Waterways
Centre for Freshwater Management

Sustainability analysis of five lakes in the Wellington Region

Lake Wairarapa, Lake Onoke, Lake Pounui, Lake Waitawa and Lake Kohangatera

WCFM Report 2015-005

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TITLE:	Sustainability analysis of five lakes in the Wellington Region: Lake Wairarapa, Lake Onoke, Lake Pounui, Lake Waitawa and Lake Kohangatera
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Executive Summary

This report sets out a sustainability framework based on nested adaptive systems and then applies this framework to the management of five lakes in the Wellington Region: Lake Kohangatera, Lake Waitawa, Lake Pounui, Lake Onoke and Lake Wairarapa.

The foundation of the sustainability analysis framework is the adaptive cycle for describing biophysical and management systems, such as lakes. The adaptive cycle comprises four phases of: exploitation of resources, the accumulation of material or energy resulting from resource use, the disturbance of the accumulated material which can potentially change the structure and function of the system, and, the reorganisation phase which is the system response to the disturbance. The system response can be the recovery of the original system (i.e. sustainable) or a shift to an alternative degraded state (i.e. unsustainable).

Systems can be nested, i.e. operating at different spatial and time scales which are linked. For lakes it is common to have to consider both the larger catchment of the lake as well as the lake itself. System sustainability analysis identifies failure pathways that create the greatest vulnerability for the system or threaten the values of significance of the system. There are critical variables that characterise the processes on failure pathways. There are threshold values of these critical variables that represent tipping points for changing the state or function of the system (i.e. a shift to an unsustainable state).

For sustainability analysis, critical variables and their thresholds provide the basis for defining management interventions to address sustainability issues for systems such as lakes. For management interventions to ensure sustainability they need to be of sufficient scale to keep critical variables within the relevant thresholds and be supported by appropriate institutional arrangements, i.e. organisational arrangements, implementation programmes and funding, to deliver the management interventions.

The results of the sustainability analysis for each lake are presented in terms of the values associated with each lake, the critical variables for the management of those values and known thresholds associated with those critical variables, the adaptive cycles associated with the critical variables and potential management interventions for each phase of the adaptive cycle, and, the management approach and institutional arrangements in place for each lake.

The proposed Natural Resources Plan and the Regional Freshwater Plan provide a comprehensive list of values for water bodies in the Wellington Region, including the five lakes. These values reflect the cultural, ecological, recreational and social significance of the lakes. There are similar values between the lakes; however, there are sufficient differences that each lake has a unique combination of values. This means there are similarities and differences in the failure pathways and the critical variables relevant to the sustainable management for each of the lakes. The need for different management approaches for each

lake is further accentuated by the unique combination of adaptive cycles and potential management interventions for each lake.

The analysis highlights the limited measurement data on critical variables and the variation in information on thresholds for these critical variables. While generic management approaches are set out in policies and plans, there is a need for specific management plans for each lake. Establishment of appropriate institutional arrangements such as the formation of Whaitua committees, and community and mana whenua co-governance mechanisms are in progress but not complete. There is still considerable work to be undertaken to formulate funded implementation programmes and there is a need to be able to quantify the level of intervention needed to achieve sustainable outcomes.

Contents

Section 1 Introduction

This report sets out a sustainability analysis of five lakes in the Wellington Region: Lake Wairarapa, Lake Onoke, Lake Pounui, Lake Waitawa and Lake Kohangatera. The location of these lakes is shown in Figure 1.

Section 2 describes the sustainability framework which is based on the concept of nested adaptive systems. Section 3 sets out the results of applying the sustainability framework to each of the lakes. The discussion of the results is set out in Section 4. Section 5 provides overall conclusions from the analysis.

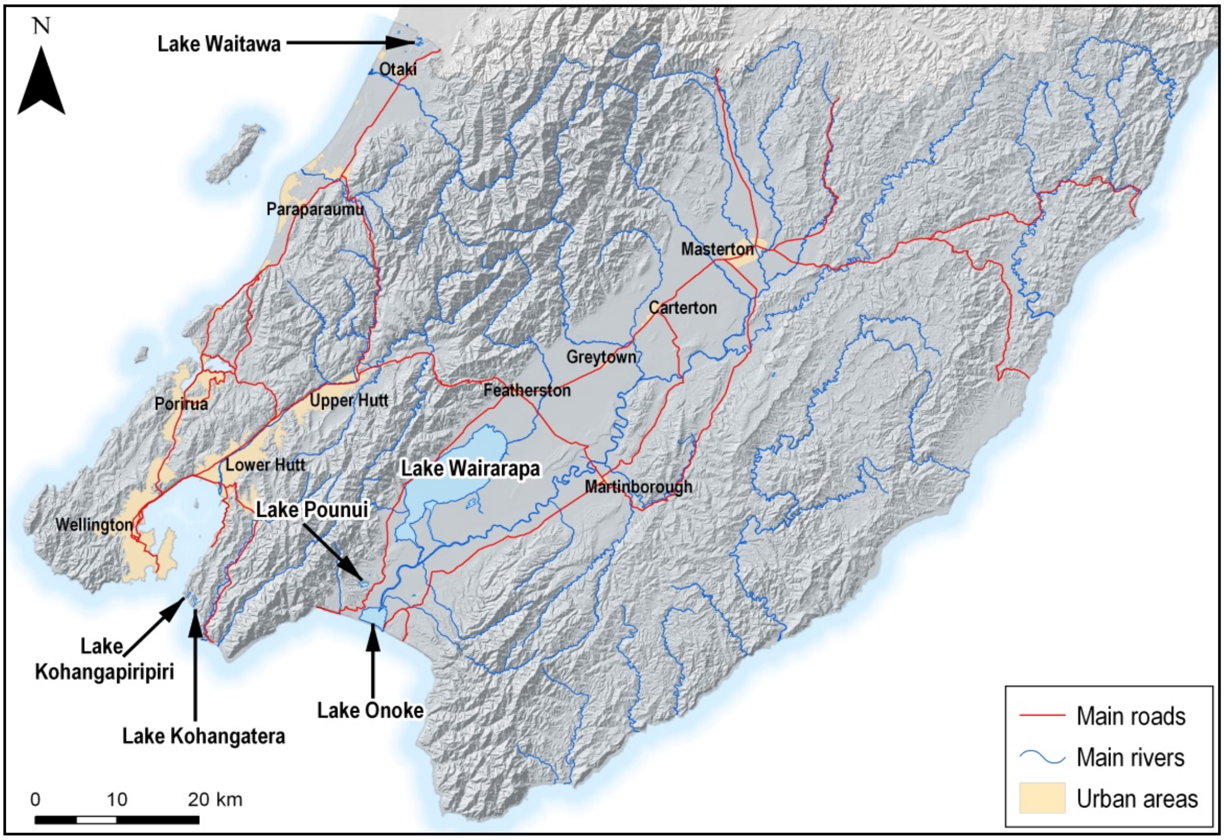

Figure 1 Location of lakes used in sustainability analysis (Source: Perrie and Milne, 2012)

Section 2 Methodology: Sustainability Analysis Framework

The sustainability analysis framework is based on six elements:

- the adaptive cycle
- nested adaptive systems
- failure pathways
- critical variables
- management interventions, and
- institutional arrangements.

These components are described below.

2.1 Adaptive cycle

The framework is based on considering socio-ecological systems as nested adaptive systems. The first element is the “adaptive cycle” which describes biophysical and socio-economic systems in four phases (Gunderson and Holling 2002).The first phase is the “exploitation” phase which is the use of resources from a biophysical or socio-economic system. This leads to a second phase of “accumulation” where there is a build-up of energy or material as a result of the exploitation of resources. The accumulation phase can be disrupted by a “disturbance” phase that leads to the release of accumulated energy or material and can potentially change the structure and function of the system. Following the disturbance phase there is a “reorganisation” phase involving the restructuring of the system. System response can be a recovery of the original system, or, a shift to an alternative system. The phases are shown diagrammatically as a lissajous figure (Figure 2).

This provides an operational basis for sustainability. Sustainability is the maintenance of the structure, function and relationships in adaptive cycles across different time and geographical cycles. A key property for sustainability is “resilience” – the capacity of a system to absorb disturbance and still retain its basic function and structure (Walker and Salt 2006).

Lake eutrophication is an example of an adaptive cycle. Land use intensification (i.e. exploitation phase) can lead to a build-up of nutrients in the lake water column or sediments (i.e. accumulation phase). Sufficient increase of nutrients can change the trophic state of the lake (i.e. disturbance phase) leading to increased algal blooms (i.e. release component of the disturbance phase). The lake restructures (i.e. reorganization phase): this can be algal die-off and loss from the lake (i.e. recovery of the original system), or to long term decline in water quality (i.e. an alternative degraded system). Sustainability is the maintenance of the water quality in order to retain the structure and function of the lake.

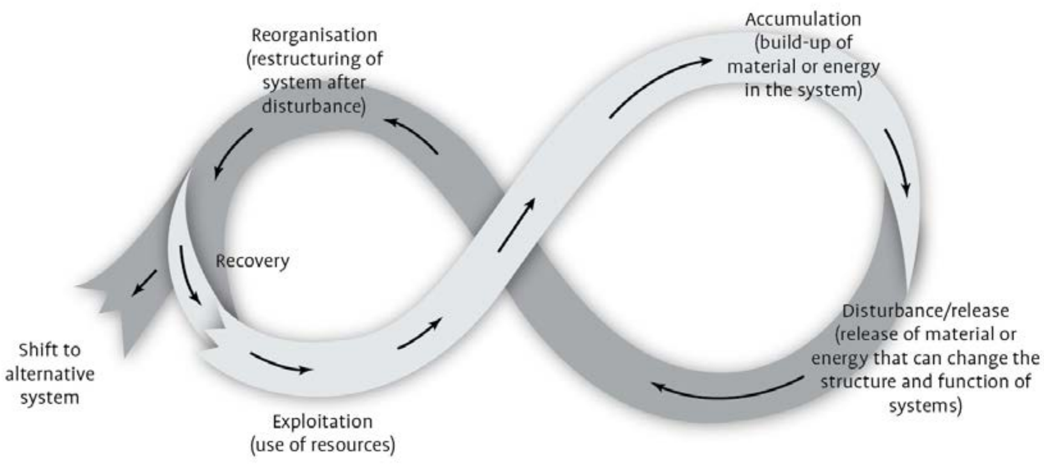

Figure 2 Adaptive Cycle

2.2 Nested Adaptive Systems

The second element is the nesting of adaptive cycles (Holling et al. 2002). Systems operate at different spatial and time scales which are linked. Describing eutrophication of lakes as an adaptive cycle involves consideration of at least two geographic scales: the lake, and the catchment upstream of the lake. The dominant cause of lake eutrophication is the increase in nutrient-intensive land uses in the catchment typically associated with agriculture (Abell et al. 2011). One linkage between the catchment and the lake is through the accumulation of nutrient levels in soils leading to a release through soil erosion and runoff to nutrient accumulation in the lake downstream (Carpenter et al. 1998). The accumulation of nutrients in the lake and the lake sediments leads to the disturbance of eutrophication in the lake. Furthermore, for reorganisation of the degraded lake back to a higher water quality level usually requires reorganisation in the catchment through a reduction in nutrient intensity of land use in the catchment (National Research Council 1992). It is a nested system with the phases in the adaptive cycle as follows (Figure 3):

- Exploitation of catchment: increase in nutrient-intensive land uses
- Accumulation in catchment: nutrient build-up in agricultural soils
- Release in catchment: soil erosion and transport of nutrients to rivers and lake
- Accumulation in lake: nutrient build-up in lake sediments and water column
- Disturbance in lake: eutrophication in lake
- Reorganisation in lake: degraded lake unless there is a reduction in nutrient-intensive land uses
- Reorganisation in catchment: reduction in nutrient-intensive farms

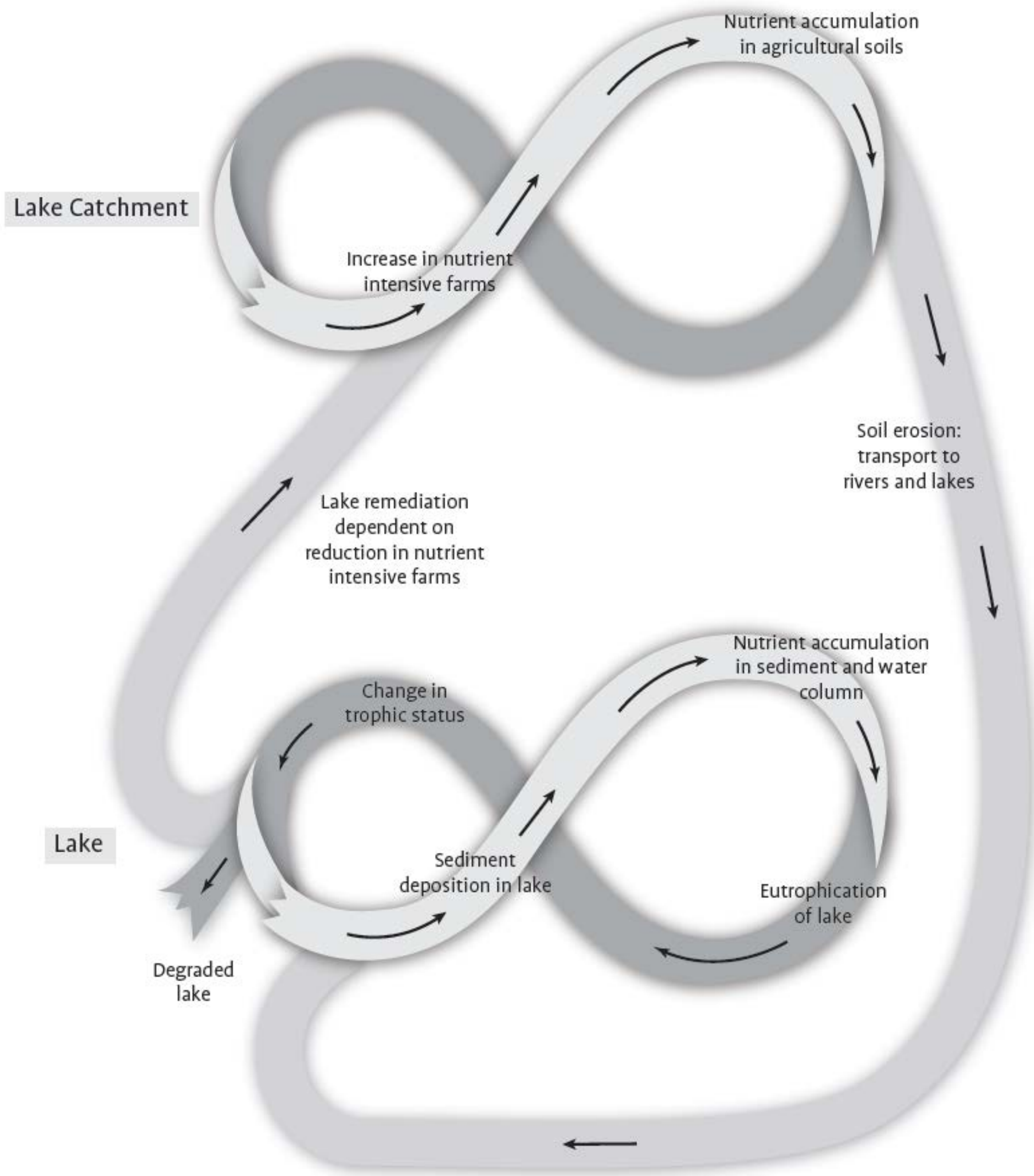

Figure 3 Nested system of catchment land use intensification and lake eutrophication (Source: Jenkins, 2016)

There can also be other linkages between the catchment and the lake, such as nutrient-laden catchment runoff entering the lake, and, nutrient leakage to groundwater from catchment land use entering the lake via the groundwater system.

There can also be different time scales. For example, if the dominant nutrient input from a catchment to the lake is via groundwater then there can be a considerable time delay between land use change and equilibrium with nutrient input to the lake.

2.3 Failure Pathways

Failure pathways are the processes that have the potential to cause system failure and shift the system to an alternative degraded state. System sustainability concerns are the failure pathways that create the greatest vulnerability for the system or that have the potential to affect the values of significance of the system.

A common failure pathway for lake systems in New Zealand is the process of nutrient enrichment leading to lake eutrophication and algal blooms. Other failure pathways for lake systems include aquatic weed invasion and introduction of exotic fish species which diminish the native species biodiversity of the lake system.

2.4 Critical Variables and Thresholds

For sustainability analysis of a nested adaptive socio-ecological system, failure pathways that create the greatest vulnerability for system collapse are given priority. Critical variables and thresholds related to system change are the third and fourth elements of the framework.

Critical variables are measures that characterise the processes on failure pathways. In lake eutrophication, critical variables include the nutrient loads from upstream catchments. Thresholds are the tipping points for critical variables that can change the state or function of a socio-ecological system. An example is the lowering of dissolved oxygen of the bottom waters of a lake to the point that triggers the release of nutrients from lake-bed sediments.

2.5 Management Interventions

Critical variables and associated thresholds become the targets for potential management interventions – the fifth element of the framework. There are three generic outcomes for management interventions in relation to the management of a natural resource system such as a lake and its catchment (Chapin et al. 2009). The first is that no action (or inadequate action) is taken leading to a degraded natural resource system. A second is that appropriate action is taken to ensure that the threshold of change is not exceeded and the natural resource system retains its structure and function (i.e. retains its sustainability). The third is where action is taken to transform the system to an alternative state that has a sustainable structure and function.

Management interventions in the biophysical system of water resources can occur at each of the phases of the biophysical adaptive cycle. In the exploitation phase, it is reducing pressure on the resource ("reducing vulnerability"): an example is reducing catchment nitrogen loads on a lake. In the accumulation phase, it is addressing legacy issues of accumulated changes in the past ("enhancing adaptive capacity"): an example is lake bed treatment to reduce remobilisation of phosphorus. In the disturbance/release phase, it is increasing resilience of systems to accommodate disturbance ("increasing resilience"): an example is lake aeration to prevent stratification. Finally in the reorganization phase it is rehabilitating adverse effects of the system ("enhance transformability"): an example is the

reestablishment of macrophytes in a lake. This can be shown diagrammatically (in the right hand part of Figure 4) for interactions in the different phases of the biophysical system.

However it is not enough to identify the biophysical component of management interventions. It is also necessary to have the socio-economic framework to implement the needed management interventions. In the terminology of the adaptive cycle this involves the following steps: firstly, the use of human and economic resources for stakeholder, cultural and community engagement to consider how to collaboratively address the issue of sustainability of our water resources as well as the investment of technical resources to understand the issues and financial resources to undertake actions (i.e. exploitation phase); secondly, the accumulation of knowledge, social, cultural and economic capital to develop integrated approaches to sustainable strategies (i.e. accumulation phase); thirdly, the formulation of new approaches to water management that change existing practices (i.e. disturbance/release phase); and fourthly, the development of new institutional arrangements to implement the new approaches to water management (i.e. reorganisation phase).

The linking of the socio-economic system and the biophysical system provides an overall framework for management intervention pathways to achieve sustainability (Figure 4).

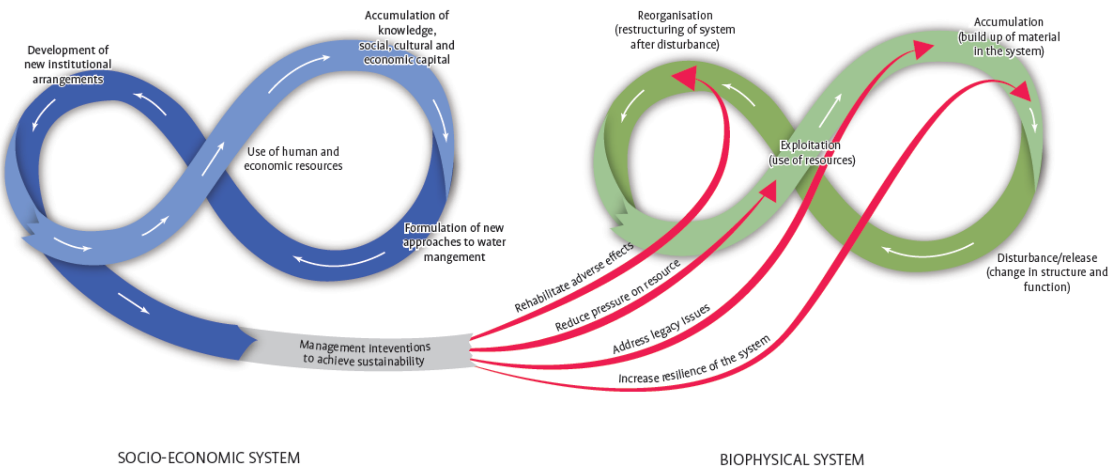

Figure 4 Management intervention pathways to achieve sustainability (Source: Jenkins, 2016)

This paper summarises the knowledge that has been accumulated by Greater Wellington Regional Council on the values of the lakes, and, the current information relating to critical variables and their thresholds. The paper also reviews the recommendations of possible management interventions within the adaptive cycles for the main failure pathways associated with each lake. The technical approaches to management interventions are derived from the measures needed to address potential failure pathways for each of the adaptive cycle phases (i.e. exploitation, accumulation, disturbance and reorganisation). However, for these interventions to be implemented there is a need for appropriate institutional arrangements to be established.

2.6 Institutional Arrangements

The key institutional arrangements needed for implementation are:

- The organisational arrangements to manage implementation
- The development of an implementation programme
- The establishment and operation of delivery mechanisms for the implementation programme
- The monitoring of the delivery and outcomes achieved.

Section 3 Results: Application of Sustainability Analysis Framework

3.1 Introduction

For each of the lakes the application of the sustainability analysis framework is addressed in the following way. Firstly, the values associated with each lake are identified. The values of the lakes that are important for lake management have been extracted from regional council planning documents. The primary source has been the proposed Natural Resources Plan (Greater Wellington Regional Council, 2015) which contains comprehensive appendices of cultural ecosystem and recreational values for lakes and rivers in the Greater Wellington Region. This has been supplemented with information from the Regional Freshwater Plan (Greater Wellington Regional Council, 1999, updated 2014) and other sources where appropriate.

Secondly, the critical variables for the management of those lake values are derived from the available scientific reports[1] for the lake and where possible the thresholds associated with those critical variables are identified. In the many instances where the management objective is maintaining or improving current water quality or ecosystem value, the threshold is at least the current water quality or ecosystem status of the lake.

Thirdly, the adaptive cycle processes associated with critical variables are described. The reports available on possible management actions were reviewed and the potential management interventions related to each phase of the adaptive cycle identified.

Fourthly, the management approach and institutional arrangements that have been established or proposed in planning and management documents are summarised.

3.2 Lake Kohangatera

Lake Kohangatera is a small (21ha), shallow (up to 2.1m depth) lake with a catchment of 2002ha. The catchment is 83% indigenous forest. It has a gravel bar at its mouth with occasional breaching to the sea after heavy rain. See Figure 5.

[1] The references section sets out the documents used for the sustainability analysis. The references are grouped for each lake. There are also regional references covering all five lakes, and some covering the three lakes in the Ruamahanga catchment: Wairarapa, Onoke and Pounui.

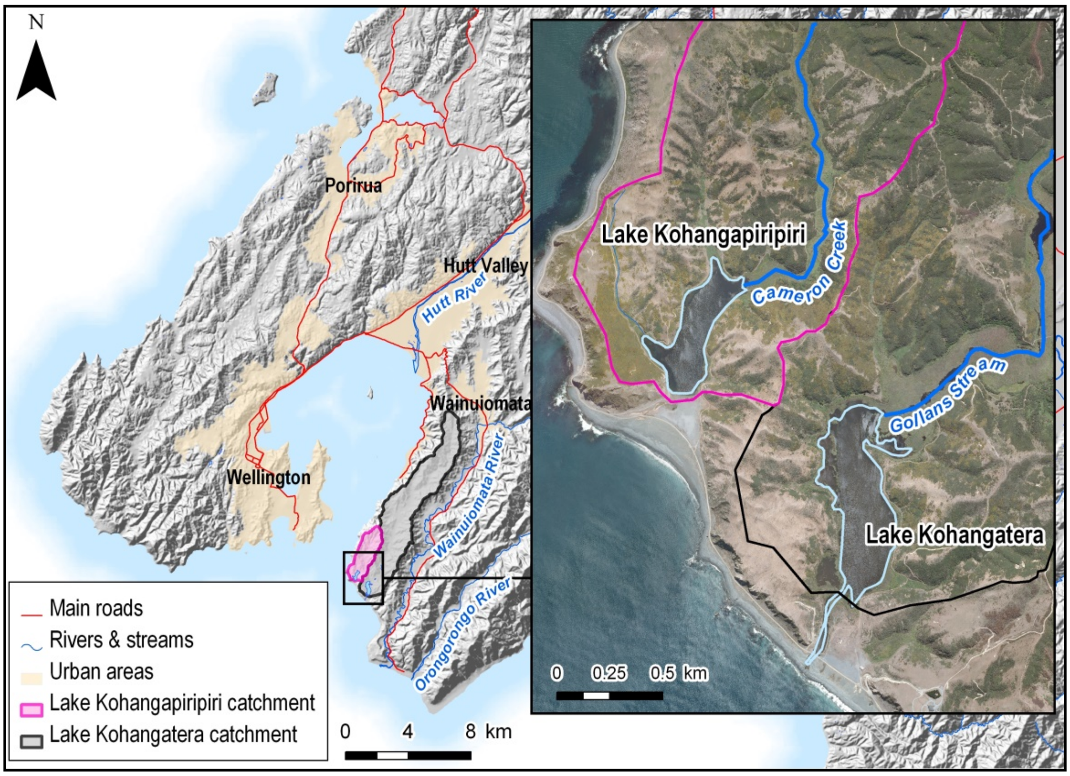

Figure 5 Lake Kohangatera (Source: Perrie and Milne, 2012)

3.2.1 Values for Lake Kohangatera

The following values for Lake Kohangatera have been identified from the proposed Natural Resources Plan and Regional Freshwater Plan:

- Significant cultural values
  - Natural Resources Plan (Sch B): significant for iwi identity, superior fishery, place of ritual, water quality, protection in times of attack, oral traditional knowledge.
  - Natural Resources Plan (Sch C4): sites of significance (sacred place, customary food gathering, weaving material, medicinal plants)
- Ecosystem values
  - Natural Resources Plan (Sch A2): lakes with outstanding indigenous ecosystem values (aquatic plants, indigenous fish diversity)
  - Natural Resources Plan (Sch A3): wetlands with outstanding indigenous ecosystem values (representativeness and diversity)
  - Natural Resources Plan (Sch F1): significant indigenous ecosystems (macroinvertebrates, threatened / at risk fish species, indigenous fish biodiversity, common bully, giant bully, giant kokopu, banded kokopu, inanga, lamprey, longfin eel, redfin bully, shortfin eel)
  - Natural Resources Plan (Sch F1c): significant aquatic plant communities (aquatic plant diversity in high ecological condition)

- Natural Resources Plan (Sch F2b): habitats for indigenous birds (dabchick – breeding population, pied shag, black shag – nesting colony, banded dotterel, pipit)
- Regional Freshwater Plan (App 2): natural character – avoid adverse effects
- Regional Freshwater Plan (App 3): indigenous fish and aquatic plants – manage water quality, manage flows and levels, maintain migratory and dispersal pathways for fish, avoid adverse effects to life cycle, promote land owner and user knowledge
- Regional Freshwater Plan (Policy 5.2.6): water quality – manage for aquatic ecosystems

3.2.2 Critical Variables and Thresholds for Lake Kohangatera

From the list of values, critical variables for aquatic ecology include: ecosystem condition, indigenous plant community, invasive plants and nutrient levels; while for cultural values the critical variables appear to be restoration of the eel fishery and kaitiakitanga.

Analysis for thresholds of critical variables in relation to vulnerability of collapse does not appear to have been undertaken. However for Lake Kohangatera maintaining its relatively pristine state would appear the goal for lake management in relation to aquatic ecology. This would make the current quality the basis for setting the thresholds. However for cultural values to be achieved improvements would be needed. Maintaining adequate flow for fish passage is needed to restore the eel fishery. For kaitiakitanga the introduction of co-governance and co-management of the lake and its catchment for tangata whenua would be an appropriate threshold.

Table 1 sets out the critical variables and related thresholds for Lake Kohangatera.

3.2.3 Adaptive Cycles and Management Interventions for Lake Kohangatera

From the available references (refer Reference sections 2 and 8), the most vulnerable failure pathways appear to be “aquatic weed invasion” and “restoration of eel fishery”.

For aquatic weed invasion, the key steps in the adaptive cycle appear to be: exploitation – the introduction of weeds through boating or fishing in the catchment; accumulation – growth and spread of weeds; disturbance/release – rainfall-driven flow events; and reorganisation – weed takeover of native species. The management interventions identified include restrictions or prohibitions on boating and fishing access: this focuses on the exploitation phase; and actions to address plant growth and spread, such as diquat application, introduction of grass carp[2], artificial shading and benthic lining: these actions focus on the accumulation phase of the adaptive cycle. Table 2 summarises the adaptive cycle phases and possible management interventions.

[2] Note that the introduction of grass carp is contrary to the values of indigenous fish diversity.

Table 1 Critical variables and related thresholds for Lake Kohangatera

CRITICAL VARIABLES	THRESHOLDS
Aquatic Ecology ***Ecosystem condition***	**Lake SPI** (% pristine) **87%** in 2013
Aquatic ecology ***Indigenous plant community***	**Native condition index** **83%** in 2013
Aquatic ecology ***Invasive plants***	**Invasive impact index** **8%** in 2013 (up 3% from 2011)
Water quality ***Nutrient levels***	**Trophic level index** **4.0**
Cultural values ***Restore eel fishery***	**?** Adequate flow for eel passage
Cultural Values ***Kaitiakitanga***	**?** Co-governance and co-management

Table 2 Aquatic weed adaptive cycle phases and management interventions for Lake Kohangatera

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION Boating or fishing introducing weeds	Boating and fishing access restricted or prohibited
ACCUMULATION Plant growth and spread	Diquat application Introduction of grass carp Artificial shading Benthic lining
RELEASE Rainfall driven flow events	
REORGANISATION Weed takeover of native species	

The adaptive cycle for the eel fishery appears to be: exploitation – eel larvae drift from the South Pacific Ocean over a period of about 17 months, glass eels home in on freshwater sources, and, there needs to be a sufficient hydraulic connection in the spring season for eels to transfer to a particular freshwater source like Lake Kohangatera; accumulation – elvers migrate upstream in summer and adults reach maturity over decades; disturbance/release – mature adults migrate from freshwater to seawater in autumn as the initial step in their spawning cycle; and, reorganisation – adults swim to tropical waters to spawn, females release eggs which the males fertilise, and then the adults die. The adaptive cycle then repeats itself. The concern is that longfin eel numbers are declining suggesting that the adaptive cycle may not be sustainable in the long term.

Management interventions to improve Lake Kohangatera's contribution to the eel fishery have been identified in the references. One issue is that natural accretion of sand and gravel is reducing the connection of the lake to the sea. A second issue is that there is a culvert blocking eel passage into the lake. For restoration to occur there needs to be an adequate lake level and flow to the ocean in spring to facilitate glass eels migrating from the ocean to freshwater i.e. for the exploitation phase. There also needs to be adequate lake level and flow in autumn for adults to migrate from freshwater to the ocean i.e. for the disturbance/release phase. In addition habitat in the catchment for adults to reach maturity can also be improved. Table 3 summarises the adaptive cycle phases and management interventions to facilitate the lake's contribution to the restoration of the eel fishery.

Table 3 Eel fishery adaptive cycle phases and management interventions for Lake Kohangatera

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION: Larvae drift from Pacific Ocean; glass eels seek connection to freshwater	Natural: Accretion of sand and gravel reducing connection to sea Manmade: Road culvert blocking eel passage into lake Restoration: adequate lake level and flow in spring
ACCUMULATION: Elvers migrate upstream; Adults reach maturity	Improve habitat for eels
RELEASE: Adults migrate from freshwater to seawater	Adequate lake level and flow in autumn
REORGANISATION: Adults swim to tropical waters; Females release eggs, males fertilise, adults die	

3.2.4 Management Approach and Institutional Arrangements for Lake Kohangatera

The management approach for Lake Kohangatera has been derived from the proposed Natural Resources Regional Plan for the Wellington Region, Pencarrow Lakes - Conservation values and management document, and the Parangarahu Lakes Area Co-Management Plan.

The Co-Management Plan identifies the key management objectives as: restoration of mouri and maintain ecological integrity, control of pest plants and animals, restoration of the eel fishery, protection and management of cultural heritage, fostering kaitiakitanga, lake decision making to be informed by Maori and non-Maori perspectives, establishing strategic partnerships, and, recreation opportunities to lead to appreciation of the natural environment. These objectives are a fair reflection of the lake values.

For values associated with Lake Kohangatera, within the proposed Natural Resources Regional Plan the key policies in relation to biodiversity appear to be: adverse effects are to be avoided (policy 39), more than minor effects on species are to be avoided (policy 33), indigenous fish passage to be restored (policy 35), and barriers to fish passage to be avoided (policy 34). While in relation to the protection and restoration of ecosystems key policies are: activities are in accordance with a restoration plan (policy 41); ecological connectivity is maintained or enhanced, buffers are provided, and, cumulative effects and incremental loss avoided (policy 43). For sites with significant mana whenua value, there are the following policies: sites shall be protected and restored (policy 44), and, unavoidable minor effects are evaluated and managed through cultural impact assessment. While not addressing the specifics of the issues of Lake Kohangatera, these policies provide support for the values and possible management interventions for the lake.

In terms of institutional arrangements, the recent establishment of Te Roopu Tiaki as an advisory body of Taranaki Whanui and GWRC addresses the critical variable for cultural values and the objectives for fostering kaitiakitanga and for lake decision making to be informed by Maori and non-Maori perspectives. The Co-Management Plan has the potential to set out the implementation of the vision but is still in very general terms. In addition the Parks Network Plan provides a chapter on policies for the East Harbour Regional Park which includes much of the Lake Kohangatera catchment.

However the specific management interventions have not been incorporated yet in a restoration plan nor is there reference to funding of relevant interventions in the regional council’s ten-year plan. Furthermore, there is a need to ensure that there is regular monitoring of the critical variables for lake management; this includes water quality, submerged plants and fish (in particular, eels). Such monitoring has been recommended in the references.

3.3 Lake Waitawa

Lake Waitawa is a small (16ha), shallow (<7m) coastal lake (Figure 6). It has a catchment of 278ha with 94% pastoral cover. It receives treated wastewater from Forest Lakes Camp. The lake discharges to Waitohu Stream.

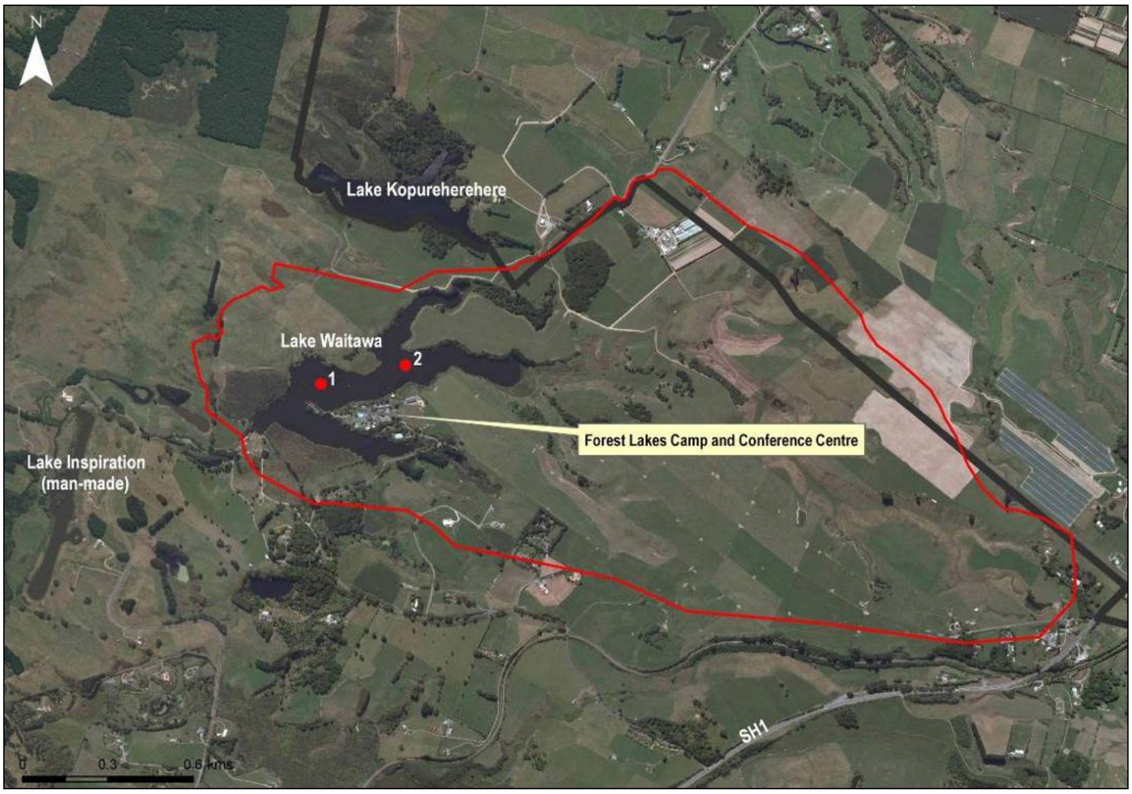

Figure 6 Lake Waitawa (Source: Perrie and Milne, 2012)

3.3.1 Values for Lake Waitawa

The following values for Lake Waitawa have been identified from the proposed Natural Resources Plan and Regional Freshwater Plan:

- Aquatic Ecology
    - Freshwater Plan (Pol 5.2.6): manage for aquatic ecosystem purposes
    - Natural Resources Plan (Obj O25): maintain aquatic system health, restoration encouraged
- Recreational Value
    - Freshwater Plan (App 5): kayaking, sailing, windsurfing (not contact recreation)
    - Natural Resources Plan (Sch H): contact recreation
- Cultural Value
    - Natural Resources Plan (Sch C1): mana whenua sites of significance
      Wahi tapu (sacred place); urupa (burial ground); tohu ahurea (traditional value); wai ora (water used for healing); puna raranga (source of weaving material); hoe waka (canoe place); waka ama (outrigger canoe)

Also New Zealand Fishing (nzfishing.com) lists Lake Waitawa as defined coarse fishing waters for perch and tench.

3.3.2 Critical Variables and Thresholds for Lake Waitawa

From the list of values, critical variables for aquatic ecology include: nutrient levels, phytoplankton blooms, invasive plants and pest fish. For recreational values, critical variables comprise bacteriological quality and cyanobacteria levels. While for cultural values the critical variables appear to be mana whenua sites of significance. For fishing dissolved oxygen is one critical variable. Also perch and tench are valued for recreational fishing but are at odds with indigenous aquatic ecology values.

For some of these critical variables there are thresholds defined by national guidelines, i.e. recreational values for bacteriological quality (540 cfu/100mL, 95th percentile) and cyanobacteria levels (1.8 mm^3/l for toxic cyanobacteria). There are also some qualitative thresholds that have been set for the lake, i.e. “low frequency of blooms” for phytoplankton blooms, “30% of naturally available area with dominance of native species” for invasive plants, and, “indigenous fish resilient” for pest fish. One threshold can be based on comparison with similar lakes i.e. national average TLI of 4.8 for coastal lakes. There are also physiological thresholds such as dissolved oxygen levels for fish survival.

Table 4 sets out the critical variables and related thresholds for Lake Waitawa.

Table 4 Critical variables and related thresholds for Lake Waitawa

CRITICAL VARIABLES	THRESHOLDS
Water quality ***Nutrient levels***	**Trophic Level Index 5.8** Compared to national average 4.8
Aquatic Ecology ***Phytoplankton blooms***	**Frequent blooms c**ompared to “low frequency of nuisance blooms”
Aquatic Ecology ***Invasive plants***	**70% hornwort** compared to 30% naturally available area with natives
Aquatic Ecology ***Pest fish***	Over **80% bullies** compared to “indigenous fish resilient”
Recreational Values ***Bacteriological quality***	Max **4cfu/100mL** compared to 540cfu/100mL (95th percentile)
Recreational Values ***Cyanobacteria levels***	**8.7 mm^3/L** compared to 1.8 mm^3/L toxic cyanobacteria
Fish Ecology ***Dissolved oxygen levels***	At depth regularly below **2 mg/L** threshold detrimental to fish

3.3.3 Adaptive Cycles and Management Interventions for Lake Waitawa

From the reference material reviewed the potential failure pathways for Lake Waitawa are from catchment runoff, wastewater disposal, and, thermal stratification leading to anoxic conditions.

For catchment runoff it is a nested adaptive cycle at the catchment and lake scales. The adaptive cycle phases are:

- Exploitation (catchment): nutrient intensive farming
- Accumulation (catchment): build-up of nutrients in soil and water
- Release (catchment): discharge from tributaries to lake
- Exploitation (lake): nutrients in soil and water enter lake
- Accumulation (lake): build-up of nutrients in water column and sediments
- Release (lake): lake sediments release nutrients when lake bottom becomes anoxic
- Reorganisation (lake): need to reduce in-lake releases and catchment inputs
- Reorganisation (catchment): need to reduce nutrient intensity of farming.

Table 5 shows the adaptive cycle phases and possible management interventions for each of the phases.

Table 5 Catchment runoff adaptive cycle phases and potential interventions for Lake Waitawa

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION (catchment) Nutrient intensive farming	Nutrient reduction; Stock exclusion from waterways
ACCUMULATION (catchment) Build-up of nutrients in soil & water	Riparian planting
RELEASE (catchment) Discharge from tributaries to lake	Re-establish wetlands
EXPLOITATION (lake) Nutrients into lake	
ACCUMULATION (lake) Build up in water column & sediments	Flocculation; Freshwater mussels; dredging; lock sediments in place
RELEASE (lake) Anoxic sediments release nutrients; Algal growth in water	Destratify lake
REORGANISATION (catchment)	Reduce nutrient intensity of farms

At the catchment scale, interventions to address the exploitation phase generation of nutrients are nutrient reduction from catchment land uses (either improved land

management practices for existing use or change to less nutrient intensive uses), and stock exclusion from waterways. To address the accumulation of nutrients in waterways, one intervention is the introduction of riparian planting. To address the release from the catchment to the lake one intervention is the reintroduction of wetlands before the stream discharges into the lake. To address accumulation in the lake water column there are interventions such as flocculation and freshwater mussels, while for accumulation in the sediments there are interventions like dredging for removal or locking the sediments in place. To counter the release of nutrients from sediments under anoxic conditions an intervention is to destratify the lake.

For wastewater process and disposal into the lake, the adaptive cycle phases are as follows:

- Exploitation (wastewater): the generation of greywater and wastewater from the camp
- Accumulation (wastewater): the build-up of wastewater and sludge in the treatment pond
- Release (wastewater): overflow from pond into lake via wetland
- Exploitation (lake): discharge of wastewater into lake
- Accumulation (lake): build-up of nutrients and pathogens in the lake
- Release (lake): algal growth in lake
- Reorganisation: lake reorganisation is dependent on reorganisation of wastewater treatment and disposal.

These adaptive cycle phases are shown in Table 6 together with possible management interventions.

Table 6 Wastewater adaptive cycle phases and potential interventions for Lake Waitawa

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION (wastewater) Generation of greywater/wastewater	Composting toilets
ACCUMULATION (wastewater) Build-up of wastewater and sludge in pond	De-sludge ponds Tree removal to improve UV treatment
RELEASE (wastewater) Overflow to lake via wetland	Wetland treatment
EXPLOITATION (lake) Discharge of wastewater to lake	Land-based disposal
ACCUMULATION (lake) Build-up of nutrients and pathogens	
RELEASE (lake) Algal growth in water	
REORGANISATION (wastewater)	Improved wastewater treatment

A number of interventions have been identified which would improve lake water quality. At the exploitation (wastewater) phase there could be a shift from flush to composting toilets. At the accumulation (wastewater) phase the treatment pond could be desludged and the UV treatment increased by moving the trees that shade the pond. At the release (wastewater) phase treatment of the overflow through the wetland could be increased through formalising wetland treatment. At the exploitation (lake) phase, rather than discharging to the lake, the alternative of land-based effluent disposal could be implemented. At the reorganisation (phase), the level of wastewater treatment could be increased to improve the quality of the effluent.

For thermal stratification the adaptive cycle has the following phases:

- Exploitation: the heating of the upper lake surface in summer
- Accumulation: the upper layer of the lake increases in temperature and decreases in density
- Disturbance/Release: density differences between upper and lower layers cause thermal stratification; reduced mixing leads to decline in dissolved oxygen at depth and release of nutrients from sediments
- Reorganisation: surface layer cools in autumn and winter; stratification ends and general mixing occurs.

Table 7 shows the adaptive cycle phases and potential interventions in relation to thermal stratification.

Table 7 Thermal stratification adaptive cycle phases and potential interventions for Lake Waitawa

ADAPTIVE CYCLE PHASE	INTERVENTION
EXPLOITATION (lake) Heating of upper layer of the lake	
ACCUMULATION (lake) Upper layer increases in temperature	
DISTURBANCE (lake) Thermal stratification Dissolved oxygen decline Release of nutrients from sediments	Aeration of bottom layer Remove or cover sediments
REORGANISATION Surface layer cools; general mixing	

Interventions at the exploitation and accumulation phases are unlikely because the phases are driven by climate. Possible interventions at the disturbance/release phase are aeration of the bottom layer of the lake to arrest the dissolved oxygen decline, and removal or covering of the sediments to counter the release of nutrients.

3.3.4 Management Approach and Institutional Arrangements for Lake Waitawa

The management approach for Lake Waitawa has been derived from the proposed Natural Resources Regional Plan and the Regional Freshwater Plan for the Wellington Region.

For aquatic ecology in the Regional Freshwater Plan, the relevant policy appears to be Policy 5.2.6 which requires water quality to be managed for aquatic ecosystem purposes. The proposed Natural Resources Plan is more explicit. Objective 25 is to manage aquatic habitats to maintain aquatic ecosystem health and restoration of aquatic ecosystem health is encouraged. Furthermore, Policy 32 is to manage significant adverse effects by avoiding, remedying, mitigating, or, use of biodiversity offsets. Lake Waitawa is specifically referenced in Method 10 for water quality investigations and remediation actions: to examine reasons for elevated nutrients, phytoplankton and planktonic cyanobacteria levels, by 2018. Having established causality the approach is to develop appropriate remediation and/or containment programmes.

For recreational values, Policy 63 from the proposed Natural Resources Regional Plan seeks the improvement of water quality for contact recreation and Maori customary use to meet over time the contact recreational requirements, i.e. bacteriological quality to be less than 540cfu/100mL and planktonic levels to be less than 1.8mm^3/L for toxic cyanobacteria and less than 10mm^3/L for cyanobacteria. Method 27 proposes that the Whaitua Committee is to identify methods and time frames that may be incorporated into the Plan by a future plan change or variation.

For sites with significant mana whenua value, there are the following policies: sites shall be protected and restored (Policy 44), and, unavoidable minor effects are evaluated and managed through cultural impact assessment (Policy 45).

In the proposed Natural Resources Plan the objective in relation to discharges of wastewater to freshwater is for discharges to be progressively reduced (Objective 50). Also relevant to Lake Waitawa are the policies: the discharge of contaminants to land is promoted over discharges to water, particularly where there are adverse effects on contact recreation (Policy 62); and, to have particular regard to improving wastewater quality from wastewater treatment plants (Policy 63).

The general institutional arrangements are described in the proposed Natural Resources Plan (Section 1.4 on Integrated catchment management). The key components for decision making are: the identification of values and associated outcomes at the catchment scale; the development of plans and programmes to reach those outcomes within a catchment context; and, that there is an emphasis on identification of local values as a basis for decision making. This involves the establishment of a Whaitua committee for Kapiti Coast whaitua. Implementation is to be achieved through regulatory and non-regulatory measures.

However the specific management interventions have not been incorporated yet in a catchment plan nor is there reference to funding of relevant interventions in the regional council's ten-year plan. In relation to the regulation of the wastewater treatment plant a review of treatment plant and discharge performance (Lowe Environmental Impact (2014)

indicates that there is inadequate monitoring information to assess treatment plant performance and there is a need to include sludge management in the consenting package. Furthermore, the consent review process is an opportunity to incorporate the broader management issues in the policies related to wastewater discharges of reducing waste, land based discharges and improving lake water quality.

3.4 Lake Pounui

Lake Pounui is a small (about 46ha) moderately shallow (9.6m maximum depth) lowland coastal lake. It is fed by two small streams that discharge into swampy wetland margins of the lake. The lake outflow is Battery/Pounui Stream which flows into Pounui Lagoon and then into Lake Onoke (Figure 7). Lake Pounui's 627ha catchment is dominated by unmodified indigenous forest with only a small amount of pastoral land cover (27ha or 4.5%).

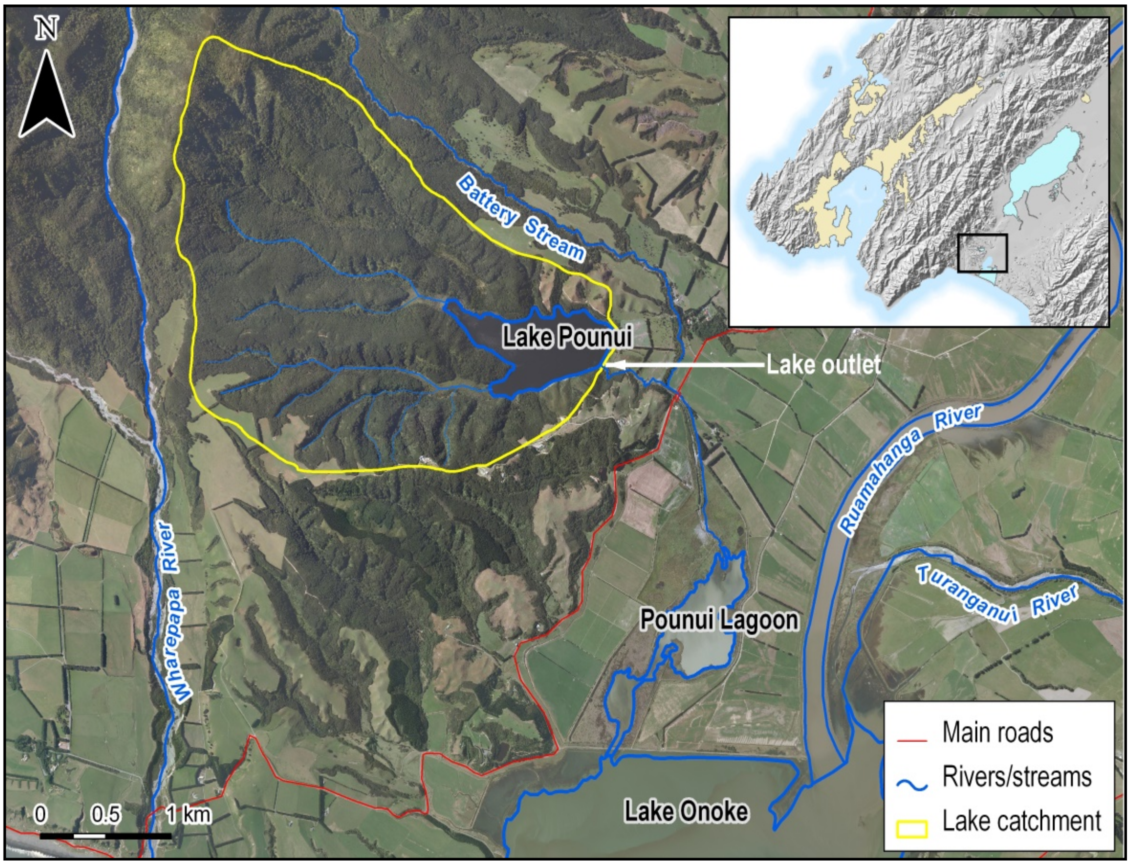

Figure 7 Lake Pounui (Source: Perrie and Milne, 2012)

3.4.1 Values for Lake Pounui

The following values for Lake Pounui have been identified from the proposed Natural Resources Plan and Regional Freshwater Plan:

- Ecosystem values

- Natural Resources Plan (Sch F1): significant indigenous ecosystems (macroinvertebrates, threatened / at risk fish species, indigenous fish biodiversity (common bully, giant kokopu, banded kokopu, brown mudfish, inanga, longfin eel, redfin bully, shortfin eel, torrentfish)
- Natural Resources Plan (Sch F1c): significant aquatic plant communities (aquatic plant diversity in high ecological condition)
- Regional Freshwater Plan (App 3): water body with naturally threatened indigenous fish (brown mudfish, giant kokopu and banded kokopu)

3.4.2 Critical Variables and Thresholds for Lake Pounui

From the references for the lake for these ecosystem values, the critical variables for aquatic ecology comprise: ecosystem condition, indigenous plant community, invasive plants and algal blooms. While for indigenous fish biodiversity the critical variables comprise the % native and % exotic fish species, and dissolved oxygen in the lake.

For these critical variables there are baseline values that could be used as thresholds if the goal is to maintain current water quality and ecological status. These are the three components of Lake SPI: the overall measure, native condition index, and invasive impact index; and %native/%exotic fish species. It should be noted that where there are past measurements of indigenous fish biodiversity the %native species is declining and %exotic species is increasing. Species thresholds can be defined for dissolved oxygen. The lake is above dissolved oxygen levels acceptable to tolerant species like eels for most of its depth but has limited capacity for sensitive species. For algal blooms there are thresholds for recreational values but not aquatic ecology. Algal bloom levels are approaching the surveillance level for recreational values. Table 8 sets out the critical variables and related thresholds for Lake Pounui.

Table 8 Critical variables and related thresholds for Lake Pounui

CRITICAL VARIABLES	THRESHOLDS
Aquatic Ecology	
Ecosystem condition	LakeSPI (%pristine, maintain current): 56% in 2011
Indigenous plant community	Native condition index: 65% in 2011
Invasive plants	Invasive impact index: 44% in 2011
Algal blooms	0.33 mm^3/L actual compared to 0.5 mm^3/L surveillance level (recreation)
Indigenous Fish Biodiversity	
% native / % exotic	78% native / 22% exotic (1997) 67% native / 33% exotic (2010)
Dissolved oxygen	3 mg/L eels (at 8.1m depth) [7 mg/L trout (at 0.4m depth)]

3.4.3 Adaptive Cycles and Management Interventions for Lake Pounui

The adaptive cycle and possible management interventions for aquatic weed invasions were set out in Table 2 for Lake Kohangatera. Table 9 summarises the adaptive cycle phases and possible management interventions for dissolved oxygen depletion. The key phases appear to be: exploitation – nutrient enrichment leads to algal blooms; accumulation – algae die, sink to the lake bottom and decompose; disturbance/release – decomposition uses dissolved oxygen and causes oxygen depletion; and, reorganisation – the lake is degraded as fish habitat.

It is important to note that there was no evidence in water quality monitoring of thermal stratification which is an alternative process for creating anoxic conditions at depth in lakes (as for example in Lake Waitawa – refer Table 7).

In considering management interventions with respect to the exploitation phase of increased nutrient inputs, one common approach is to consider the increased nutrient intensity of land use (as for example the increased nutrient loads in Lake Waitawa – refer Table 5). While water quality sampling is very limited, the Trophic Level Index is 4.7 indicating eutrophic conditions. Total nitrogen and phosphorus levels are high compared to other catchments dominated by indigenous forest cover. However nitrate nitrogen levels are very low (<0.002 mg/L), whereas total Kjeldahl nitrogen is the dominant type of nitrogen (0.57 mg/L). This indicates an organic source of nitrogen rather than nitrate nitrogen derived from land use intensification. There is therefore limited opportunity for catchment modification to address elevated nitrogen. A possible intervention is artificial aeration to address the disturbance/release phase of anoxic conditions.

Table 9 Dissolved oxygen depletion adaptive cycle phases and management interventions for Lake Pounui

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION Nutrient enrichment leads to algal blooms	Reduce nutrient input (limited opportunity – 95% forested catchment: organic nitrogen)
ACCUMULATION Algae die, sink to the lake bottom and decompose	
DISTURBANCE/RELEASE Decomposition uses dissolved oxygen and causes oxygen depletion	Artificial aeration
REORGANISATION Degraded fish habitat	

3.4.4 Management Approach and Institutional Arrangements for Lake Pounui

The Regional Water Plan has a specific policy for water bodies listed in Appendix 3 as with naturally threatened indigenous fish: Policy 4.2.13 specifies the need, where there are indigenous fish and aquatic plants, to manage water quality, manage flows and levels, maintain migratory and dispersal pathways for fish, avoid adverse effects to life cycle, and, promote land owner and user knowledge. In the proposed Natural Resources Plan there are several policies: Policy 33 requiring that more than minor adverse effects on species listed in Schedule F shall be avoided; Policy 40 seeks protection and restoration of ecosystems; Policy 41 seeks to avoid or remedy adverse effects of activities; Policy 42 requires activities in surrounding areas to have regard for ecological connections, provision of adequate buffers, and avoiding cumulative effects; and Policy 43 allows activities as part of a restoration plan.

In relation to institutional arrangements, 284ha of lake wetland areas and secondary beech-podacarp forest in the Lake Pounui catchment are subject to a QEII Covenant. The catchment is in private ownership and a QEII Covenant is a voluntary land management agreement for biodiversity protection. There are also the general arrangements under the proposed Natural Resources Plan (Section 1.4) for integrated catchment management. This includes: Identification of values and associated outcomes at the catchment scale; Plans and programmes to reach those outcomes within a catchment context; an emphasis on identification of local values as a basis for decision making; establishment of a Whaitua committee for Ruamahanga whaitua; and, implementation of regulatory and non-regulatory measures.

3.5 Lake Onoke

Lake Onoke is the second largest lake in the Wellington Region with an area of 622ha. It has a maximum depth of around 5-6m but the majority of the lake is shallow (<1m). It is a barrier bar coastal lake that is intermittently open. The main inflow is from the Ruamahanga River. The lake is tidal when the mouth is open. When closed, lake height can rise to generate backflow to Lake Wairarapa and result in extensive flooding of the lower Wairarapa Valley. Lake levels are now managed by the regional council to reduce flood risk. See Figure 8.

3.5.1 Values for Lake Onoke

The following values for Lake Onoke have been identified from the proposed Natural Resources Plan and Regional Freshwater Plan:

- Significant cultural values
  - Natural Resources Plan (Sch B): significant for fishery, supporting well-being, and annual eel migration (lake health affected by development).
  - Natural Resources Plan (Sch C5): sites of significance (ancestral place, canoe landing and traditional canoe route, sea water, original home, weaving material

and medicinal plants, food resources and eel harvesting, seafood harvesting, and traditional values).

- Ecosystem values
  - Natural Resources Plan (Sch F1b): inanga spawning habitat.
  - Natural Resources Plan (Sch F2c): habitats for indigenous birds in coastal marine area (at least ten threatened / at risk species, nesting colonies on spit barrier).
  - Natural Resources Plan (Sch F3): significant wetlands (Lake Onoke wetlands).
  - Natural Resources Plan (Sch F4): sites with indigenous biodiversity values (part of Lake Wairarapa Wetland Conservation Area), wetland and saltmarsh habitat, national importance of fisheries, eight threatened indigenous migratory species.
  - Natural Resources Plan (Sch J): significant geological feature.
  - Natural Resources Plan (Sch U1): trigger levels for mouth cutting (10.6m at Lake Onoke recording station).
- Recreational Value
  - Freshwater Plan (App 5): canoeing, kayaking, power boating and angling.
  - Natural Resources Plan (Sch H): contact recreation.

Figure 8 Lake Onoke (Source: Perrie and Milne, 2012)

3.5.2 Critical Variables and Thresholds for Lake Onoke

From the list of values, critical variables have been identified from the reference material for water quality with respect to nutrients, sediments and pathogens; for lake openings in relation to flushing capacity, duration of closure, timing of openings and lake level; and saltmarsh/wetland habitat with respect to area of habitat and area of macrophyte beds.

For some of the critical variables thresholds have been defined. This has occurred through a variety of approaches: national guidelines (i.e. pathogens for recreational water quality), water conservation orders (i.e. levels for lake opening for flood management), relationship to original area (i.e. area of saltmarsh/wetland habitat), current levels (i.e. in-lake trophic level index for nutrients), or vulnerability analysis (i.e. flushing capacity for contaminant removal). These thresholds provide a quantitative basis for monitoring and management.

However other thresholds need to be quantified. The catchment nutrient load needs to be assessed and the threshold for maintaining the TLI at current levels needs to be determined. The sedimentation rate in the lake and the sediment yield from the catchment also need to be quantified and analysis undertaken to determine threshold values. With respect to lake openings, the duration of closure limits to prevent unacceptable contaminant build-up are needed; also, the timings of openings for eel and fish migration need to be defined. The area of macrophyte beds needs to be measured and monitored in order to assess whether the area is being maintained.

Table 10 sets out the critical variables and related thresholds for Lake Onoke.

3.5.3 Adaptive Cycles and Management Interventions for Lake Onoke

The adaptive cycle and possible management interventions for lake openings were set out in Table 3 for Lake Kohangatera. For Lake Onoke, artificial openings to meet fish and eel migration requirements are also a possible management intervention. The flood management considerations are considered in the next section on Lake Wairarapa.

The adaptive cycle phases for catchment contaminants (nutrients and sediments) and possible interventions are set out in Table 11. At the catchment scale, the exploitation phase is the increase in nutrient-intensive farms. In the accumulation phase there is nutrient build-up in agricultural soils. For the release phase, nutrients and sediment are transported by surface water. There can also be nitrate transport in groundwater. At the lake scale, the exploitation phase is the discharge of nutrients and sediment into the lake. In the accumulation phase, nutrients and sediment accumulate in the water column and the lake bed. There are a number of components of the release phase. One is the nutrient build-up leading to lake eutrophication. A second is wind re-suspension of sediments (particularly in shallow water). The third is lake openings to allow the discharge of contaminants. The reorganisation phase at the scale of the lake is for closure of the channel to the sea and continuing contamination build-up leading to further lake degradation. For sustainable management of the lake there is a need for reorganisation at the catchment scale that involves reduction in catchment contaminants.

Table 10 Critical variables and related thresholds for Lake Onoke

CRITICAL VARIABLES	THRESHOLDS
Water Quality	Maintain or improve from current level
Nutrients	In lake: TLI 5.1 (TN 0.721mg/L; TP 0.076mg/L; chlorophyll a 5 mg/m^3; Seechi depth 0.43) In catchment: N load; P load
Sediments	In lake water: non-volatile suspended solids In lakebed: sedimentation rate In catchment: sediment yield
Pathogens	E Coli 540 cfu/100mL 95th percentile
Lake Openings	
Flushing capacity (contaminant removal)	Flushing potential: inflow (40m^3/s)/estuary volume (9m m^3) = 0.4
Duration of closure (contaminant build up)	(to be determined)
Timing of openings (fish passage)	Duration to match migration cycle
Lake level (flooding)	10.6m at recording station
Saltmarsh / Wetland Habitat	
Area of habitat (clearance, inundated area)	% of original area (40-47%)
Area of macrophyte beds	Maintain or increase current area

Intervention at the reorganisation phase (or exploitation phase) at the catchment level is for improved land management practices. For the accumulation phase at the catchment scale one intervention is the use of nitrate inhibitors that reduce the conversion of insoluble ammonium nitrogen to soluble nitrate nitrogen. One intervention to reduce nutrients and sediment at the release phase (catchment scale) is to introduce constructed wetlands to treat farm runoff to facilitate settlement of sediment (and phosphorus bound to sediment) and plant uptake of nitrogen and phosphorous. At the lake scale there is also the possible intervention of re-establishing natural wetlands to reduce suspended sediment and nutrient levels. At the release phase (lake scale) two possible interventions are to increase macrophyte cover in order to reduce wind re-suspension, and to increase lake openings to increase the discharge of contaminants from the lake.

Table 11 Catchment contaminants adaptive cycle phases and potential interventions for Lake Onoke

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION (catchment) Nutrient intensive farming	Improved land management practices
ACCUMULATION (catchment) Build-up of nutrients in soil & water	Nitrate inhibitors
RELEASE (catchment) Nutrients and sediment in streams	Constructed wetlands
EXPLOITATION (lake) Nutrients and sediments into lake	Re-establish natural wetlands
ACCUMULATION (lake) Build up in water column & sediments	
RELEASE (lake) Eutrophication, wind re-suspension, lake openings	Increase macrophyte cover Increase lake openings
REORGANISATION (lake) Channel closure contaminant build up, degradation	
REORGANISATION (catchment) Reduction in catchment contaminants	Improved land management practices

3.5.4 Management Approach and Institutional Arrangements for Lake Onoke

The management approach and institutional arrangements have been derived from the proposed Natural Resources Plan.

For the biodiversity and native fisheries values the management approach from the proposed Natural Resources Regional Plan is the same as indicated for Lake Kohangatera (Section 3.2.4 above) for these values. Key policies in relation to biodiversity appear to be: adverse effects are to be avoided (policy 39), more than minor effects on species are to be avoided (policy 33), indigenous fish passage to be restored (policy 35), and barriers to fish passage to be avoided (policy 34). While in relation to the protection and restoration of ecosystems key policies are: activities are in accordance with a restoration plan (policy 41); ecological connectivity is maintained or enhanced, buffers are provided, and, cumulative effects and incremental loss avoided (policy 43). For sites with significant mana whenua value, there are the following policies: sites shall be protected and restored (policy 44), and, unavoidable minor effects are evaluated and managed through cultural impact assessment.

For recreational values, the management approach is the same as indicated for Lake Waitawa. Policy 63 from the proposed Natural Resources Regional Plan seeks the improvement of water quality for contact recreation and Maori customary use to meet over time the contact recreational requirements, i.e. bacteriological quality to be less than 540cfu/100mL and planktonic levels to be less than 1.8mm^3/L for toxic cyanobacteria and less than 10mm^3/L for cyanobacteria. Method 27 proposes that the Whaitua Committee is to identify methods and time frames that may be incorporated into the Plan by a future plan change or variation.

For flood management, lake opening trigger levels are specified in Schedule U and Lake Onoke forms part of the Lower Wairarapa Valley Development Scheme.

The institutional arrangements for Lake Onoke have been integrated with Lake Wairarapa as part of the arrangements for Wairarapa Moana[3]. These are discussed in more detail in Section 3.6.4 below.

3.6 Lake Wairarapa

Lake Wairarapa is the largest lake in the Wellington Region (about 7,850ha). It is typically very shallow (around 2.5m at its deepest point). The lake is in the catchment of the Ruamahanga River. There have been significant modifications for flood protection and drainage through the Lower Wairarapa Valley Development Scheme principally during the 1960s and 1970s. The changes included the diversion of the Ruamahanga River from its direct course into Lake Wairarapa to bypass the lake and discharge into Lake Onoke. Barrage gates were installed at the outlet of Lake Wairarapa to regulate water levels. The outlet discharges into the Ruamahanga River. The main surface water inflow into the lake is the Tauherenikau River. Groundwater inflows are relatively minor (refer Figure 9).

While there has been regular water quality monitoring of the lake, there is limited information on catchment, nutrient and sediment balances. The current catchment is 57,245ha. Pastoral land cover makes up just over 50% of the catchment while indigenous forest and scrub makes up around 44% of the catchment. Prior to the diversion the catchment was much larger (302,390ha). However flood flows from the Ruamahanga can enter the lake via the Oporua Floodway or backflow through the barrage gates.

[3] Wairarapa Moana is made up of the beds of Lake Wairarapa and Lake Onoke and the publicly owned reserves around them including mudflats, lagoons, sand flats, marshlands, salt marshes and backwaters.

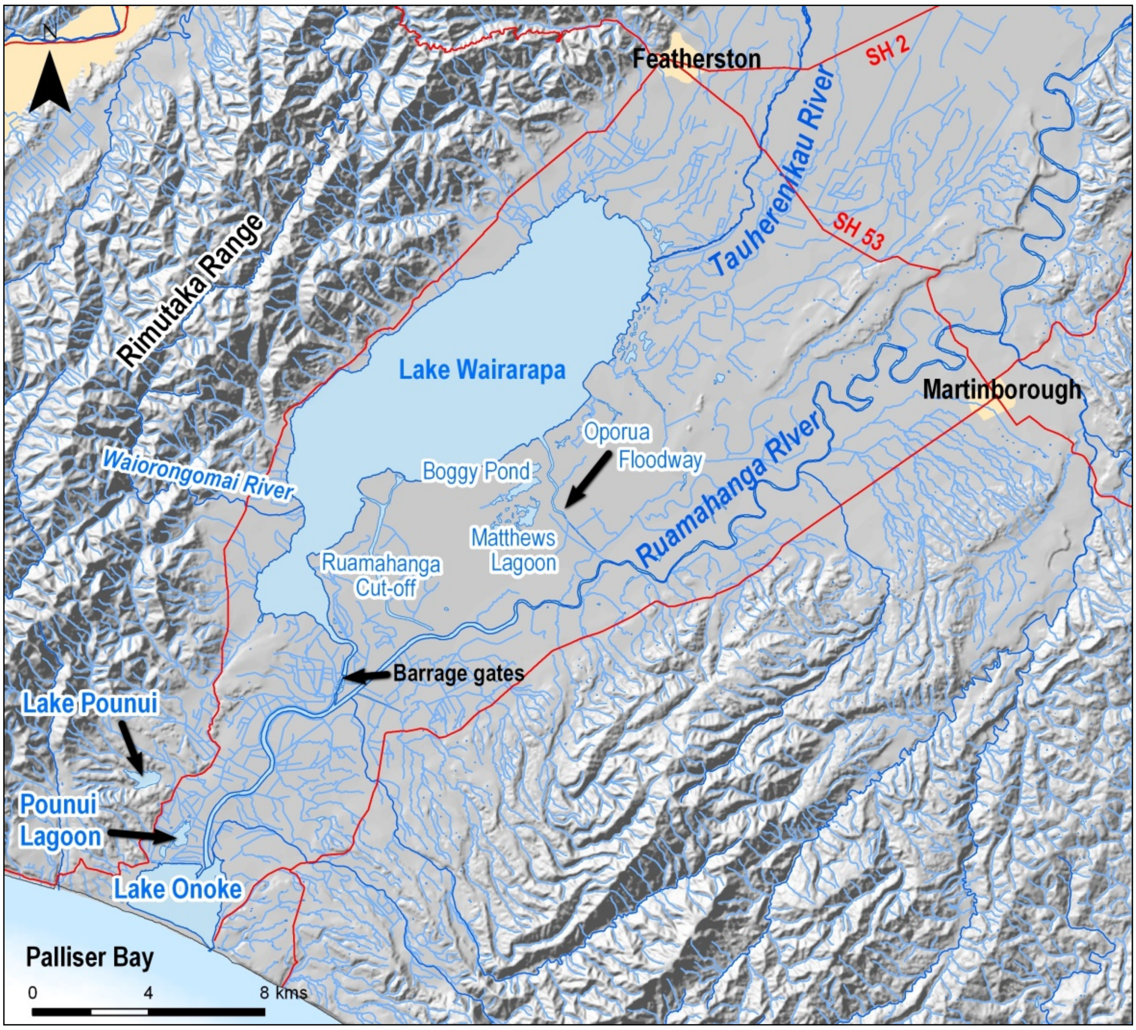

Figure 9 Lake Wairarapa (Source: Perrie and Milne, 2012)

3.6.1 Values for Lake Wairarapa

The following values for Lake Wairarapa have been identified from the proposed Natural Resources Plan, the Regional Freshwater Plan and the National Water Conservation Order for Lake Wairarapa:

- Significant cultural values
  - Natural Resources Plan (Sch B): Wairarapa Moana – freshwater eye of Maui; fishery, supported well-being, annual eel migration, lake health affected by development, integral to Maori identity
- Ecosystem values
  - Natural Resources Plan (Sch A2): Indigenous ecosystem values
  - Natural Resources Plan (Sch F1): Lakes with indigenous ecosystems – threatened / at risk fish species (banded kokopu, black flounder, common bully, common smelt, giant kokopu, grey mullet, inanga, lamprey, longfin eel, shortfin eel, torrentfish)
  - Natural Resources Plan (Sch F2b): Indigenous birds – all year round, summer habitat for arctic breeding shorebirds, winter habitat for NZ breeding shorebirds.

- National Water Conservation Order: Wildlife habitat – natural fluctuations of water level
- Recreational values
  - Freshwater Plan (App 5): duck shooting, power boating (not contact recreation)
  - Natural Resources Plan (Sch H): Contact recreation
- Flood control
  - National Water Conservation Order
  - Natural Resources Plan (Policy P7): Flood protection activities
- Water supply
  - Natural Resources Plan (Policy P7): uses of land and water

3.6.2 Critical Variables and Thresholds for Lake Wairarapa

Lake Wairarapa has a broad range of values and this is reflected in a large number of critical variables. From the reference material critical variables have been identified for water quality (nutrient levels), ecological values (bird habitat and bird numbers), indigenous fish biodiversity (% native fish and migratory fish passage), recreational values (bacteriological quality, cyanobacteria levels, duck shooting), water supply values (consented volume and lake levels), and flood control (flood storage). Table 12 lists the critical variables and information on related thresholds for those variables.

In relation to the thresholds for the critical variables, there are different levels of information available. For some critical variables there are evidence-based thresholds. For bird habitat, waders have been observed on lake margins between lake levels of 9.9 and 10.4m. For fish passage, barriers are either present or not, and more specifically at the barrage, stream velocity needs to be less than 0.3m/s to allow upstream migration. For flood storage, having the lake level as low as possible provides the greatest available storage. Some of the thresholds are based on standards. For contact recreation there are standards for bacteriological quality (540 cfu/100mL 95th percentile) and cyanobacterial levels (1.8 mm^3/L biovolume). Other thresholds are based on maintenance of current levels: for water quality maintaining the TLI at 5.4, and, for indigenous fish biodiversity maintaining the percentage of native species at 70%. There are thresholds based on RMA processes: the consented volume for water supply of 1800L/s; and, the minimum lake levels set by Water Conservation Order.

However there are also some critical variables where the thresholds are not known. One is the catchment nutrient loads for nitrogen and phosphorus. Another is the water levels for duck shooting for duck breeding and duck hunting. A third is the non-volatile suspended sediment level for wind resuspension of lake bed sediments.

Table 12 Critical variables and related thresholds for Lake Wairarapa

CRITICAL VARIABLES	THRESHOLDS
Water Quality	Maintain or improve from current level
Nutrients	In lake: TLI 5.4 In catchment: N and P load from tributary catchments, drains, groundwater, flood flows, waste discharges, saline backflow Wind re-suspension: NVSS level (TSS-VolatileSS)
Ecological values	
Bird habitat	Lake level fluctuating between 9.9 and 10.4 m
Bird numbers	(to be determined)
Indigenous Fish Biodiversity	
% native species / % exotic species	100% native (1961) 70% native / 30% exotic (2009)
Migratory fish	Barriers to fish passage (Barrage openings, Lake Onoke openings) at times of migration Stream velocity less than 0.3 m/s for upstream migration
Recreational Values	
Bacteriological quality	Max 150 cfu/100mL compared to 540 cfu/100mL 95^{th} percentile
Cyanobacteria levels	1.4 mm^3/L biovolume compared to 1.8 (action level)
Duck shooting	Level in wetlands for duck breeding and hunting
Water Supply	
Consented volume	1,800 L/s
Minimum lake levels	Summer 10.15m, Autumn 10.0m, Winter 9.55m, spring 10.0m.
Flood Control	
Flood storage and control	Level in lake as low as possible

3.6.3 Adaptive Cycles and Management Interventions for Lake Wairarapa

From the available references (refer Reference sections 2, 3 and 4), the most vulnerable failure pathways for Lake Wairarapa appear to be “water quality” (principally in relation to nutrients), “indigenous fish species” (with the decline from 100% native to 70% native species), and “wader habitat” (incorporating flood management).

Table 13 sets out the adaptive cycle phases and possible management interventions for water quality in Lake Wairarapa. It is a nested system based on the lake catchment and the lake itself. At the catchment level, the exploitation phase is both nutrient intensive farming and wastewater discharges. The accumulation phase (at the catchment scale) is the nutrient build-up in soils, discharge of surface runoff to streams from intensive land use, and, discharge of wastewater to streams (e.g. municipal wastewater from Featherston and piggery wastewater from Windy Farm piggery). The release phase not only includes the nutrients and sediment transported by the Tauherenikau River and other upstream rivers entering Lake Wairarapa, but also flood flows from the Ruamahanga River through the Oporua Floodway and brackish backflow through the barrage gates.

At the lake scale, the exploitation phase is the discharge of nutrient, sediment and salinity into the lake. The accumulation phase is the build-up of nutrients, sediment and salinity in the water column and lake bed. There is also a longer term accumulation phase of infilling of the lake. The release phase comprises a number of components: the increase of nutrients leading to lake eutrophication, the wind resuspension of sediments increasing the nutrient loads in the lake water column, and, barrage openings allowing the release of contaminants from the lake. In terms of reorganisation within the lake, the prospect is for ongoing degradation unless there is reorganisation within the catchment through improved land use practices and reduction in wastewater discharges.

The main interventions for improving lake water quality are improved land management practices and reduced wastewater discharges at the catchment exploitation phase. Other interventions are the greater use of land-based disposal rather than river discharges (at the catchment accumulation phase) and the use of constructed wetlands before discharge to the lake (at the catchment release phase). Within the lake there are interventions like increased macrophyte cover in order to reduce wind resuspension of sediment.

Table 13 Lake water quality adaptive cycle phases and potential interventions for Lake Wairarapa

ADAPTIVE CYCLE PHASES	INTERVENTIONS
EXPLOITATION (catchment) Nutrient intensive farms Wastewater effluent	Improved land management practices Increased treatment of wastewater
ACCUMULATION (catchment) Nutrient build-up in soils Discharge of surface runoff to streams Discharge of wastewater to streams	Land-based treatment of wastewater
RELEASE (catchment) Nutrients and sediment transported by surface water Flood flows from Oporua Floodway Brackish backflow through barrage gates	Constructed wetlands before discharge to lake
EXPLOITATION (lake) Nutrient, sediment and brackish water discharged into lake	
ACCUMULATION (lake) Nutrient, sediment and salinity in water column and lake bed Infilling of lake	
RELEASE (lake) Eutrophication of lake Wind re-suspension of sediment Barrage openings: discharge of contaminants	Increase macrophyte cover
REORGANISATION (lake) Lake degradation	
Reorganisation (catchment)	Improved land management practices Reduction in wastewater discharges

Table 14 displays the adaptive cycle phases for indigenous fish species and possible management interventions in Lake Wairarapa. The adaptive cycle phases are similar to those for Lake Kohangatera. However in the case of Lake Wairarapa the openings to the sea relate to openings of Lake Onoke to the sea. The disturbance phase in relation to Lake Wairarapa concerns the barriers to migration that have been created by the diversion of the Ruamahanga River from the lake and the control structures (the barrage gates at the lake outlet) as part of the Lower Wairarapa Valley Development Scheme. The disturbance has led to the reorganisation within the lake with a reduction in indigenous fish and improved habitat for exotic species.

In relation to management interventions within Lake Wairarapa, there is a need to address the disturbance phase by re-establishing river flow and managing control structures for fish

passage, e.g. ensuring that the downstream velocity at the barrage gates is less than 0.3 m/s during periods of upstream migration. With respect to the reorganisation phase, possible interventions include controls on fishing of indigenous species, modifying habitat suited to exotic species, and removal of exotic species.

Table 14 Indigenous fish species adaptive cycle phases and potential interventions for Lake Wairarapa

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION Breeding at sea, Attraction to freshwater	Openings to the sea at Lake Onoke
ACCUMULATION Migration to freshwater	Openings to the sea at Lake Onoke
DISTURBANCE Barriers to migration: River diversion Control structures	Re-establish river flow Manage control structures for fish passage
REORGANISATION Reduction in indigenous fish Improved habitat for exotic species	Controls on fishing of indigenous species Modify exotic habitat Removal of exotic species

The adaptive cycle phases for wader habitat are shown in Table 15. The exploitation of the lake margins by waders is related to the presence of invertebrate prey associated with marsh turf plants. The accumulation of birds at the lake margins is dependent on suitable habitat being available. The disturbance to wader presence is related to lake level. If the lake level is above 10.3m then the marsh turf plant habitat is too deep for waders to feed. If the level is below 9.55m then the habitat is not suitable to invertebrates. The reorganisation phase is when the lake level is between 9.55m and 10.3m, and then the waders will return.

The key management interventions for sustainable wader presence are, for the exploitation phase, the protection of marsh turf plants from weed invasion and stock grazing, and for the disturbance phase, the maintenance of lake levels in the range 9.55 and 10.3m.

Table 15 Wader habitat adaptive cycle phases and potential interventions for Lake Wairarapa

ADAPTIVE CYCLE PHASES	INTERVENTION
EXPLOITATION Presence of invertebrate prey Associated with marsh turf plants	Protect marsh turf plants from weed invasion and stock grazing
ACCUMULATION Bird species present when habitat suitable	
DISTURBANCE Level above 10.3m: too deep – habitat inaccessible to waders Level below 9.55m – loss of invertebrates	Maintain water levels in range 9.55 and 10.3m
REORGANISATION Birds return when lake level between 9.55 and 10.3m	

3.6.4 Management Approach and Institutional Arrangements for Lake Wairarapa

With a wide variety of values, Lake Wairarapa has many provisions in the proposed Natural Resources Plan and Regional Freshwater Plan. In addition it has a Water Conservation Order.

Within the proposed Natural Resources Plan the key policies in relation to biodiversity appear to be: adverse effects are to be avoided (policy 39), more than minor effects on species are to be avoided (policy 33), indigenous fish passage to be restored (policy 35), and barriers to fish passage to be avoided (policy 34). While in relation to the protection and restoration of ecosystems key policies are: activities are in accordance with a restoration plan (policy 41); ecological connectivity is maintained or enhanced, buffers are provided, and, cumulative effects and incremental loss avoided (policy 43). For sites with significant mana whenua value, there are the following policies: sites shall be protected and restored (policy 44), and, unavoidable minor effects are evaluated and managed through cultural impact assessment.

For aquatic ecology in the Regional Freshwater Plan, the relevant policy appears to be Policy 5.2.6 which requires water quality to be managed for aquatic ecosystem purposes. The proposed Natural Resources Plan is more explicit. Objective 25 is to manage aquatic habitats to maintain aquatic ecosystem health and restoration of aquatic ecosystem health is encouraged. Furthermore, Policy 32 is to manage significant adverse effects by avoiding, remedying, mitigating, or, use of biodiversity offsets. Lake Wairarapa is specifically referenced in Method 9 to restore the ecological values and improve water quality of Wairarapa Moana working with tangata whenua (Kahungunu ki Wairarapa and Rangitane o Wairarapa) and the community. This includes monitoring, protecting and restoring habitats, managing pest plants and animals, and, incorporating ecological, cultural and economic values into flood protection practices.

For recreational values, Policy 63 from the proposed Natural Resources Regional Plan seeks the improvement of water quality for contact recreation and Maori customary use to meet over time the contact recreational requirements, i.e. bacteriological quality to be less than 540cfu/100mL and planktonic levels to be less than 1.8mm^3/L for toxic cyanobacteria and less than 10mm^3/L for cyanobacteria. Method 27 proposes that the Whaitua Committee is to identify methods and time frames that may be incorporated into the Plan by a future plan change or variation.

In the proposed Natural Resources Plan the objective in relation to discharges of wastewater to freshwater is for discharges to be progressively reduced (Objective 50). Also relevant to Lake Wairarapa are the policies: the discharge of contaminants to land is promoted over discharges to water, particularly where there are adverse effects on contact recreation (Policy 62); and, to have particular regard to improving wastewater quality from wastewater treatment plants (Policy 63).

In relation to institutional arrangements, the provisions of Section 1.4 of the proposed Natural Resources Plan regarding the establishment of a Whaitua Committee for the catchment have already occurred for the Ruamahanga in 2013. The purpose of the Ruamahanga Whaitua Committee is to facilitate community and stakeholder engagement in the development of a Whaitua Implementation Programme (WIP). The WIP is a non-statutory report with recommendations for specific plan provisions and work programmes for integrated management of land and water resources.

In addition, there are already work programmes in place to address sustainability issues at the scale of the lake. The Wairarapa Moana wetlands project began in 2008 to enhance the native ecology, recreation and cultural opportunities on public land in the area. The Project is a partnership between the Department of Conservation, Greater Wellington Regional Council, South Wairarapa District Council, Ngati Kahungunu ki Wairarapa, Rangitane o Wairarapa, and, Papawai and Kohuni marae. A $2.2m project with a $1m contribution from central government has been funded to restore wetland habitat around the edge of Lake Wairarapa and Lake Onoke. There has been implementation of on-farm projects to improve water quality and biodiversity; an extensive weed control programme targeting willows and alder; aerial surveys to monitor regeneration of native species; pest control programmes targeting ferrets, stoats and feral cats; a trial of exotic fish removal; wetland restoration works; monitoring of water quality and bird species; and drain management projects.

4 Discussion

The discussion considers the sustainability analysis from two perspectives. One is from the perspective as a biophysical system: the discussion focusses on the similarities and differences of the lakes in relation to biophysical processes relevant to the interventions needed for sustainable management. The second is from the perspective as a socio-economic system for lake management: the adequacy of the resources, accumulated knowledge, management approaches and institutional arrangements to implement the needed management interventions.

4.1 Lake Management from Biophysical System Perspective

Comparisons of the values, critical variables, adaptive cycles and possible management interventions show some similarities and some differences between the five lakes. Table 16 compares the main values for each of the lakes identified in Section 3. As can be seen in the table there are similar values between lakes, however, there are sufficient differences that each lake has a unique combination of values.

The similarities and differences in values between the lakes means there are also similarities and differences in failure pathways and the critical variables relevant to the sustainable management for each of the lakes. For example, nutrient levels are critical variables for all five lakes, whereas it is Lake Kohangatera and Lake Pounui that are recognised for their significant aquatic plant communities. The unique combination of values, failure pathways and critical variables means that each lake will have specific monitoring and management requirements.

Furthermore the differences in environmental conditions for each lake can lead to differences in the thresholds for critical variables. If maintenance of current water quality is the objective then each lake will have a different threshold value for measures such as trophic level index, e.g. Lake Kohangatera 4.0 compared to Lake Wairarapa 5.4.

The differences between lakes in relation to the adaptive cycles further highlight the need for different approaches required for sustainable lake management. Table 17 sets out the adaptive cycles identified from the literature reviewed as the most relevant for sustainable lake management. Some of the adaptive cycles are very similar, e.g. aquatic weed invasion for Lake Kohangatera and Lake Pounui. Other adaptive cycles can be different for the same critical variable, e.g. dissolved oxygen depletion at depth is associated with thermal stratification for Lake Waitawa whereas for Lake Pounui is associated with algae decomposition on the lake bed. Some adaptive cycles are nested with significant linkages between catchment processes and lake processes. From a management perspective it is important to note that no two lakes have the same combination of adaptive cycles. This means each lake has a unique combination of management interventions for its sustainable management.

Table 16 Comparison of main values for the five lakes

VALUES	Kohangatera	Waitawa	Pounui	Onoke	Wairarapa
Taonga	**B**			**B**	**B**
Maori Sites	**C4**	**C1**		**C5**	
Lake Ecosystems	**A2**				**A2**
Wetland Ecosystems	**A3**		**A3**		**A3**
Indigenous Fish	**F1 /App3**		**F1/App3**		**F1/App3**
Inanga				**F1b**	
Aquatic plants	**F1c**		**F1c**		
Indigenous Birds	**F2b**			**F2c**	**F2b/WCO**
Biodiversity				**F4**	
Natural Character	**App2B**				**App2B**
Water quality	**P5.2.6**	**P5.2.6**	**P5.2.6**	**P5.2.8**	**P5.2.6**
Primary Recreation		**H**		**H**	**H**
Secondary Recreation		**App5**		**App5**	**App5**
Coarse fish		**NZFish**			**NZFish**
Flood management				**U1**	**WCO**
Water supply					**P7**

Notes: “letter or letter/number” code refers to schedule in proposed Natural Resources Plan; “App number” refers to appendix in Regional Freshwater Plan; “P with number codes” refers to Policy in proposed Natural Resources Plan; “WCO” refers to Water Conservation Order.

Table 17 Dominant adaptive cycles for the five lakes

LAKE	DOMINANT ADAPTIVE CYCLES FOR SUSTAINABLE MANAGEMENT
Lake Kohangatera	Aquatic weed invasion Eel fishery recovery
Lake Waitawa	Catchment runoff Wastewater discharge Thermal stratification
Lake Pounui	Aquatic weed invasion Dissolved oxygen depletion
Lake Onoke	Lake openings Catchment contaminants
Lake Wairarapa	Water quality Indigenous fish species Wader habitat

4.2 Lake Management from Socio-Economic Perspective

Following section 2.5 and figure 4 above, the elements considered in this part of the discussion are: the resources invested and knowledge accumulated for each lake; the management approaches to address sustainability issues; the institutional arrangements that have been put in place to implement the management approaches; and, the management interventions undertaken.

The proposed Natural Resources Plan provides a comprehensive listing of the values associated with each of the lakes (and other water bodies in the Wellington Region). This provides a sound basis for identification of critical variables. However the measurement of the critical variables has been limited. Lake Wairarapa has had regular monitoring of lake water quality while the other lakes mainly have only had one-off surveys. Even Lake Wairarapa where nutrient levels are linked to catchment loads there has been only preliminary information on nitrogen and phosphorus loadings from tributaries to the lake.

There is a wide variation with respect to information on thresholds of critical variables. Some thresholds can be defined by national guidelines, e.g. the recreational water quality guidelines for bacteriological quality and cyanobacteria levels. Others have been defined by RMA processes, e.g. the water that can be extracted from Lake Wairarapa. Some have evidenced-based thresholds, such as the lake water levels for waders on the margins of Lake Wairarapa. Others are qualitative in nature, e.g. “low frequency of algal blooms” and “indigenous fish resilient” for Lake Waitawa. Some are defined in comparative terms, either by the maintenance of the current water quality, such as TLI for lakes, or by comparisons with similar types of lake systems in New Zealand, e.g. the TLI for Lake Waitawa of 5.8 compared to the national average for coastal lakes of 4.8. Others are yet to be determined,

such as catchment loads for nitrogen and phosphorus, or, the flushing rates for Lake Onoke to manage contaminant levels in the lake.

In terms of management approaches, the proposed Natural Resources Plan provides generic policies to address sustainability issues. Some the methods relate to specific lakes. However with the exception of the Wairarapa Moana wetlands project there do not appear to be funded implementation programmes for lake management.

The element of the Wairarapa Moana wetlands project (refer Section 3.6.4) are a good match for many of the management interventions from the sustainability analysis (refer Section 3.6.3) and the monitoring needs of control variables (refer Section 3.6.2). However the project elements do not address all potential interventions (e.g. barriers to fish passage) nor do they provide a quantified assessment of whether the level of intervention is sufficient to achieve the desired sustainability outcomes.[4]

With respect to institutional arrangements, appropriate steps are in progress. The approach of establishing Whaitua Committees across the region (which has already occurred in the Ruamahanga catchment and proposed elsewhere in the region) provides an appropriate basis for sustainable lake management. This is being complemented with co-governance and co-management mechanisms such as Te Roopu Tiaki and the Parangaruhu Lakes Area Co-Management Plan.

[4] The inadequacy of the level of intervention needed to achieve sustainability has been a problem for the management of other New Zealand lakes (Jenkins, in press).

5. Conclusions

The application of the sustainability framework provides some useful insights into the sustainable management of the five lakes in the Wellington Region. In terms of progressing sustainable management of the lakes, the following conclusions can be drawn:

- The values for lake management have been clearly defined enabling the definition of critical variables for failure pathways.
- There has been limited measurement of critical variables often restricted to one-off surveys; making it difficult to establish trends.
- Where trends can be assessed they are in the direction of declining water quality and ecological values.
- There are similarities and differences between lakes with respect to values and adaptive cycles such that each lake has a unique combination of management interventions for sustainable management.
- Knowledge of the lakes' water quality and ecosystems could be improved by increased monitoring guided by the dominant adaptive cycle for each lake.
- Further research is required on some of the thresholds for critical variables in relation to sustainable lake management.
- There is a need for funded implementation programmes for management interventions to address lake sustainability concerns.
- While appropriate steps are in progress in establishing institutional arrangements consistent with developing implementation programmes for sustainable catchment management, there is still considerable work to be undertaken to formulate funded implementation programmes.
- There is a need to be able to quantify the level of intervention needed to achieve sustainable outcomes.

References

(1) TECHNICAL REFERENCES

Abell J, Ozkundadakci D, Hamilton D, Miller S. 2011. Relationship between land use and nitrogen and phosphorus in New Zealand lakes. Marine & Freshwater Research. 62(2):162-175.

Carpenter S, Caraco D, Correll D, Howarth R, Sharpley A, Smith V. 1998. Nonpoint Pollution of Surface Waters with Phosphorus and Nitrogen. Ecological Applications. 8(3):559-568.

Chapin F, Kofinas G, Folke C. 2009. Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World. New York: Springer.

Gunderson LH, Holling CS. 2002. Panarchy: Understanding Transformations in Human and Natural Systems. Washington: Island Press.

Holling C, Gunderson L, Peterson P. 2002. Sustainability and Panarchies. In*:* Gunderson L, Holling C, editors. Panarchy: Understanding Transformations in Human and Natural Systems. Washington: Island Press.

Jenkins B. 2016. Sustainability analysis of the approach to the management of six New Zealand lakes. Lake and Reservoir Management 32 (2):101-115.

National Research Council. 1992. Restoration of aquatic ecosystems: science, technology and public policy. Washington: National Academy Press.

Walker B, Salt D. 2006. Resilience Thinking: Sustainaing Ecosystems and People in a Changing World. Washington: Island Press.

(2) REGIONAL REFERENCES (relevant to all lakes)

Greater Wellington Regional Council (2015) Proposed Natural Resources Regional Plan for the Wellington Region.

Greater Wellington Regional Council (1999, updated 2014) Regional Freshwater Plan for the Wellington Region.

Heath MW, Perrie A and Morar SR (2014) Rivers State of Environment monitoring programme; Annual data report 2013/14.

Perrie A, Conwell C, Milne JR and Cockeram B (2012) Annual freshwater quality monitoring report for the Wellington region, 2010/11.

Perrie A and Milne JR (2012) Lake water quality and ecology in the Wellington Region.

(3) REFERENCES FOR LAKES WAIRARAPA, ONOKE & POUNUI

Airey S, Puentener R and Rebergen A (2000) Lake Wairarapa wetlands action plan 2000-2010.

Bunny T, Perrie A, Milne J and Keenan L (2014) Lake water quality in the Rumahanga Whaitua.

McEwan A (2010) Wairarapa Moana Fish Survey 2010.

(4) LAKE ONOKE

Aquanet (2011) Nutrient status of rivers and streams in the Wellington Region: An analysis of the State of Environment monitoring data.
Milne JR (2010) Annual coastal monitoring report for the Wellington Region 2009/10.
Oliver MD (2012) Annual coastal monitoring report for the Wellington Region 2010/11.
Robertson B and Stevens L (2007) Lake Onoke Vulnerability Assessment & Monitoring Recommendations.

(5) LAKE WAIRARAPA

Gillon AK (2014) Ecological Restoration of Wairio Wetland, Lake Wairarapa: The Response of Native Wetland Vegetation to Eutrophication and Revegetation Strategies.
MWH (2004) Lower Wairarapa Valley Development Scheme Review: Environmental Effects – An Overview.
Ogle C, Moss T and Drace T (1990) Vascular Flora of Lake Wairarapa and its adjacent wetlands.
Thompson M and Mzila D (2015) Lake Wairarapa water balance investigation Stage 1 report – interim findings and recommendations.
Tidswell S and Sorensen P (2010) Water quality of Lake Wairarapa's tributaries and adjacent shallow groundwater: results of one-off sampling in December 2009.
Trodahl MI (2010) Lake Holocene Sediment Deposition in Lake Wairarapa.

(6) LAKE POUNUI

de Winton M, Champion P and Wells R (2011) Lake SPI assessment of the Parangarahu Lakes and Lake Pounui.
Jellyman DJ (1990) Meteorology and Limnology of Lake Pounui, Wairarapa.
Joy M (2002) Lake Pounui Fish Survey.

(7) LAKE WAITAWA

Anonymous (undated) Lake Waitawa Discussion Document plus Diagrams.
Cahill M et al (undated) Management Plan Proposals For Lake Waitawa, Otaki.
Dugdale T and Champion P (2002) Control of hornwort in Lake Waitawa using herbicide diquat.
Gaboroit-Haverkort T (undated) Proposed remediation program: Wastewater treatment, Forest Lakes Camp, Lake Waitawa.
Lowe Environmental Impact (2014) Review of Waste Water Treatment Plant and Discharge Performance, prepared for Forest Lakes Camping and Conference Centre.

(8) LAKE KOHANGATERA

de Winton M (2013) LakeSPI survey of Lake Kohangatera – 2013.
de Winton M (2013) Aquatic weed status and management options for Lake Kohangatera: 2013.
de Winton M, Champion P and Wells R (2011) Lake SPI assessment of the Parangarahu Lakes and Lake Pounui.
Gibbs G (2002) Pencarrow Lakes: Conservation values and management.
Greater Wellington Regional Council (2015) Parangarahu Lakes Area Co-Management Plan.
Wells R and Champion P (2004) Lakes Kohangapiripiri and Kohangatera (Pencarrow Lakes): survey of submerged aquatic flora.
Wells R, Taumoepeau A and de Winton M (2011) Delimitation of weed incursions in Lake Kohangatera.

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