short-term and seasonal variations. However, the seasonality of wetland performance can also improve lake water quality by reducing the concentration of dissolved nutrients during the growing season when it is in greatest demand by lake phytoplankton.

Further work would be needed to incorporate seasonality into the overall effectiveness of treatment wetlands and its interaction with nutrient cycling and phytoplankton growth in the lake.

Further work

These estimates assume a number of assumptions about wetland treatment performance, costs, current state and availability of land. Some of these assumptions regarding the amount of wetland area in the catchment are based on rough estimates and it is recommended that work is done to confirm them, in particular:

- Identify the current area and state of seepage wetlands in the Rotorua catchment.
- Improve understanding of nutrient removal performance of natural and degraded wetland systems.
- Confirm using site visits the total amount of land available for constructing treatment wetlands near major streams and the potential for consistent hydraulic loading of possible wetland sites near minor streams.
- Improve understanding about the performance and costs associated with floating wetlands in natural streams and lakes.
- Record the breakdown of costs for establishing and restoring wetlands to improve information available for future cost-effectiveness assessments.
- Ensure any model used to estimate nitrogen and phosphorus removal accurately accounts for wetland treatment.
- Undertake a cost-benefit analysis of the wider social and economic benefits / costs of wetlands compared to other interventions for reducing nutrient loads to Lake Rotorua. This could include how expenditure on this intervention stimulates the economy, biodiversity values and cultural values.

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9 Appendix 1: Wetland processes and performance

9.1 Wetland processes for removing nitrogen and phosphorus

9.1.1 General

There are many processes by which nutrients are processed within a wetland but only a few of these result in long term, sustainable removal. Wetlands remove phosphorus by four main mechanisms:

a) sorption on substances;

b) uptake and storage in wetland biota (plants, algae, microorganisms);

c) particulate precipitation and settling; and

d) the burial of plant material and accretion of new sediments.

Similarly, wetlands remove nitrogen by three main mechanisms:

a) Uptake and storage in wetland biota;

b) The burial of plant material and accretion of new sediments.

c) Denitrification

Only denitrification, particulate settling and accretion of sediments are long term, sustainable processes for nutrient removal. In contrast, sorption is a reversible process, and most nutrients taken up by wetland plants are eventually cycled back into the system. These processes are discussed below.

9.1.2 Sorption (short term P removal)

Soils have a finite ability to sorb phosphorus, over time the sorption capacity becomes saturated. If soils are deficient in phosphorus they may serve as a sink for phosphorus until its capacity for sorption is saturated. Conversely, if pools of phosphorus are already present in the soils these may be released when a wetland is constructed due to a change in water chemistry (e.g. anaerobic conditions) or if there is a reduction in the concentration of incoming phosphorus in the overlying water.

Iron and aluminium enhances sorption as a removal mechanism (Kadlec 2005b), and the amount of P removed by sorption can, in the short term, be very high e.g. >90% of P removed from treated sewage effluent added to the Cyprus Dome (Dierberg and Brezononik 1983, in Howard-Williams 1985)).

9.1.3 Uptake by plants (short term, seasonal N and P removal)

Dissolved phosphorus is sequestered in the growth of new plant matter. This is released seasonally when plants die and some of this material is buried. The uptake rates by microflora (e.g. algae) can be very high (about 50%) but the turnover rates are very fast and most nutrients are returned to sediment and water. Kadlec (2005) estimated annual uptake of nitrogen is in the order of 15 g N/y^2.yr (i.e. 100 g/m^2.yr of growth times 1.5% nitrogen).

Plant uptake rates are variable. Some studies have found the rate of uptake by plants is small compared to denitrification e.g. 7% compared to 62% (in Kadlec 2005), while others have found the plant uptake to be the major process, e.g. ~328 to 550 $g/m^2/yr$ during maximum growth compared to a denitrification rate of ~0.4 to 30 $g/m^2/yr$ (Howard-Williams & Downes 1984, in Howard-Williams 1985).

Seasonal patterns

Wetlands can have strong seasonal patterns in nutrient removal due to plant growth and higher rates of denitrification in warmer temperatures. Some studies have shown 80-100% utilisation of phosphorus and nitrogen during the growing season, but most nutrients are returned during the autumn senescence. In the constructed Lake Okaro wetland higher nitrate removal rates in summer effectively starves the lake of dissolved nitrogen which limits algae growth during this critical season. Some of this retained nitrogen will be released again as vegetation decomposes and its availability for algae growth will be controlled by a complex set of biophysical processes (Hudson *et al.* 2009).

This report calculates nutrient removal based on annual average reductions and does not account for seasonal nutrient uptake which can further reduce concentrations of dissolved nutrients during periods most critical for algae growth.

Harvesting

Harvesting of plant biomass is generally ineffective at enhancing nutrient removal. It is difficult to harvest rooted emergent macrophytes and only a small fraction of applied nutrients can be harvested i.e. less than 10% of annual phosphorus load is removed from even lightly loaded systems; and 4 - 21% removal of nitrogen in moderately loaded systems (Kadlec 2005b, Kadlec and Wallace 2009). Floating aquatic plants are easier to harvest (20% TP removal in some studies). Kadlec and Wallace (2009) concluded that the cost of harvesting and disposal of wetland plants means that it is seldom used except for very small wetlands or for floating plants.

Harvesting of watercress (*Nasturtium officiinale*) was investigated as a way to reduce nutrient loads entering the Rotorua lakes (Sukias *et al*. 2009). Total nitrogen and dissolved phosphorus removal rates were 19% (598 $g/m^2/yr$) and 15% (2.7 $g/m^2/yr$) respectively at high flow (hydraulic retention time of 0.1 days). The practical application of this technology requires more investigation but is outside the scope of this project.

9.1.4 Particulate settling (sustainable P removal)

Settling and chemical precipitation of particulate phosphorus is a significant process for phosphorus removal, particularly for inorganic particulate phosphorus (e.g. phosphorus associated with soil particles and erosion). Some studies have measured phosphorus retention due to precipitation and settling of agricultural runoff as high as 26 - 71 $g/m^2/yr$ (Braskerud 2002, in Kadlec and Wallace 2009). Phosphorus bound to particles can be remobilised during floods (Howard-Williams 1985), so it is important to design wetlands to prevent this from occurring (e.g. having system for flood bypass flow).

Kadlec and Wallace (2009) found that plants and submerged vegetation promote a major fraction of phosphorus removal in wetlands. The plant community type can have a significant effect on phosphorus removal (e.g. emergent or submerged) but species composition of any given community makes little difference (Kadlec and Wallace 2009).

A settling pond is often used to provide initial treatment in a wetland complex. Ponds trap rapid settling particles and are easily cleared of deposits. In some wetlands, the settling ponds occupy 15% of the area and account for ~95% of the solids removed. However phosphorus tends to be preferentially bound to smaller particles, which are better removed in vegetated sections rather than open water, so the wetland itself is needed for most of the phosphorus removal (Kadlec and Wallace 2009).

9.1.5 Burial and accretion (sustainable N and P removal)

Accretion and burial of nutrients can be a significant process of nutrient removal in lightly loaded wetland. Wetland plants and algae utilise phosphorus as a nutrient and decomposition processes release most of the phosphorus back to the water. However, not all dead plant material is decomposed. A small amount (about 10-20 percent) is permanently stored as new sediments and soils in the wetland. Kadlec and Wallace (2009) recorded phosphorus burial in wetlands with low phosphorus loading (<1 mg/l) in the range of 0.06 to 0.36 g $P/m^2/yr$. The net removal of nitrogen by burial is in the order of 10 g $N/m^2/yr$ for wetlands with low N concentrations (Kadlec and Wallace 2009).

9.1.6 Denitrification (sustainable N removal)

Denitrification is a natural process occurring where nitrate is available, oxygen conditions are low and there is sufficient organic carbon (Seitzinger et al 2006 in McKergow *et al* 2007). Wetlands can provide ideal conditions for denitrification by providing a mosaic of aerobic and anaerobic conditions. There are a number of features of treatment wetlands that should be considered for optimising denitrification, including hydraulics, carbon supply and vegetation cover.

There are other processes that remove nitrogen by degassing such as ammonia volatilisation and anaerobic ammonia oxidation (Anammox), but these are considered minor processes compared to denitrification in most wetland systems (Kadlec and Wallace 2009).

Hydraulics

Internal hydraulics has an important role in nitrogen removal, with high removal rates when there is longer residence time and less short circuiting or dead zones. Surface flow wetlands have longer residence time when they have a longer length to width ratio.

Improving retention time by creating deeper water does little to improve nitrate removal by denitrification. This is because denitrifying microbes are located on underwater surfaces (e.g. soil and plant matter) with low dissolved oxygen and deeper water does little to improve these conditions. Arheimer and Wittgren (1994) (in Kadlec and Wallace 2009) found low removal rates (expressed as k-value constant) for ‘pond type wetlands’ (1.5m depth, 17 m/yr) and for streams (12 m/yr).

Carbon supply

Denitrification of nitrate requires carbon. In an established wetland the carbon supply can usually be supplied by decay of litter, and carbon is only expected to be limiting at high loading rates. Wetlands with low nutrient loading generally form plant biomass at a rate above 1000 g/m^2/yr (Kadlec and Wallace 2009). At this rate a typical carbon content of 43% will provide enough carbon to potentially denitrify about 175 g/m^2/yr (on the basis that 2.5 g carbohydrate is required to denitrify 1 g of nitrate N, Kadlec and Wallace 2009). Natural waters tend to have low nitrate concentrations (~<3 mg/l) compared to effluent, consequently carbon will only become limiting when the hydraulic loading is very high (>100 m/yr) and greater than what is hydraulically feasible in many surface flow wetlands. However, it is possible that carbon may limit denitrification in a new constructed wetland, before plants establish, unless there are carbon supplements (e.g. sawdust was added to the soils in newly constructed wetland at Lake Okaro).

Vegetation

Vegetated wetlands tend to have better nitrogen and phosphorus removal rates than non-vegetated wetlands (Kadlec 2005, Kadlec and Wallace 2009). Unvegetated open water does not promote denitrification while vegetation provides a source of carbon for denitrification and the stems of emergent vegetation provide more surface areas for biofilms and denitrifying bacteria. Nitrate removal has been shown to be proportional to the number of shoots in a *Schoenoplectus* spp. dominated wetland (Smith *et al* in Kadlec 2005).

9.2 Wetland treatment performance

The approach to assess treatment performance of different types of wetlands is discussed below.

9.2.1 Constructed surface flow wetlands

There is considerable variation of removal rates and percentage removal for surface flow wetlands recorded in the literature. The key variables driving wetland performance are hydraulic loading, incoming nutrient concentration, seasonal temperatures and wetland hydrology (e.g. residence time). The removal rate constants can also vary with vegetation type, and carbon supply maintenance.

Misch *et al.* (2000) reported summarised data from a wide range of wetlands and reported nitrate retention rates of 3 to 1022 g N/m^2/yr and phosphorus retention rates of 0.4 - 39 g P/m^2 /yr. They concluded that sustainable rates of removal for non-point source nitrate-nitrogen and phosphorus are generally in the range of 10 – 40 g N /m^2/yr and 0.5 – 5 g P/m^2/yr respectively.

Monitoring of the constructed wetland at Lake Okaro during 2008 (its third year of operation) found nitrogen and phosphorus removal rates of 45 - 47% (about 26.8 g/m^2/yr) and 47 – 58% (about 8.4 g/m^2/yr) respectively (Hudson *et al.* 2009). Much of the phosphorus removal was attributed to sedimentation. This wetland is early in its establishment. It is possible that short term removal mechanisms (e.g. plant uptake and soil sorption) are not saturated so these results may over estimate long term performance.

We have used simple models to constrain this variation and assess the effectiveness of wetlands constructed in the Rotorua catchment for removing nutrients. The model outputs were within the range of removal rates derived from the literature. A more detailed description of assumptions used is provided in Appendix 2.

We have assumed that future constructed wetlands will have a similar design to that used for Lake Okaro (Tanner 2003). In particular:

- Hydraulic efficiency equivalent to a well-designed, vegetated surface-flow wetland with approximate length to width ratios of between 4:1 and 6:1.
- A settling pond at the beginning of the wetland to provide initial removal of sediments and attached phosphorus load.
- Treatment will be for a portion of stream base flow to allow for fish passage and diversion of flood flows.
- Hydraulic loading rate similar to Lake Okaro constructed wetland i.e. 46 m/yr (range 35-55).

Constructed wetland nitrogen removal

A key feature of wetlands designed for nutrient removal is a trade off between removal efficiency and load reduction. The actual mass of nitrogen removed increases with loading, thus increasing the hydraulic loading results in more kilograms of nitrogen (N) removed, but this is at the expense of less percentage reduction in concentration.

The nitrogen removal of constructed wetlands can be reasonably predicted by using first-order, 'tanks-in-series' kinetic approach (Kadlec and Wallace 2009, Kadlec 2005) represented by the formula:

$$LR = LI\ .\ eff = q.Ci\ .\left[1-\left(1+\frac{k}{N.q}\right)^{-N}\right]$$

Where:

eff =factional concentration reduction

LI = incoming nitrogen load (g N/m^2 . yr)

LR = nitrogen *LI* load reduction

Ci = inlet N concentration (g/m^3)

k = first order uptake rate constant (m/yr)

N = hydraulic efficiency parameter

q = hydraulic loading rate (m/yr).

We assessed wetland nitrogen treatment performance using the model and by refining the input parameters for the Lake Rotorua catchment. These are further described in Appendix 2. Wetlands have substantial seasonal variation in nitrate removal in part because denitrification is significantly higher when temperatures are higher e.g. during summer or if incoming water is warmed by geothermal activity.

The nitrate uptake rate constants used in the model were adjusted to correspond to the annual average water temperature in Lake Rotorua (i.e. 15 ^{o}C). The estimated impact of global warming was included by adding half of the MfE (2008) predicted increase from 1990 to 2040. This resulted in a estimated mean temperature of 15.5^{o}C, and range of 15.1 – 16.3^{o}C.

Nitrogen loads to Lake Rotorua are predicted to increase over time due to a lag in elevated nitrate concentrations in groundwater entering the catchments rivers. Our analysis assumed a median nitrate concentration of 1.9 mg/l which accounts for nitrogen load increases predicted by 2030 (see Section 4 for further explanation). This is about half the 50 year life assumed for annualising our cost analysis.

The results are illustrated in Figure 8.1, this shows how percentage removal reduces with increasing hydraulic load and how the amount of nitrogen attenuated increases with hydraulic loading. Increasing the hydraulic load above about 50 m/yr [11]has increasingly marginal benefit for load reduction.

It also illustrates the direct linear correlation between load reduction and nitrate concentration of the incoming water – the higher the concentration of nitrate the more that will be removed. The line representing 2 mg/l concentration is about the same as average catchment nitrate used in this report (i.e. 1.9 mg/l by 2030), 1 mg/l is at the lower end of stream water concentrations found in the Rotorua catchment.

The error bars represent two standard errors for the average uptake rate constant (k-value) used in the model (Kadlec 2005), plus uncertainty surrounding the extent of global warming by 2030.

When all of a catchments runoff is passed through a wetland, then the hydraulic loading is inversely proportional to the size of the wetland as a percentage of the catchment and the x-axis can be expressed as a percentage of catchment (e.g. Tanner 2010). However, this is not meaningful if the wetland is treating only a proportion of the total catchment load (e.g. base flow) as we have assumed.

[11] Hydraulic load is directly proportional to flow. A hydraulic load of 10.5 m/yr corresponds to a flow of 10 l/s in a 3 ha wetland.

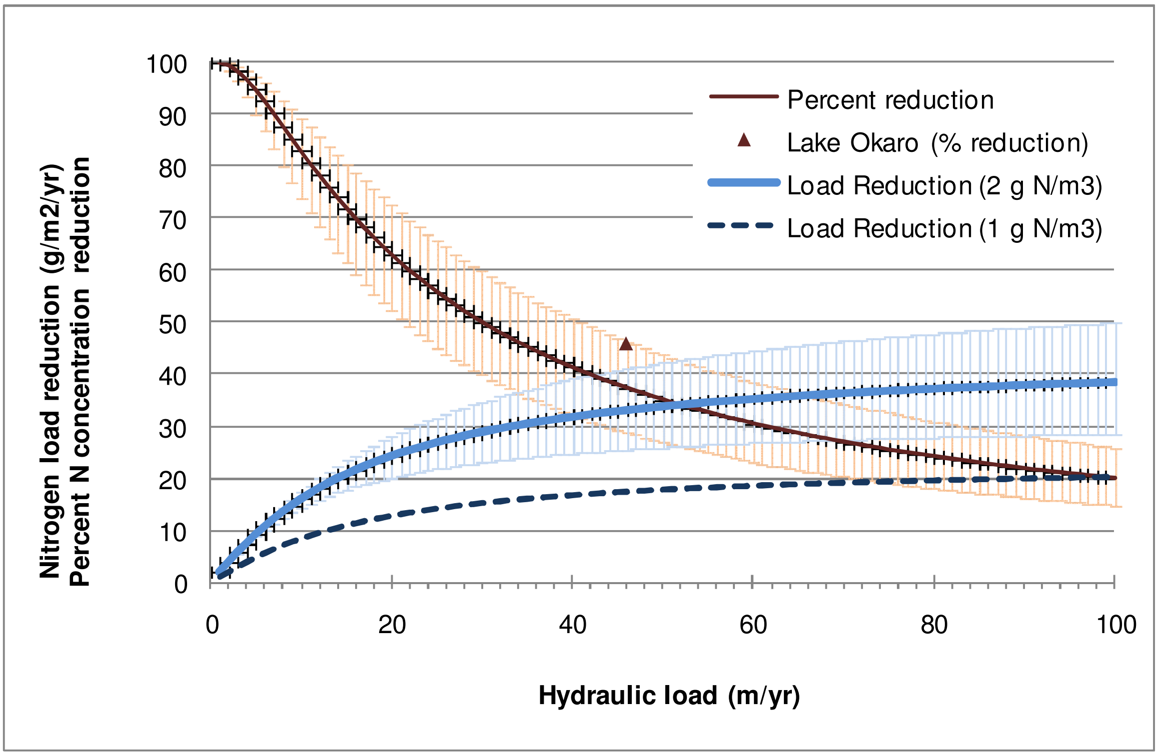

Figure 8.1: Estimated nitrogen reduction with increasing hydraulic load for surface flow wetlands in Rotorua catchment. Error bars are +/- three standard errors plus uncertainty around global warming. Parameters: Ci=2 mg/l, $k_{15.5}$ = 23 m/yr, N = 3.5. (1 g/m^2/yr = 10 kg/ha/yr)

Constructed wetland phosphorus removal

Kadlec and Wallace (2009) found that essentially the same simple first-order, 'tanks-in-series' kinetic equation used to describe nitrogen removal can be used to quantify long-term average wetland phosphorus removal. However, the processes operating to remove phosphorus are complex, and predictions of the phosphorus model results are less precise than for nitrogen. The model indicated wide variability in removal rates (8-40% removal), and these predictions for phosphorus removal do not incorporate biotic features and are not as precise as for nitrogen removal (about 5-20% through uptake and burial). The input parameters for phosphorus are described in Appendix 2.

9.2.2 Natural surface flow wetlands

Natural surface flow wetlands perform in essentially the same way as constructed wetlands in terms of nutrient removal (Kadlec and Wallace 2009). Thus protecting the nutrient attenuation potential of natural wetlands is much more cost-effective than constructing new wetlands. This essentially means avoiding drainage or channelization and ensuring vegetation cover.

The potential to modify natural wetlands to improve nutrient attenuation primarily depends on how well the natural wetland is currently performing. For the purpose of this report we have assumed that interventions will be made to natural wetlands that are currently degraded by channelization and/or drainage. In particular, we assume:

- Natural wetland nutrient removal rates per hectare are slightly lower (k_{20}=29 m/yr) than for constructed wetlands because of limited ability to control the water depth throughout the wetland.

- Restoring a natural wetland will primarily involve physical works to change the drainage. Thus only natural wetlands with channelization and bypass flow will be candidates for restoration. We have assumed minimal wetland plantings.

- The cost of restoring nutrient attenuation in a natural wetland will be the same as the cost of rejuvenating a constructed wetland (i.e. half the per hectare construction cost).

We have also included an estimate of the effectiveness of protecting natural wetlands from drainage. This estimate assumes a cost for leasing (at median rate for sheep and beef farm land), and the same maintenance costs as for constructed wetlands.

9.2.3 Seepage wetlands and lake edge seepage wetlands

The overall ability of a particular wetland type to reduce total nutrient loads depends on the total area of wetland that can be established with a high nutrient loading. The ability of seepage wetlands to maximise nitrate removal is often limited by the small amount of flow that can be routed through them.

Lake edge seepage wetlands form where springs and seeps rise near the lake edge. Gibbs and Lusby (1996) investigated the ability of lake edge seepage wetlands to remove nutrients and pathogens entering Lake Rotorua. They concluded that where they existed lake edge wetlands were a last resort protection that could remove a substantial (>95%) amount of dissolved inorganic nitrogen from the groundwater mainly by plant uptake, sediment storage and denitrification. Where wetlands were drained (e.g. Hannah's Bay), water bypassed the wetland with little or no nutrient removal.

Seepage wetlands are often recorded with very high percentage removal rates for nitrate, but this is often because the hydraulic loading is small. Gibbs and Lusby (1996) provided estimates of incoming flow for three of the wetlands in their study. We used this to calculate the hydraulic loading rate and estimate the percent removal using the model adopted for this report. The percent removal of nitrogen was consistent with estimates provided by the model used in this report. The lake edge seepage wetlands with very high percent removal (95% and 98% for Okareka and Rotorua 3-D Maze) had very low hydraulic loading (<1 m/yr). Similarly the Owhata Road (Rotorua) lake edge seepage wetland had only 16% removal rate but very high hydraulic loading rate (>150 m/yr).

Seepage wetlands and lake edge seepage wetlands act like horizontal flow subsurface wetlands (HSSW) and the nitrogen removal ability of seepage wetlands can be modelled with the same ‘tanks-in-series’ approach taken with constructed wetlands. Kadlec and Wallace (2009) recorded higher removal rate coefficients (i.e. median of 42 m/yr compared to 34 m/yr) for HSSW but the dataset all had high nitrate concentrations (>9 mg/l). We have taken a conservative approach and assumed seepage wetlands will have the same removal rate coefficient as for constructed wetlands.

Seepage wetlands typically have poor phosphorus removal rates. We have assumed phosphorus removal rates of 14% (+/- 6%) - consistent with what can be achieved with plant uptake.

The potential to modify seepage wetlands to improve nutrient attenuation primarily depends on how well the natural wetland is currently performing. For the purpose of this report we have assumed that interventions will be made to natural wetlands that are currently degraded by channelization and/or drainage. In particular, we assume:

- Nutrient removal rates per hectare will be the same as for constructed wetlands after fencing and removing artificial drainage;
- We have assumed that carbon supply is not limiting denitrification even in a degraded seepage wetland.
- The cost of restoring a seepage wetland is based on a 0.25 ha wetland. Cost-effectiveness will be much better for larger wetlands.

9.2.4 Floating wetlands

Floating wetlands consist of emergent wetland plants on buoyant mats. The plant roots grow through the mat forming a dense mass of roots that hang in the water below. This is a new technology and there is little information about their effectiveness at removing nutrients from natural waters. We have assumed that the performance of floating wetlands to treat nutrients will be equivalent to results reported in the draft report by Sukias (2010). Total nitrogen (TN) removal rates were: 85.4 g $N/m^2/yr$ (45% removal) with 4 day retention time (equivalent hydraulic loading of 31.9 m/yr), and 56.6 g $N/m^2/yr$ (77% removal) with 10 day retention time (equivalent hydraulic loading of 12.27 m/yr). Total phosphorus removal rates were: 1.13 g $P/m^2/yr$ (20% removal) with 4 day retention time, and 0.51 g $P/m^2/yr$ (23% removal) with 10 day retention time.

This microcosm study was done in water with an incoming TN concentration of ~2 mg/l and TP concentrations of 0.062 mg/l. This is similar to the average concentrations entering Lake Rotorua, but the TN was 4.4 times higher than the concentration in Lake Rotorua itself (0.45 mg/l), and TP twice as high as concentrations in the lake (0.032 mg/l). Thus the mass removal rate for TN and TP will be respectively 4 times and 2 times less if these floating wetlands were installed in Lake Rotorua (assuming the same retention times).

The data from Sukias (2010) show floating wetlands to be about twice as effective at removing nitrogen compared to constructed wetlands. This could be realised if placed in a stream environment (split flow through an adjacent wetland on the streamside). However, floating wetlands are expected to be only half as effective at removing nitrogen if placed in the lake due to lower nutrient concentrations in Lake Rotorua compared to the inflowing streams and springs.

Appendix 2: Detailed method and assumptions

9.3 Calculation of nitrogen reduction using 'tanks-in-series' model

The rate of nitrate removal by wetlands is strongly influenced by the hydraulic loading, the concentration of incoming nitrate and the hydraulic efficiency of the wetland (i.e. minimal short circuiting). A key feature of wetlands designed for nutrient removal is a trade off between removal efficiency and load reduction. The actual mass of nitrogen removed increases with loading, thus increasing the hydraulic loading results in more tonnes of N removed, but this is at the expense of less percentage reduction in concentration.

The nitrate load reduction by a wetland can be expressed by the first-order, 'tanks in series' kinetic approach represented by the formula below (Kadlec 2005; Kadlec and Wallace 2009). This differs from the formula for TN by assuming that the background wetland TN concentration (C*) is negligible. We consider this to be a more appropriate formula to use for this work because estimates of background N concentrations (C*) are not reliable at low (<5 mg/l) inlet concentrations (Kadlec and Wallace 2009) and because streams entering Lake Rotorua have the majority of their TN load in the form of nitrate (Rutherford and Timpany 2008).

$$\frac{Co}{Ci} = \left(1 + \frac{k}{N.q}\right)^{-N}$$

This formula can be rearranged to be expressed as a load reduction.

$$LR = LI\ .\ eff = q.Ci\ .\left[1 - \left(1 + \frac{k}{N.q}\right)^{-N}\right]$$

Where:

eff =factional concentration reduction

LI = incoming nitrogen load (gm N/m^2 . yr)

LR = nitrogen load reduction

Ci = inlet N concentration (g/m^3)

Co = outlet N concentration (g/m^3)

k = first order uptake rate constant (m/yr)

N = hydraulic efficiency parameter

q = hydraulic loading rate (m/yr).

Denitrification, and hence the uptake constant (k) is strongly influenced by temperature. This estimates of k-values should account for temperature. The temperature effect upon denitrification can be described by a modified Arrhenius temperature relation (in Kadlec 2005):

$$\mathbf{k = k_{20}\theta^{(T-20)}}$$

Where:

K_{20} = first order uptake rate constant at 20°C (m/yr)

T = water temperature (°C)

θ = temperature factor.

Kadlec (2005) calculated mean hydraulic efficiency (N), uptake rate constant (k), and temperature factor (θ) for surface flow wetlands from long term datasets. The results were:

- The hydraulic efficiency parameter (N) depends on the wetland design. Flow through systems have typical N values of 1 to 5 with higher values where there is less bypassing (short circuiting). The mean hydraulic efficiency parameter (N) of 30 wetlands tested by Kadlec (2005) was 4.5 $^{+}/_{-}$ 0.4 (mean +/- standard error).

- The mean k_{20}-value from 62 wetlands was 34 +/- 3 m/yr (mean +/- standard error). The removal rate constant was adjusted for temperature in Lake Rotorua catchment i.e. $k_{15.1}$ to $k_{16.3}$, median of $k_{15.5}$ was 23.1. We assumed a range of three standard errors (25-43 m/yr).

- The mean temperature factor (θ) from 31 wetlands was 1.09 +/- 0.01 (mean +/- standard error). The nitrate removal rates will be significantly higher when temperatures are higher, e.g. during summer or if incoming water is warmed by geothermal activity. A theta value of 1.088 produces a halving of the rate constant over a temperature drop of 8°C.

The concentration of incoming nitrate used in the model was 1.93 mg/l (range of 1 – 3 mg/l), which is the average concentration of nitrate from catchments defined as having 'high potential for nitrogen removal', after adjusting upward to account for estimated increases by 2030 (see Table 6 of Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust 2007).

The 10 year annual average surface water temperature of Lake Rotorua is about 15.5°C, The nitrate uptake rate constants used in the model were adjusted to correspond to the annual average water temperature in Lake Rotorua (i.e. 15°C). The estimated impact of global warming was included by adding half of the MfE (2008) predicted increase from 1990 to 2040. This resulted in a estimated mean temperature of 15.5, and range of 15.1 – 16.3°C.

Kadlec (2005b) considered hydraulic loading rates greater than 100m/yr not hydraulically feasible for most surface flow systems.

Summary of model inputs

Parameter	median	range
Nitrate in (g/m^3)	1.9	-
N	3.5	-
θ	1.09	-
k_{20} (m/yr)	34	25 - 43
temperature (°C)	15.5	15.1 - 16.3
$k_{15.5}$ (m/yr)	23.1	18.4 - 29
TP in (g/m^3)	0.081	-
k (phosphorus) (m/yr)	10	3 - 24
K (natural wetlands) (m/yr)	29	12 - 37

Phosphorus removal was represented by the formula:

$$\frac{(Co - C^*)}{(Ci - C^*)} = \left(1 + \frac{k}{P.q}\right)^{-P}$$

Where:

*C** = background phosphorus concentration (mg/l) (assumed to be 0.005 mg/l)

P = mixing and speciation parameter (assumed to be 4 tanks-in-series)

The uptake rate coefficient for phosphorus (k) was assumed to be 10 m/yr (range 3-24); which is the median (20^{th} and 80^{th} percentile) of 282 wetlands reviewed by Kadlec and Wallace (2009). Phosphorus uptake rate constants were not adjusted for temperature because temperature has only a minor effect on phosphorus attenuation.

Uptake 5-15% was added to estimates to account for uptake and burial by biota.

9.4 Cost efficiency model

9.4.1 Removal rate inputs

A summary of load reduction inputs for the cost-efficiency model is provided below.

Table A1: Cost-efficiency model Nitrogen removal rate inputs (median, and range in brackets)

Parameter	Constructed	Natural SF	Seepage	Floating
Load (m/yr)	46 (35-55)	46 (35-55)	30 (15-55)	75 (25-90)

Parameter	Constructed	Natural SF	Seepage	Floating
% reduction	37.4 (36-41)	33.2 (20-37)	49.1 (60-41)	45 (42-77)
Reduction (kg/ha/yr)	332 (240-435)	295 (132 - 390)	294 (178-435)	714 (480-850)
Catchment leaching removed (kg/ha/yr)	28	0	28	0

Table A2: Cost-efficiency model Phosphorus removal rate inputs

Parameter	Constructed	Natural SF	Seepage	Floating
Concentration (g/m^3)	0.08 (0.07-0.13)	0.08 (0.07-0.1)	0.08 (0.07-0.13)	0.08
% reduction	26 (9-50)	26 (9-50)	5 (2-15)	21 (20-25)
Reduction (kg/ha/yr)	10 (2.2-33)	10 (2.2-27.5)	2.4 (0.2-8.2)	13 (4-19)
Catchment leaching removed (kg/ha/yr)	0.8	0	0.8	0

Note: The range includes the lower and upper ends of uncertainty related to k values etc, thus for constructed and natural wetlands, higher percent removal appear to have a higher percent reduction.

The average loss coefficients for land uses in the Rotorua catchment are: dairy (50 kg N/ha/yr), beef (35 kg N/ha/yr) and sheep/beef (18 kg N/ha/yr) (Bay of Plenty Regional Council, Rotorua District Council and Te Arawa Lakes Trust (2007). After weighting the coefficients according to the area of each landuse in the Rotorua catchment the average nitrogen loss coefficient is 28 kg N/ha/yr and the average phosphorus loss coefficient is 0.8 kg P/ha/yr. Since wetlands take land out of production, these weighted average loss coefficients were added to the estimate of nutrient attenuation by constructed wetlands – accounting for this reduction in leaching increases overall wetland nutrient attenuation by about 10%.

Protecting natural wetlands was assumed to have the same removal rates as natural wetlands however the minimum hydraulic load was reduced to 15 m/yr.

9.4.2 Total costs[12]

Constructed wetlands

Calculations of the likely cost of wetland construction have been drawn from information provided about the Lake Okaro wetland. Actual costs of constructing the Lake Okaro wetland was not differentiated from other expenditure in the catchment, so we instead have used the 2006 budgeted cost of construction from that project and added 14% for inflation to produce a likely 2010 cost.

The total acquisition, maintenance and renewal costs used for constructed wetlands are described in the table below. Total acquisition costs are based on the cost of constructing Lake Okaro wetland and converted to a "per ha" basis (assuming a 3 ha wetland). Kadlec and Wallace (2009) estimated capital costs for 84 wetlands as US\$194,000 x $A^{0.69}$ (R^2=0.79). This formula was converted to NZ\$ and adjusted to reflect a inflation adjusted cost (+14%) of Lake Okaro (\$684,000), to give NZ\$385,000 x $A^{0.69}$. This adjusted formula was used to scale up to 3 ha wetland. The effect of wetland size on total acquisition cost is shown in Figure A1 below.

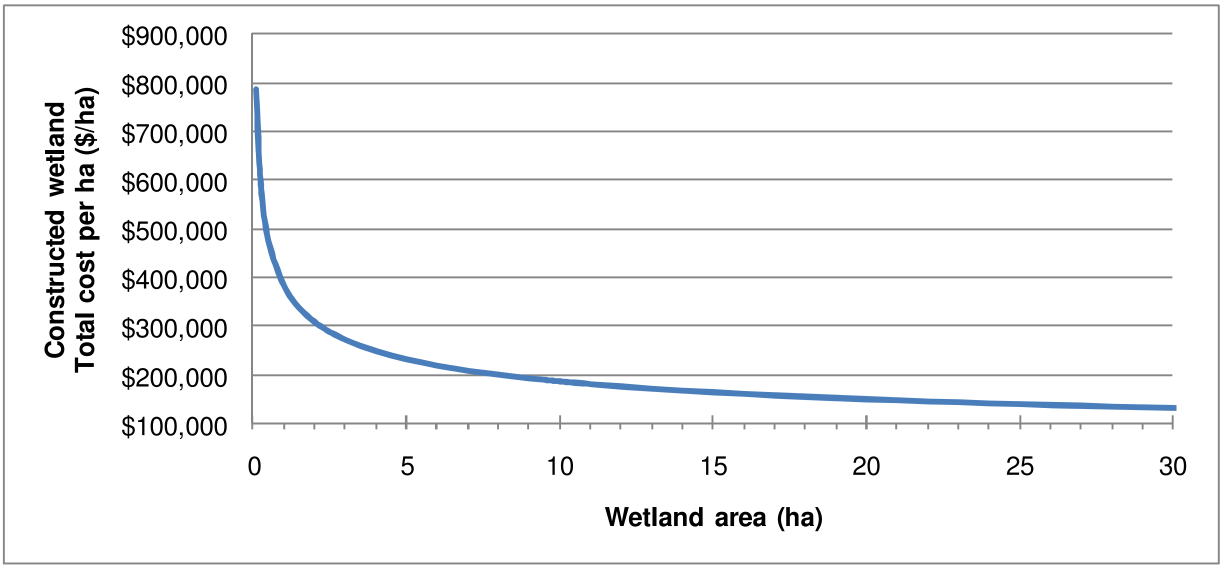

Figure A.1: Effect of wetland size on total acquisition cost per hectare (\$385,000 x $A^{0.69}$ adapted from Kadlec and Wallace 2009)

Renewal costs refer to the infrequent maintenance activities (also called 'corrective maintenance'), these may include improving access tracks, re-contouring and replanting a wetlands macrophyte zone. A study of constructed wetlands found the renewal costs to be 50% of total acquisition costs (Music Model manual). The renewal period was assumed to be 25 years. There is a lot of uncertainty around renewal costs and the renewal period Fletcher *et al.* (2005) suggested 20-50 years.

[12] All costs are in NZ$ unless otherwise stated.

Lake Okaro has had very few maintenance costs, sediment was removed from the wetland after 3 years and spread on the farm. Ongoing maintenance was estimated to be $500/yr. However maintenance costs for constructed treatment wetlands are often in the order of $5000 /ha/yr (MUSIC model user manual). Kadlec and Wallace (2009) reported median operation and maintenance costs of US$2000 /ha/yr.

Acquisition costs had a range of +/- 30%, maintenance and renewal costs had an assumed variation of +/- 20%.

Table A3: Constructed wetland cost-estimates

	Okaro Wetland (2006) 2.3 ha		2010 Estimated 3.0 ha		2010 Estimated 10 ha		Period
	Total cost	$ / ha	Total cost	$ / ha	Total cost	$ / ha	
Catchment size (ha)	**359**		**714**		**429**		
Wetland design	$80,000	$34,783	$109,550	$36,517	$251,420	$25,142	year 0
Wetland construction	$420,000	$182,609	$575,138	$191,713	$1,319,954	$131,995	year 0
Wetland planting	$100,000	$43,478	$136,938	$45,646	$314,275	$31,427	year 0
Maintenance				$4,000		$4,000	annual
Renewal				$136,938		$94,282	50% of aquisition cost, every 25 years
Total cost $ (excl GST)	$600,000	$260,870	$821,626	$273,875	$1,885,648	$188,565	

Assumptions:

1. 14% added to construction, planting and design and planning costs to account for price increases since 2007.
2. Total cost adusted for area using: $385,000*Area $^{0.69}$ (adapted from Kadlec & Wallace 2009)
3. All costs based on Okaro wetland budget; actual costs not confirmed.
4. Costs include construction of fencing and establshment of riparian margin plants

Natural wetlands

The cost of rejuvenating a natural wetland was assumed to involve correction of drainage works and replanting sections of wetland. In some cases large sections of stream would need to be rerouted through a wetland. We have assumed the cost would be equivalent to the cost of renewing a constructed wetland, i.e. **$137,000 per ha** (see discussion above).

Using natural wetlands for nutrient reduction is expected to have additional consenting requirements. To account for this, an additional design costs of $30,000 (+/- 50%) were included to address issues relating to consents (although this is partially accounted for in the renewal cost estimate). These were converted to $ /ha assuming a 3 ha wetland size.

Maintenance and renewal costs were also assumed to be the same as for constructed wetlands. All estimates were +/- 20%. Lease costs reflect rates for sheep and beef.

Seepage wetlands

Seepage wetlands were priced assuming a 0.25 ha wetland. There are considerable economies of scale if a larger wetland size is used. The rehabilitation costs used in our calculations are summarised in the table below.

Table A4: Seepage wetland acquisition and maintenance cost estimates.

Wetland area (ha)		0.1 ha seepage wetland		0.5 ha seepage wetland	
		Total cost	Cost/sq metre	Total cost	Cost/sq metre
Rehabilitation cost - MEDIAN	Fencing	$2,767	$2.77	$5,887	$1.18
	Drainage	$1,340	$1.34	$2,680	$0.54
	Planting	$3,193	$3.19	$7,008	$1.40
Total median cost of wetland rehabilitatio		**$7,300**	**$7.30**	**$15,575**	**$3.11**
Rehabilitation cost - Low (assumes no planting)		**$2,767**	**$2.77**	**$5,887**	**$1.18**
Rehabilitation cost - High (assumes twice the amount of drainage repair)		**$11,834**	**$11.83**	**$25,262**	**$5.05**

Fencing costs

Normal post and batten stock fencing costs approximately $12/m to construct but because these seepage wetlands are small and scattered a fence cost of $15/m erected has been used.

Because springs often occur in small valleys or gullies seepage wetlands are typically longer than they are wide. The greater the length to width ratio the longer the length of fence required to enclose the wetland. A length to width ratio of 5:1 chosen on the basis that a well-designed surface flow constructed wetland is considered to range from 4:1 to 6:1 length to width (Tanner 2003)

Gate access to each wetland has been included to enable management and the possibility of mowing if appropriate.

Drainage costs

Some seepage wetlands will have had surface drainage installed to improve pasture growth. It is likely that these surface drains will need to be in-filled to increase water residence time and soil contact. This work would probably be best done using a small digger. For a 0.1 ha. wetland, an allocation of 4 hours of digger time (at $120/hr) and 1.5 hours of travel (at $80/hr) per wetland is likely to be a maximum requirement.

Planting costs

If plants do need to be planted into the wetland an estimate of cost is $3.19/m of wetland (this includes the cost of the plant, planting, releasing at time of planting and travel). Assumptions:

- Planting area = area disturbed by digger over the length of wetland x 10 metres wide
- Reeds and sedges planted at 0.75 metre spacing = 18,000/hectare
- Plant numbers increased by 10% to allow for replacement of 10% first year mortality
- Plants in root trainers (RTH) or bare rooted
- Planting cost per plant inflated because of allowance for daily travel time
- Assume planters doing 300 plants/man/day; team of 4, so 1200 plants per team per day; paid $20 /hour
- Assumes plants transported to site by planters; average distance to site 80km at $1/km

Maintenance costs

Once the drainage of a wetland has been corrected and wetland plants established, the maintenance requirements of these wetlands are likely to be relatively low. Annual visits to undertake weed removal is the most likely activity.

Seepage wetland annual maintenance costs were estimated to be $850/ha +/- 20%. This assumed:

- Two site inspections per year. 2hrs travel per visit plus 1 hr on site.
- Average distance to site assumed to be 80km, 160 km return, 320 km/yr
- No significant pest management issues after plant establishment
- One weed management visit per year: 1 man hr on site 0.1 ha wetland, plus 2 hrs travel per day. 120 km return trip per day @$1.00/km
- Assumes plants transported up by planters and average distance to site 80km at $1/km.

Floating wetlands

The cost of constructing a floating wetland on Lake Rotoehu was estimated to be $700,000 for a 2800m^2 wetland within a 4000m^2 enclosure. Costs were estimated by Kauri Park and included instalment and planting (John MacIntosh pers comm.). Recent discussion with Kauri Park Nursery staff indicated $250/m^2 to $400m^2 for large scale catchment use. We have assumed a median of $3 million /ha ($2.1M/ha - $4.5M/ha). Maintenance costs were estimated to be about $6 /m^2 ($60,000/ha). We have optimistically assumed $50,000 per year maintenance. We assumed a cost range of +/- 20%.

9.4.3 Obtaining land

The cost of land purchase makes a big difference to the cost-effectiveness of wetland options for removing nutrients. Purchasing land requires the additional cost of subdivision, which makes it inefficient for small areas. This project did not allow for a complete economic analysis of all land purchase options, instead we have assumed that the land would either be available at no cost or would be leased from the existing land owner, depending on the wetland type. The assumptions for each wetland type are described in the table A5.

Table A5: Assumptions regarding land purchase for different wetland types

Wetland type	Land purchase assumption and Rational
Constructed surface flow wetlands	Assume: Land will be leased so no cost of purchase. Constructing a lowland wetland to treat surface water takes a significant amount of land. When on public land this may be available at no cost, but if on private land it could remove a significant amount of land from production. We have thus assumed that the land will be leased. We believe leasing is the most practical option for most situations because it allows clear definition of rights, avoids problems with owning (and selling) isolated pockets of land, and allows for ongoing involvement of the landowner.
Natural surface flow wetlands	Assume: Land will be leased at median rate for 'sheep and beef'; no cost of land purchase. We have assumed that degraded natural wetlands will mostly be in private ownership. Thus a lease cost was included (at a lower rate) to allow for natural wetlands that may be in private ownership.
Seepage wetlands and lake fringe seepage wetlands	Assume: Land will be leased so no cost of purchase. Seepage wetlands are generally small areas on poorly drained land. Creating seepage wetlands has additional benefits in terms of aesthetics. Including a cost of leasing accounts for lost production.
Constructed floating wetlands	Assume: No cost of purchase and no lease. Floating wetlands will be within the riparian margin of a stream or in the lake itself and not impacting on productive land.

For natural lowland wetlands, lake fringe wetlands and constructed floating wetlands we have assumed that the wetlands will be established on publicly owned land or the land will be offered voluntarily so there will be no cost of land purchase.

For 'seepage wetlands' and 'constructed surface flow wetlands' we assume that the land will be leased although it is possible that land will be made freely available by private land owners (e.g. in the case of Lake Okaro wetland). Taking out a long term lease over land on which wetlands are established both compensates landowners for potential loss of production and makes clear that any nutrient credits accrued (under a nutrient trading regime) are owned by the council.

We have not priced the option of purchasing land for establishing wetlands for any wetland type. In particular, purchasing land to establish a seepage wetland was considered to be impractical in most situations because of the small areas involved and the access easements required.

9.4.4 The cost of land

The values used for the price of land is given in the table below. Land rental values used were the median price from sheep and beef after giving a 4 times weighting to 'sheep and beef' prices. Sheep and beef farming (723 ha) occupies about 5.8 times more catchment area compared to dairy farming (124 ha), so this assumes wetland construction will be slightly biased towards dairy farms in proportion to the catchment area occupied. The minimum lease was assumed to be half the median and the maximum lease 2.5 times the median.

Table A6: Land values and rental costs

Land use		land values ($/ha)	land rentals ($/ha/yr)
Dairy	Min	27,000	1000
Dairy	Avg	29,000	1200
Dairy	Max	31,000	1500
Sheep & beef	Min	14,000	170
Sheep & beef	Avg	17,000	210
Sheep & beef	Max	26,000	700
Values use	Min		336
Values use	Avg		408
Values use	Max		860

Source: Taylor and Park (2007), Sinclair et al (2010), Greenhalgh (2009), MAF farm statistics.
The values adopted give a 4x weighting to sheep and beef

9.4.5 Discounted Cash Flow Analysis

To estimate the expected cost of the different wetland restoration scenarios a discounted cash flow analysis (Boardman *et al*. 2006) was undertaken using data on area of wetland restoration and type of wetland constructed, together with assumed costs (i.e. design, construction, planting, fencing, maintenance and land purchase or rental costs). Estimates of minimum, maximum and average values for land in dairy, and in sheep and beef in the Rotorua District for 2007/2008 were from Greenhalgh (2009). Estimates of minimum, maximum and average rentals for land in dairy, and in sheep and beef in the Rotorua region for 2007/2008 were annuities estimated from net present values reported in Taylor & Park (2007) and Sinclair *et al.* (2010).

A well maintained and ‘renewed’ wetland could have an indefinite life span. We have used 50 years as a conservative life span. The expected costs over a 50-year period for each wetland restoration scenario were discounted (assuming discount rate of 8% yr^{-1} real) back to the present and summed to give the net present value (NPVR, \$ ha^{-1}) of the costs:

$$NPV_R = \sum_{t=1}^{T} \left(\frac{C_t}{(1+r)^t} \right) - C_0$$

Where: t is the time of the cash flow

T is the period of analysis; 50 years

r is the discount rate (assumed to be 8% yr^{-1} real)

C_t is the cost at time t.

C_0 is the initial investment in the wetland, including design, construction and land purchase.

To then express project costs in annualised terms (\$ ha^{-1} yr^{-1}) the annuity for each scenario was estimated using the PMT() function in MS Excel. An annuity spreads the net present value equally across the period of analysis.

An 8% yr^{-1} real discount rate corresponds to the typical rate used to assess long-term projects, such as forestry (Manley 2005). A 50-year period of analysis ensures the long-run maintenance costs are considered, while costs beyond the period will have very little influence on the net present value and annuity calculated due to discounting.

Appendix 2 References

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