Informing management of aquatic plants in the Rotorua Te Arawa Lakes

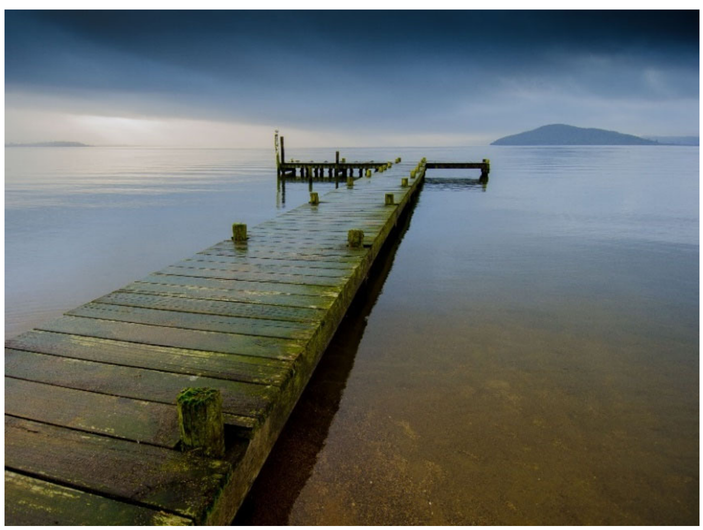

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Photo front cover: Lake Rotorua Jetty and Mokoia Island (Rob Murdock, NIWA)

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Executive summary

This technical document was prepared to inform Bay of Plenty Regional Council (BOPRC) on management aspects for aquatic weeds and native plants (macrophytes) relating to the Rotorua Te Arawa lakes. The scope of this document was informed by the project brief entitled 'Aquatic Weeds on Rotorua Lakes: A position paper', prepared by BOPRC in October 2016.

Co-management by Te Arawa as owner of the lakebed and subsoil is acknowledged and constitutes an overarching influence in management of these lakes. An outline of agency responsibilities for aquatic plant management and legislative drivers (acts, strategies and policies) shows the potential for management to become fragmented. However, operation of an Aquatic Pest Coordination Group by BOPRC assists with agency co-ordination.

Management of aquatic weeds, guided by the (proposed) Regional Pest Management Plan (RPMP), currently includes surveillance by BOPRC for new incursions in lakes that are relatively weed free, control works under the LINZ Biosecurity Control Programme and inspections of control outcomes by BOPRC. Control works are undertaken for biosecurity and amenity purposes, but as yet there is little management for biodiversity outcomes. Development of Aquatic Plant Management Plans for the Rotorua Te Arawa Lakes is underway to guide future weed management.

A range of published papers and important grey literature documented by a literature search showed the chronology of vegetation management in the Rotorua Te Arawa Lakes. Historical weed issues at the lakes from the late 1950's led to early herbicide research and autecology investigations for weed species, with detailed baseline descriptions of the lakes vegetation in the 1980's. This was followed by documentation of further weed and algal invasions in lakes during the 1990's to 2000's. While water quality became the prime focus of lake management from the 1990's, with interventions for eutrophication and outcome monitoring, the potential for increased weed issues with improved water quality is being realised.

Monitoring of lake condition using submerged plants as indicators (LakeSPI) has been adopted for the Rotorua Te Arawa Lakes since 2005 and current vegetation status is well documented. Native vegetation status (Native Condition Index) of lakes in 2017 ranged from 22% to 57% of potential. Invasive plant status (Invasive Impact Index) in 2017 ranged from 29% to 93% of potential and more invaded lakes have a lower native status.

Differences are identified between the ecological role that native aquatic plants provide, compared to the impacts of the invasive aquatic weeds that replace them. For native plants different roles relate to their main functional group; as emergents, turf, isoetes, milfoils and pondweeds or charophytes. Native emergent reeds and rushes provide interception for nutrients from the catchment, particularly nitrogen from groundwater. Turf species represent a high endemic diversity and have a 'geotextile' role on moderately exposed shores. Isoetes is an indicator for good water quality, has unusual carbon harvesting capabilities and has strong influences on sediment processes. Tall vascular plants that most commonly include milfoils and pondweeds provide a structurally diverse, large surface area for biota, and their seed is recognised as a rich food source for waterfowl. Charophytes (macroalgae resembling higher plants) can grow deeper than vascular plants, are suspected to 'groom' and improve local water quality and have a key role in persistent seed banks. Aquatic plants with a New Zealand threat status provide another value for the Rotorua Te Arawa lakes, with some species linked to the unique geothermal character of some lakes.

Four submerged weed species are problems in the Rotorua Te Arawa Lakes due to their ability to develop tall, dense monospecific beds. *Ceratophyllum demersum*, *Egeria densa* and *Lagarosiphon major* have high rankings according to an Aquatic Weed Risk Assessment Model. *Elodea canadensis* can dominate but is frequently displaced by the more aggressive weeds. Although they produce no seed in New Zealand, these weeds dominate by merit of easy vegetative regeneration, competitive ability, flexible light, nutrient and carbon harvesting, and their perennial nature. Contrary to popular belief, controlling eutrophication is not a successful strategy to reduce weed biomass.

Suggested ecological impacts by invasive weed beds include replacement of the structural and functional diversity of native vegetation. Dense weed beds create strong diurnal cycles in pH and dissolved oxygen and may also enhance sedimentation of organic matter. Seed banks are buried and weed beds present a barrier to the movement and littoral occupation by fauna. Cultural, amenity and utility impacts from weeds are also well documented.

The history of weed invasion of the Rotorua Te Arawa Lakes is strongly linked to human activities, the four worst weeds being reliant on the transfer of vegetative propagules between catchments on contaminated equipment, or possibly purposeful transfer. A succession pattern for weeds in the lakes is generally from less to more aggressive weeds over time. Future risks from additional weeds is possible from other naturalised or new-to-New Zealand species. Climate change and improving water quality of lakes is also likely to increase the future risk-scape for weed invasion or expansion.

Aquatic weed management starts with proactive measures that includes advocacy to change the human behaviour resulting in pest transfers between/within waterbodies. Related actions include controls on recreation/rāhui, wash-down facilities, sound decontamination advice, inspections and punitive action for exacerbators. To focus initiatives and site priorities for proactive management, a risk-based approach should consider pest pathways and vectors, habitat availability for weeds and their likely impact. High priority boat launch sites in the Rotorua Te Arawa Lakes have been installed with weed cordons (enclosures) as a capture area, or as a weed-free area for haul out. Regular surveillance of priority sites as directed by the RPMP is essential for early responses to new weed incursions. BOPRC operate inhouse surveillance that has been reviewed as best practice. It is essential that incursion response is pre-planned so rapid action can be taken in the event of a new detection.

There is no one best control method, with selection of the appropriate option strongly driven by the objectives for control and site characteristics, especially weed biomass. Options change along a gradient of weed biomass from hand weeding, bottom lining, suction dredging to herbicide (diquat and endothall), with grass carp and mechanical control being options when a system is already habitat or propagule saturated. Impacts from control works should also be considered, but context needs to include the environment impacts of doing nothing to manage damaging invasive weeds.

Future aquatic plant management is set to benefit from advances in tools and technologies to detect, measure, control and monitor aquatic weeds. A future management focus on native aquatic plants would be beneficial, where additional investment in weed control is likely to achieve significant biodiversity gains for the Rotorua Te Arawa Lakes.

Early findings from this report were reviewed for knowledge gaps in a workshop involving BOPRC staff, representatives from the Lakes Water Quality Society and NIWA. The perceived list of key knowledge gaps constraining the management of aquatic vegetation in the Rotorua Te Arawa Lakes is presented.

1 Introduction

Bay of Plenty Regional Council (BOPRC) seek a technical document to help develop and support Council's position on aquatic weed and native plant (macrophyte) management. The scope of this document was informed by the project brief entitled 'Aquatic Weeds on Rotorua Lakes: A position paper', prepared by BOPRC in October 2016. More specifically, this report seeks to answer (within supporting context) a number of questions posed by the Water Quality Technical Advisory Group in Appendix 1 of that brief. The agreed content for this report is represented in Figure 1.

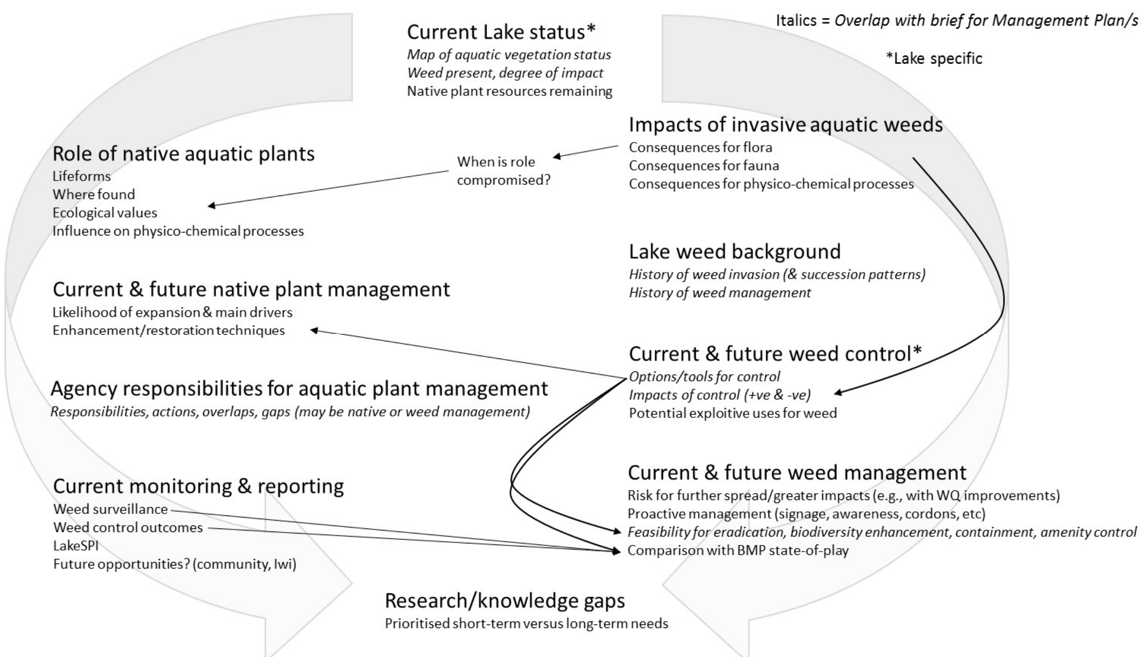

Figure 1: Schematic of the proposed structure and content of the report.

This technical report summarises the current state of knowledge on aquatic vegetation in the Rotorua Te Arawa Lakes that is relevant to vegetation management and associated ecological restoration. It was envisaged that this resource would provide a knowledge basis for resource managers to undertake appropriate management actions, identify key knowledge gaps that create uncertainty for lake managers and inform future discussions with the community. This report may also provide content to develop into resources for Iwi, the public, or community groups such as the Lakes Water Quality Society (LWQS).

2 Agency responsibilities for aquatic plant management

A recognised issue with the management of aquatic plants is the fragmented responsibilities between agencies depending on the nature of the issue (i.e., weed vs native plant, biosecurity vs amenity, weed status) and the location of impacts (i.e., lake bed ownership, reserve type). Agency responsibilities with regard to aquatic plant management in the Rotorua Te Arawa Lakes are briefly outlined in this section, and the role of a co-ordination group outlined. Acts, policies and strategies that currently direct aquatic plant management are also briefly introduced (Section 3). **Figure 2** summarizes current responsibilities and documents that drive weed control activities.

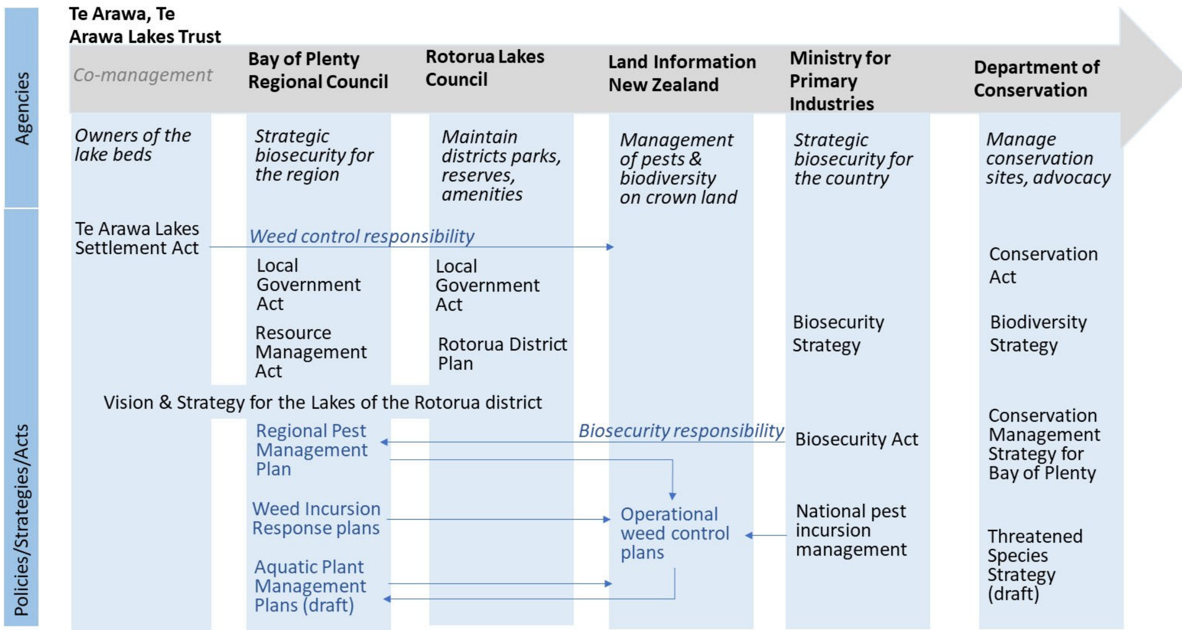

Figure 2: Diagram representing the responsibilities for aquatic plant management in the Rotorua Te Arawa Lakes. Blue arrows and text represent direct responsibilities and activities for aquatic weed control.

2.1 Te Arawa

Te Arawa is the owner of the lakebed and subsoil of ten of the Rotorua Te Arawa Lakes under the Te Arawa Lakes Settlement Act (2006), which gives effect to the Deed of Settlement. The Act states that Te Arawa is not liable for the weeds present in the lakes or responsible for their control or removal (Te Arawa Lakes Settlement Act 2006). Instead the Crown (via Land Information New Zealand) is responsible for weed management and the water and air stratum above the lake beds. Te Arawa tribal entities are private owners of two additional Rotorua Te Arawa Lakes (Lake Rotokakahi and Lake Ōkaro) and it appears weed management responsibilities have not been clarified in these cases. Although Te Arawa is not responsible for pest plants within the lakes, it is essential that consultation is undertaken over proposed aquatic plant management.

2.2 Bay of Plenty Regional Council

Amongst BOPRC's responsibilities is the management of natural ecosystems such as lakes and rivers in the region. More specifically, the Biosecurity Act 1993 requires regional councils to 'provide regional leadership in pest management'. Pest management encompasses activities that '…prevent, reduce, or eliminate adverse effects from harmful organisms that are present in New Zealand' (section 12(b) Biosecurity Act 1993). A Regional Pest Management Plan (RPMP) is the key policy document to direct the management of pests and demonstrate regional leadership on pest management (see Section 3). BOPRC has obligations to maintain biodiversity under Part 6 of the Resource Management Act, but although a biodiversity program is delivered through Councils catchment management team, there is no direct work done on freshwater plant biodiversity in the lakes (but see LakeSPI, Section 4.2.1). Traditionally Department of Conservation has the focus on biodiversity and BOPRC on maintaining habitats.

2.3 Land Information New Zealand

Land Information New Zealand (LINZ) is responsible for the management of aquatic weeds within the Rotorua Te Arawa lake beds (except in Lake Rotokakahi and Lake Ōkaro) and is the lead central government agency in the management of these weeds. Although the Crown is not the owner of the lake bed, this responsibility is recognised under the Te Arawa Lakes Settlement Act (2006). National and regional pest management plans (required under the Biosecurity Act 1993) are the primary drivers of LINZ's biosecurity obligations.

2.4 Rotorua Lakes Council

Rotorua Lakes Council (RLC) has the responsibility to clear stranded aquatic weeds upon or around park and lake reserves, including associated structures. As part of their management, RLC is also a member of the Rotorua Te Arawa Lakes Programme, which is responsible for improving and protecting the water quality in the Rotorua Te Arawa Lakes.

2.5 Department of Conservation

The Department of Conservation (DOC)'s primary role is to implement the Conservation Act 1987. DOC advocates for the protection of indigenous freshwater species and their habitats. It supports other agencies by advocating under the Biosecurity Act 1993 and supporting containment and management of threats and pests. DOC carries out the service delivery of aquatic weed control at sites of high importance under Acts it administers (e.g., National Parks Act 1980, Conservation Act 1987). Approvals for the translocations of freshwater species (e.g., for aquatic plant restoration) are administered by DOC. DOC are also charged with actioning the Threatened Species Strategy (2018 draft), which may be relevant to aquatic plants of threat status that are present or have been lost from the Rotorua Te Arawa Lakes.

2.6 Ministry for Primary Industries

The Ministry for Primary Industries (MPI) is the lead agency for biosecurity in New Zealand, via its business unit Biosecurity New Zealand. MPI administers the Biosecurity Act 1993 and advises the Minister for Primary Industries on biosecurity issues. MPI maintain a system for rapidly responding to detections of new-to-New Zealand harmful pests and diseases and for National Interest Pests.

2.7 Aquatic Pest Coordination Group (APCG)

APCG provides for communication and co-ordination between agencies with pest management or associated aquatic resource management responsibilities. The group comprises representatives from Te Arawa Lakes Trust, DOC, BOPRC, RLC, LINZ and their Biosecurity Partner Boffa Miskell, and Eastern Fish and Game. Technical input is provided from other agencies including universities and NIWA. APCG provides a useful forum for oversight of aquatic weed management activities and discussion of approaches.

3 Policies and strategies pertaining to aquatic plant management

3.1 Regional Pest Management Plan

The most important strategy pertaining to aquatic plant management in the Rotorua Te Arawa Lakes is the RPMP, which is currently under revision. The proposed RPMP (BOPRC 2018) lists ten aquatic weeds as 'organisms declared as pests' (Table 1). Also identified is the management programme for each pest and the geographic area to which the programme applies. Programmes follow the intent and terminology of the National Policy Direction for Pest Management (2015).

The RPMP states the control and management of lake weed in the Rotorua Te Arawa lakes is primarily the responsibility of Land Information New Zealand (LINZ), on behalf of the Crown as a result of the Te Arawa Lakes Deed of Settlement' (except in Lake Rotokakahi and Lake Ōkaro). Under the proposed RPMP, Generic rule 6 for programmes listed for the aquatic weed pests in Table 1 includes measures preventing interference with monitoring or control activities, movement of pests or contaminated equipment, or propagating/culturing pests. Generic rule7 specifically states 'vessels or craft (including trailers) are free from freshwater pest fish and lake weed including fragments'.

Exclusion programmes manage new incursions into the region, or organisms with an exclusion status with a specified area. Bay of Plenty Regional Council may be the lead or partner agency for exclusion programmes. Principal measures include (at least annual) surveillance in places at risk, advocacy, support of other agencies with an interest or management role, and support of relevant science.

Bay of Plenty Regional Council will lead Eradication programmes. Principal measures include control leading to reduced densities and distribution, consideration of best practice for management, searches of vulnerable places (frequency unquantified), identification of vectors for detected incursions and their control, and monitoring of known incursions (annually until zero density). As for exclusion programmes, other measures are advocacy, support of other agencies with an interest or management role, and support of relevant science.

Under Progressive Containment programmes, Council will maintain control and management of *Alternanthera philoxeroides* and *Iris pseudacorus*. Council may provide service delivery for some other progressive containment pests and state they will work with crown agencies for the progressive containment of these pests on crown owned/managed land. Inspection, advocacy and monitoring are other measures undertaken in relation to Progressive Containment pests.

Council may undertake management of Sustained Control pests as part of its biosecurity programme, with the focus on preventing the spread of these pests across boundaries. Management may be based on the level of complaint, with other principal measures being advocacy and support of relevant science.

Table 1: List of aquatic weeds addressed in the Regional Pest Management Plan for the Bay of Plenty Region. Programme refers to the intended intermediate outcome under the National Policy Direction (2015).

Species	Programme (geographic extent)
Alternanthera philoxeroides	Exclusion (central region including Rotorua Te Arawa Lakes). Eradication (northern region). Progressive Containment (eastern region).
Egeria densa	Exclusion (Lakes Rotomā, Rotoehu, Ōkataina, Tikitapu, Rotokakahi, Ōkaro). Progressive Containment (Lakes Rotorua, Rotoiti, Ōkāreka, Tarawera, Rotomāhana, Rerewhakaaitu).
Elodea canadensis	Exclusion (Lake Rotomāhana). Sustained Control (Lakes Rotomā, Rotoehu, Ōkataina, Tikitapu, Rotokakahi, Ōkaro, Rotorua, Rotoiti, Ōkāreka, Tarawera, Rerewhakaaitu).
Ceratophyllum demersum	Exclusion (Lakes Rotomā, Tikitapu, Rotokakahi, Ōkaro, Rerewhakaaitu). Eradication (Lakes Ōkataina, Ōkāreka). Progressive Containment (Lakes Rotorua, Rotoiti, Rotoehu, Tarawera, Rotomāhana).
Lagarosiphon major	Exclusion (Lakes Rotokakahi, Ōkaro, Rotomāhana). Progressive Containment (Lakes Rotorua, Rotoiti, Rotoehu, Rotomā, Ōkataina, Ōkāreka, Tikitapu, Tarawera, Rerewhakaaitu).
Lythrum salicaria	Eradication.
Sagittaria platyphylla / Sagittaria montevidensis	Eradication.
Gymnocoronis spilanthoides	Eradication.
Hydrocleys nymphoides	Exclusion.
Iris pseudacorus	Progressive Containment.

An Operational Plan is required by the Biosecurity Act and sets out how the RPMP will be implemented. The Biosecurity Act requires Council to report annual progress on the Regional Pest Management Plan (RPMP) Operational Plan.

3.2 Aquatic Plant Management Plans

Recently, aquatic pest plants were the subject of numerous public and community group submissions for the development of the regional Long-Term Plan. In response BOPRC together with LINZ have commissioned aquatic plant management plans to provide clarity and guide control efforts. Draft plans (prepared by Boffa Miskell Limited) have been produced for the lakes which outline goals, objectives and expected outcomes; and propose management areas and control methods.

3.3 Other documents

Several other documents for the region contribute to the planning environment for management of aquatic vegetation in the Rotorua Te Arawa Lakes.

The Te Arawa Cultural Values Framework (undated) recognizes that pest plants are impacting on the health and wellbeing of the lakes. The Bay of Plenty Regional Policy Statement (BOPRC 2014) seeks to preserve the natural character of lakes and their margins and protect areas of significant indigenous vegetation. The Bay of Plenty Regional Water and Land Plan (BOPRC 2008) states that aquatic pest plants are not to be introduced into the beds of streams, rivers and lakes. Also activities on the beds of the lakes are to allow aquatic ecosystems, habitats of indigenous species, spawning areas and significant aquatic vegetation to be maintained and enhanced. The Bay of Plenty Regional Long-Term Plan (BOPRC 2015) focus is on nutrient management, but mentions an intent to 'harvest lake weed in priority amenity areas'. The Rotorua District Plan (RLC 2016) manages the recreational use of the Rotorua lakes and rivers to avoid, remedy or mitigate adverse effects on visual, cultural, social and environmental values of water bodies. Also, it seeks to preserve the natural character of lakes and their margins and protect them from inappropriate subdivision, use, and development. The Rotorua Lakes Recreation Strategy (Environment BOP 2005) acknowledges the impact of weed on recreational activities, the role of recreators in spread of new weeds, and potential for weed management activities to influence recreational use.

The Conservation Management Strategy for the Bay of Plenty (DOC 1997) is currently undergoing a consultative phase (2018). The existing plan acknowledges 'the impacts of introduced plants and animals dominate most lakes means that those lakes without these pests are very important' and 'lakes with mainly indigenous species are vulnerable to the introduction of plant and animal pests'. There was a stated intention to 'work with landowners, local authorities and recreational groups to prevent the introduction of plant and animal pests to lakes' and 'Control aquatic macrophytes'. Three roles of DOC were stated as 'manage plants that are damaging or could damage significant natural and historic resources on lands administered by the Department', 'discharge obligations as specified in national and regional weed pest management strategies under the Biosecurity Act 1993' (responsibilities that are now superseded by the RPMP) and 'manage plant pests that are adversely affecting recreation use of sites and facilities on land the Department administers'.

Under the current Vision and Strategy for the Lakes of the Rotorua District, 'number of pest plants and animals in the catchment' and 'level of regeneration of indigenous plant species in the lakes' were proposed as possible indicators of progress towards goal 7: The health of ecosystems including habitat for kai roto has improved since 2013.

Individual action plans for nine of the lakes have focussed mainly on water quality, however some lake plans mention aquatic weed aspects. The Rotoehu Action Plan (BOPRC 2007) outlined weed harvesting for nutrient remediation and gave some consideration to the lake as a potential source of weed. The Lake Ōkataina Action Plan (2013) refers to implementation of a weed eradication plan for a new incursion, with annual progress updates and encouragement for boat checks before launching. The Lake Ōkāreka Hornwort Management Plan (Bathgate 2015) outlines an incursion response and ongoing management for new submerged weed.

4 Information review

NIWA carried out a literature search using key terms to discover all published papers and important grey literature relating to vegetation management in the Rotorua Te Arawa Lakes. Key search terms included: the Māori and other names for the 12 Rotorua Te Arawa Lakes; submerged vegetation (or vegetation); aquatic weeds (or weed/s); freshwater weeds; lake plants; lake weeds; macrophytes. We also extracted references from our library database for past NIWA client reports provided to the BOPRC on related matters.

References that have relevance to aquatic plant management in the Rotorua Te Arawa Lakes are listed in Appendix A.

Additional appropriate reference material was sought on aspects such as native plant roles and known weed impacts. Literature was reviewed to provide scientific validation for findings or conclusions in the technical report.

4.1 Information sources

4.1.1 1950 to 1980

In the 1960's, the focus of literature was initially on the unprecedented weed issues caused by the early invasion of lagarosiphon (*Lagarosiphon major*) from 1958 onwards (Chapman 1970). Papers and reports from this time were primarily produced by government ministries and departments (Marine, Scientific and Industrial Research, Internal Affairs, Lands and Survey, Agriculture and Fisheries and Electricity). These dealt with the perceived causes of the invasion (e.g., citing nutrient loading) to exploring herbicidal solutions leading to the adoption of diquat use. It was also the time of establishment of the 'Society for Lake and River Weed Eradication' (1961), the forebear of the Lakes Water Quality Society.

In the 1970's, emphasis had changed to gaining baseline knowledge on submerged vegetation and weed ecology in research mostly undertaken by the University of Auckland (Chapman, Brown and students Dromgoole, Coffey and Clayton). Included were the first descriptive accounts of submerged plant communities recognised in the lakes and investigations into the invasive processes of lagarosiphon in particular.

4.1.2 1980s to 1990

The early 1980s saw continuation of fundamental research on submerged plants and publication of earlier work initiated by the University of Auckland. Understanding of how weeds were spreading and the role of human activities was growing. Knowledge on aquatic weed management was consolidating with ongoing herbicide practices using diquat. Additionally, other herbicides were also tested (e.g., fluoridone). This decade saw comprehensive surveys of the aquatic vegetation of the Rotorua Te Arawa Lakes by the Ministry of Agriculture (later NIWA) which provided detailed descriptions (e.g., Coffey and Clayton 1988a, Clayton et al. 1990) and historic baselines for future LakeSPI monitoring (Burton 2017a).

4.1.3 1990s to 2000

By the 1990's, other plant invasions were the focus of literature on submerged vegetation of the Rotorua Te Arawa Lakes. This included establishment and dominance in Lake Rotorua, first by *Egeria densa* and then by the algae *Hydrodictyon reticulatum* (waternet), with *Ceratophyllum demersum* (hornwort) dominance in Lake Tarawera concluding a sequence of successive weed invasions. There were also monitoring and reported outcomes of weed management in the lakes using diquat. In this period there was an increasing emphasis placed on water quality of the lakes following widespread eutrophication.

4.1.4 2000 to present

More recently, the focus of lake management has been the application of a wide range of actions to mitigate eutrophication and on monitoring of outcomes. Improvements in water quality have been linked to more vigorous weed growth. Further advances were made in understanding how submerged plants interact with their environments, particularly light and water level fluctuations. Utilizing this understanding led to the development of a bioassessment method, LakeSPI, using submerged plants as indicators and ongoing monitoring of the Rotorua Te Arawa Lakes using this method.

4.2 Current vegetation monitoring

4.2.1 LakeSPI

LakeSPI is a bioassessment method that uses submerged vegetation metrics as indicators of lake ecological condition. Key concepts driving the LakeSPI method are that native plant species and high plant diversity represent healthier lakes or better lake ecological condition, while invasive plants are ranked for undesirability based on their displacement potential and degree of measured ecological impact (Clayton & Edwards 2006). LakeSPI measures have been found to relate to measures of lake trophic status and catchment attributes (de Winton et al. 2012).

LakeSPI monitoring involves a scuba survey of carefully selected baseline sites that are representative of the lake or area of interest (e.g., a bay). A number of measurements are recorded that are converted to weighted metric values and used to generate three indices: the Native Condition Index that captures the diversity and extent of indigenous plant communities; the Invasive Impact Index that reflects the degree of impact in a lake by invasive weed species; and the overall LakeSPI Index. The LakeSPI Index ranges from 0% (heavily impacted, non-vegetated lakes) to 100% (pristine, unimpacted lakes) and provides five categories of condition including excellent, high, moderate, poor and non-vegetated.

Analysis of changes across the baseline sites of indices values between different surveys is the basis of identifying trends, using both a statistical and ecological method to determine significance. Raw survey data is curated in a NIWA-administered LakeSPI database and lake results are loaded to freely available web-reporting pages (https://lakespi.niwa.co.nz/).

The initial condition of the Rotorua Te Arawa Lakes was surveyed using this method between 2003 and 2005 (Clayton et al. 2005). Since this time the lakes have been surveyed biennially to maintain a consistent record (Burton 2017a). In many cases earlier vegetation data existed (1980s) that was reassessed using the LakeSPI method to indicate the 'historical' condition of lakes. An annual LakeSPI report updates the latest results, compares Rotorua Te Arawa Lakes to lakes nationally and provides an account of how lakes have changed over time (Burton 2017a).

4.2.2 Weed surveillance

BOPRC have carried out monitoring and surveillance for aquatic weeds at eight Rotorua Te Arawa Lakes since 2005 (Kelly 2013), continuing to the present. The extent of monitoring and surveillance for submerged weeds in the Rotorua Te Arawa Lakes (and budget) is outlined in an annual

Operational Plan (e.g., BOPRC 2011b) which gives effect to the Regional Pest Management Plan (RPMP).

BOPRC proactively monitors high risk areas in selected lakes for new infestations as part of a weed surveillance programme and responds to all reports of new infestations. These areas are inspected twice per year (February/March and October/November). BOPRC divers 'complete approximately four weeks' worth of diving each monitoring period. Areas searched are selected and prioritised according to updated assessments of risk for weed entry and establishment. Reviews of BOPRC practices and search methodologies (Champion et al. 2006, Champion 2009, de Winton et al. 2014) has guided the best practice weed surveillance carried out by BOPRC.

4.2.3 Weed control works and outcomes

Proposed lake areas for weed control were identified with stakeholder consultation (APR Consultants Ltd 2011a-c) and a prioritisation methodology was developed to aid in the allocation of funding for aquatic pest plant control, particularly for amenity control (Dragten Consulting 2016).

Boffa Miskell Limited (BML) undertake annual planning and reporting of the weed control works carried out under the Land Information New Zealand (LINZ) Biosecurity Control Programme (BML 2017a and b). Planning information provided includes the proposed areas for control (mapped), the method of control and the expected dates of works (BML 2017a). Reporting information confirms the date and extent (ha) of works undertaken (BML 2017b).

Pre-inspections and outcomes from control works in the Rotorua Te Arawa Lakes are undertaken by BOPRC staff and reported to BML (Marcus Girvan, BML, pers. comm.).

5 Current lake vegetation status

The 12 Rotorua Te Arawa Lakes encompass a range of invasive weed species, levels of infestation and impact, with remaining native vegetation elements. The following section summarises the current (2017) status of lakes in terms of invasive weeds and native vegetation recognised in the lakes.

5.1 Invasive weed status

The Aquatic Weed Risk Assessment Model (Champion and Clayton 2000) captures the 'weediness' of species in terms of biological propensity for invasion and resistance to management. Model results for the submerged weeds that are known from the Rotorua Te Arawa Lakes are listed in Table 2 and their distribution is shown in Figure 3.

The highest ranked (weediest) submerged weed in the Rotorua Te Arawa Lakes is hornwort, followed by egeria and then lagarosiphon, which have scores ≥60 out of a theoretical 100 (Table 2). More benign weeds with scores <50 comprise elodea, curled pondweed, water buttercup and bulbous rush (Table 2).

Table 2: List of invasive weeds known from the Rotorua Te Arawa Lakes ranked by scores of the Aquatic Weed Risk Assessment Model (AWRAM) of Champion & Clayton 2000.

Species	Common name (code)	AWARM score
Ceratophyllum demersum	Hornwort (H)	67
Egeria densa	Egeria (Eg)	64
Lagarosiphon major	Lagarosiphon (L)	60
Elodea canadensis	Elodea (El)	46
Potamogeton crispus	curled pondweed (Cp)	44
Ranunculus trichophyllus	water buttercup (Wb)	42
Juncus bulbosus	bulbous rush (Br)	28

The current level of impact of weeds on the Rotorua Te Arawa Lakes are indicated by recent (2016-2017) surveys using the LakeSPI bioassessment method (Burton 2017a). The Invasive Impact Index derived by this method (see Section 4.2.1) provides a value representing the degree of invasive weed impact out of a theoretical 100%. In Figure 3, the darker the shading of lakes, the higher the Invasive Impact Index, while the Invasive Impact Index % value is also listed.

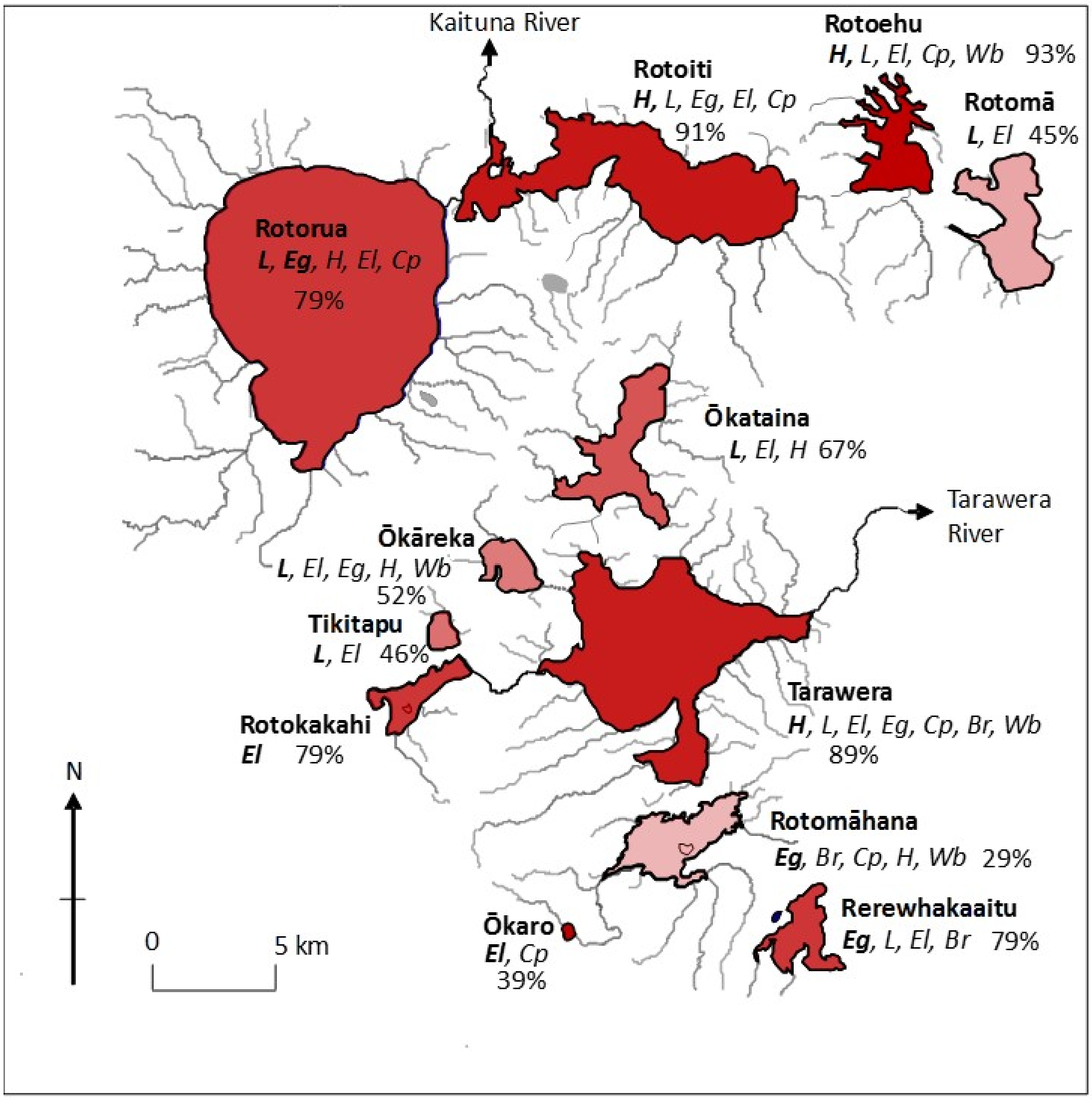

Figure 3: Map of lakes showing 'invaded status' of submerged vegetation. The latest Invasive Impact Index generated by LakeSPI surveys over 2016 to 2017 (Burton 2017a) is shown by the degree of orange shading and % value. Species records (code explained Table 1) drawn from Clayton et al. 1990 and NIWA's LakeSPI database.

5.2 Native vegetation status

The LakeSPI bioassessment method provides a Native Condition Index value that represents the diversity, occupation and depth extent of native submerged plants within lakes. Figure 4 shows the Native Condition Index of the Rotorua Te Arawa Lakes, with darker shading indicating higher values and the % value also shown. It is no coincidence that those lakes with a lower Invasive Impact Index (Figure 3) have greater development of native vegetation (Lakes Rotomā, Ōkaro, Rotomāhana) as invasion by weeds is one of the greatest impacts on indigenous lake vegetation, with other important influences including water quality (clarity) and pest fish impacts.

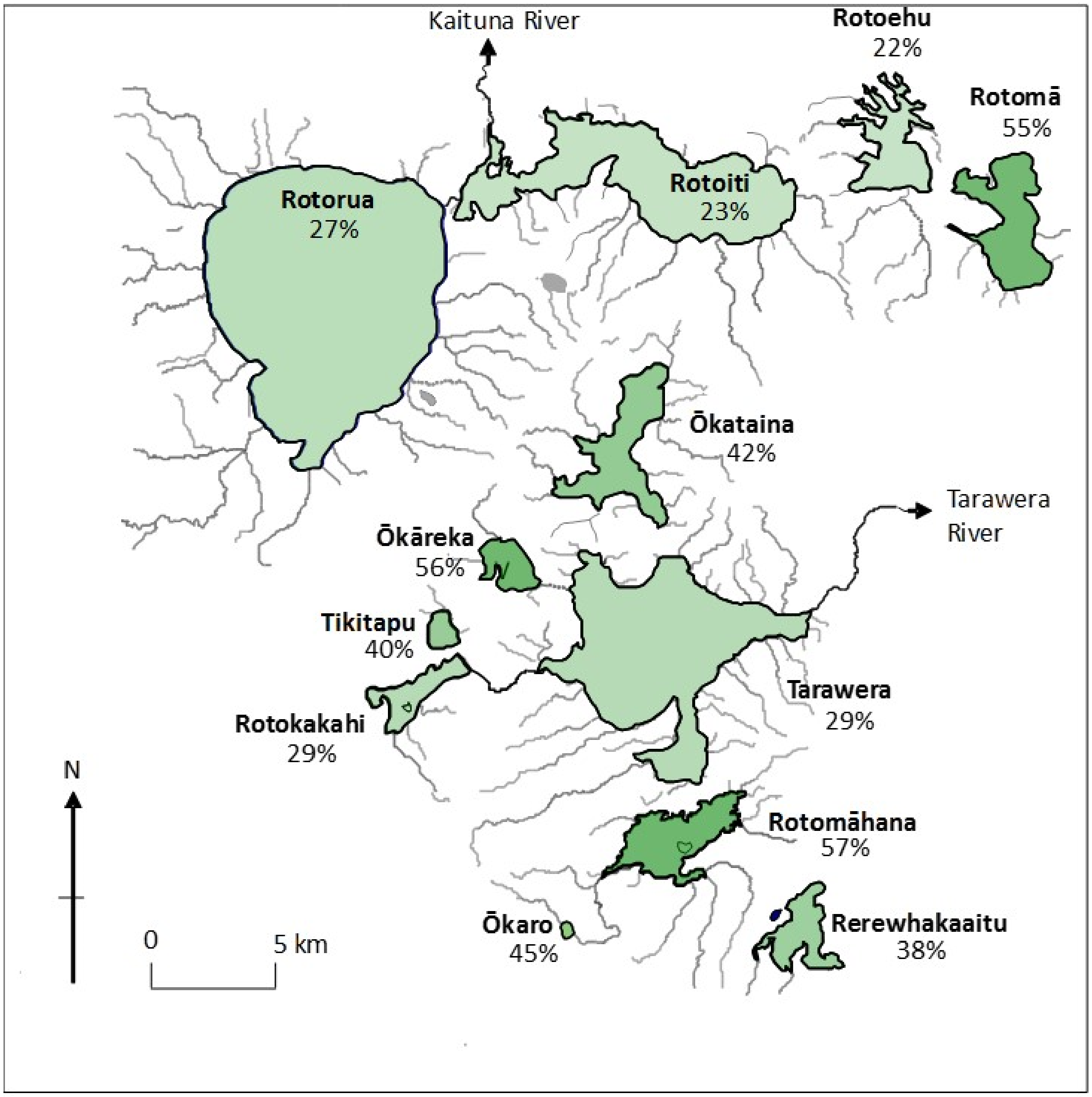

Figure 4: Map of lakes showing 'native status' of submerged vegetation. The latest Native Condition Index generated by LakeSPI surveys over 2016 to 2017 (Burton 2017a) is shown by the degree of green shading and % value.

6 Vegetation of the Rotorua Te Arawa Lakes, roles and impacts

Littoral vegetation is a prominent feature of all the Rotorua Te Arawa Lakes, regardless of lake size, shape, bathymetry and trophic status. This vegetation has an important role in lake ecology. In the following sections we describe vegetation components and explore unique roles of different vegetation types that are represented in the lakes, both native plants and invasive weeds. However, there are some commonalities which are recognised for all vegetation types of the lake littoral zone. All lake plants to some extent will:

- Increase habitat complexity, physical variability and surface area for algae and fauna, including spawning surfaces.
- Create refuges from predation for macroinvertebrates and small fish.
- Modify water flows, physio-chemical processes and increase sediment attenuation.
- Provide a substrate for epiphytic algae. Although macrophytes do not tend to contribute carbon flow directly to higher trophic levels (James et al. 2000), they are an important substrate for epiphytic algae which form the base of the food chain in New Zealand lakes.

One key question is what are the differences between the ecological role that native plants provide compared to the impacts of the invasive weeds that replace them.

6.1 Native aquatic plants

Native vegetation represented in the Rotorua Te Arawa Lakes include five depth-related ‘communities’, ‘life-forms’ or ‘functional groups’ - emergents, turfs, isoetes, tall vascular natives (e.g., milfoils and pondweeds) and charophytes (Figure 5). All of these would be expected to be present in these lakes where water quality, weed invasions and pest fish have not had a major impact.

Where invasive weeds dominate they greatly modify the mid-depth communities of milfoils, pondweeds and charophytes by exclusion. The depth limit for turf communities and isoetes can be constrained via competition and replacement by invasive weeds. Poor water quality restricts the development of deeper communities, such as the charophytes, and eutrophication is also likely to impact on the quality of habitat (substrate and light) for isoetes.

Indigenous biodiversity as represented by these plant communities are valued in their own right, representing a novel association of species found only in New Zealand freshwaters. Endemic species are found nowhere else in the world. Some aquatic plants found in the Rotorua Te Arawa Lakes have a national threat status (Section 14.2), which raises their importance for management. In the following sections we describe native plant communities found in the lakes and summarise the particular roles or values they hold.

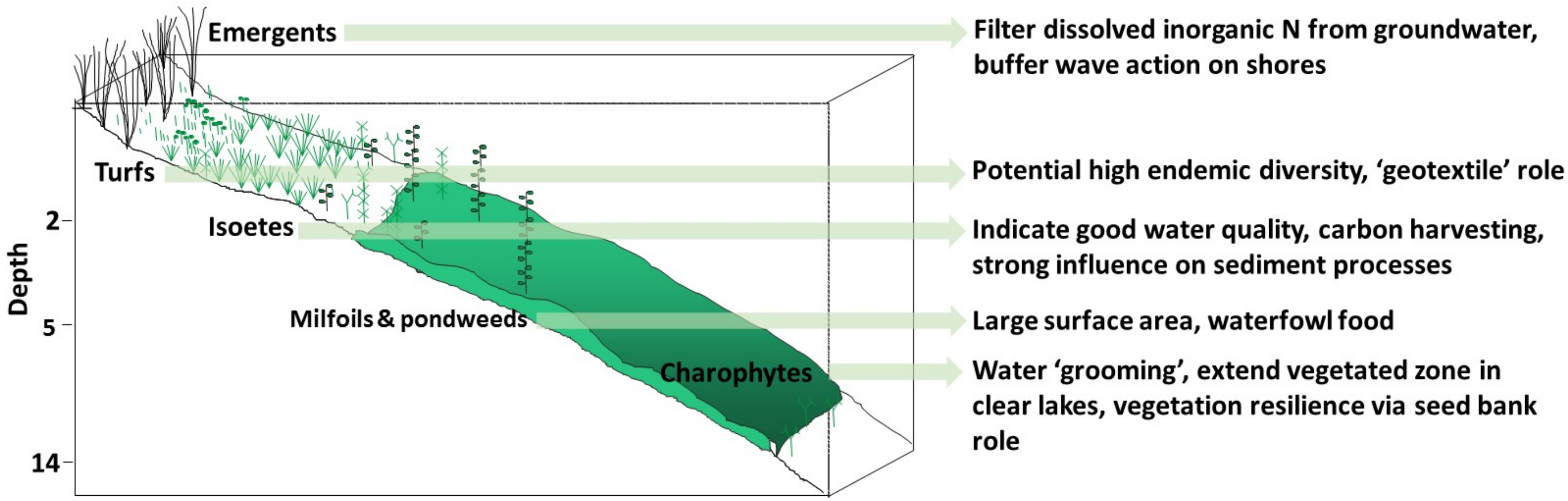

Figure 5: Diagram of the five native aquatic vegetation communities known from the Rotorua Te Arawa Lakes and their key ecological roles. Position of communities along the depth gradient is indicated by approximate maximum extent (m depth).

6.1.1 Emergents

Emergent development in the lakes

Emergent plants, or reeds and rushes, are found around the lake margins in areas with a low to moderate wave exposure and where slope is gradual and substrates are not too rocky. The most common emergents in the Rotorua Te Arawa Lakes are represented by *Typha orientalis* (raupo), *Eleocharis sphacelata* (kuta), *E. acuta*, *Machaerina articulata*, *M. rubiginosa* and *Schoenoplectus tabernaemontani* (kuawa).

Emergent vegetation is best developed in sheltered bays and inlets of northern Lake Ōkāreka, along the western shore of Lake Tikitapu, and the northern and western shores of Lake Rotokakahi (Clayton et al. 1990). Emergents are also widespread in the northern arms of Rotoehu, but cattle access and grazing has restricted this community in the past. Intermediate levels of emergent development have been described from sheltered bays of Lakes Tarawera and Rerewhakaitu (south east bay and crater only) (Clayton et al. 1990). By contrast there is little emergent vegetation development (≤5% shoreline) in Lakes Rotorua, Rotoiti (well developed in small bays), Rotomā, Ōkataina, Rotomāhana (emergents in the southern bay only) or Ōkaro (Clayton et al. 1990).

In general, the development or extent of emergent plants into deeper water is understood to be a consequence of which species are present and their intrinsic ability to provide below ground tissues with oxygen (convective gas flow). Emergent plants in New Zealand lakes were recorded down to a median maximum of 1.8 m, however, their depth potential was frequently constrained to shallower depths by high wave exposure, high sediment oxygen demand and/or low light attenuation (Sorrell and Hawes 2010).

Figure 6: Emergent community at Lake Ōkāreka comprising *Eleocharis sphacelata* (lakeward) and *Schoenoplectus tabernaemontani* (landward).

Ecological value of emergent vegetation

A two-year study looked at the role of nine natural lake edge wetlands containing emergent plants as nutrient buffer zones for groundwater entering Lakes Ōkāreka, Rotomā and Rotorua (Gibbs and Lusby 1996, Lusby et al. 1998, Gibbs and Matheson 2001). This study showed the potential of emergent vegetation to remove significant amounts of dissolved inorganic nitrogen (DIN), which would otherwise enrich the lake water (Gibbs and Matheson 2001). Shallow groundwater inflows may be many times more nutrient enriched than surface water inflows and is estimated to represent the largest source for DIN addition to the Rotorua Te Arawa Lakes (Gibbs and Matheson 2001). Emergents occupying permanently inundated sediment were shown to support moderate nitrification (Lusby et al. 1998). Reductions in DIN as groundwater moved through the emergent zone was attributed to plant assimilation or coupled nitrification-denitrification in surface sediment layers. Emergents contributed carbon-rich litter as a substrate for microbial transformations and were responsible for recycling DIN deeper in the substrate to the surface where it could be transformed.

Emergent plants that grow along the shores of lakes have been experimentally shown to be able to absorb significant amounts of wave energy and thereby reduce erosion (Coops et al. 1996) and re-mobilisation of sediment (Jordanova and James 2003).

6.1.2 Turfs

Turf development in the lakes

Turfs (or low mound communities) include a diverse range of small-stature, creeping native plants, generally <0.1 m tall (Figure 7). They are found in shallow water (c. <3 m) on fine substrates or between rocks, where dense emergents are not present and wave exposure is moderate.

Turfs are currently best developed in Lakes Tikitapu, Rotorua, Rotoiti (mostly southern shore), Rotokakakhi, Ōkāreka, Rerewhakaaitu, Tarawera (south-eastern shoreline), and have recently increased in Lake Ōkaro. Turfs are restricted in extent in Lakes Rotoehu, Rotomā, Rotomāhana and Ōkataina. The most common species are *Glossostigma elatinoides, G. diandrum* and *G. cleistanthum* (mudworts), *Lilaeopsis ruthiana*, *Elatine gratioloides* and *Limosella lineata*. Also locally abundant are *Eleocharis pusilla* (Lakes Rotoiti and Rotokakahi), *Myriophyllum pedunculatum* (Lake Tikitapu), whilst *Crassula sinclairii*, *Ranunculus limosella* and *Triglochin striatum* are occasionally recorded (NIWA unpublished survey data).

Turf species are amphibious and can withstand periods of exposure and submergence. Studies have established that monthly fluctuations in water level of up to 1 m are optimal for establishing and maintaining diverse amphibious turf zone communities in lakes (Riis and Hawes 2002). Greater fluctuations allow only the very tolerant species to survive. Smaller fluctuations in water level result in a narrower band occupied by fewer, more competitive turf species. Lake level stabilisation in Lake Rotoiti since the installation and operation of the Okere Gates in 1982 was predicted to have reduced the vertical extent of any turf zone, but not exclude this community from the exposed shores of the lake (Hawes 2003). Turf communities are lost where levels are high or low for prolonged periods (where inter-annual variation is higher than intra-annual variation) (Riis and Hawes 2002), such as noted at Lake Ōkataina in the past (Clayton et al. 1990).

In studies of Lake Wanaka (South Island), turf presence or absence was well explained by physical disturbance estimated from measures of wave exposure, shore slope and substrate mobility (Riis and Hawes 2003). Cover of this community and their upper and lower depth limit were also partially explained by physical disturbance (Riis and Hawes 2003).

Figure 7: Turfs in shallow water of Lake Ōkaro, dominated by mudwort (*Glossostigma diandrum*).

Ecological value of turfs

Turf vegetation can support areas of high plant diversity over small spatial areas, with the greatest endemism in submerged plants represented within this group. Turf species have a short stature and a strategy of horizontal expansion via runners or stolons. As such, they provide for sediment binding in shallow areas of the lake littoral zone under moderately high wave energy environments. The original descriptions for this community in New Zealand lakes refer to Lake Rotoiti (Chapman et al. 1971). These describe the cyclic nature of community dynamics as 'mounds' of turfs stabilise sediments, and are then eroded by wave energy in more exposed areas. This 'geotextile' function of turf plants would contribute to beach building and retention as well as securing fine sediments against resuspension to overlying waters.

6.1.3 Isoetes

Isoetes development in the lakes

Isoetes (*Isoetes kirkii*) is recognised as a separate community group as it can form dense, monospecific swards in slightly deeper water than the turfs in some lakes. Isoetes is an obligate submerged plant that has a greater stature than turfs (up to 0.20 m tall) and comprises individual rosette plants that may coalesce into a tightly packed bed. The lower depth limit of isoetes (when unconstrained by competitors) is suggested to be set by light availability at a higher level than that required by other submerged plant life-forms (Middelboe and Markager 1997). In exceptionally transparent New Zealand lakes isoetes species have been recorded to depths of up to 12 m (Hawes et al. 2003).

Isoetes is locally common in Lake Rotoiti and Ōkāreka, common at low covers in Lakes Rerewhakaaitu, Rotokakahi (Figure 8) and rare in Lake Rotorua (Mokoia Island only). It appears that Isoetes has decreased in distribution and abundance in the Rotorua Lakes since the 1980's, with the greatest reduction apparent for Lake Rotokakahi. Isoetes decline in the Rotorua Te Arawa Lakes contributed to a conservation status assessment as At Risk: Declining (de Lange et al. 2017).

Elsewhere, light reduction and sediment organic matter addition have been found to impact on isoetes growth and survival, with a combination of both having a synergistic effect (Gacia et al. 2009, Chappuis et al. 2015). Similar factors are likely to have impacted on isoetes in the Rotorua Te Arawa Lakes given the history of water quality deterioration.

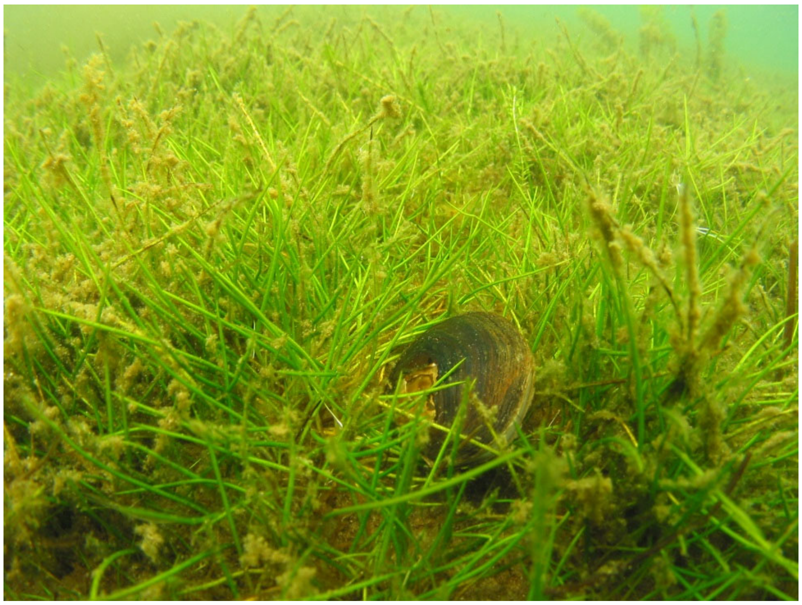

Figure 8: Isoetes bed and kākahi in Lake Rotokakahi, 2005.

Ecological value of Isoetes

Isoetes kirkii found in the Rotorua Te Arawa Lakes is endemic to New Zealand, although other species and similar lifeforms (isoetids) are found elsewhere. The status of *isoetes* species have elsewhere been used as ecological indicators of lake condition as they are sensitive to eutrophication (Lyche Solheim et al. 2008), and their presence contributes to improved scoring of LakeSPI metrics and indices (see Section 4.2.1).

Isoetes possesses a specialist photosynthetic strategy; crassulacean acid metabolism, as a means of enhancing carbon capture which provides an advantage in oligotrophic environments with typically low inorganic carbon availability (Rattray et al. 1992). This functional trait may contribute to aquatic plant primary production when other plants are limited.

Isoetes beds are also recognised for their oxygenation of rhizosphere and influence over sediment-microbial environments and transformations. Isoetes vegetation has been associated with mineralization of organic matter, enhanced nitrification rates and higher coupled nitrification-denitrification leading to overall high N losses compared to bare sediments or other plant species (Vila-Costa et al. 2016). Isoetes was also associated with phosphorus immobilization in the sediments suggested to contribute to oligotrophic conditions (Andersen and Olsen 1994) as well as reoxidation of sulphides (Holmer et al. 1998). Some of these sediment-mediated influences are likely to be reduced or lost under eutrophic sediment and water conditions.

6.1.4 Tall vascular native plants

Development in the lakes

Tall vascular native plants occur in all the Rotorua lakes, but are often displaced to sub-optimal shallow waters by dense beds of invasive weed species. The most frequent components of this community are the milfoils (*Myriophyllum triphyllum*, *M. propinquum*) and pondweeds (*Potamogeton ochreatus*, *Potamogeton cheesemanii*). Native pondweed is currently dominant in Lake Ōkaro and common in Lakes Rotomāhana and Ōkāreka. Milfoil species tend to dominate shallow water (<3 m) in Lake Rotomāhana and as pockets within Lakes Rotoiti, Rotorua and Rotoehu. Beds of these tall native vascular plants tend to have open canopies and co-exist with an understory of charophytes and other plants.

Few vascular plant flowers can be fertilised when submerged and most in this group must produce flowers at the water's surface for pollination and successful fruiting. Summer development of surface floating leaves in *Potamogeton cheesemanii* is a further strategy to support flowers at the water surface. This leads to seasonally variable and dynamic beds heights and senescence patterns within this community of tall native vascular plants. Seasonally surface-reaching milfoils and pondweeds may result in public complaints about weeds, yet are a normal phenomenon in our lakes.

Geothermal inputs and unusual water chemistry in some Rotorua Te Arawa Lakes has an influence on the tall vascular native plants in terms of composition and development. Higher conductivity in areas of Lakes Tarawera and Rotomāhana are associated with a range of normally saline adapted plants that are more frequently encountered in lowland coastal lagoon with seawater inputs. These species include *Stuckenia pectinata* (sago pondweed), *Zannichellia palustris* (horned pondweed), and *Ruppia megacarpa* (greater horses mane). These three species are generally limited to coastal waterbodies and have a national threat status of At Risk - Naturally Uncommon (de Lange et al. 2017). Low alkalinity conditions of Lake Tikitapu are suspected to limit the development of vascular plants (including weeds) and may account for the notable absence of pondweeds from this lake.

Figure 9: **Lake Ōkāreka vegetation of tall pondweed (*Potamogeton ochreatus*) and milfoil (*Myriophyllum triphyllum*).**

Ecological value of tall vascular native plants

The tall and open canopy formed by native vascular plants acts to increase the surface area available for biofilms/algae and their macroinvertebrate consumers. This surface area receives greater light levels and water movement than would be the case for dense beds of invasive weeds (see Section 6.2.2). Although macrophytes do not make a major contribution to carbon flow to higher trophic levels (macro-invertebrates or fish) either directly or as detritus (James et al. 2000), they are an important food for waterfowl with the tall growths accessible to surface-grazing birds and seed production, representing a potential energy-rich dietary component for birds.

6.1.5 Charophytes

Development of charophytes in the lakes

Charophytes (genera *Chara* and *Nitella*) are macroalgae that have a similar architecture to vascular plants, but differ in some key respects. They are anchored in lake sediments via rhizoids (instead of multicellular roots) and have stems and whorls of branchlets which resemble higher plants (Figure 10) but have no vascular tissue (tissues that transport fluid and nutrients internally). They produce long-lived oospores instead of seed.

Charophytes can grow in shallow water to depths beyond the extent of vascular plants as the latter are restricted by hydrostatic pressure. The depth limits of charophytes are closely linked to light penetration through the water column, both for the community overall (Schwarz et al. 2000) and for individual charophyte species (Schwarz et al. 2002). As a general rule, clearer lakes have greater depth limits and higher charophyte diversity. Charophyte depth limits will therefore retract with deteriorating water quality, as documented in Lakes Tikitapu and Rotokakahi (Burton 2017a), and extend in response to improved water clarity, as in Lake Rerewhakaaitu between 1973 and 1988 (Clayton et al. 1990). There is also the suggestion that the minimum depth of charophytes is a species characteristic, with more complex cellular architecture resisting wave disturbance compared to a simpler cellular architecture being more shade adapted (Schwarz et al. 2002). Charophytes are considered to grow more efficiently than vascular plants under low-carbon conditions (Van den Berg et al. 2001), such as within dense charophyte meadows in oligotrophic lakes.

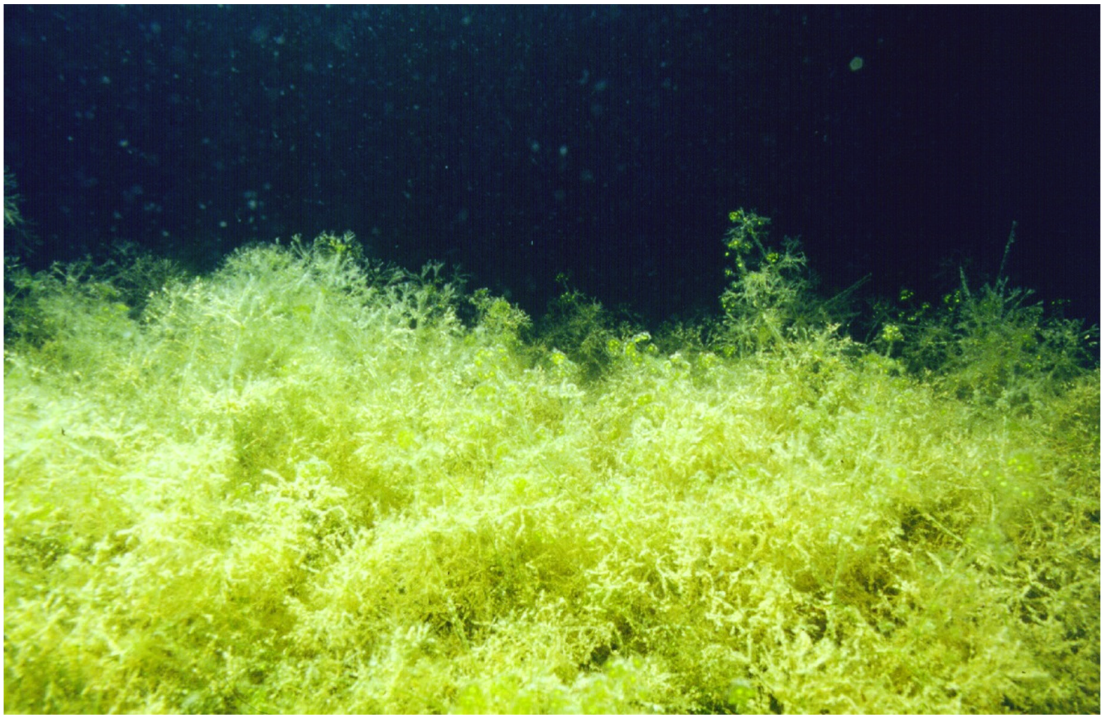

Figure 10: Charophyte meadow comprising *Nitella pseudoflabellata* within Lake Tikitapu.

In the Rotorua Te Arawa Lakes charophytes grow in low covers in shallow water and may form meadows (covers ≥75%) under open canopies of tall native plants or in deeper water. Charophytes currently have the greatest development (cover, areal extent and depth) in Lakes Rotomā (6 species, meadows to 14 m depth), Ōkataina (4 species, meadows to 11.3 m), Rotomāhana (4 species, meadows to 11 m), Ōkāreka (6 species, meadows to 10 m), and Rerewhakaaitu (5 species, meadows to 7 m). Poorer charophyte development is recorded from Lakes Ōkaro (3 species, no meadows), Rotoiti (4 species, no meadows), Rotoehu (3 species, occasional meadows to 2.2 m), Rotorua (2 species, occasional meadows to 6.8 m), Tarawera (5 species, occasional meadows to 8.4 m), Rotokakahi (5 species, occasional meadows to 9.2 m) and Tikitapu (2 species, occasional meadows to 17.4 m).

A rare charophyte, *Nitella opaca,* was previously recorded from Lakes Ōkāreka, Tikitapu, Rotokakahi, Tarawera, Ōkataina (also Ngapouri and Tutaeinanga), but has not been recorded in the last decade. This species is otherwise found only in Lakes Taupo, Waikaremoana, and a Hawkes Bay lake (Rotonuiaha). It is not endemic to New Zealand, but only female plants have been recorded here, which may contribute to its limited distribution and a suggested conservation status of Nationally Critical, due to a relatively recent loss from 70% of its range (criteria under Townsend et al. 2007).

Ecological value of charophytes

Charophytes are widely suggested to contribute to maintenance of water transparency in lakes. Reviews and investigations (Coops 1992, Casanova et al. 2002, Schneider et al. 2015) suggest mechanisms by which charophytes 'groom' overlying water include:

- effects on the planktonic food web (e.g., hosting grazing zooplankton)
- increased sedimentation or prevention of re-suspension
- phosphorus binding and carbon limitation by dense beds
- allelopathy
- production of flocculant substances
- calcite incrustation (not a feature in New Zealand lakes).

Charophytes numerically dominate the submerged seed bank of lakes (de Winton and Clayton 1996) and also the germination response (de Winton et al. 2000), so have a major role for native vegetation recovery following disturbance.

6.2 Invasive aquatic weeds

The most problematic submerged weeds in the Rotorua Te Arawa Lakes are four species in the Hydrocharitacean and Ceratophyllaceae Families (Figure 11), which share an ability to develop tall, dense monospecific beds. It is this growth habit of these introduced plants, and the fact that New Zealand lake conditions favour their wide environmental tolerances, that results in the development of problematic weed beds. Invasive potential may be aided by a number of specific features common to the group, however, no one invasion theory posed to date has sufficient evidence to explain the success of invasive submerged weeds (Fleming and Dibble 2015).

The major submerged weed species are hornwort (*Ceratophyllum demersum*), egeria (*Egeria densa*), lagarosiphon (*Lagarosiphon major*) and elodea (*Elodea canadensis*) (Figure 11). These weeds have a growth form comprising long stems with leaves in whorls, or in spirals (lagarosiphon only). They reproduce solely via vegetative means, with no seed production known in New Zealand, due mostly to absence of plants of one of the sexes. Buds are present at the stem apex, clustered at the root crown base of plants (except hornwort which does not produce roots) and distributed at some nodes along the stem (double nodes for egeria).

All of these species are very effective at regenerating from small vegetative propagules. For instance, just a 7.5 mm length of egeria stem (including a bud) proved viable (Getsinger and Dillon 1984) and 50% of lagarosiphon fragments with mean length of just 32 mm containing buds were found to regenerate (Redekop et al. 2016). Longer stem fragments were found to establish more successfully and establishment was aided by the development of adventitious roots in root forming species such as egeria (Pennington 2008). Floating fragments of egeria were found to grow and survive in tap water for at least 13 weeks (Pennington 2008). High rates of survival by freshly detached fragments have been reported for hornwort (100%) and egeria (95% with 88% rooting) over 6 weeks, with apical fragments most successful (Vari 2013). It is suggested that weeds (e.g., lagarosiphon) have a competitive advantage over tall, vascular native plants (e.g., *Myriophyllum triphyllum*) in colonising new habitats easily from fragments (Rattray et al. 1994). Fragmentation is an effective means of dispersal and once a weed is introduced to a lake, entire shoreline invasion is possible in a short period of time (Wells et al. 1997). Subsequently, weed bed development by these species is rarely propagule limited.

While it is tempting to relate the occurrence of large weed beds to excessive water nutrients fuelling growth, eutrophication is not a major driver of weed issues in the Rotorua Te Arawa Lakes. Elsewhere, nitrogen and phosphorus requirements of weed species are suggested to be satisfied by the high concentrations in the sediment and inorganic carbon shortage has proved to be a greater limiting factor for weed growth (Schwarz and Howard-Williams 1993, de Freitas and Thomaz 2011). Thus, controlling eutrophication as a strategy to reduce their biomass is not likely to be successful (de Freitas and Thomaz 2011).

A high growth rate is not necessarily related to a high standing biomass of weed species. For instance, high values of standing biomass for egeria elsewhere have resulted from the combination of slow decay rates and low but continuous growth throughout the year (Carrillo et al. 2006). Moreover, photosynthetic performance potential and growth rates of the major weeds was not strongly associated to their perceived invasiveness (Dollerup et al. 2013).

Although growth rates are not critical for standing biomass or plant architecture achieved, a high growth rate leads to rapid establishment and subsequent dispersal for new incursions of weeds, as well as recovery rate from control works. It is thus a critical consideration in management responses. A range of growth rates are reported in published literature for the major weeds (Appendix B). Growth rates will be maximal where low density plants access nutrients (i.e., form roots or in contact with sediments) and are not competing for light or carbon sources. Growth rates will decline as weed beds form, due to self-shading of shoots and local shortages of carbon, or possibly nutrients. Therefore, growth rates for an establishing weed bed will take the form of an S-curve (Appendix B).

Greater efficiency of bicarbonate utilization (Cavali et al. 2012, Hussner et al. 2016) allows the major weeds to maintain higher photosynthetic rates than many native plants, even under prolonged periods of high pH (Stiers et al. 2011). Equally weed growth performance may be enhanced by inflows of CO_2 rich spring waters in the Rotorua Te Arawa Lakes within groundwater (Périllon and Hilt 2016), or tributary inflows, as CO_2 is a more energetically-efficient carbon source shown to enhance growth of egeria (Takahashi and Asaeda 2014).

The major weeds are perennial and evergreen, thus occupying the lake littoral zone year-round., However, hornwort undergoes seasonal abundance cycles with maximal biomass usually in autumn, whilst egeria beds may reduce in buoyancy and height during winter ‘quiescence’ (Getsinger and Dillon 1985). Even though these seasonal fluctuations occur, the dense cover of quiescent plants prevent establishment of other plant species.

Figure 11: Invasive weeds (from left) *Elodea canadensis*, *Lagarosiphon major*, *Egeria densa* and *Ceratophyllum demersum* (hornwort).

Additional submerged weeds (Figure 12) that are less invasive in the Rotorua Te Arawa Lakes are curled pondweed (*Potamogeton crispus*), water buttercup (*Ranunculus trichophyllus*), and bulbous rush (*Juncus bulbosus*). These can be transported between lakes by waterfowl as seed and tend to occur sporadically in the lakes (Figure 3).

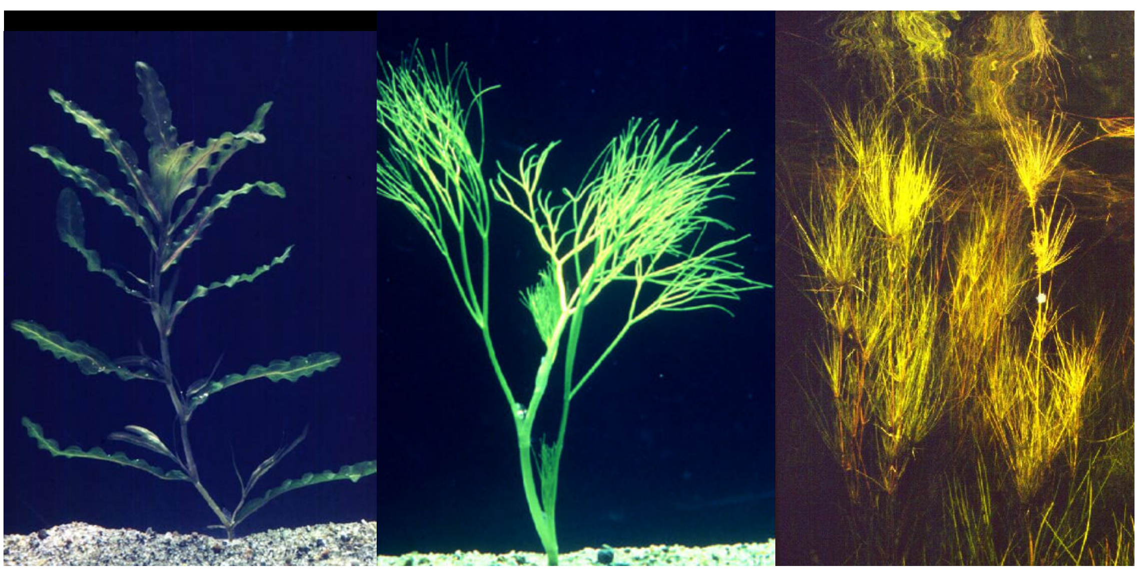

Figure 12: Less invasive weeds (from left) curled pondweed, water buttercup and bulbous rush.

6.2.1 Development of invasive weeds in the lakes

Hornwort

Hornwort (known as coontail in the USA) has a cosmopolitan distribution, being present in North America, tropical Asia, Australia, and South Africa and considered native to these regions (Hyldgaard et al. 2017). Generally, where hornwort is considered native, it is not weedy. However, two different genotypes of a Eurasian-related haplotype found in New Zealand have also been recorded as non-native additions to aquatic vegetation in North America, Australia and South Africa, suggesting a 'cryptic' invasion (Hyldgaard et al. 2017). Hybridisation between *Ceratophyllum* species was not ruled out as the origin of this invasive haplotype. One New Zealand genotype was most closely related to material from South Africa and the east coast of Australia, while the other genotype collected from Lake Tarawera had no close relatives. The commoner New Zealand genotype was confirmed to have a higher level of phenotypic plasticity in photosynthesis and relative growth rate in response to temperature and nitrogen concentration in the water compared to the genotype native to Denmark, which was thought to aid invasiveness (Hyldgaard et al. 2017).

Hornwort does not form roots and instead is loosely anchored in sediment by the buried bases of stems. This makes plants vulnerable to dislodgement by waves and currents and it is a major contributor to lakeshore stranding's. Hornwort does not perform well in exposed, shallow lake areas, although development in these areas can be facilitated by rooted beds of other plants as a substrate for hornwort attachment.

There is an assumption that hornwort relies on nutrient uptake from the water and is commonly assumed to respond to water enrichment (Lombardo and Cooke 2003). However, hornwort growth (as biomass increment over time) was found to decrease across a nutrient gradient of eutrophic to hyper-eutrophic (James et al. 2006). The performance of this weed under oligotrophic conditions (e.g., Lake Tarawera) also suggests higher water nutrient concentrations are not a requirement for excessive weed growth.

Hornwort is the deepest-growing of the invasive weeds, growing beyond 10 m depth within clearer lakes, where light does not strongly constrain depth extent.

Hornwort is currently dominant in Lakes Rotoehu (up to 3.5 m tall, 8 m depth), Rotoiti (maximum 4 m tall, 8.4 m depth) and Tarawera (up to 3 m tall, 13 m depth) according to recent LakeSPI surveys (Burton 2017a). This weed is also a minor part of vegetation in Lakes Rotorua and Rotomāhana, and is the focus of management (progressive containment or eradication) in Lakes Ōkāreka and Ōkataina (Figure 13). Established hornwort has not been recorded from Lakes Rotomā, Tikitapu, Rotokakahi, Ōkaro or Rerewhakaaitu.

Figure 13: Hornwort in Lake Ōkataina has been the focus of an incursion response and this weed bed has subsequently been removed.

Egeria

Egeria appears to be most invasive species in relatively nutrient-enriched lakes, especially shallow, sheltered systems. It has not been as invasive as expected in some Rotorua Te Arawa Lakes, or has gone through boom and bust cycles (see Section 7.3), suggesting some resource required by egeria is lacking or is quickly exhausted. Elsewhere, there is evidence that egeria is prone to collapse where it forms extensive weed beds in shallow lakes (Champion 2002, Schallenberg and Sorrell 2009, Marín et al. 2014), possibly as a victim of its own success. Nevertheless, this species shows tolerance of the high pH and oxygen conditions created by dense, photosynthesising weed beds during daylight and is known to maintain a high photosynthetic rate under high pH conditions (Hussner et al. 2016). Egeria is known to be relatively tolerant under hypoxia and sulphide exposure, suggested as two environmental stresses found in freshwater ecosystems (Parveen et al. 2017).

Egeria showed no significant variation in dry weight across five rates of fertilization from 0 - 4 g of controlled slow-release fertilizer per kg sand after two months growth (Mony et al. 2007). These results suggest that sufficient nutrients were up-taken through passive diffusion from water on nutrient-poor sediment and from sediment when it is nutrient-rich (Mony et al. 2007, Carignan and Kalff 1980).

Egeria is dominant in Lakes Rerewhakaaitu (up to 3 m tall, 7.2 m depth), and Rotorua (up to 2.5 m tall, 6.8 m depth) according to recent LakeSPI surveys (Burton 2017a). It contributes to the submerged vegetation in Lakes Rotoiti, Rotomāhana, Tarawera and Ōkāreka but does not dominate. It has not been recorded from Lakes Rotokakahi, Ōkaro, Tikitapu, Ōkataina, Rotoehu and Rotomā.

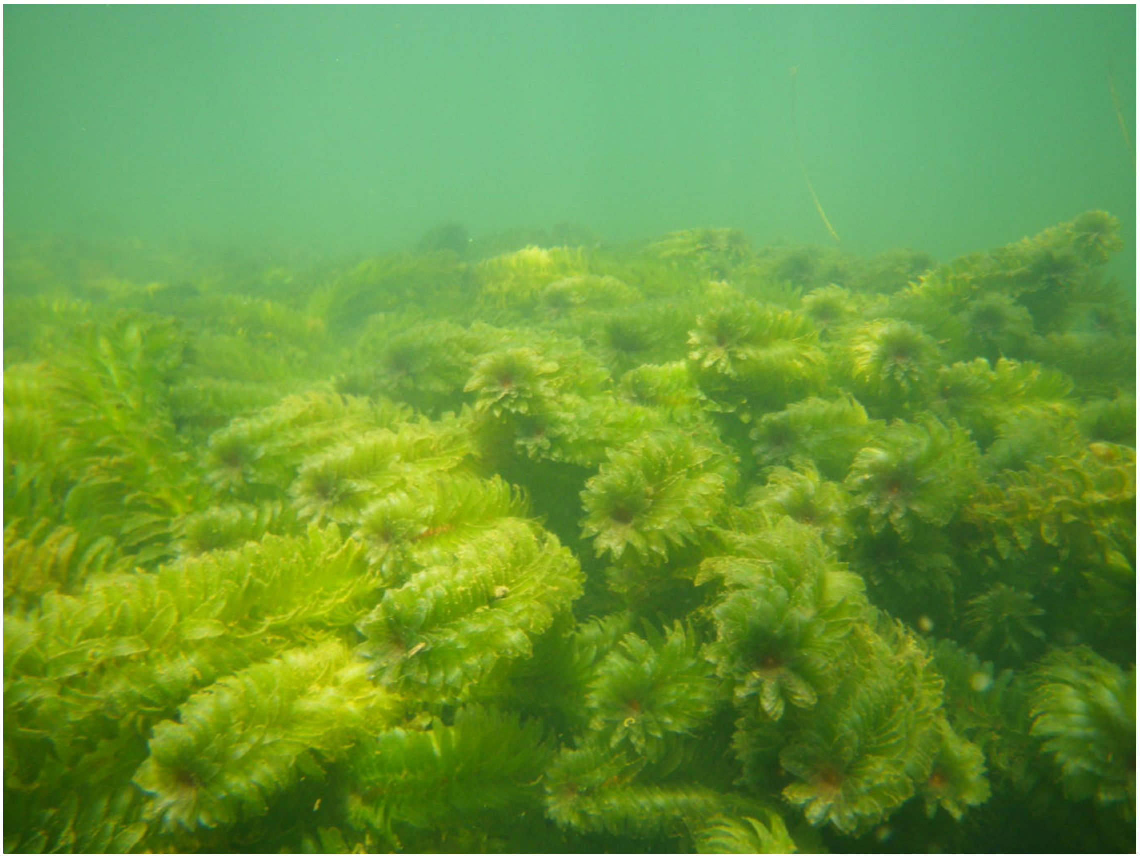

Figure 14: Egeria in Lake Rotomāhana.

Lagarosiphon

Lagarosiphon has been a very successful invader of the Rotorua Te Arawa Lakes but has been partially displaced by later invasions of hornwort or egeria in some lakes. Lagarosiphon forms the largest beds along shorelines that are sheltered from prevailing winds and consequent wave action, with nuisance surface reaching weed beds limited to areas with a wind-wave fetch <4 km in Lake Taupo (Howard-Williams and Davies 1988).

Results of experiments on shoot establishment under different light and temperature conditions (Riis et al. 2012) suggest lagarosiphon is most competitive in water colder (<25°C) than the optima for egeria (30°C). Lagarosiphon had a higher photosynthetic rate and bicarbonate use efficiency than hornwort and egeria when grown at low alkalinity (Cavali et al. 2012). By contrast, nutrient enrichment did not appear to explain the competitive ability of lagarosiphon over elodea (James et al. 2006).

Lagarosiphon has the narrowest depth range of the major weeds, recorded to 6.5 m under stable water levels and non-light-limited environments. The determinant of this maximum depth limit has been demonstrated to be hydrostatic pressure effects on root anchorage (Coffey and Wah 1988).

Lagarosiphon is dominant in Lakes Rotomā (up to 3 m tall, 6.1 m depth), Ōkataina (up to 3.3 m tall, 5.4 m depth), Ōkāreka (up to 2.5 m tall, 5.2 m depth) and Rotorua (up to 3 m tall, 6.8 m depth) according to recent LakeSPI surveys (Burton 2017a). It also contributes significantly to vegetation in Lakes Tikitapu, Rotoiti, Tarawera, Rerewhakaaitu and Rotoehu. Lagarosiphon is not recorded from Lakes Rotomāhana, Rotokakahi or Ōkaro.

Figure 15: Lagarosiphon bed in Lake Ōkataina.

Elodea

Results of experiments on elodea shoot establishment under different light and temperature conditions, were in keeping with the observed pioneer status of this species (Riis et al. 2012). This weed in New Zealand lakes is a primary coloniser of disturbed sites such as at stream deltas. It tends to be less competitive than the other major weeds, therefore it is usually a minor part of the vegetation of the Rotorua Te Arawa Lakes where it occurs with other more invasive species, occurring shallower or deeper than beds of other weeds such as lagarosiphon.

Elodea is the only major weed in Lake Rotokakahi (up to 3 m tall, 9.7 m depth). Although it is also the only invasive weed present in Lake Ōkaro, it has recently lost dominance to native pondweed (Burton 2017a), possibly due to more stable plant growth conditions as a result of water quality improvements. Elodea is not recorded from Lake Rotomāhana, and contributes in a minor way to the submerged vegetation of the remaining lakes.

6.2.2 Ecological Impacts of invasive weeds

There is general support in the published literature that invasive aquatic weeds have an influence on the ecology and habitat conditions where they invade (Schultz and Dibble 2012). This is despite the fact that invasive weeds share fundamental vegetation functions with native plants but instead may reflect invasive traits of weedy species that are responsible for deleterious impacts (Schultz and Dibble 2012).

Biological impacts

The most obvious biological impact by invasive weeds in the Rotorua Te Arawa Lakes is the displacement or replacement of native submerged aquatic vegetation (Howard-Williams and Davies 1988). This effect is most prominent in the mid-depth range with greatest consequences for tall vascular native plants, but also for charophytes, especially when compounded by depth limitation due to low water transparency. Burial and aging of the seed bank of native plants occurs with dominance by the major weeds (de Winton and Clayton 1996), which would reduce native vegetation resilience to disturbance events.

Weed invasions result in fundamental changes to the architecture of the vegetated littoral zone, causing a shift from a diverse, multi-layered structure with high community surface area to a less complex, one level surface layer provided by dense monospecific weed beds. This change is likely to have complex flow-on effects for biofilm organisms, zooplankton and macroinvertebrates.

A positive effect of macrophyte complexity (e.g., contrasting architecture) on macroinvertebrates richness has been attributed to an increase in the number of niches, and the 'microhabitats hypothesis' suggests greater macroinvertebrate numbers occur where there are more spaces in complex habitat (Ferreiro et al. 2014). By contrast, the 'refugia hypothesis' postulates that complex architecture has a negative effect on fish predation, whilst the 'food availability' hypothesis suggests that complex architecture favors the presence of epiphytic algae and detritus as food for macroinvertebrates (Ferreiro et al. 2014). There is also evidence that numerical macroinvertebrate abundance and composition may be driven by factors other than those for macroinvertebrate biomass (Ferreiro et al. 2011).

Generally, macroinvertebrate diversity appears to reflect the variety or complexity of habitat present (Sloey et al. 1996, Celewicz-Gołdyn and Kuczyńska-Kippen 2017). Moreover, species-specific preferences for differing types of macrophytes shown by taxonomically diverse organisms suggest a level of habitat mosaic is required to ensure the well-being of aquatic food webs (Celewicz-Gołdyn and Kuczyńska-Kippen 2017). Differences have been detected in the composition of macroinvertebrates between invasive weed beds and native vegetation, with increased numerical dominance by chironomids and snails in lagarosiphon beds but impacts on overall diversity were not apparent (Kelly and Hawes 2005, Caffrey and Acevedo 2007).

For dense weed beds, higher macroinvertebrate biomass, density, and taxa richness was observed in the canopy and edges of the bed (Sloey et al. 1996). This may explain contradictory findings for lagarosiphon effects on macroinvertebrates in New Zealand. In Lake Wanaka, the numerical abundance of macroinvertebrates was higher per unit area within taller lagarosiphon beds than the low-stature native vegetation (isoetes, milfoil, charophytes) at an equivalent depth (Kelly and Hawes 2005). However, where lagarosiphon biomass in Lake Dunstan was reduced by harvesting, macroinvertebrate abundance was enhanced per unit macrophyte biomass (Bickel and Closs 2009). Lagarosiphon biomass was 12-fold greater in Lake Dunstan than Lake Wanaka, suggesting very dense beds provide poorer habitat for macroinvertebrates.

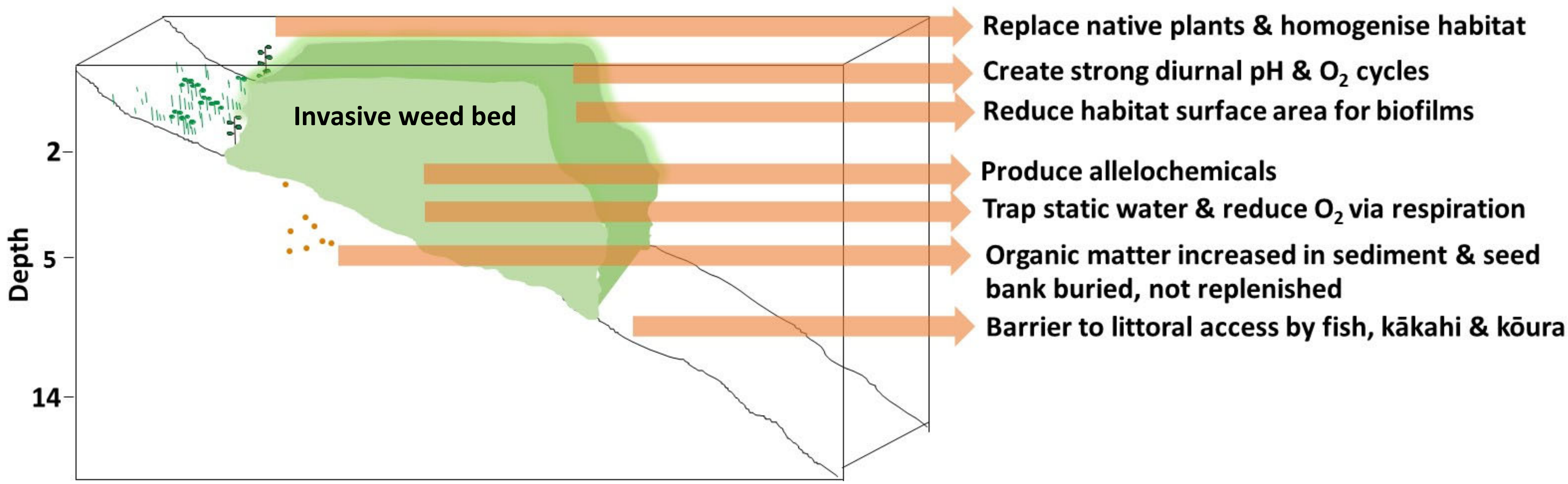

Figure 16: **Conceptual diagram of ecological impacts of dense invasive weed beds in lakes.**

Also controversial is the role of native versus invasive weeds in providing a refuge for fish prey species and ultimately whether this role is of value for fisheries. For instance, it is thought that lagarosiphon in New Zealand lakes may reduce fish access to macroinvertebrate food (Kelly and Hawes 2005), whereas harvested channels within large lagarosiphon beds may enhance fish access and feeding (Bickel and Closs 2009). Stable isotope studies showed invasive weed-dominated assemblages in a North American lake were contributing lower energy to higher trophic level, as littoral fish, than assemblages associated with native vegetation (Kovalenko and Dibble 2014). Predator-prey experiments with different plant species and artificial plants indicated modification of predator-prey interactions would only occur where invading plants were radically different in growth form, density and rigidity compared to native plants (Grutters et al. 2017).

Trout fisheries are a recognised value in the Rotorua Te Arawa lakes. Fishermen can equate the presence of invasive weeds with enhanced sport fishing as they often target the interface between dense weed beds and open water where fish can congregate. This observation does not necessarily mean invasive weed beds are better for the fishery.

Freshwater mussels are excluded from dense beds of invasive macrophytes (James, 1985, Burlakova and Karatayev, 2007), possibly directly through occupation of lake bed, by modifying water currents and food availability, creating diurnal fluctuations in oxygen and pH, or by modifying sediments. Kākahi in Lake Rotorua were found to be reduced in numbers where flocculent organic substrates were found under dense invasive weed beds (Wells and Clayton 1996).

The physio-chemical alterations to the littoral zone caused by dense invasive weed beds (see Section below) appear to promote cyanobacterial blooms and hence enhance conditions for harmful algal blooms. For instance, strong thermal stratification and internal loadings of phosphorus created by weed appeared to promote cyanobacteria (Vilas et al. 2018). It is likely that the diurnally driven increases in pH also create conditions that favour cyanobacteria over other phytoplankton and that reducing weed biomass may alleviate cyanobacterial blooms (Gibbs 2015).

Physico-chemical impacts

Dense weed beds restrict water movement, reduce light and locally modify water chemistry (Schwarz and Howard-Williams 1993) due to diurnal photosynthetic processes such as oxygen production or respiration (Figure 17). Lagarosiphon beds in an Irish lough accentuated diurnal fluctuations of dissolved oxygen and pH (Caffrey and Acevedo 2007) and under experimental conditions some of the major weed species were found to create progressively stressful conditions of high pH and low CO_2 (James et al. 1999). It is also known that the lower stems of dense weed beds can deplete local DO as water movement and plant transport of O_2 are insufficient to meet their respiratory needs (Sorrell and Dromgoole 1987). Monitoring of the DO within a large egeria bed in Lake Rotorua (Wells and Clayton 1996) showed such depletion in the bottom waters (Figure 18).

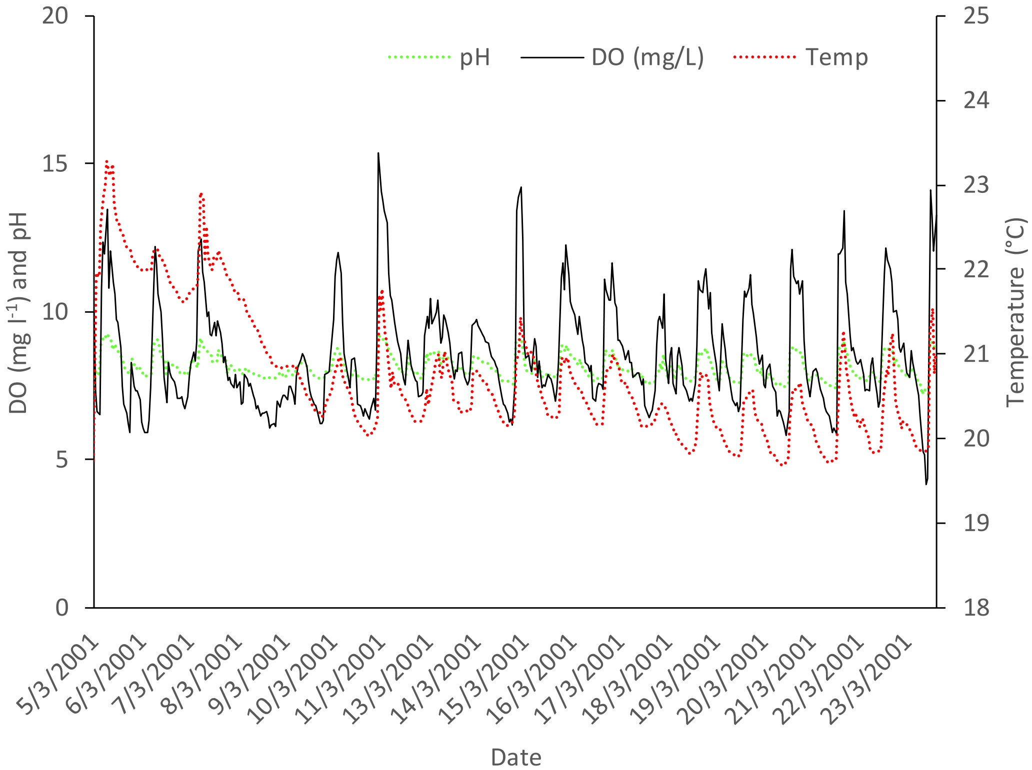

Figure 17: Diurnal fluctuations in dissolved oxygen (mg l^{-1}), pH and temperature (°C) logged within an invasive weed bed. Logger placed within the upper canopy of *Hydrilla verticillata*, Lake Waikōpiro, Hawkes Bay.

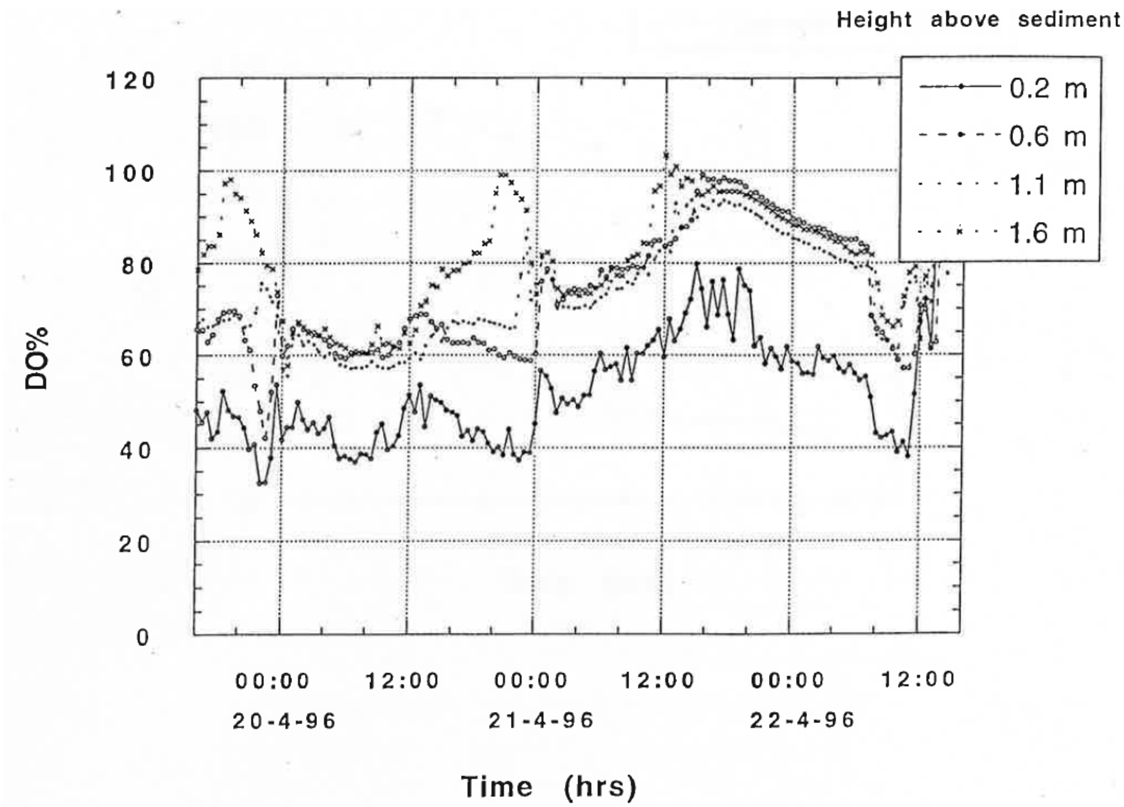

Figure 18: Dissolved oxygen within an egeria weed bed in 2.5 m depth, Lake Rotorua. DO saturation (%) was logged (Datasondes) over three days at four heights above the sediment within a 2.3 m tall weed bed.

Lagarosiphon beds in Lake Wanaka were found to be more productive (carbon fixation) per unit area than native vegetation in the comparable depth zone, with higher productivity again suggested for large weed beds in more nutrient enriched New Zealand lakes (Kelly and Hawes 2005). This productivity may contribute to the observation that dense lagarosiphon beds accumulate deep deposits of flocculent organic mud (Caffrey and Acevedo 2007). High productivity has also raised questions whether organic matter produced by weed beds can fuel significant hypolimnetic oxygen demand in the Rotorua Te Arawa Lakes. Subsequent calculations for Lake Rotoiti suggested the contribution to hypolimnetic deoxygenation represented no more than 10% of oxygen loss, based on weed area, production and assuming all production is available for decay (Gibbs and Howard-Williams 2017). This figure was acknowledged as an overestimation of the role of weed beds in deoxygenation.

The question has been raised whether successful invasive plants are more chemically defended than native plants, having what is termed 'novel weapons' (Schultz and Dibble 2012). Production of allelochemicals is reported for hornwort (Pełechata and Pełechaty 2010), egeria (Espinosa-Rodriguez et al. 2016) and elodea species (Erhard and Gross 2006, Erhard et al. 2007) that may confer advantage in competing with algae, enhance zooplankton grazers of algae, or deter herbivores. Consequences of these traits for lake ecosystems are poorly understood.

6.2.3 Cultural, amenity and utility impacts

Large beds of canopy-forming weeds are associated with depressed quantity and quality of boating, swimming and nearshore recreation (Eiswerth et al. 2000). Entanglement and drownings have been linked to invasive weed beds (Getsinger et al. 2014), while dense mats of weed provide good habitat for the snail hosts of parasites that cause ‘swimmer’s (duck) itch’ (Eiswerth et al. 2000). Weed strandings create aesthetic and odour issues, especially where they occur close to population centres, such as experienced at the Rotorua township foreshore.

The cost of biodiversity loss following biological invasion often goes unvalued. However, of relevance is the New Zealand economic analysis study showing Waikato residents were willing to pay significant amounts to prevent exotic weed infestations in a local lake to protect indigenous biodiversity (Bell et al. 2009). For example, the study revealed ‘willingness to pay’ of NZ$234 per regional household over 5 years to prevent *Hydrilla verticillata* (hydrilla) establishment (Hydrocharitacean family) and NZ$146 to avoid the loss of charophytes (Bell et al. 2009, WRA 2014).

Similarly, economic estimates of weed impacts on recreation are rare. In one study of hydrilla on a Florida lake (108 km^2), recreational values at risk from hydrilla were estimated at US$857,000 annually (Bell and Bonn 2004). The willingness to pay by users to preserve recreation where it was deemed at risk from invasive aquatic weeds was estimated at US$4.62 per person per day (Bell and Bonn 2004).

Also at risk from weed invasion are local property values. In an economic assessment, lakefront property values were compared for US lakes with and without the presence of canopy-forming weed (*Myriophyllum spicatum*) and showed invasion corresponded to a 19% decline in mean property values (Olden and Tamayo 2014). However, specific analysis of the value of industries associated with lake quality and public perception of acceptable levels of degradation by the weed would be needed to confirm relevance to the Rotorua Te Arawa Lakes.

Weed beds also interfere with cultural practices, with traditional tau kōura fishing methods for koura declining with the introduction of invasive weeds that fouled the lines (Parkyn and Kusabs 2007).

Evidence of impacts on trout fishing are mostly anecdotal and dependent on the techniques and experience level of fishers.

7 History of weed invasion

The major (vegetative) weeds of the Rotorua Te Arawa Lakes are spread between lakes solely by human activities in the absence of hydrological connections between waterbodies (de Winton et al. 2009). There has been a sequence of invasion of submerged weed species for the Rotorua Te Arawa Lakes.

The first major weed to establish in the Rotorua Te Arawa Lakes was elodea (Figure 19). Elodea is likely to have established in Lake Rotorua during the 1930s, given that the Ngongotaha trout hatchery had ‘oxygen weed’ (common term for several weeds in the family Hydrocharitaceae) in their hatchery around that time and ponds were flushed annually into the Ngongotaha Stream, which flows into the lake (Chapman 1970). The majority of lakes were known to contain elodea by the 1970’s (Figure 19), the exceptions being Lakes Rotomāhana and Rerewhakaaitu that are more remote and less intensively used by recreational craft. Elodea is the only vegetative weed ever recorded from Lake Ōkaro and also Lake Rotokakahi, the latter probably on account of the restricted public access (hapu owners only). It currently only dominates in Lake Rotokakahi (Figure 3, Figure 19).

By the mid-1950s, lagarosiphon had appeared in Lake Rotorua (Figure 19) and by 1957, it was recorded in Lake Rotoiti. By the late 1950’s, major weed problems attributed to lagarosiphon were apparent in these two lakes. From 1958, large onshore accumulations of weed drift occurred after storms, resulting in an aquatic weed nuisance unprecedented in New Zealand. Lagarosiphon spread rapidly, with Lakes Rotomā, Ōkataina and Tarawera likely to have been colonised in the mid to late 1960s (Coffey 1970, Brown and Dromgoole 1977, Clayton 1982). Invasion of the more isolated, less used lakes occurred later, with Lake Rerewhakaaitu estimated to have been invaded by lagarosiphon in the mid-1980s (Figure 19). Lagarosiphon currently dominates in Lakes Rotomā, Ōkataina, Ōkāreka, and co-dominates in Lakes Tarawera, Rotorua and Rotoiti (Figure 3, Figure 19).

Egeria was first recorded in Lake Rotorua in 1983 (Wells and Clayton 1991), from Lake Rotoiti in 1987 (de Winton et al. 2009), and was soon established in Lake Tarawera by 1988 (Clayton et al. 1990). It was not until 2001 that egeria was first recorded in Lakes Ōkāreka and Rerewhakaaitu, with Lake Rotomāhana the most recently invaded by egeria in 2007 (de Winton et al. 2009). Presently (2018), egeria is dominant in Lake Rerewhakaaitu and co-dominant in Rotorua and Rotoiti (Figure 3, Figure 19).

Hornwort was first recorded in Lake Rotorua in 1975 (Wells and Clayton 1991) and had spread via the hydrological connection to Lake Rotoiti by 1977 (de Winton et al. 2009). Hornwort was first found in Lake Tarawera, together with egeria, in 1988 (Clayton et al. 1990). There was a substantial time frame before the first records of hornwort were subsequently made in Lake Rotoehu (2006), with Lakes Rotomāhana, Ōkataina and Ōkāreka following closely in the invasion sequence (Figure 19) but with different outcomes (see Section 5.1). Hornwort dominates Lakes Tarawera and Rotoehu and co-dominates in Lakes Rotorua and Rotoiti. In contrast, hornwort is currently progressively contained in Lakes Ōkataina and Ōkāreka with the objective of eradication (Figure 3, Figure 19).

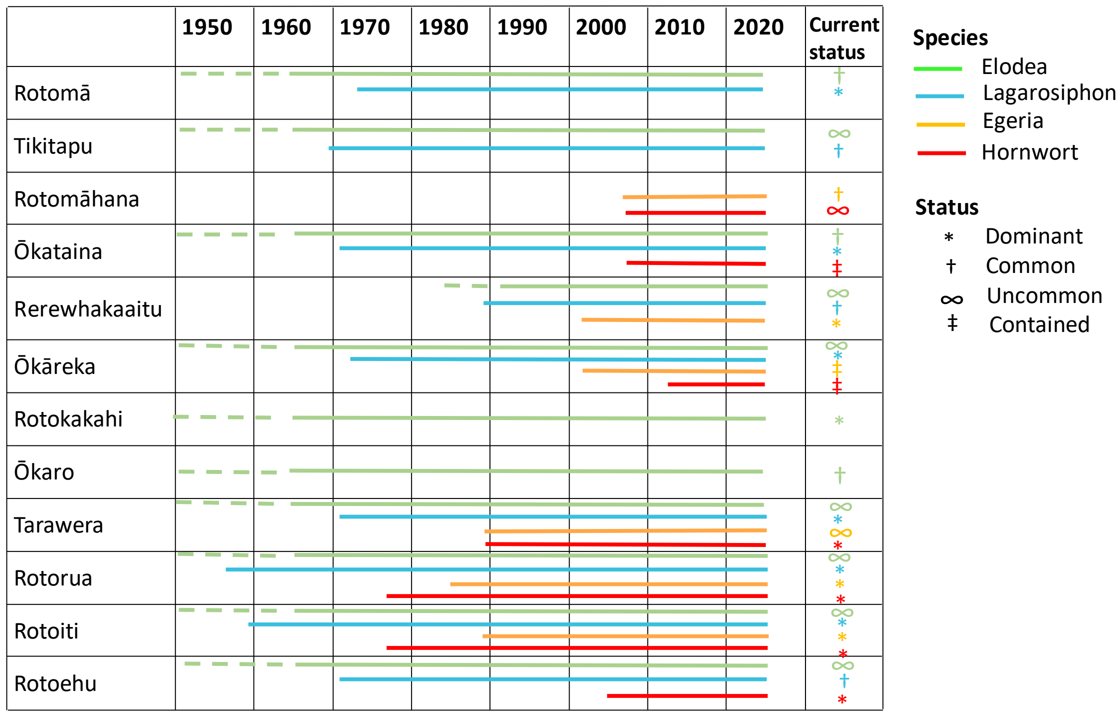

Figure 19: Diagram showing the timing of weed introductions to the Rotorua Te Arawa Lakes and current (2018) status. Dominant is major representation of weed beds in a lake, common means likely to be encountered widely, uncommon means present but unlikely to be encountered widely, contained means actively managed to very low presence.

7.1 Drivers of spread

The spread of invasive vegetative weeds across the Rotorua Te Arawa Lakes has a strong correlation with boat traffic, lake accessibility and attractiveness for recreation (Johnstone et al. 1985, de Winton et al. 2009, Compton et al. 2012). Early weed introductions were noted mainly at boat ramps (Johnstone et al. 1985). Lake Rotomāhana was the last of the large lakes to remain relatively weed free because of its more remote location and difficult public access. However, the discovery of egeria and hornwort around casual boat launch areas in 2007 highlights that no lake can be considered immune to weed invasion. Although Lake Rotokakahi is widely impacted by elodea, it is free of the worst invasive weed species (lagarosiphon, egeria and hornwort), primarily due to its restricted public access controlled through the Lake Rotokakahi Board of Control. Lake Ōkaro has only elodea present. For this lake, the absence of weeds is likely related to a lower attractiveness for recreational boating, but also the past poor water quality that would reduce establishment success by introduced weed fragments. Weed risk for this lake may now be higher following improving water quality and recent signs of habitat improvement for submerged vegetation.

7.2 Succession patterns

Descriptions of the weed invasions at Lake Tarawera established a sequence of succession where the more recently introduced major weed tended to replace earlier established weeds (Wells et al. 1997). The outcome of competitive interactions between the weed species suggested a general pattern of elodea beds being replaced in the shallower region of its depth range (0.5 to 5 m depth) by lagarosiphon, which were then both replaced beyond c. 2 m depth by hornwort and/or egeria to 10 m depth or more (Wells et al. 1997).

Whilst this pattern has been the general observation for eventual hornwort dominance in Lakes Tarawera, Rotoehu and Rotoiti, there have been other lake exceptions. For instance, hornwort does not seem to be suited to the wave-exposed littoral areas in the shallower Lake Rotorua. Hornwort has not dominated in Lake Rotomāhana and is now uncommon in that geothermally influenced lake. Management of hornwort at the early incursion stage in Lakes Ōkataina and Ōkāreka means its invasion potential there has not yet been determined. Although egeria established in Lake Tarawera, it largely remained restricted to one bay (Kotukutuku Bay) in the vicinity of a tributary inflow. As well as these patterns relating to displacement by more invasive species, weeds have shown other temporal patterns in the Rotorua Te Arawa Lakes.

7.3 Booms and busts

Egeria was first recorded in Lake Rotorua in 1983 and by 1988 had established weed extensive beds around most sheltered littoral zone, estimated at more than 80% of the vegetation in the lake with an area of 440 ha (Wells and Clayton, 1991). In the early 1990s, egeria underwent a major decline following extensive weed control using diquat. It has never recovered to its former state, possibly due to ongoing control works (Burton 2017a).

More recently, LakeSPI surveys in Lake Rotomāhana have detected a major reduction in the development of egeria compared to its abundance two and four years previously (Burton 2017a). This has occurred in the absence of any control works.

Another invasive plant to undergo a boom-bust pattern in the Rotorua Te Arawa Lakes was the algae *Hydrodictyon reticulatum* (water net). Water net was first recorded from Lakes Rotorua and Rotoiti in 1989 (Hawes et al. 1991) and extensive surface floating mats caused major issues for lake utility and amenity in Lake Rotorua (Wells et al. 1999). In the 1990-1991 season, approximately 1,000 m^3 of water net was removed from 400 m along the Rotorua City lake front reserve area alone (Figure 20). Over 1994-1995, there was a failure of water net populations to re-establish nuisance growths after overwintering of vegetative material and, although it persisted at low levels, it was no longer a management problem (Wells et al. 1999).

Figure 20: Shoreline accumulations of water net along the Lake Rotorua foreshore in the early 1990's.

7.4 Weed eradications and containment

Other aquatic weeds previously found in the Rotorua Te Arawa Lakes and their surrounds have been subject to control programmes and are now considered eradicated from these waterbodies. Initiatives are also currently underway to contain hornwort in two of the Rotorua Te Arawa Lakes with a view to eradication.

Water hyacinth

Water hyacinth (*Eichhornia crassipes*) was first recorded in New Zealand in 1899 (Glue 1956) and described as naturalised in 1914, prohibited from further introduction in 1927and targeted for eradication since 1956 under several pieces of legislation (Healy and Edgar 1980). It is a Notifiable Organism under the Biosecurity Act 1993, which requires anyone who finds this species to notify MPI of its presence.

It was found in Lakes Rotorua and Rotoiti and the Ohau Channel, with the first record there in 1955 (MAF unpublished records). Mature plants and seedlings were found in Lake Rotorua at Te Ngae, the lake edge near Rotorua Airport, Hinemoa Point, Ohinemutu and Hamurana, with a few plants also recorded from the Okere Inlet and Te Weta Bay in Lake Rotoiti. Annual treatment using hand removal or herbicide (2,4 D amine) was undertaken until 1959, also in 1964, and in 1966 when the last plant (a seedling) was hand removed. Inspections up to 1971 failed to find any further water hyacinth plants and the status of this species was declared historic for the lake in 1980 (MAF unpublished records). No plants have been reported since that time and water hyacinth can be considered eradicated from these lakes.

Figure 21: A globally recognised floating weed, water hyacinth, was eradicated from the Rotorua Te Arawa Lakes.

Water poppy

Water poppy (*Hydrocleys nymphoides*) was first recorded as naturalised in New Zealand in 1914 (Healy and Edgar 1980) and prohibited from sale and distribution (as a Class B Noxious Plant under the Noxious Plants Act 1978) in 1986. It is targeted for eradication in all regions where it occurs and few field sites currently require control. It is an Unwanted Organism under the Biosecurity Act.

Figure 22: Water poppy is a water lily type plant that has been eradicated from ponds adjacent to the Rotorua Te Arawa Lakes.

Water poppy was found in a lagoon adjacent to Te Pohue Bay, Lake Rotoehu in 1976 when the plant occupied an area of 350 m^2. All plants were sprayed with 2,4 D amine by Rotorua District Noxious Plant Officer (J. McNaught) with no plants seen for the following 10 years when the site was subsequently declared eradicated. Since that time three small infestations of water poppy have been found in the Rotorua District. Plants were found and removed from the Rotorua Orchid Gardens in 1986 (J. McNaught) and water poppy was also found and removed from a pond in Otamarae, close to Lake Rotoiti in 2013 (S. Bathgate, Bay of Plenty Regional Council) as part of an ornamental pond surveillance programme. Most recently the plant was found at Te Puna.

Entire marshwort

Entire marshwort (*Nymphoides montana*), also known as marshwort, was first reported as naturalised in in New Zealand in 1981 (Clayton and Tanner 1985) when it was known as *N. geminata*. More recently, this species has been recognised as *N. montana*, a perennial species from upland New South Wales, whereas *N. geminata* is an annual species found in northern Australia (Aston 2009).

The first reported site was in Lake Ōkāreka, on both sides of Acacia Point occupying 1 ha in area. It was prohibited from sale and distribution (as a Class B Noxious Plant under the Noxious Plants Act 1978) in 1986 and is a designated Unwanted Organism. It is targeted for eradication in all regions where it occurs and only one New Zealand field site (near Timaru) currently requires control.

The entire Lake Ōkāreka infestation was covered with black polythene sheeting (left side photo) in 1986 and the majority of the infestation was clear within two years. Occasional plants were discovered in 1989 and were hand removed, with no further plants seen at the site. It is now considered eradicated from the lake.

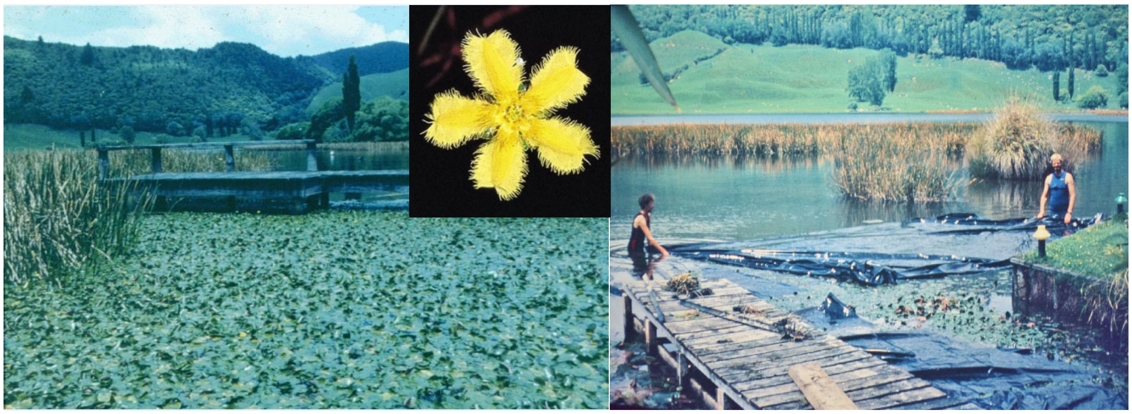

Figure 23: Entire marshwort was eradicated from Lake Ōkāreka by surface lining to shade and smother the infestation, followed up by hand weeding.

Other species removals from the region

Three other species that are designated Unwanted Organisms have been found in cultivation in Rotorua and subsequently removed, but had not been recorded as naturalised in any of the lakes. Eelgrass (*Vallisneria australis*) was found in a pond in the Centennial Gardens, Rotorua in 1982. The pond was hand weeded in 1983 and drained in 1987. No plants have been found since that time. Humped bladderwort (*Utricularia gibba*) was collected from a cultivated aquarium by C. Schipper in 1984 (NZFRI15520). Mexican waterlily (*Nymphaea mexicana*) was found in the Centennial Gardens, Rotorua in 2006, and has since been eradicated.

Hornwort incursion responses

The discovery of hornwort in Lake Ōkataina in 2010 and in Lake Ōkāreka in 2012 led to the development of incursion response plans (Lass 2017, Bathgate 2015) that have included delimitation surveys, containment nets within contaminated bays in Lake Ōkataina, control works at infested sites and ongoing surveillance. To date the amount of hornwort discovered in both lakes has been reducing and eradication remains possible.

8 Changed aquatic weed risk-scape

There is ongoing risk of new weed incursions from aquatic plants maintained in cultivation in the vicinity of the Rotorua Te Arawa Lakes, including freshwater pest plants in New Zealand described in Champion et al. (2012). Also possible is naturalisation by species believed to have been eradicated from this country, or that are new-to-New Zealand. Management needs to be response-ready and able to act in the event that new weeds are discovered that threaten the lakes (e.g., Table 3). Responsible agencies are BOPRC for pests listed on the RPMP or designated as Unwanted Organisms and MPI for National Interest Pest Response species or new-to-New Zealand weeds (Notifiable Organism).

Table 3: Examples of submerged weed species as yet unrecorded from the Rotorua Te Arawa lakes and the managing agency. Included are species that have the potential to impact on freshwater amenity or environmental values and that are assigned a biosecurity status in New Zealand. * = species that have naturalised, † = species subsequently eradicated/contained, ‡ = species not known from New Zealand.

Weed species	Status	Agency
**Utricularia gibba* (alien bladderwort)	Unwanted Organism	BOPRC
**Cabomba caroliniana* (fanwort)	Unwanted Organism	BOPRC
**Vallisneria australis* (eel grass)	Unwanted Organism	BOPRC
†*Hydrilla verticillata*	Notifiable Organism, National Interest Pest	MPI
†*Potamogeton perfoliatus* (clasped pondweed)	Notifiable Organism	MPI
‡*Myriophyllum spicatum* (Eurasian watermilfoil)	Notifiable Organism	MPI
‡*Najas guadalupensis* (southern naiad)	Notifiable Organism	MPI
‡*Najas marina* (sawtooth)	Notifiable Organism	MPI
‡*Stratiotes aloides* (crab's claw)	Notifiable Organism	MPI

Expansion of existing weeds is also a likely consequence of ongoing improvements in the water quality of the Rotorua Te Arawa Lakes. Lower phytoplankton abundance will mean a better light climate for aquatic weeds, with responses including possible depth expansion and greater growth rates (e.g., faster recovery from control works). Release from algal competition for inorganic carbon may also benefit the weeds. Reduction in Harmful Algal Blooms (HAB) and produced toxins might have a flow on effect for aquatic weeds, with the major weeds possibly showing physiochemical responses to toxin exposure (Romero-Oliva 2015a), but also evidence that weeds can remediate some toxins (Romero-Oliva 2015b).

Identification of weed threats to New Zealand are generally based on current climate, so climate change may increase risk from additional species as yet unconsidered. Climate change influences on existing aquatic weeds might be mediated via temperature increases and lead to increases in growth or changes in the intra-specific competitiveness of the major weeds (McKee et al. 2002, Thiébaut, et al. 2016, Silveira and Thiébaut 2017). Changes in the composition of dissolved inorganic carbon would be driven by increased partial pressure of CO_2 under climate change scenarios. Predicted outcomes for weed performance range from little effect or even loss of competitiveness relative to non-bicarbonate using plants (Eller et al. 2015), to suggestions it will increase growth, biomass allocation and physiology of submerged aquatic plants (Dülger et al. 2017).

9 History of aquatic weed management

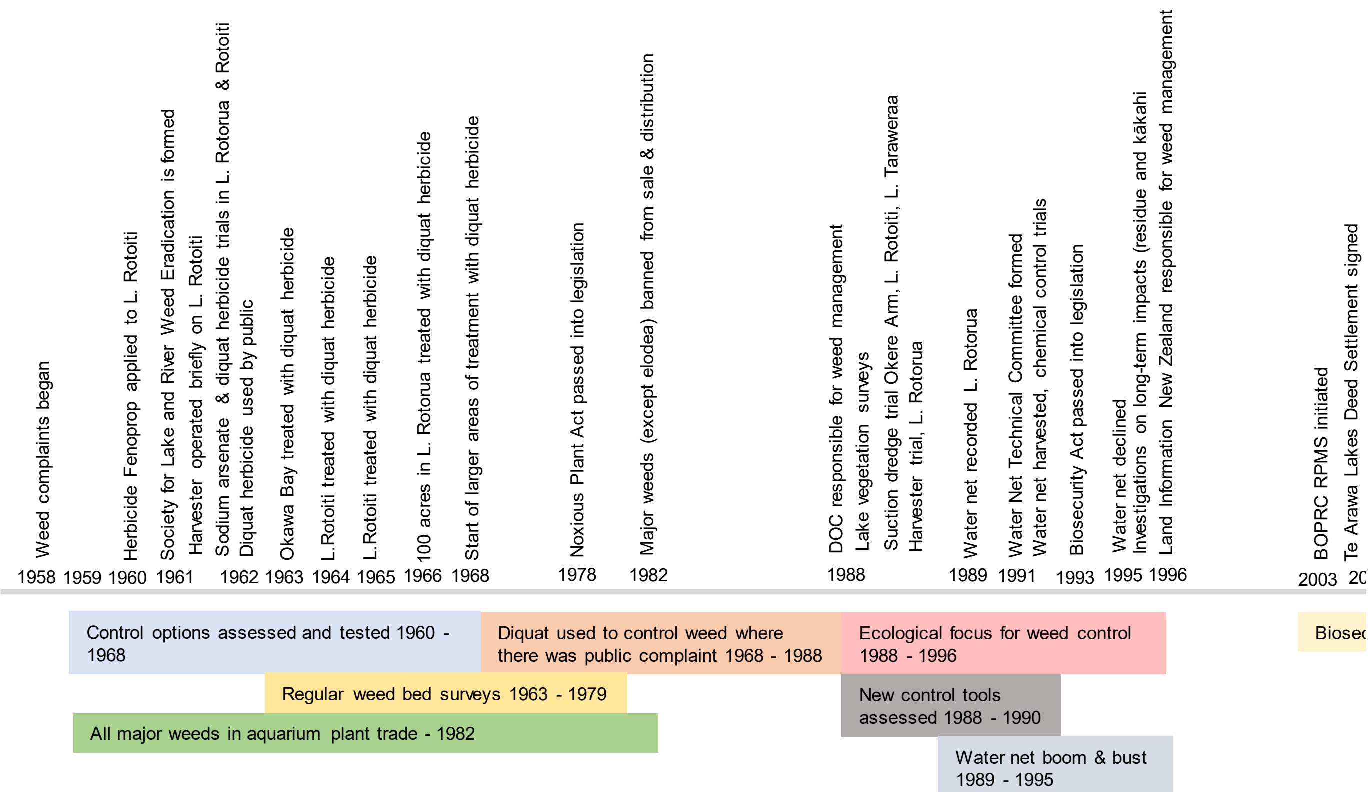

Figure 25 provides a diagrammatic overview of the main events in weed management of the Rotorua Te Arawa Lakes, including the long history of diquat use, and legislative background.

10 Proactive weed management

10.1 Pathway management

The first step in proactive weed management to intercept weeds before they spread and establish in lakes is pathway management.

Pathway management should include increased public awareness of their role as vectors for aquatic weed spread and seek to modify behaviour via campaigns (e.g., Stop the Spread; Check, Clean, Dry), signage, or other education and incentives. Currently in the Bay of Plenty Region, targeted awareness is undertaken every summer using advocacy funding contributed by MPI for the promoting the Check, Clean, Dry message. Summer students are employed to raise awareness about biosecurity, and to survey lake user's knowledge and compliance with Check, Clean, Dry recommendations (Lass 2017). A portable wash-down unit deployed by a contractor at events and high use areas also has the dual purpose of decontamination and reinforcing the message (Lass 2017).

The BOPRC have also used the MPI advocacy funding to survey participants on the movement of vessels and decontamination precautions. More recently, MPI have launched an advocacy 'app' to capture consistent survey information from recreational boaters around the country. Derived information may be used to build a network analysis of movements, risks and intervention points (e.g., current project under Biological Heritage National Science Challenge).

Other precautionary management may potentially include prohibition of motorised vessels, restricted access or rāhui. Inspections of high-risk vectors (primarily vessels and trailers) can be incorporated into awareness programmes and supported by wash down facilities (Miller et al. 2006) and by fines or other punitive action (e.g., revoking event permissions). Overseas initiatives have included compulsory vessel inspections and fines for evidence of contamination when seeking to launch.

Essential here is that decontamination procedures are effective against the weed targets. A study to validate the Check, Clean, Dry protocols for aquatic weeds has identified that treatments recommended to date using detergent, bleach or salt would not be sufficient to cause 100% mortality of weed fragments (Burton 2017b). However, hot water treatment (55°C for 20 minutes or 60°C for 1 minute) was effective, as was complete freezing or drying.

10.2 Prioritisation for proactive weed management

Proactive weed management must consider the pathways and vectors for weed spread but also habitat for pests and likely level of impact, in determining where to focus initiatives (Champion 2009). Exercises to identify lake and site priorities for proactive weed management in the Rotorua Te Arawa Lakes were undertaken in 2005 (Champion et al. 2006), reviewed in 2009 (Champion 2009) and priorities are reconsidered annually by BOPRC Biosecurity staff.

10.3 Early detection and rapid response

Bay of Plenty Regional Council conceived, developed and installed weed cordons, a netted containment area at boat ramps designed to capture weed fragments introduced on trailers or vessels arriving from infested sites. Research indicates cordons are up to 85% effective at retaining weed fragments (Lass 2012) and in combination with regular surveillance of the area, provide a first line of defence against weed introduction. Weed cordons are installed at eight locations across six Rotorua Te Arawa Lakes (Lass 2017), including weed-cleared cordons in Lakes Rotoehu and Rotoiti to reduce vessel/trailer contamination at haul-out.

The current aquatic weed surveillance practices of BOPRC were assessed as best practice as summarised in Section 4.2.2. In addition to in-lake surveillance, BOPRC monitor retail outlets and nurseries for National Pest Plant Accord species (plants banned from propagation, sale and distribution). BOPRC also provide guidance for pond owners and survey back-yard ponds leading to the detection and eradication of weeds (e.g., water poppy).

In the event of detection of an incursion (as identified in the Regional Pest Management Plan or a new to region pest plant) the steps shown in Figure 24 should be followed.

Incursion responses considered to date include egeria and hornwort in Lake Rotomāhana (Clayton and de Winton 2007), and hornwort in Lake Ōkataina (BOPRC 2013) and Lake Ōkāreka (Bathgate 2015).

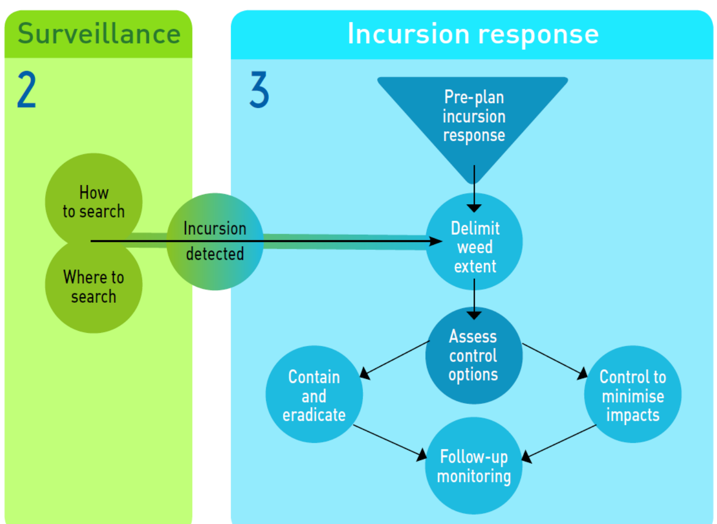

Figure 24: Steps for the early detection of aquatic weeds and rapid response (from Clayton et al. 2014).

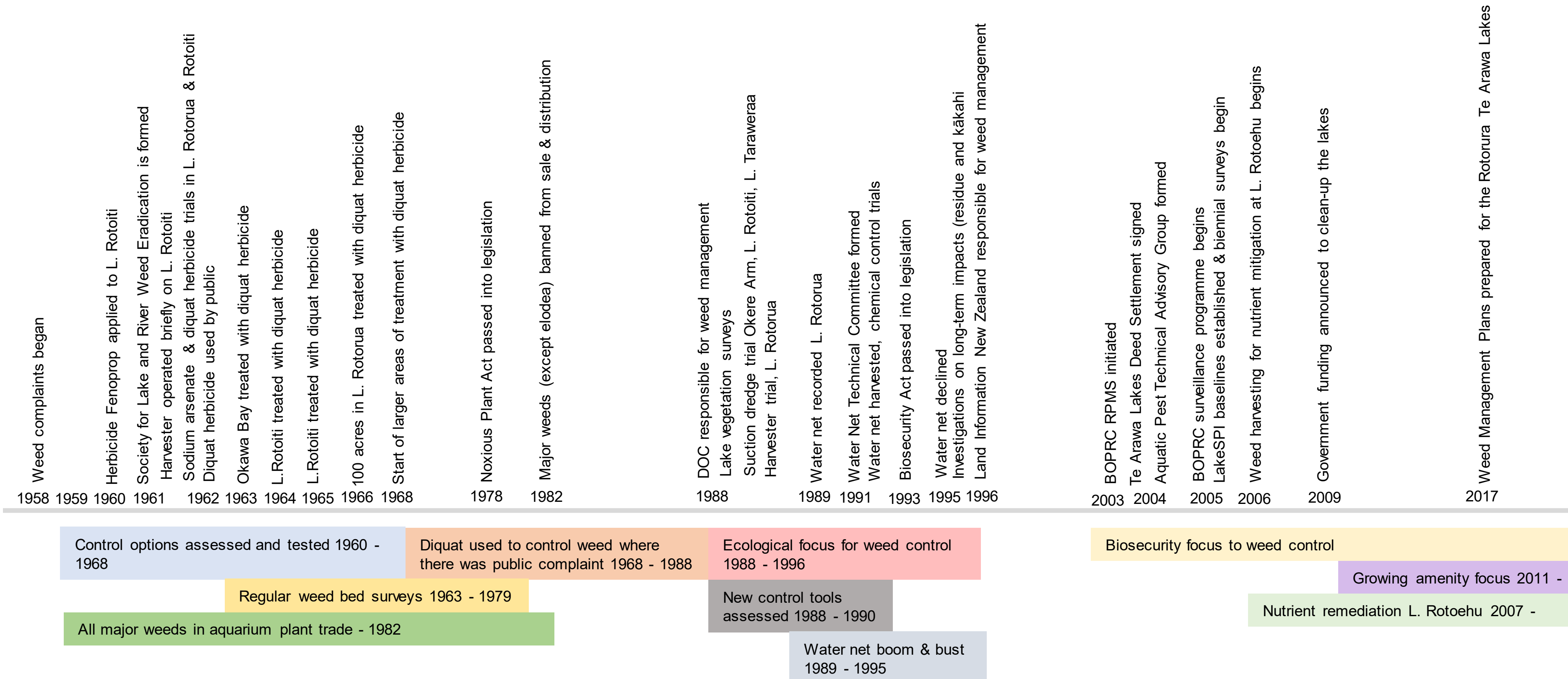

Figure 25: Diagrammatic timeline (not to scale) of the main events in the history of weed management in the Rotorua Te Arawa Lakes.

11 Current weed control tools

There is no one best method for weed control, with selection of the appropriate option strongly driven by the objectives for control and site characteristics (e.g., weed biomass, species, site size, slope, sediment type), the most important of these being the weed biomass (Figure 26). Integrated control should also be considered, both spatially or temporally, to achieve objectives. For instance, incursion response could require application of several control tools to reduce weed biomass to a point where eradication is achievable (e.g., suction dredging and bottom lining, leading to hand weeding). The benefits of weed management for both incursion management and amenity control are also only realised if the worst weed present is controlled.

Objectives that determine the application of particular control methods in the Rotorua Te Arawa Lakes may include one of three intermediate objectives that are included in the National Policy Direction for Pest Management 2015[1] These include **eradication** as an incursion response for a newly introduced weed, **progressive containment** seeking to continuously reduce the extent or abundance of a pest and **sustained control** that is aimed at moderating impacts of the pest. Also recognised is ecological restoration (Section 14.2) that sees the reduction of invasive weeds to the point that native vegetation values are returned **Other terms are amenity or utility control** to reduce the impacts of high biomass weed beds on lake or water usage, and **suppression** is an ongoing pressure that prevents weeds forming nuisance growths.

Control methods that have been utilised for submerged weeds in the Rotorua Te Arawa Lakes (Table 4) and with the circumstances where these are most appropriate for control aims are described below.

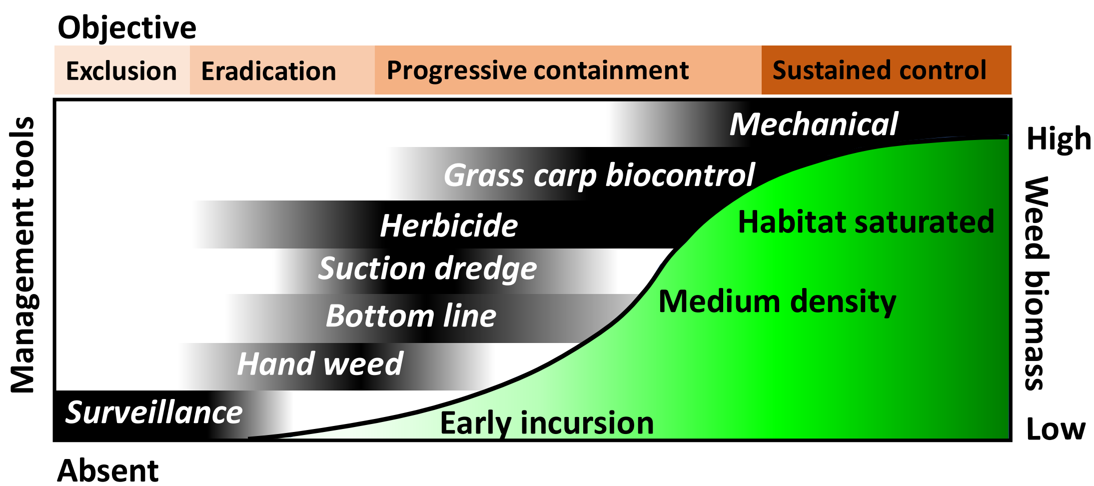

Figure 26: Selection of appropriate control tools. Weed control tools (italics) are indicated across a gradient of increasing weed biomass from left to right, together with the intermediate objectives from the National Policy Statement for Pest Management 2015 (top).

Monitoring is essential for effective weed control. Pre-control monitoring helps to assess priorities, identify the treatment area, determine the most suitable method and appropriate timing of control. Post-control monitoring is necessary to confirm outcomes and identify next steps.

[1] https://www.mpi.govt.nz/protection-and-response/overview/national-policy-direction-for-pest-management/

11.1 Hand weeding

Hand weeding removes individual plants. It is an appropriate method for early weed eradication (incursion response) in situations where a target weed can be easily identified (e.g., sufficient water clarity, low background vegetation) and the target weed is distributed at a low density of <125 shoots per 0.1 ha (Bellaud 2009) or patches do not exceed 1 m^2. It is not practical once infestations expand as it becomes a very labour intensive method. Hand weeding has been used in the US (Bellaud 2009), Ireland (Caffrey et al. 2011) and Lakes Wanaka, Wakatipu and Waikaremoana in New Zealand.

It is vital to completely remove all viable plant material when hand weeding (e.g., avoiding shoot breakage, excavating root crowns) and the method requires experienced divers. Effective visual coverage for detection and subsequent removal of scattered plants in open areas of gradual slope can be difficult and may require demarcation of an underwater search grid (i.e., lines and marker buoys).

11.2 Bottom lining

Bottom lining is the placement of opaque materials to cover weed beds and sediments, which operate by excluding light for submerged plant growth and by removing root access to new colonising shoots fragments. This option is suitable for one-off site eradication (with follow up hand removal), or to provide medium-term control (years) in reducing vegetation biomass.

The outcome of bottom lining depends upon the extent of installation, the properties of the material used (Caffrey et al. 2010) and the degree of exposure to water movement. Too much water movement can remove the lining material, while high sedimentation rates can bury the lining enabling weed recolonisation. Some materials have proved difficult to lay.

Use of jute hessian was found to be successful in controlling lagarosiphon in an Irish lough in as little as four months (Caffrey et al. 2010) and NIWA trials have also shown that hessian and coconut fibre linings could successfully kill weeds within five months (Hofstra and Clayton 2012). More recently, jute hessian has been successfully deployed over almost 1 km of shoreline in Lake Wanaka for the control of lagarosiphon. Jute hessian is biodegradable, lasting up to 10 months before beginning to disintegrate (Caffrey et al. 2010). Another advantage of materials with an open weave is they allow sediment gases to escape, and jute can saturate and become neutrally buoyant so is easier to lay.

Limitations to use of bottom lining include spatial scale of application, although treatment of sites up to 5000 m^2 has proved possible (Caffrey et al. 2010). Steep slopes or areas with numerous obstacles are difficult to bottom line and reduction of high weed biomass is required prior to laying. Although linings can be weighed down by sand bags, rocks, or else pinned in place, they are susceptible to dislodgement in high wave energy environments. High rates of sedimentation will reduce effectiveness, with rooted plant re-colonisation possible when sediment reaches a depth of 4 cm (Laitala et al. 2012).

11.3 Suction dredge

Suction dredge or diver-operated Venturi suction pump takes uprooted plants and discharges weed into a floating barge or fine mesh collection bag (Clayton 1993) to be disposed of. This method is only feasible for moderate biomass beds in limited areas, usually as part of an incursion response. Suction dredging is slowed by hard-packed sediments, requires good underwater visibility and is high cost (Champion et al. 2002). If on-site disposal of weed is feasible by mulching and/or deep-water disposal (without the generation of large numbers of viable fragments), then suction dredging will become far more cost effective. Up to 20 days labour per ha is likely for dense weed beds and one of the major rate limiting steps is the time taken to navigate to and from targeted sites, and to off-load and dispose of bulky weed. Suction dredging can be effective for up to three years for lagarosiphon weed beds, however, it is unlikely to achieve weed eradication alone (without some follow-up hand weeding) because of recovery from any remaining weed fragments (Wells et al. 2002). Suction dredging may be less effective against hornwort due to its brittle nature and subsequent mobility and re-dispersal of viable fragments. Suction dredging was used to eradicate submerged weed from a 610 m length of river in Texas, USA (Alexander et al. 2008) and to remove large lagarosiphon beds in Lake Wanaka and Waikaremoana.

11.4 Herbicides

There are two herbicides registered for use by the New Zealand Environmental Protection Agency (NZEPA) for use in freshwater; diquat and endothall. They are contact herbicides that desiccate and defoliate plant tissue that come into contact with the herbicide (Clayton and Severne 2005, MacDonald et al. 2002). The outcome of successful treatment is a substantial reduction in the standing biomass of weed beds, but eradication is not normally expected from amenity use.

11.4.1 Diquat

Diquat is a widely used herbicide (Clayton 1993) that is relatively fast acting (Cassidy and Rodgers 1989). The active ingredient is diquat dibromide, with a concentration of 1 mg a.i. per litre (i.e., a 1:100,000 dilution) recommended to control weeds. Diquat can be applied by boat using surface booms or subsurface injection via trailing hoses or booms. Helicopter application is appropriate for large areas under suitable weather conditions. Diquat is applied at a rate of 30 litres per ha water surface, regardless of water depth, with over 0.5 m depth further diluting applied diquat to <1 mg per litre (Clayton and Severne 2005). However, weed control has been achieved with application through several metres depth, at extremely low concentrations, as long as a sufficient contact time with plant tissue is achieved.

Diquat is highly effective against lagarosiphon, elodea, egeria and hornwort yet has far less effect on native submerged plants, with no effect on isoetes and charophytes. Control of these weeds is expected to last for a season or up to 1 year from treatment depending on species.

Diquat performance is best in dense weed beds that retain the herbicide for longer. Effectiveness can also be enhanced by the addition of gelling agents that help place the herbicide within the weed bed. Double application of the herbicide at half application rates is also thought to extend the contact time. Diquat efficacy is reduced in turbid water (Hofstra et al. 2001) or where plants are covered in organic matter or deposits of silt, which can rapidly bind the diquat (Clayton and Matheson 2010). Therefore, checks of plant and water conditions are a necessary step before proceeding with application.

Label instructions for diquat (and endothall below) give consideration to the risk of deoxygenation from decaying weed, and further precautions are advised to mitigate this risk (See Section 12.3).

11.4.2 Endothall

Endothall has an advantage of over diquat is that it is not deactivated by turbid water or dirty plant surfaces. Moreover, there is recent evidence for systemic action of the herbicide (Ortiz et al. 2017), with concurrent observations of action against the root crown of lagarosiphon not achieved by diquat. Disadvantages are that target weeds egeria and elodea have a low level of susceptibility to this herbicide and much longer concentration exposure time is required for effective control of susceptible species using endothall compared to diquat. Eradication of lagarosiphon and hornwort has been achieved in small water bodies using this herbicide (Wells et al. 2014). Due to the requirement for a long concentration exposure time, further research to evaluate endothall as a control (or potentially an eradication) tool in the Rotorua Te Arawa Lakes is required before this option could be widely recommended.

11.4.3 Regulatory environment for herbicide use in the Rotorua Te Arawa Lakes

The Bay of Plenty Regional Natural Resources Plan (RNRP) states that discharge of aquatic herbicide over water for weed control is a permitted activity (DW R1 (Rule 16). However, Rule 16 only applies to emergent aquatic weeds (growing above the water surface). Treatment of submerged weeds (growing and spreading below the water surface) is classified as a discretionary activity requiring resource consent under Rule 37 of the RNRP.

Resource consents are currently held by BOPRC for the discharge of endothall in Rotorua Lake catchments, and jointly with LINZ for diquat use in the Rotorua Te Arawa Lakes.

Endothall use is additionally subject to NZEPA controls under Hazardous Substances and New Organisms Act 1996 and the granting of a regional permission. Diquat use is not currently regulated by the NZ EPA.

11.4.4 Future herbicides

A range of aquatic herbicides used in other countries have not been registered for use in New Zealand. Amongst these are new generation herbicides that are effective at lower concentrations than diquat or endothall. Two such herbicides, Flumioxazin (contact action) and ProcellaCOR (systemic action), have had action against New Zealand aquatic weed targets confirmed. New aquatic herbicides must go through the registration process with the NZEPA before adoption here.

Also in use overseas is dual formulation diquat and endothall (e.g., Aquastrike). This herbicide combination has the advantage in treating mixed combinations of weed targets with differing herbicide susceptibility with one application cost. Requirements for use in New Zealand have not yet been explored.

Also unexplored is the application of diquat according to the water depth instead of flat area rate, as there is some label guidance according to depth given for this herbicide in the United States.

11.5 Mechanical harvesting

Mechanical harvesting refers to the cutting and collection of lake weed. Typically, a boat-mounted sickle bar cuts the weed below the water surface and the weed is entrained onto a conveyor belt as the harvester moves forward. The collected lake weed may then be transported to shore directly for "out-of-lake" disposal. Weed may also be shredded using a boat-mounted unit to reduce the bulk of harvested material thereby increasing the amount of weed that can be harvested prior to offload at the shore. Most mechanical harvester units extract weed from water depths down to c. 2 m below the water surface. However, some recent models are able to extract weed (at limited volumes) from water depths up to 5 m (e.g., Freshwater Environmental Management Pty Ltd FEM 625-8). The 70 ft "Kelpin" harvester with a 5 m cutting swath and 3 m depth range can reportedly harvest up to 1 acre (4047 m^2) of surface-matted hydrilla (*Hydrilla verticillata*) per hour (Haller and Jones 2012). In contrast to mechanical harvester units, boat-mounted shredders are not as readily available on the commercial market. The few units currently in operation in New Zealand have been constructed in-house (e.g., "Lois" by Mighty River Power).

Currently a commercially available mechanical harvester unit (Lakeweed harvester) is utilized on Lakes Rotoehu and Rotoiti. The prime purpose for harvesting on Lake Rotoehu is not for weed control, but for nutrient remediation; the removal of sufficient nutrients in weed tissue that offset nutrient loading to the lake from the catchment. Harvesting is focussed on Te Wairoa Bay, a natural collection point for drifting hornwort and a shallow area suited to a fast growth rate. This means that the short distances travelled by the harvester and locally available off-load site enable efficient, high volume removal of weed. This situation differs fundamentally from a weed control scenario where harvesters must cover a long distance of shoreline to harvest in situ weed and return to limited offload sites.

The operational attributes of the unit operating on Lake Rotoehu are as follows (H Emeny pers comm., Lakeweed Harvesters & Contractors, August 2015):

- moves at a speed of 4 km/h with a full load and at a speed of c. 3 km/h when cutting
- it can accommodate 10 m^3 of wet weed which takes c. 6 min to load (if the weed is dense)
- it cuts in a 2 m wide swath to a maximum depth of 1.8 m (ideal maximum cutting depth is 1.2 m)
- it can clear a ca 5 ha area of dense weed in approximately 120 h with a 50 m distance to offload onshore; this is equivalent to a harvesting rate of 400 m^2/h.

Offloading and land disposal of harvested weed is usually the primary cost and time factor in mechanical weed control operations (Sabol 1987). It requires suitable lake-side offloading sites for the required heavy machinery (often excavators and trucks) (McComas 2011). Transport costs can also be high for bulky wet weed. Disposal of invasive weeds from the Rotorua Te Arawa Lakes raises issues about their transportation as designated Unwanted Organisms' (requiring permits) and disposal due to high component levels of arsenic posing a contamination risk. Some these costs might be offset by weed disposal 'subsidies' generated by use of harvested weeds in composting, vermiculture or for the generation of biogas energy (Hofstra et al. 2015). As with other control methods such as herbicide application, optimal weather conditions are required, for example harvesters cannot operate in strong winds or currents

In-lake disposal by shredding, eliminates the need for transport of harvested weed to shore (Sabol 1987, Madsen 2000). Shredding damages air spaces in submerged weed species like hornwort and the shredded material is negatively buoyant and sinks to the lake bed (Sabol 1987, Kuczynski et al. 2018) so there is minimal amenity nuisance associated with floating shredded fragments. An exception to this is the practice of weed cutting only where fragments often remain buoyant for some time. Nutrient release and decay of shredded weed, if returned to the water, could potentially enhance phytoplankton growth and oxygen consumption (e.g., James et al. 2002).

Sabol (1987) reported that in-lake disposal of hydrilla reduced harvester down time by 50%. The in-lake shredding unit operated by Mighty River Power for management of drifting weed (not littoral weed beds) can process weed at the following estimated rates which vary depending on weed density: 603 m^3/h for very dense weed, 186 m^3/h for dense weed, 93 m^3/h for medium density weed and 46 m^3/h for low density weed (Mitchell 2009, Matheson 2014). Thus the processing capacity of the shredding unit exceeds the collection capacity of the Lakeweed mechanical harvester even for areas with dense weed stands, the latter being 100 m^3/h if in continuous operation with in-lake shredding and disposal.

Mechanical harvesting will not remove all weed biomass, and weed beds may re-establish relatively quickly from root crowns or remnant stems that are not removed. Calculations for hornwort based on known growth rates and realistic standing crop suggested recovery from harvesting to the point where surface reaching weed beds re-established would take as little as four weeks over spring to summer (Hofstra et al. 2015). Harvesting of weed beds to a depth of 2.5 m (deeper than the operating depth of most harvesters) in the Waikato hydro-lake provided 6 months control for egeria in Lake Ohakuri and 1 year of control for lagarosiphon in Lake Aratiatia (Howard-Williams et al. 1996).

Table 4: Control methodologies screened for use in the Rotorua Te Arawa Lakes. Methods are summarised by their application, likely effectiveness, relative cost (by application), advantages and disadvantages. Green shading indicates the method has current application to the lakes, amber indicates possible use after further investigation, red shading indicates method is unlikely to be useful/acceptable.

Method	Application	Effectiveness	Relative cost	Advantages	Disadvantages
Hand removal	Incursion response only	Highly effective given small isolated plants & experienced divers. Can achieve site eradication.	High cost as labour intensive ($10k per ha)	Immediate removal, no adverse effects, easily integrates with surveillance activities.	Limited to isolated plants or clumps ≤1m², needs good water clarity & low surrounding vegetation for detection. Small plants may not be detected until they have grown larger.
Suction dredge	Incursion response only	Highly effective at reducing biomass in medium size patches/narrow beds.	High cost as labour intensive $7k – 20k per ha).	Immediate removal, fragments well contained, but follow-up hand removal required, selective therefore few adverse effects.	Debris, rocky or hard packed substrates reduce effective removal and increase cost.
Bottom lining (jute hessian)	Incursion response Long-term amenity control	Can eradicate outlier colonies, amenity control in limited areas, medium-term control (up to a few years), control in 4-5 months.	High cost as labour intensive ($30k per ha).	New biodegradable materials are easier to lay, may act as geotextile in stabilising sediments when weed removed and facilitate native plant recovery .	Requires consent, questionable feasibility for areas >5000 m², requires reduction of weed biomass first, sedimentation allows re-colonisation of area, lining can be dislodged by wave/currents.
Mechanical harvesting	Nutrient remediation Short-term amenity control	Can remove c. 80% of biomass if depth ≤ 2m and gradient suitable.	Machinery outlay is the major cost (c. $200k).	Large areas can be controlled quickly for amenity benefit. Lake nutrient remediation.*	Limited to cut of ≤2 m depth, rapid regrowth, non-selective, large release of fragments, machinery difficult to decontaminate therefore usually dedicated to a waterbody. Operations are weather dependent.
Diquat herbicide	Medium-term amenity control	Capable of removing >90% of biomass, control lasts at least a growth season, unlikely to achieve site eradication.	Moderate cost $1.6k per ha (permitted activity).	Large areas can be controlled quickly, slows recovery as plants reallocate reserves to undamaged buds, moderately selective, few adverse effects.	Deactivated in turbid water, lake currents may remove or dilute herbicide, woody stems and root crowns highly resistant.

Method	Application	Effectiveness	Relative cost	Advantages	Disadvantages
Endothall herbicide	Long-term amenity control	Capable of removing >90% of biomass, control lasts at least a growth season.	Moderate to high cost (need to meet conditions of EPA controls/permissions and regional council consents) – subject to re-assessment and new permissions.	Not deactivated in turbid water, partially selective, few adverse effects, aqueous or pellet formulations.	Needs a long contact time, currently only used in small waterbodies or enclosed areas, use requires additional NZEPA approvals .
Rototiller	Medium-term amenity control	Can provide >6 months control over 1.5 to 4 m depth under suitable depth and sediment conditions (Clayton et al. 2000, Wells et al. 2002).	Machinery outlay is the major cost.	Deep rototilling can provide longer control (but is more expensive).	Consent required, non-selective, poorer control on harder substrates or shallow rototilling, large release of fragments, machinery difficult to decontaminate.
Grass carp	Eradication	Capable of weed eradication on whole lake basis within a few years.	Very high cost based on containment structure, fish numbers required & approvals process.	Achieves eradication from a lake.	Non-selective control, removal of native plants. Long-term impact (30 years+), containment required (prevent escape to Kaituna River, up tributaries).
Water drawdown	Medium-term amenity control	Desiccation or freezing can reduce biomass temporarily, unlikely to eradicate.	Construction of a water level control structure would be extremely costly.	Relatively easy to carry out if water level control structure (e.g., dam) and any necessary consents for drawdown already in place.	Not applicable to lakes without an outflow. Requires water level control structure, large, sustained fluctuation required, large adverse effects (erosion, loss of habitat).

12 Potential impacts of control tools

12.1 Bottom lining

Use of jute hessian material would have a lower impact on macroinvertebrates than other lining materials. The weave of hessian allows small macroinvertebrate species to migrate between the sediments and water column, and for some native plants (e.g., charophytes) to grow through the mesh (Caffrey et al. 2010, Hofstra and Clayton 2012).

Outcomes of bottom lining for larger, non-motile organisms like kākahi (freshwater mussels) is not known, but it is observed that kākahi avoid dense weed beds that are the target of this control method. As mats break down, they could provide a colonisation opportunity for juvenile kākahi.

12.2 Harvesting

Harvesting is a non-selective method, so native plant species are removed along with weed species. Entrapment and death of non-target biota (particularly fish and invertebrates) in harvested weed has also been identified as significant (Wile 1978, Haller et al. 1980, Engel 1990). Disturbance of bottom sediments during harvesting operations results in localised increases in water turbidity and dissolved nutrient concentrations (e.g., James et al. 2002). Finally, motor noise associated with harvesting may be an annoyance for residents and potentially restrict hours of operation.

12.3 Herbicide

The toxicological information for herbicides registered for use in New Zealand is extensive and no risk to biota and human health is expected when they are used according to the label and other legal requirements (e.g., Clayton and Severne 2005). They have been assessed and permitted for aquatic use by the NZEPA. Therefore, toxicology is not covered in detail here. Of note is that diquat is available in the water column for a very short time-frame (minutes to hours). Adsorbed diquat has no residual toxicity, is not biologically active and is degraded slowly by microbial organisms within sediments. No accumulation of diquat could be detected in sediment at sites that have been regularly treated for decades (HortResearch 2001).

A PhD Thesis (Graham 1976) found no evidence of impacts from diquat use in Lake Rotoiti on trout fisheries, plankton or benthic organisms, with the conclusion that deactivation via sedimentation, adsorption and degradation of diquat meant continued long-term use was acceptable. Studies on the outcomes of herbicide use for lake ecology are limited. However, in one example responses to the selective reduction of an invasive macrophyte using herbicides had no detrimental impact on littoral fish and macroinvertebrates due to rapid restoration of the native vegetation (Kovalenko et al. 2010).

An investigation into the impact of weed beds and diquat spraying on kākahi in Lake Rotorua (Wells and Clayton 1996) showed the negative influence of unconsolidated substrate, often associated with dense weed beds (egeria), was significant whilst diquat treatment history (including sampling before and after) was not. It also established that chronic exposure of kākahi to diquat in excess of that which would be experienced during operational use (five times the allowable diquat concentration for two months) did not result in mussel death (Wells and Clayton 1996).

Physico-chemical outcomes from herbicide use in lakes are more relevant and potentially include impacts on dissolved oxygen and/or nutrient release stimulating algal blooms (Scholes 2015). Nevertheless, these risks can be largely mitigated by timing herbicide use at times of low water temperature and by limiting the plant biomass that is targeted (e.g., New Zealand label requirements to treat no more than 25% of a waterbody at once).

Evidence for simultaneous rapid nutrient release following operational herbicide use is generally lacking. The herbicide effect does not usually result in immediate tissue death, both diquat and endothall having an extended 'biostatic' effect on target plants. Tissue damage and death leading to breakdown of material after treatment may take weeks to months depending on the water temperature (Figure 27). Nutrient release from dead plant material may occur over a long time (Asaeda et al. 2000), but N release was also found to be rapid (leaching over the first 2 days) in macrophyte cells damaged by freezing (Howard-Williams et al. 1988). Therefore, the timing and degree of nutrient release following herbicide use may vary under different situations, with a further unknown nutrient component likely to be contributed directly to sediments. Nutrient release from herbicide use should also be considered against the continuous contribution of ongoing senescence of high biomass weed beds.

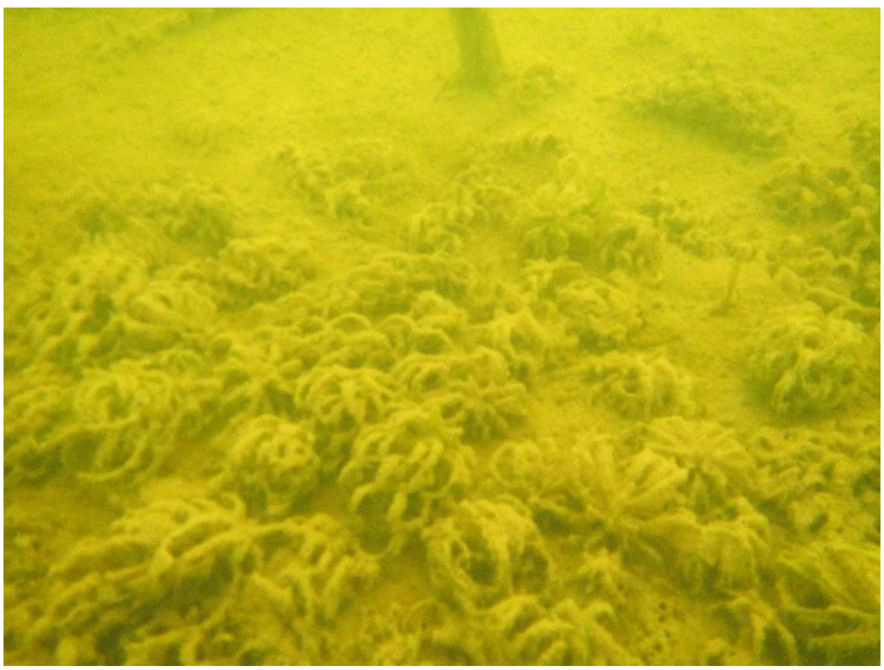

Figure 27: Detached, inviable apices of lagarosiphon accumulated on the sediment four months after diquat treatment at the Ahuriri Delta, Lake Benmore.

Elsewhere, modelled decomposition from seasonal macrophyte dieback has shown, via sensitivity analysis, that factors influencing nutrient release were the composition of rapid versus labile decomposable fractions, oxygen concentrations (determining aerobic and anaerobic processes), time and the most importantly water temperature (Asaeda et al. 2000).

Instances of large DO reductions following herbicide use are unusual, even when substantial weed biomass is treated. No marked changes in DO or nutrients were detected in monitoring for 12 days post treatment in two US lakes treated with diquat (5% and 81% of area treated) in combination with other herbicides (Serdar 1997). Even in a US lake where the target plant (egeria) dominated the vegetation and the entire littoral zone was treated (27% of this 11 ha lake), DO in the epilimnion declined by about 10% within 1 to 2 weeks after treatment (Parsons et al. 2007). In a 10 ha, New Zealand lake dominated by hornwort to 3 m tall, the use of endothall resulted in a 95% weed removal but weekly DO measurements at four depths showed a lowest reading of 6.4 mg l^{-1} occurred in the bottom of the lake after 14 days after treatment (Wells et al. 2014). Ecological impacts from herbicide use should also be considered against the ongoing influence of dense weed beds on DO (Section 6.2.2) as there is potential for control to improve local conditions.

This account highlights the need for better knowledge around risks of adverse effects from operational herbicide use, but we note the difficulty in linking observational water quality data to herbicide events as a causal factor amongst many other environmental variables.

13 Current and future aquatic plant management

13.1 Current weed management strategies

Continuation of proactive management including summer awareness programmes and surveillance will be important to protect the remaining lakes with limited weed species presence (i.e., Rotomā, Ōkaro, Rotokakahi). Newly drafted weed management plans provide lake specific goals, objectives and control approaches for the identified weed issues. These plans consider biosecurity, amenity and ecological aspects together for the first time. It will be important that these plans remain current and adaptive to changing lake situations and annual operational plans are derived from them.

Surveillance undertaken by BOPRC to detect new weed incursions at an early stage has been assessed (sites, frequency and search techniques) and confirmed as current best practice (Champion 2009, de Winton et al. 2014).

Currently, pre- and post-treatment monitoring is communicated between BOPRC staff and the operational manager of weed control (Boffa Miskell Limited). It would be beneficial to formally document these monitoring results to ensure transparency and efficiency in the operational programme. Reporting of weed management outcomes to demonstrate the value of works and progress achieved is a further consideration. However, there is an important balance to be struck between the cost of monitoring and reporting and impacts on the budget available for carrying out control works.

13.2 Future weed management

13.2.1 Use of LakeSPI for monitoring and reporting

LakeSPI targets and limits are currently being considered for the Rotorua Te Arawa Lakes in respect to weed management and also as an attribute for lake ecological health under the National Policy Statement for Freshwater Management. A *present-day target* and *limit* set for the lakes might be based on the highest and lowest LakeSPI value generated for each of the Rotorua Te Arawa Lakes since regular LakeSPI surveys began in 2005 (Figure 28). This combined *present-day target* and *limit* would represent a commitment for council to maintain and/or improve the condition of the lakes based on achievable conditions experienced over the past 12 years. Furthermore, an aspirational *longer-term target* is being considered that would aim to improve the condition of all 12 Rotorua Te Arawa Lakes over the next ten plus years to a condition more similar to what they are likely to have been in the 1960's (Figure 28).

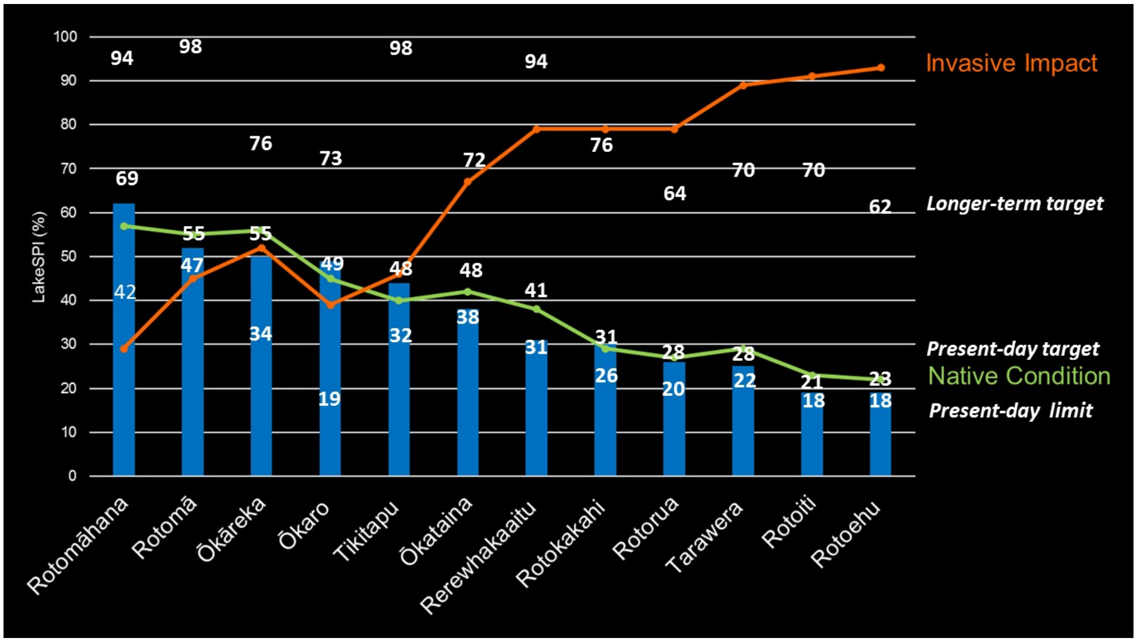

Figure 28: LakeSPI results for the Rotorua Te Arawa Lakes from 2016 and 2017 surveys. Current LakeSPI Index (blue bars) and accompanying indices (coloured lines), with white values indicating the position of potential present-day limits (lower value), present-day targets (middle value) and longer-term targets (upper value).

13.2.2 Future weed monitoring

'Apps' for devices such as mobile phones (e.g., https://www.imapinvasives.org/) open up many possibilities for participation of the community and general public in reporting weed issues or status for recreational use. Amongst the most useful application of this technology would be public submission of GPS-tagged observations of weed bed status, supported by photos. Another potential dimension of such an app would be provision of information on aquatic pests, identification resources and Check, Clean, Dry principles and precautions. Mapping of submerged vegetation is economically viable on a wider scale than ever before using hydro-acoustic data, GIS referenced aerial photography with multi-spectral imagery and LIDAR from Unmanned Aerial Vehicles. Regardless of the method(s) used, ground truthing of the mapped resources is essential.

Advances in hydro-acoustic technologies now provide off-the-shelf functionality in recording and mapping bathymetric, vegetation (as % biovolume) and bottom substrate hardness. Processed hydro-acoustic information in the form of % biovolume (a measure of occupancy of the water column) provides an indication of likely interference with recreation (Figure 29) and can be used to assess weed control outcomes. Application of hydro-acoustics to the lake is also aided by use of autonomous/unmanned survey vessel (e.g., HyDrone autonomous survey vessel purchased by NIWA) that can navigate programmed run-lines, allowing surveys to be undertaken cheaply with minimal supervision. C-Map (http://www.genesismaps.com/) allows hydro-acoustic data files from compatible sonar/GPS units (Lowrance, Simrad and B&G) to be uploaded and processed to develop maps of bottom features. Again, this raises possibilities for involvement by the public in recording vegetation status in lakes. 'Social Map' takes crowd-sourced hydro-acoustic data to generate bathymetric charts (http://www.genesismaps.com/SocialMap/Index) that are available and updated as more data is added (including some Rotorua Te Arawa Lakes). Unfortunately, vegetation mapping capacity is only possible via a subscription services (Genesis Edge or BioBase), so one agency would have to receive, upload and manage hydro-acoustic data.

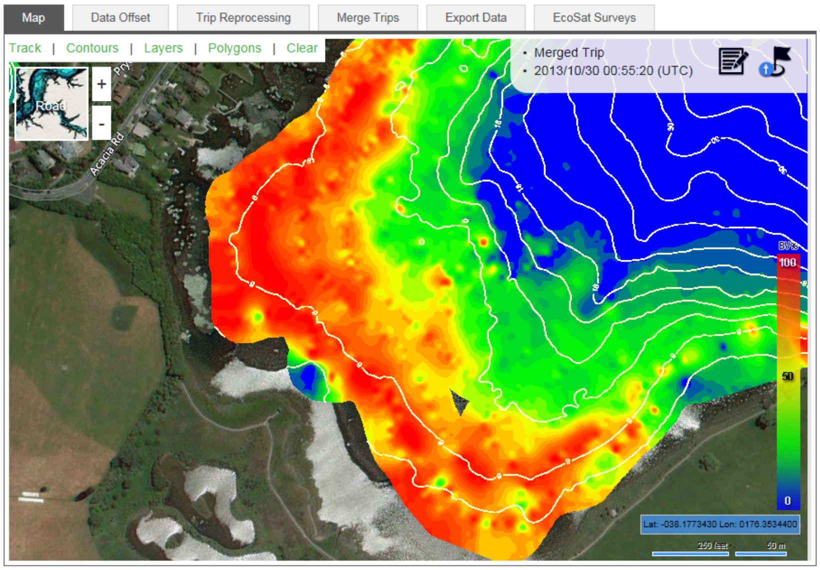

Figure 29: Vegetation biovolume (% occupation of the water column) generated from logged hydro-acoustic data taken at Acacia Bay, Lake Ōkāreka, and processed via BioBase (http://www.cibiobase.com/).

Environmental DNA (eDNA) is a recently developed and increasingly utilised biosecurity tool for detecting target organisms DNA amongst background DNA. To date, eDNA does not appear to have been used operationally for detecting aquatic weeds however some investigations have been published. Potential eDNA markers have been identified for hornwort, elodea (Sciver et al. 2015) and egeria (Fujiwara et al. 2016). Detection of eDNA of egeria and another Hydrocharitacean species has been demonstrated for small ponds, and some evidence of use for quantitative assessment has been gathered (Fujiwara et al. 2016, Masuhashi et al. 2016). Identified issues included changing levels of plant eDNA over time, speed of DNA degradation, lack of detectable quantities of eDNA and non-detections (false negatives) (Fujiwara et al. 2016). Application as an incursion detection tool in large lakes, with very limited initial weed occurrence, is as yet unclear. It is important to note that eDNA will not substitute for delimitation surveys required as the first step in an incursion response.

Technological advances in underwater vehicles, and underwater 'computer vision' opens possibilities for new ways to detect low incidence aquatic weeds (i.e., incursions), for monitoring and documenting outcomes from submerged vegetation management. BOPRC have invested in a remotely operated underwater vehicle (ROV), which has a number of potential applications (e.g., water and sediment sampling) (Lass 2017). A growing field is 'computer vision' - the analysis of real-time or captured images to detect/distinguish target weeds on the basis of colour spectrum, reflectance and/or shape factors (automated plant recognition). Application to underwater environments may be challenging due to complications of variable water clarity, colour and epiphytic algal coverings on target plants.

14 Future native plant management

14.1 Likelihood of native expansion and main drivers

Natural expansions in the development of native vegetation are expected with ongoing improvements in water quality of the Rotorua Te Arawa Lakes. Charophyte 'meadows' would expand in depth extent and in area where they are present, and would also develop wherever light penetration provides a niche habitat beyond the deepest potential depth of weeds (which are possibly pressure-limited).

Another plant community to benefit from water quality improvements is isoetes. However, recovery would be on a longer time-frame than for charophytes as isoetes plants are slow-growing and part of the response may reflect slower, sediment-mediated changes relating to lower lake productivity.

Invasive weeds are a major structuring influence on native vegetation of the Rotorua Te Arawa Lakes and continued or expanded weed control would be a strong driver for native vegetation expansion (see Section 14.2).

Native vegetation stability would be maximised where conditions allow diversity of plant form and function and conditions are maintained for a sufficient time-frames for seed bank development. Accelerating or augmenting native vegetation establishment may require specific techniques which are outlined below.

14.2 Enhancement/restoration techniques for native plants

Native plant translocations would be required in situations where no colonising sources are available, or propagule numbers restrict recovery potential. For the Rotorua Te Arawa Lakes opportunities exist to introduce conservation species with a national threat status such as *Isolepis lenticularis* (known from Lake Taupo), *Utricularia australis* (known from pre-eruption Lake Rotomāhana) or other submerged or marginal plants. *Nitella opaca* and isoetes are species that have declined in the lakes and may be augmented by plantings at historical sites.

Changes to the application of control tools or intensity of their use can take aquatic weed management beyond biosecurity or amenity use to achieve biodiversity outcomes. This concept is encapsulated in (Figure 30) showing that the target of restoration requires more initial investment but achieves higher native values than nuisance control alone.

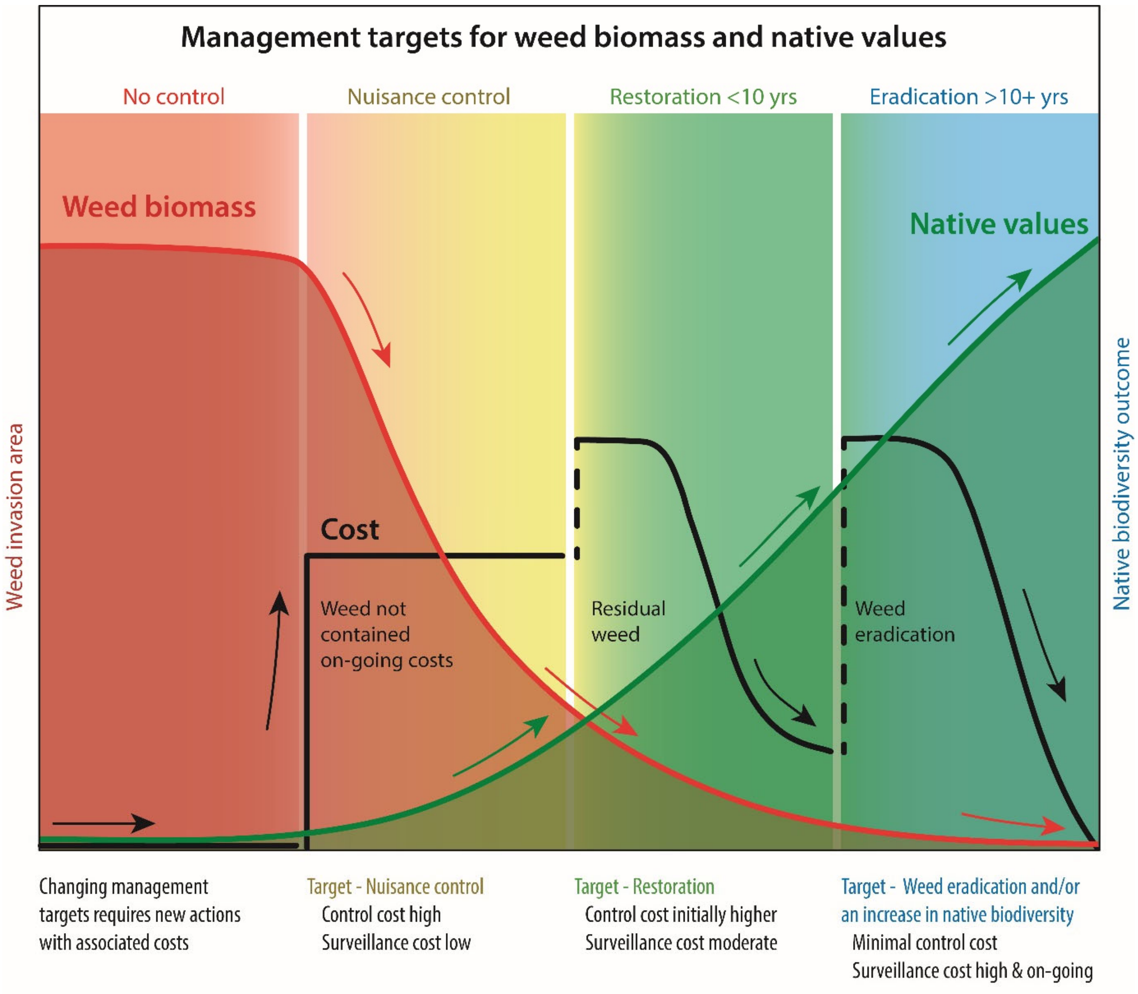

Figure 30: Diagrammatic illustration of management targets for weed biomass reduction and outcomes for native biodiversity restoration. The four vertical panels represent key decision points and targets for weed control; the black, red and green lines indicate (respectively) the relative cost (dollars), weed biomass, and increasing native values as weeds diminish.

Control tools that can have outcomes for restoration of native vegetation include bottom lining using jute hessian. This material smothers target weeds but allows native plants to grow through the materials mesh, including charophytes (Caffrey et al. 2010, Hofstra and Clayton 2012), pondweeds and the quills of isoetes. Other restoration benefits as yet unexplored include geotextile stabilisation of lake sediments as an anchorage for native plants, or as a means to introduce propagules of native plants.

Herbicide use can release native plants from competition from weeds. The specificity of herbicides used in New Zealand means that many native plants are much less susceptible to diquat or endothall at the concentrations used to control target weeds. Endothall has the potential for a long weed control period that would maximise native plant recovery. Diquat applied as a double application (i.e., twice annually) to follow up initial results by controlling fresh regrowth can also have an effect lasting greater than 1 season or year. This result has been seen in Lake Okareka, where twice yearly treatment for the hornwort incursion response, achieved a significantly more native lake (Burton

2017a). Herbicide might also be strategically used to periodically allow a flush of native vegetation to augment sediment seed banks.

Likewise repeated mechanical harvesting of weed beds close to substrate level (as suction dredge or cutting) can allow regeneration of native plants from sediment seed banks (e.g., Howard-Williams et al. 1996).

In addition to enhancement actions, protection of native vegetation should be considered. One major threat would be disturbance by introduced pest fish, especially herbivorous rudd (*Scardinius erythrophthalmus*), koi carp (*Cyprinus carpio*) and catfish (*Ameiurus nebulosus*). Catfish are newly established in Lakes Rotoiti and Rotorua. Further biosecurity initiatives to prevent the spread and establishment of these species would be advised.

Elsewhere, shoreline armouring (hardened and reconfigures shorelines and structures) have been shown to have a negative influence on submerged vegetation (Patrick et al. 2016). This suggests care should be taken in modifying shorelines and that redesigning or removing shoreline armouring structures may benefit nearshore native submerged vegetation.

15 Research/knowledge gaps

This section was informed by a workshop (7th June 2018, attended by BOPRC staff, Lakes Water Quality Society, and NIWA) and is provided in bullet form only. Once important knowledge gaps are identified they may be prioritised as short-term versus long-term needs.

15.1 Weed management

1. In the cases of lakes outside of the Te Arawa Lakes Deed of Settlement (Lake Rotokakahi and Lake Ōkaro), it is unclear who is responsible for aquatic plant management (no devolved landowner responsibilities) or incursion response should a major weed invade.
2. Improving early detection and rapid response – what is possible?
3. What future control technologies will be suited to weed targets, goals and lake conditions? (widescale Endothall use, Diquat application rate by depth, Aquastrike, Flumioxazin and ProcellaCOR, biocontrol)?
4. Placement methods for herbicides – how best to get them to the target weed bed to achieve required Concentration-Exposure-Time.
5. Good aquatic plant maps (areas of each species and heights and/or biovolumes) for each lake would provide useful current baseline for future progress and add to temporal sequences of maps dating back to 1970s.
6. What future invasions are the lakes vulnerable to? (bladderwort, hydrilla, cabomba, waternet, *Lindavia* (lake snow), didymo).
7. Social license – how to get the community onboard with initiatives, raise profile/understanding (agreed that laypersons resources could be developed from this report, LWQS also want to develop resources). Changing the from biosecurity emphasis to restoration for more inspirational messaging. Involving community in lakeside monitoring (NIWA initiative underway).
8. What are the possible impacts resulting from herbicide use and how to assess risk? (de-oxygenation and nutrient release).
9. Can we accurately predict success of hornwort or egeria under different lake and nutrient conditions?
10. Risk assessment – what are the risks of new incursions, changed impacts (climate change, water clarity improvements) compared to risk of doing nothing? This informs social licence.

15.2 Ecology

1. What are the impacts of large weed beds on fish, kākahi and kōura in the lakes or their customary or recreational take?
2. What is the role of invasive weed beds in interception and uptake of nutrients/sedimentation and O_2 depletion.

3. What is the natural turn-over rate for invasive weed beds compared to the turn-over achieved by herbicide and temporary removal of biomass? May require a modelling approach.

4. Nutrient remediation using hornwort– is harvesting predominantly removing sediment-based nutrients?

5. How do pest fish interact with aquatic plants.

16 Acknowledgements

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Appendix A Literature review

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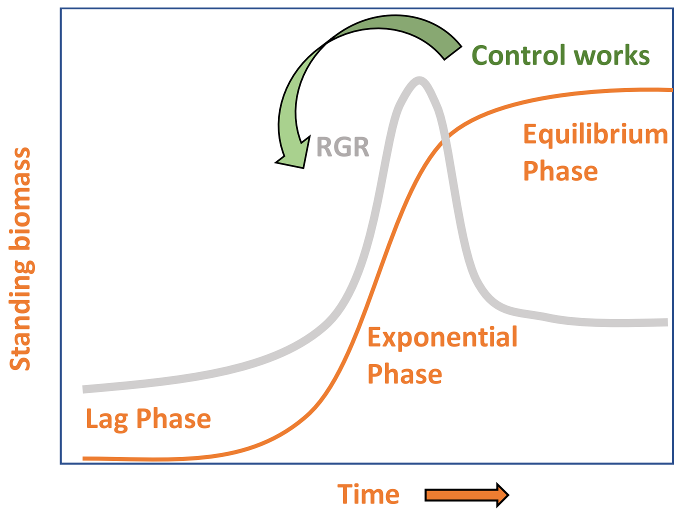
Appendix B Growth rates of major weeds

Table B-1: Range of reported growth values for the major weeds as relative growth rates (RGR) expressed on a length or biomass basis or doubling time.

Species	Shoot length RGR	Dry weight RGR	Doubling time (days)	Reference
Elodea canadensis		0.038–0.13 day^{-1}	11.0	Cedergreen Forchhammer 1999, Bianchini et al. 2015.
Egeria densa	0.018-0.032 day^{-1}	0.04-0.069 day^{-1}	14.3	Thiébaut et al. 2016, Bianchini et al. 2015, Dollerup et al. 2013.
Ceratophyllum demersum	0.04-0.07 $week^{-1}$	0.03-0.17 $week^{-1}$ 0.06-0.08 day^{-1}	16.1	Stiers et al. 2011, Bianchini et al. 2015, Hyldgaard et al. 2012.
Lagarosiphon major	0.02-0.063 day^{-1} 0.17-0.21 $week^{-1}$	0.10-0.19 $week^{-1}$		Stiers et al. 2011, James and Eaton 2006.



Lag phase. Weed fragments lodge in a suitable location, root extension and anchorage begins (except for hornwort) with access to sediment nutrients and growth rate increases.

Exponential growth phase. Plants are growing at maximal rates within the limitations of resource supply (light, carbon, nutrients). Upper values for RGR in Table B-1 are reflective of this phase.

Equilibrium phase. Self-shading and intra-bed competition for resource limit growth to maintenance only.

Note control works can be associated with a return to exponential growth.