Assessment of the health and the restoration potential of the Putere Lakes, Hawkes Bay

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Executive Summary

1. Rotongaio, Rotoroa and Rotonuiaha (collectively referred to here as the Putere Lakes) are located approximately 50km north-west of Wairoa in northern Hawkes Bay. Ngāi Tūhoe, Ngāti Ruapani and Ngāti Pāhauwera are the mana whenua that share interests in the Putere area.

2. This report combines (1.) a community consultation process with mana whenua to determine the values that the lakes provide to the local community, (2.) a scientific assessment of the current conditions of the lakes and the ecological stressors that prevent the lakes from reaching their mahinga kai and recreational potentials, and (3.) the development of a set of recommendations to begin the process of lake restoration.

3. The Putere Lakes are of great signficance to mana whenua. as reservoirs of native aquatic biodiversity, as sites of mahinga kai gathering, and for recreation.

4. The water quality of Rotongaio is very poor and, furthermore, the lake appears to be on the cusp of losing its submerged macrophyte community. The loss of macrophytes would substantiate the transformation of the lake into a persistent, highly degraded, eutrophic state characterised by low water clarity and nuisance cyanobacterial blooms.

5. In contrast, the water quality of Rotonuiahā and Rotoroa has improved substantially since first reported in 1983, but this has at least partly been due to the proliferation of invasive hornwort, which negatively impacts biodiversity, recreation and mahinga kai gathering.

6. Due to the differences in the condition and trajectories of the lakes, recommended restoration actions for Rotongaio differ to some extent from those recommended for Rotonuiahā and Rotoroa. Reducing external nutrient and sediment inputs are likely to benefit all three of the lakes; however the focus in restoring Rotonuiahā and Rotoroa should be on hornwort control. Caution will have to be exercised when attempting to reduce hornwort cover and biomass so that this does not result in increased nutrient availability to phytoplankton.

7. Currently, there is a lack of information regarding the magnitudes of sediment and nutrient inputs to the lakes. In particular, it is not apparent whether internal nutrient loads from the lakebed sediments to the water column contribute substantially to phytoplantkon and macrophyte biomasses in the lakes.

8. Significant knowledge gaps exist that hinder the identification of a robust and cost-effective set of restoration actions that will deliver desired restoration outcomes. However, the undertaking of some feasibility studies, together with the collection of more data and information will allow for the co-development of a focused and effective restoration/management plan for the lakes.

9. Below is a set of recommendations for moving forward with a restoration plan.

Recommendation	Relevant sections in this report	Timing
1. Estimate catchment contaminant loads	7.2, 8.8.2, 8.2.4	Immediate
2. Undertake a feasibility study for hornwort control in high-value, localised areas of Rotonuiahā	7.1, 8.1.2	Immediate
3. Undertake a feasibility study to determine whether lake-side wetland areas could be re-established to remove contaminants from tributary inflows	7.2.3, 8.2.4	Immediate
4. Expand monitoring programme	8.1	Immediate
5. Determine lake bathymetry, volumes, and water residence times	7.3.3, 8.2.1	Immediate
6. Develop a riparian planting programme to protect streams and lake shores from stock access and from overland flows	7.2.2	Immediate
7. Calculate nutrient and sediment budgets for lakes	8.2.2	Contingent on recommendations 1, 4, and 5
8. If internal phosphorus loading is determined to be substantial, undertake a feasibility study to assess the potential to reduce internal phosphorus loading	7.3.1, 8.2.2, 8.2.3	Contingent on recommendation 7

10. It could be useful to hold a wānanga together with some experts in lake restoration science and mātauranga to discuss this report, to delve deeper into potential restoration actions, and to help initiate a restoration plan for the lakes.

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1 PART A: PUTERE LAKES COMMUNITY VALUES, DATA AND MĀTAURANGA (BY KATHRYN GALE)

1.1 BACKGROUND/WHAKAPAPA

Rotongaio, Rotoroa and Rotonuiaha (collectively referred to here as the Putere Lakes) are located approximately 50km north-west of Wairoa in northern Hawkes Bay. Ngāi Tūhoe, Ngāti Ruapani and Ngāti Pāhauwera are the mana whenua that share interests in the Putere area. The Putere Lakes are of great signficance to mana whenua. Putere Marae is located at the southern end of Rotonuiaha (Kathryn Gale, pers. comm.).

It is important to acknowledge that this report has been written by Ngāti Pāhauwera from a Ngāti Pāhauwera perspective. Ngāti Pāhauwera recognises the mana of the other iwi with interests in the Putere area and works with other mana whenua groups whenever possible.

1.2 DATA AND MĀTAURANGA SOURCES

Mātauranga sources that inform this document include:

- Oral histories passed down through generations of Ngāti Pāhauwera shared by iwi members
- Interviews and personal comunications with mana whenua
- Tribal written sources including submissions, hearings evidence, interview transcripts
- Iwi documents such as Treaty Settlement documents and legislation, and iwi plans and policies
- Wānanga with the community at Putere Marae

Due to the sensitive nature of this mātauranga, some information is kept separately by mana whenua and has not been included in this report.

1.3 LOCAL HISTORY AND ASSOCIATION WITH THE AREA

1.3.1 Ownership

Rotongaio was vested in the Ngāti Pāhauwera Development Trust Ltd ("NPDT") when Treaty Settlement occurred in 2012. This lake has a Conservation covenant. Land surrounding Rotongaio is in private ownership.

Half of the bed of Rotoroa was also vested in fee simple title in the name of NPDT. The rest of the lake is in Maori land title and private ownership. Rotoroa also has a conservation covenant. (NPDT 2015).

Rotonuiahā is in private ownership including whenua Māori. The island of Te Putere (in Rotongaio) is privately owned Maori Freehold Land.

It is important to acknowledge that at the time of Ngāti Pāhauwera's settlement in 2012, Ngāti Pāhauwera and Ngāi Tūhoe had kōrero about the ownership of the lakes coming to Ngāti Pāhauwera through settlement. It was acknowledged that although these areas would be vested in NPDT, this did not extinguish any other iwi or hapū interests in the area and that all mana whenua in the area would work together to care for the lakes.

There are wāhi tapu and sites of extremely high cultural significance in and around the lakes (NPDT 2015). These include a settlement supported by mahinga kai from the lakes. This is also supported by the location of an urupā beside Rotongaio and references to other unrecorded sites (Pishief & Bain 2009).

There are many sites of singificance in the area. Four archaeological sites have been recorded in the area. These include a pā close to Rotongaio (W19/122), pits and terraces (W19/123), an eeling ditch (W19/125) and a pā (W19/124) on the edges of Rotonuiaha. Many of the hills around and overlooking Rotoroa have kākahi middens on them. Another eleven sites at Putere have not been officially recorded yet (Pishief & Bain 2009).

To the west along Putere Road from Rotongaio is the Putere Scenic Reserve, which is a significant wāhi tapu site (Pishief and Bain, 2009).

Pu Kakaramea is the name of the maunga that makes up most of the reserve. It is sacred and is of great significance to the hapū of the area (Pishief & Bain 2009). King (1975) notes that Pukakaramea was one of the main areas of permanent Māori occupation. Roto nui a hā can be translated as 'the lake of great breath'. Rotoroa can be translated as 'long lake'.

Figure 1. Rotonuiahā

1.3.2 Mahinga kai

The Putere Lakes are known for a variety of mahinga kai including:

- tuna/eels (Hill 1998; NPDT 2015)
- tī kouka/cabbage tree (Huata, date unknown)
- kākahi/freshwater mussel (Pishief & Bain 2009; Kathryn Gale, pers. comm.)
- kōura/freshwater crayfish (Kathryn Gale, pers. comm.)
- watercress (Putere Marae Wānanga, 11th June 2022)
- ducks (Putere Marae Wānanga, 11th June 2022)
- trout (Putere Marae Wānanga, 11th June 2022)
- raupō is present and is likely to have been a mahinga kai resource

Pishief and Bain (2009) note that "The area has high cultural significance to Ngāti Pāhauwera and is recorded as an area that is very good for eeling. Evidence of settlement in the area is extensive as would be expected from a significant eeling location." The community continues to use the lakes for eeling today (Putere Marae Wānanga, 2022).

Rongoā species (having medicinal values) found in the area include kōwhai, kānuka, mānuka, mamaku, karamū, kareao, ponga and houhere (Perception Planning 2020).

Putere was a significant hua manu (bird hunting area) (Waaka 2018). As noted above, tītī were a signficant traditional food source in the area. Unfortunately these manu can no longer be harvested, but restoration efforts are underway at the nearby Maungaharuru.

1.4 ECOLOGICAL VALUES AND TAONGA SPECIES

Species valued as mahinga kai and rongoā are also taonga species.

Jackie Huata noted that native orchids could be found around Putere, mostly growing on trees. He had seen about 10 varieties in the area (Huata, date unknown).

1.5 RECREATIONAL VALUES

The Putere Lakes are valued by the local community as places to swim, fish, go duck shooting and go boating (Putere Marae Wānanga, 2022). Locals value shallow, sandy sections of the lakes for swimming and noted that one favoured swimming site at Rotonuiahā had recently become covered in hornwort and unsuitable for swimming. Duck shooting occurs on the lakes and fishing included both native and non-native species such as eels and trout.

1.6 ISSUES AND MANAGEMENT MEASURES UNDERTAKEN TO DATE

Mana whenua have been working to protect and restore the Putere Lakes and their associated values for many years.

A common theme for management and restoration at Putere is the difficulty getting the necessary expertise and resources to do the work. Putere is a remote location and local and central government departments tend not to have enough resources to complete the work mana whenua would like to see done (Kathryn Gale, pers. comm.). This has resulted in the community and mana whenua having to take the lead in restoration efforts.

The Biodiversity Strategy for the Ngāti Pāhauwera Core Area identifies management opportunities to protect taonga species in the NPDT and DOC lands at Putere. These include fencing to exclude stock, pest control and weed control. NPDT have also been supportive of detailed biodiversity surveys being undertaken. This would improve the currently limited understanding of the species present in the area, and provide an update on species distributions as much of the existing information is out-of-date. It is expensive to undertake biodiversity surveys and this has been a barrier to this work being undertaken.

Local kaumatua Gunner Gilbert identified problems as early back as 1948 when the first top dressing planes started work. Nutrient run off, invasive aquatic weeds and stock being in the waters have been the main problems (Biodiversity Hawkes Bay 2020). The Putere Lakes Restoration Project Plan 2015 states that "water quality, the mauri ora and the biodiversity of the lakes and the adjoining wetlands have been degraded by a lack of protection from stock, invasive weeds and pests. Additionally there are negative impacts from phosphates and nitrates that leach into the lake from the adjoining farms. Locals are worried about the impact of sedimentation and the lack of eels and other water life."

Mana whenua have been working to address these issues for many years. This has included a discussion about how to remove invasive weeds such as hornwort from the lakes. Mana whenua are concerned about the effects of hornwort noting that "the weed chokes waterways, smothers native plants, impacts biodiversity, swimming and recreation" (Hape 2019). Correspondence between NPDT and Putere Marae noted the complexities in determining the best way to reduce/remove hornwort and the difficulty accessing the resources needed to do so (Hape 2019).

As a result, NPDT worked with HBRC to begin monthly water quality sampling at all three lakes. This monitoring has now been taking place for approximately 18 months.

Fencing to exclude stock has been constructed at Rotongaio and Rotoroa. Riparian planting has taken place around some of the lake margins of Rotongaio, Rotoroa and Rotonuiaha and has included 3000 native seedlings of mānuka, kānuka, karamu, kahikatea and carex. (Biodiversity Hawkes Bay 2020; Kathryn Gale, pers. comm.;; Hape 2019). Pest and weed control has also been undertaken in the area (Hape 2019).

Mana whenua have identified the following aspirations for restoration at Putere:

- Biodiversity surveys undertaken by suitably qualified expert(s)
- Continuation of pest control
- Continuation of weed control including removing wilding pines
- More fencing for stock exclusion at the reserve
- Writing of a management plan(s) to restore the lakes, particularly to control hornwort.

2 PART B: PUTERE LAKES SYNTHESIS OF STUDIES AND RESTORATION OPTIONS (BY MARC SCHALLENBERG)

2.1 BACKGROUND

Today, over 60% of regularly monitored lakes in New Zealand/Aotearoa are in a poor or very poor condition (https://www.stats.govt.nz/indicators/lake-water-quality). Many lakes experience cyanobacterial blooms, periods of bottom water anoxia, and other symptoms of eutrophication. The degradation undergone reduces the perceived value of the lakes for drinking water, for contact recreation, for fishing, as reservoirs of biodiversity, as sites for the collection of high quality mahinga kai, and as contributors of scenic beauty/aesthetic values in the New Zealand landscape.

Another factor that contributes to the decline in freshwater values is the increasing spread of non-indigenous, aquatic pest species among lakes (Champion et al. 2002; Closs et al. 2004; Champion et al. 2019). Invasive species often cause an imbalance in the ecosystem and food web which can either mitigate or exacerbate eutrophication problems.

As was described in Section 1, the Putere Lakes comprise a group of three small lakes in northern Hawkes Bay, perched above the Waiau River (Table 1; Fig. 2). The lakes were probably formed by the forces of both earthquakes and landslides (Wilmshurst 1995). The catchments of the lakes are small, relatively steep, and are underlain by sandstone and mudstone. Rotoroa flows into Rotonuiahā which then flows into the Waiau River. Rotongaio has the smallest catchment, without an apparent inflow stream. The lake flows out to the Waiau River separately from the other two lakes.

Rainfall in the Putere Lakes area is around 2000 mm yr^{-1} and the predominant winds come from the north and northwest directions (Thompson 1987). The area is subject to severe storms, including occasional tropical cyclones, which can cause landslips and severe soil erosion. Stratigraphic signatures of severe soil erosion events are evident in sediment cores from the lakes (Wilmshurst 1995; 1997).

Landcover in the catchments includes pasture that supports sheep and beef grazing, forestry, and regenerating scrub. Most of the wetlands that were once adjacent to the lake have been drained and converted into flat, grazable lands (Fig. 3).

Table 1. Physical and morphological data of the Putere Lakes and their catchments. Data sources: Wilmshurst (1995), Hussain & Jones (2022a, b), and Burton (2017).

Lake	Northing	Easting	Altitude (m asl)	Thermal stratification	Surface area (ha)	Maximum depth (m)	Catchment area (km^2)
Rotonuiahā	-38.94669	177.03921	c. 370	Seasonal	44	30	2.0
Rotoroa	-38.94742	177.02902	c. 400	Seasonal	14	16	4.2
Rotongaio	-38.94352	177.01176	c. 390	Polymictic	9.4	4.6	0.5

Figure 2. Satellite image of the Putere Lakes showing typical land cover in the region.

Thus, the Putere Lakes have not escaped the typical effects of agriculture and forestry on water quality and lake ecological integrity (Larned et al. 2018). In addition, invasive aquatic plants have proliferated in Rotonuiahā and Rotoroa. As was described in Section 1, the lakes historically provided tuna/eels, kākahi/freshwater mussels, kōura/freshwater crayfish, waterfowl, trout and raupō resources to support the local mana whenua. However, the effects of both land use change and invasive aquatic plants have compromised the water quality of the lakes as well as their ecological, cultural, and recreational values (Section 1).

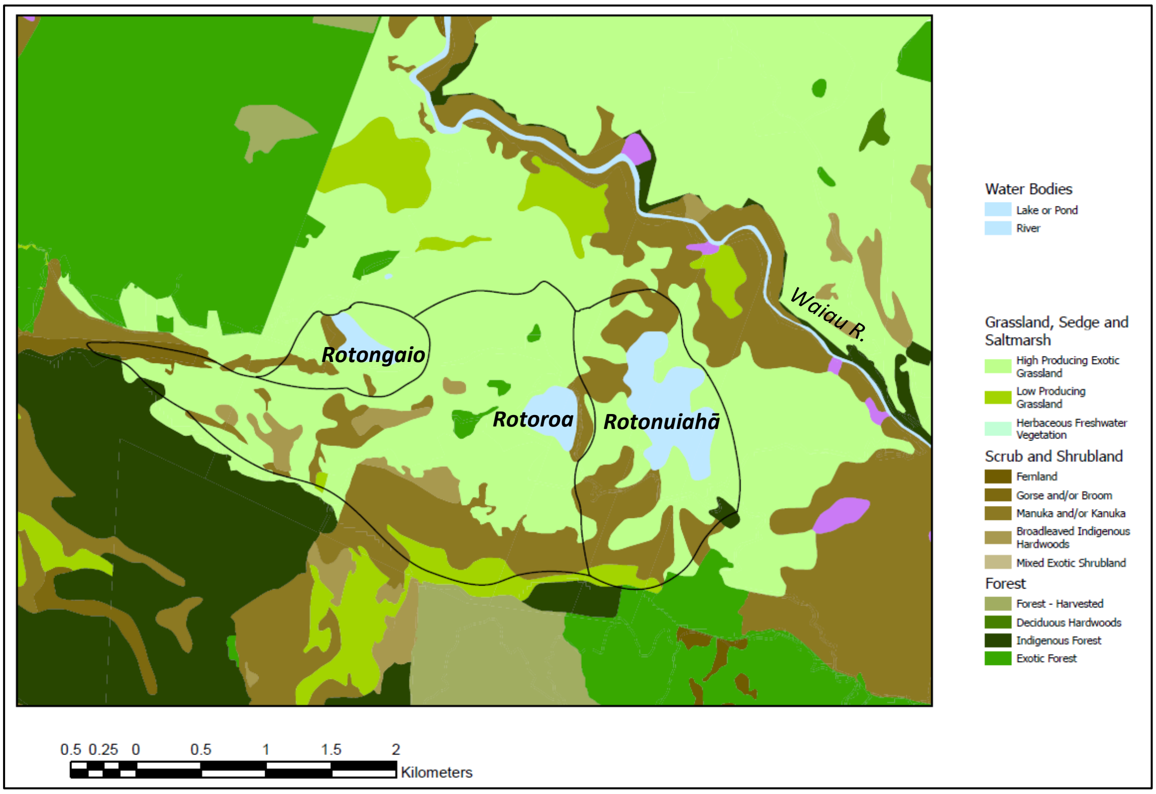

Figure 3. Land cover map of the catchments of the Putere Lakes. Map and legend provided by Hawkes Bay Regional Council. The catchment perimeters were estimated using a map in Wilmshurst (1995) and a 1:50,000 topographical map.

3 Aims and scope

This report is part of an Envirolink-funded project in collaboration with the Hawkes Bay Regional Council and the Ngāti Pāhauwera Development Trust. The aims of the project were to:

1. Review existing data and reports on Putere Lakes.
2. Hold a wānanga with the local mana whenua, Ngāti Pāhauwera Development Trust and other community representatives to discuss values, perceptions of state and options for lake improvement.
3. Analyse and report on current state of the lakes, considering values identified through the hui process.
4. Assess, and provide recommendations on, management/restoration options to protect and enhance freshwater values.

Part A of the report presents information on community connections and values regarding the lakes. Much of the information presented was obtained from a wānanga held at Putere Marae on June 11, 2022. Notes of the hui are presented in the Appendix to this report.

The rest of this report presents information on the historical and current state of the lakes and provides recommendations for the protection and enhancement of the freshwater values of the lakes, which were partly informed by the community's values presented in Section 1 and in the Appendix.

4 ECOLOGICAL AND WATER QUALITY VALUES

4.1 COMMUNITY AND STATUTORY VALUES

To effectively manage and/or restore lakes it is important to understand what the goals are and to translate these into specific, measurable outcomes. The National Policy Statement for Freshwater Management (NPSFM) mandates that freshwater management be guided by community and iwi values (MfE 2020a, Sections 3.3, 3.4 and 3.7). The elicitation of community values is a common starting point for different freshwater management frameworks (e.g., Sinner et al. 2015; Langhans & Schallenberg 2021) and community values work was, therefore, also the starting point for this project and report.

A comprehensive management/restoration plan needs to consider not only community values, but also statutory values, such as water quality limits that are set in regional and national plans and policies. It is not unusual for some of diverse values to be contradictory, appearing to reflect conflicting interests and goals. In such cases, the use of a decision support system can assist in resolving the differences (e.g., Langhans & Schallenberg, 2021). Within the NPSFM, the safeguarding of statutory values and attribute bottom lines may also be negotiable if it can be shown that a lake would not meet the national attribute bottom line targets under natural (unimpacted) conditions (MfE 2020a).

All three of the Putere Lakes have been identified in Hawkes Bay Regional Council Plan Change 7 as outstanding water bodies due to their mahinga kai values (HBRC 2020). In planning documents, iwi stated that all three lakes and all tributaries of the Waiau River have outstanding spiritual and cultural values.

Part A/Section 1 of this report, discussed the community values of the Putere Lakes in detail, as determined from interviews and the wānanga that took place at Putere Marae. The mahinga kai values highlighted by the community were:

- tuna/eels
- tī kouka/cabbage tree
- kākahi/freshwater mussel
- kōura/freshwater crayfish
- watercress
- ducks
- trout
- raupō

Other values mentioned included:

- native aquatic plants
- native biodiversity
- swimming
- recreation

The lakes are not used for drinking water, so, according to the values, water sanitation to the standard for primary contact recreation is appropriate for these lakes. Setting a primary contact recreation sanitary standard would not compromise any of the other listed values, although watercress harvested at locations where it might contact lake water would need to be thoroughly washed before consumption.

In comparing the information on the biological communities of the lakes with the biological values highlighted by the community, it is apparent that there are knowledge gaps concerning the present conditions of the lakes, but it is clear from local knowledge and scientific reports that the native submerged macrophyte communities are in a poor state (Table 2). No information was found on kōura presence in these lakes or on indicators of suitability for contact recreation (e.g., *E. coli* concentrations and cyanobacteria biovolume). However, information from the wānanga indicated that kōura were present in the stream between Rotoroa and Rotonuiahā.

Table 2. Biological values identified for the Putere Lakes. (yes) indicates historical record. The macrophyte native condition and invasive plant impact indices are assessed as part of the NIWA's LakeSPI macrophyte community assessments (Burton 2017).

	Macrophytes		Fish					Invertebrate
Lake	**Native plant condition**	**Invasive plant impact**	**Tuna**	**Smelt**	**Crans bullies**	**Banded kōkopu**	**Trout**	**Kākahi**
Rotonuiahā	11%	95%	Yes	(yes)	(yes)	(yes)	(yes)	Yes
Rotoroa	6%	97%	Yes	Yes	?	?	?	?
Rotongaio	0%	47%	?	?	?	?	?	?

The National Objective Framework (NOF) in the NPSFM sets statutory water quality and aquatic ecosystem health guidelines for lakes (MfE 2020a). Table 3 shows the recent conditions of the lakes in relation to the targets set in the NOF.

Table 3. Water quality and macrophyte attributes from the National Objectives Framework (NOF) of the National Policy Statement for Freshwater Management (MfE 2020a). Values are calculated from water quality data and LakeSPI surveys for the Putere Lakes. Year 1 is from May 2020 to April 2021 and Year 2 is from May 2021 to April 2022. Water quality attributes are chlorophyll *a* (Chla), total nitrogen (TN), total phosphorus (TP), nitrate-N and ammonium-N concentrations, all measured in μg L^{-1} (parts per billion). The macrophyte attributes are the native condition index and the invasive impact index, presented as percentages. The higher the native score and the lower the invasive score, the better the condition of the macrophyte communities are. The letters in parentheses are the NOF bands that correspond to the lake condition. A is excellent (blue shading), B is good (green shading), C is fair (pink shading) and D is unacceptable (red shading).

Lake/year	Chla median	Chla maximum	TN median	TP median	Ammonium median	Native score %	Invasive score %
Rotonuiahā / Y2	4.4 (B)	39 (C)	200 (B)	13 (B)	5 (A)	11 (D)	95 (D)
Rotonuiahā / Y1	3.8 (B)	50 (C)	190 (B)	11 (B)	5 (A)		
Rotoroa / Y2	6.9 (C)	133 (D)	250 (B)	20 (C)	5 (A)	6 (D)	97 (D)
Rotoroa / Y1	2.2 (B)	118 (D)	190 (B)	10 (B)	5 (A)		
Rotongaio / Y2	27 (D)	300 (D)	745 (C)	88 (D)	5 (A)	0 (D)	47 (C)
Rotongaio / Y1	44 (D)	197 (D)	1200 (D)	98 (D)	36 (B)		

There are other compulsory attributes for lakes in the NOF, but insufficient data are available for the Putere Lakes to properly assess these. The attributes are:

- *E. coli* (Human contact)
- *E. coli* (Primary contact sites)
- Planktonic cyanobacteria (Human contact)
- Bottom water dissolved oxygen
- Mid-hypolimnetic dissolved oxygen (For seasonally stratified lakes)

While the data do not yet exist to assess the condition of the lakes against these attributes, some information does exist which provides a rough indication as to how the lakes are faring with regard to these attributes. In the water quality dataset for the lakes (up until April 2022) there is one *E. coli* count for each of the lakes, sampled on June 29, 2020. For all the lakes, the data suggested excellent water quality for primary contact recreation at the time (but this is not a time when people swim in the lakes). More data are required regarding *E. coli* counts and planktonic cyanobacterial biovolume concentrations to properly assess the suitability of the lakes to primary contact recreation.

While data on the surface water dissolved oxygen concentrations are available in the dataset, no data exist on bottom water or hypolimnetic dissolved oxygen concentrations. However, anecdotal evidence suggests that both Rotonuiahā and Rotoroa do at times show anoxic conditions in their bottom waters (Hussain & Jones 2022a, b). If confirmed, this would indicate that those two lakes would be in the D-band (unacceptable) for the NOF bottom water anoxia attribute, an important lake ecosystem health indicator.

4.2 ASSESSMENT OF CURRENT LAKE CONDITIONS AGAINST LAKE VALUES

Having identified the community and statutory values, as well as some attributes that relate to those values, it is possible to compare the current conditions of the lakes against the identified lakes (Table 4). While some of the lakes' attribute states are unknown and require further research, monitoring and assessment, the analysis in Table 4 shows that the lakes achieve the various values targets to different degrees. In terms of mahinga kai, native biodiversity and recreational values, there are many knowledge gaps regarding the current states of the lakes, however the proliferation of hornwort in Rotonuiahā and Rotoroa threatens many of these values (Burton 2017; Hussain & Jones 2022a, b), making mahinga kai harvesting and swimming problematic. In terms of the native aquatic plant values, all lakes perform poorly due to the proliferations of hornwort (*Ceratophyllum demersum*) in Rotonuiahā and Rotoroa, which out-competes native aquatic plants, and due to the poor development of macrophyte communities in Rotongaio, in which only Canadian pondweed (*Elodea canadensis*) was found (Burton 2017). How the lakes fare in terms of suitability for contract recreation is a clear knowledge gap.

Assessment of the current conditions of the lakes in terms of the statutory values shows that there is a gradient in water quality among the lakes with Rotonuiahā and Rotoroa having mostly good to excellent water quality, while the water quality of Rotongaio is substantially poorer. Overall, for water quality, Rotonuiahā scores slightly better than Rotoroa. As stated above, the LakeSPI indicators of aquatic plant community health place all three lakes are in a poor condition - Rotonuiahā and Rotoroa due to proliferation of hornwort and Rotongaio due to restricted macrophyte cover and the absence of any native macrophytes in the lake (Burton 2017). As stated above, data is lacking with which to assess the suitability of the lakes to contact recreation based on the NOF guidelines.

Table 4. Summary of the assessments of current conditions of the Putere Lakes in relation to the values targets identified in Tables 2 and 3.

Values	Attributes	Rotonuiahā assessment	Rotoroa assessment	Rotongaio assessment
Community values				
Mahinga kai	Tuna	Present (no data on abundance)	Present (no data on abundance)	Presence likely, but unconfirmed
Mahinga kai	Kākahi	Present	Likely absent (surveys reported absent)	Likely absent (surveys reported absent)
Mahinga kai	Kōura	No data	No data	No data
Mahinga kai	Watercress	No data	No data	No data
Mahinga kai	Ducks	No data	No data	No data
Mahinga kai	Trout	Historical presence (current presence unknown)	No data	No data
Mahinga kai	Raupō	Present	Present	Present
Ecosystem health/aquatic life	Native aquatic plants	Severely threatened	Severely threatened	Severely threatened
Ecosystem health/aquatic life	Native biodiversity	Historical fish records indicate reasonable fish diversity	Insufficient data	Insufficient data
Human contact	Swimming	Declining use due to macrophytes	No data	No data
Human contact	Recreation	No data	No data	No data
Statutory values (from the National Objectives Framework)				
Ecosystem health/water quality	Chlorophyll *a*	Good/Fair	Fair/Poor (occasional algal blooms)	Poor (algal blooms common)
Ecosystem health/water quality	Total nitrogen	Good	Good	Poor
Ecosystem health/water quality	Total phosphorus	Good	Good/Fair	Poor
Ecosystem health/water quality	Ammonium (toxicity)	Excellent	Excellent	Excellent/Good
Ecosystem health/aquatic life	Native aquatic plants	Poor (displaced by hornwort)	Poor (displaced by hornwort)	Virtually absent (unfavourable conditions, displaced by elodea)
Ecosystem health/aquatic life	Invasive aquatic plants	Poor (hornwort proliferation)	Poor (hornwort proliferation)	Fair (elodea restricted by unfavourable light and oxygen conditions)
Human contact	*E. coli*	No data	No data	No data
Human contact	Planktonic cyanobacteria	No data	No data	No data
Ecosystem health/water quality	Dissolved oxygen	Poor (based on anecdotal evidence of bottom water anoxia)	Poor (based on anecdotal evidence of bottom water anoxia)	No data

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5 CONDITION AND TRENDS OF THE LAKES

5.1 HISTORICAL CONDITIONS

To provide context to the current assessment of condition and trends of health of the lakes, some information on the historical conditions of the lakes is presented below.

5.1.1 Palaeolimnological reconstructions

Analysis of sediment cores collected from the bed of Rotonuiahā by Wilmshurst (1995; 1997) indicates that the catchment of the lake was dominated by podocarp/hardwood forest up until the arrival of Māori in the region, c. 800 years ago. The fossil pollen and charcoal found in older sediment strata indicates that deforestation by fire occurred soon after settlement, with the catchment vegetation then rapidly converting to scrub, dominated by bracken fern, coprosmas, and wineberry. At Rotonuiahā, this early phase of deforestation did not seem to increase soil erosion as markedly as analyses of Lake Tutira implied (Wilmshurst 1997). During the period of Māori settlement, pulses of sediment entered the lake as a result of storm events, but the amount of sediment mobilised in storms was less than that mobilised by storms after European arrival and after the conversion of catchment vegetation to grasses. European settlement resulted in a replacement of scrub and forest vegetation by pastoral land, and pollen from non-native trees (e.g., *Pinus radiata*) became abundant in the sediment strata laid down during this era. The amount of soil/sediment washed into the lake during storms became more pronounced during this era (https://lakes380.com/lakes/rotonuiaha/) and in recent decades, algal pigment indicators also increased, indicating increasing phytoplankton biomass in the lake (https://lakes380.com/lakes/rotonuiaha/).

5.1.2 Mātauranga

As described by mana whenua in Section 1, historical Māori settlements and eeling ditches existed on the shores of the lakes, indicating that the lakes provided mahinga kai for the people living there. In addition to the lakes being good for eeling, kākahi middens in the hills overlooking Rotoroa indicate that kākahi werea also abundant in the lakes. A kaumatua indicated that, following World War II, topdressing, nutrient runoff, invasive aquatic weeds and impacts of livestock on the lakes resulted in the degradation of "water quality, the mauri ora and the biodiversity of the lakes and the adjoining wetlands".

5.1.3 Previous studies

A study of Rotonuiahā and Rotoroa was undertaken by the Department of Scientific and Industrial Research in 1983 (Howard-Williams et al. 1983). Both lakes exhibited anoxic hypolimnia and internal nitrogen and phosphorus loading at the time. Phytoplankton biomass near the surface of the lakes was approximately 15 and 5 µg Chla L^{-1} for Rotonuiahā and Rotoroa, respectively. At the time, the macrophyte community in Rotonuiahā consisted of a diverse native community with the inclusion of the non-native, *Potamogeton crispus*, extending to a depth of just over 4 m. In Rotoroa, the macrophyte community was less diverse, comprising only three species, including *P. crispus*, also extending to 4 m. The lakes were considered to be eutrophic and impacted by nutrient inputs and recommendations were made regarding possible restoration actions that could be undertaken to improve water quality.

The macrophyte survey report by Burton (2017) also provided some insights regarding changes to the lakes over time. For example, hornwort was inferred to have colonised the lake between the two macrophyte surveys in 2003 and 2008. Whereas macrophytes extended to 4 m depth in 1983, hornwort extended to between 9 and 16 m depth in the lake by 2016, suggesting an increase in water clarity, compared to 1983. The lake still had a diversity of native macrophytes in 2016, but these were limited to depths between 0 and 2 m. Although no kākahi were reported in 2003, 2008 and 2011 macrophyte surveys, a survey conducted in 2022 (Hussein & Jones 2022b) reported low densities of kākahi (approximately 2 to 4 per m^2) from surveys at two locations in the lake.

For Rotoroa, hornwort was also inferred to have colonised the lake between 2003 and 2008 and elodea seemed to colonise between 1983 and 2003. Whereas macrophytes extended to 4 m depth in this lake in 1983, hornwort extended to between 8 and 9.5 m depth in the lake by 2016. No substantial change from macrophyte conditions in 2016 was reported by Hussein and Jones (2022a), although these authors noted signs of anoxia and decomposing plant matter beyond a depth of 5 to 6 m. No kākahi have been reported from any of the studies on Rotoroa.

Rotongaio was surveyed less often than the other two lakes. Burton (2017) reported elodea as the only submerged macrophyte in the lake, extending down to 3.2 m depth. Within this zone, macrophyte cover was between 5 and 70% of the lakebed. Water clarity was reported to be very low and no kākahi were observed. Burton (2017) suggested that the lake could be on the cusp of becoming devegetated when it was assessed in 2016.

5.1.4 Historical conditions inferred from other New Zealand lakes

Schallenberg (2019) carried out an analysis of the likely reference (unimpacted) conditions of New Zealand lakes, based on a gradient analysis of the current conditions of a wide range of lakes. The indicators of impact included the percentage of native vegetation cover in the lakes' catchments and a ranking of expert-assessed ecological integrity in a set of 34 shallow New Zealand lakes distributed around the country. This analysis inferred that lakes with the highest ecological integrity and highest percentage cover of native vegetation in their catchments exhibited total phosphorus levels < 12 µg L^{-1}, total nitrogen levels < 277 µg L^{-1}, and chlorophyll *a* levels < 3.2 µg L^{-1}, in mid-late summer. The lakes considered to be unimpacted also lacked non-native fish and non-native macrophyte species. These guidelines are useful for assessing the current conditions of the Putere Lakes because they allow an assessment of the degree of departure of the lakes compared to the expected condition of similar unimpacted lakes.

5.2 Current water quality and macrophyte health conditions and trends

5.2.1 Water quality

Through a joint project by Hawkes Bay Regional Council and the Ngāti Pāhauwera Development Trust, water quality has been measured on a roughly monthly basis since January 2020. This data enables an assessment of the recent and current water quality of the lakes. Time series of phytoplankton biomass measured as chlorophyll *a* in the three lakes are shown in Figure 4. Phytoplankton biomass was much higher in Rotongaio than in the other two lakes, where it often exceeded the NPSFM national bottom line for the annual maximum chlorophyll *a* concentration. Phytoplankton biomass in the lake was well-above the range expected for unimpacted shallow lakes. In contrast, Rotoroa only breached the national bottom line twice in the two-year period, while Rotonuiahā never breached the national bottom line.

Similar patterns were observed for total phosphorus and total nitrogen (Figs 5 and 6), where Rotongaio often exceeded the national bottom lines, while Rotoroa and Rotonuiahā rarely exceeded the bottom line for total phosphorus and never exceeded the bottom line for total nitrogen. The water clarity of the lakes, as measured by the Secchi depth, was higher in Rotoroa and Rotonuiahā (averaging approximately 2.5 m) than in Rotongaio (averaging approximately 1.5 m)(Fig. 7). The data time series for these water quality variables were not extensive enough to be able to show any statistically significant trends over time.

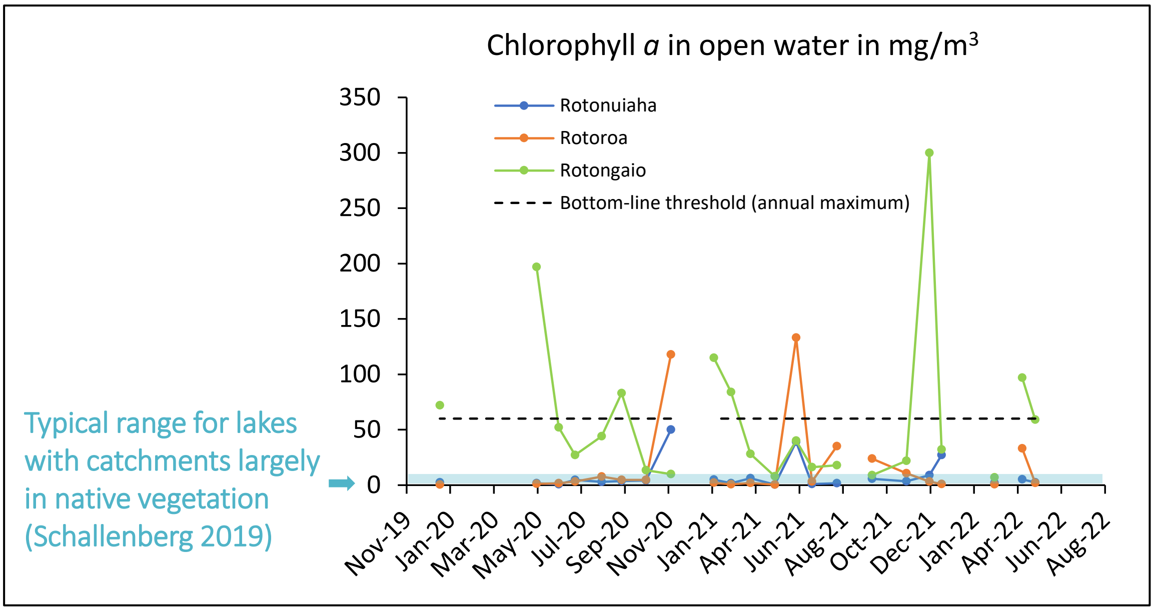


Figure 4. Time series of phytoplankton biomass as measured by chlorophyll *a*. The horizontal dashed line is the national bottom line for annual maximum chlorophyll *a* concentration from the National Objectives Framework. Lakes that exceed the national bottom line must be managed to undergo improvement. The shaded blue area indicates the expected range for unimpacted shallow lakes.

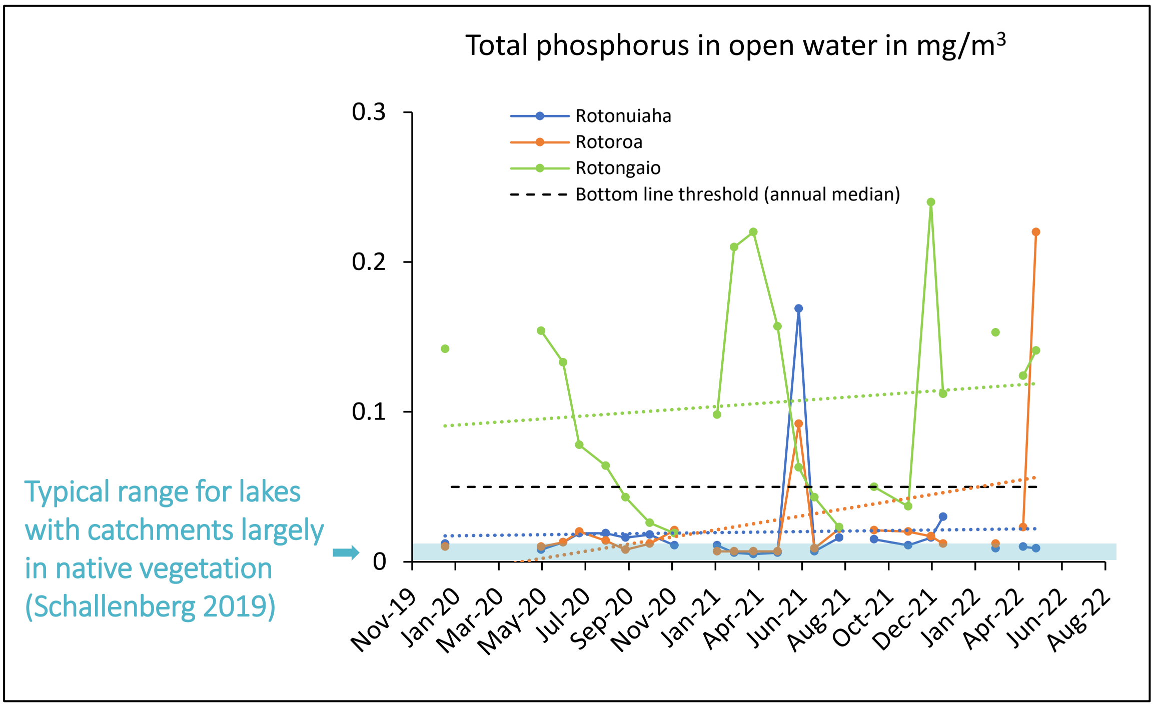


Figure 5. Time series of total phosphorus concentrations. The horizontal dashed line is the national bottom line for annual median total phosphorus concentration from the National Objectives Framework. Lakes that exceed the national bottom line must be managed to undergo improvement. The shaded blue area indicates the expected range for unimpacted shallow lakes. The dotted coloured lines are the linear trends over time. None of these are statistically significant.

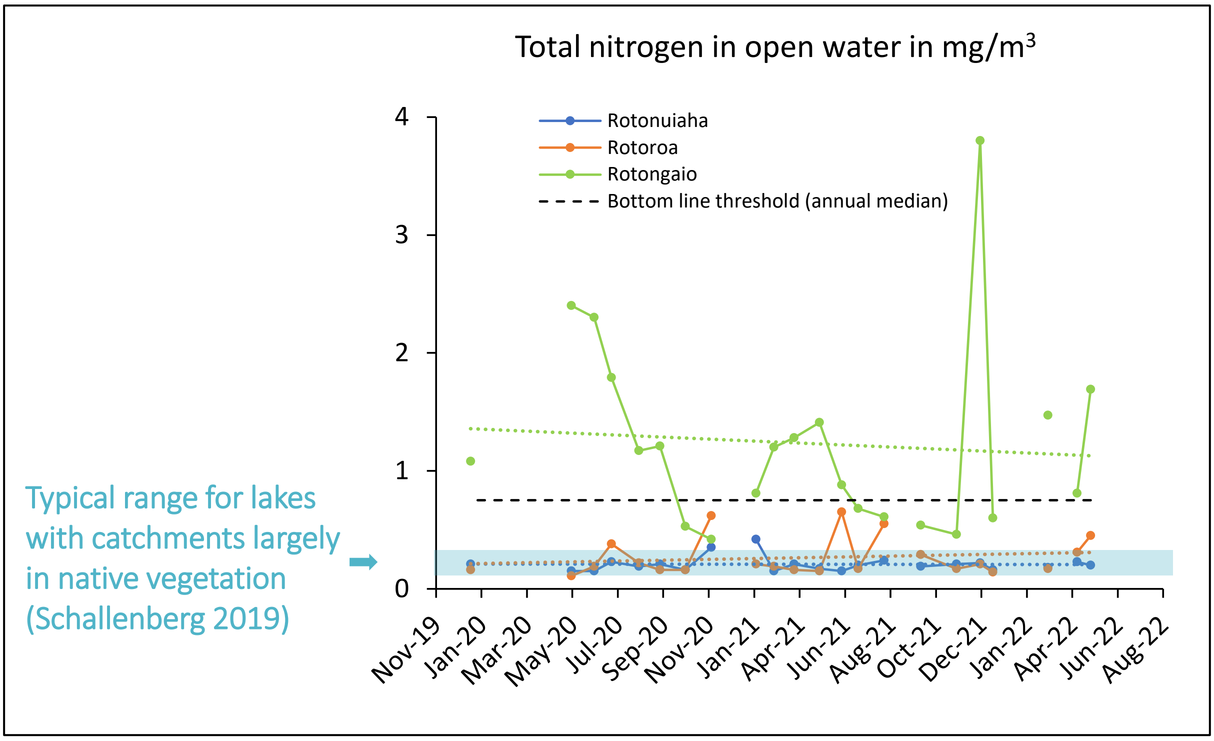


Figure 6. Time series of total nitrogen concentrations. The horizontal dashed line is the national bottom line for annual median total nitrogen concentration from the National Objectives Framework. Lakes that exceed the national bottom line must be managed to undergo improvement. The shaded blue area indicates the expected range for unimpacted shallow lakes. The dotted coloured lines are the linear trends over time. None of these are statistically significant.

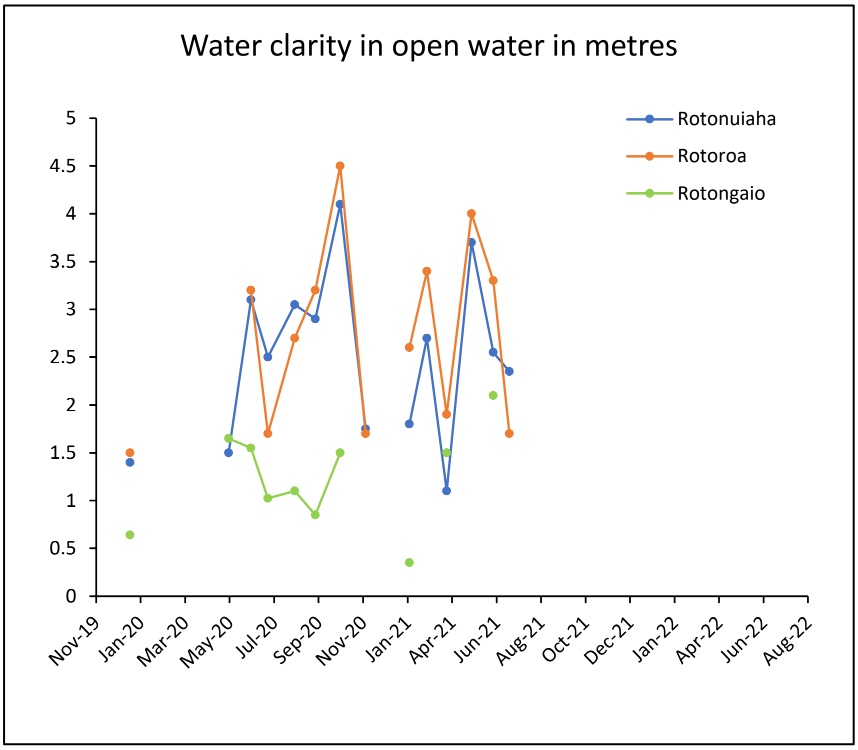


Figure 7. Time series of water clarity, measured as the Secchi disk depth.

The study carried out on Rotonuiahā and Rotoroa in the summer of 1983 by Howard-Williams et al. (1983) allows the comparison of summer concentrations of chlorophyll *a*, total phosphorus, and total nitrogen in the surface waters of the lakes between 1983 and 2021 (Figure 8).

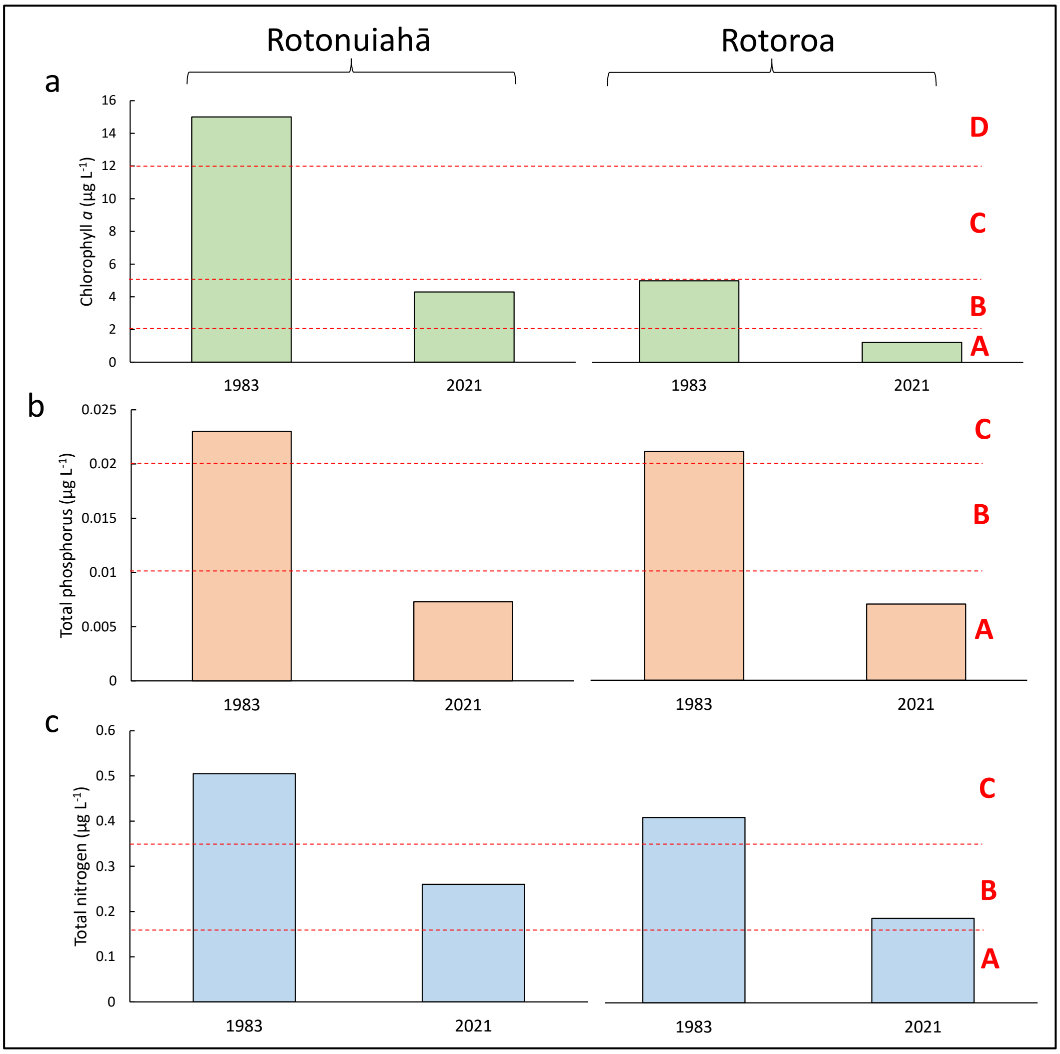


Figure 8. Comparison of summer water quality of Rotonuiahā and Rotoroa between 1983 and 2021. The lines and letters in red indicate the water quality bands from the National Objectives Framework (MfE 2020a). These bands are based on the annual median concentrations, and so the lake data are only suggestive of placement in NOF bands. Band A is generally considered to be excellent, band B is good, band C is fair, and band D is unacceptable.

The data indicate that the water quality of both lakes has improved markedly since 1983, as measured using all three water quality attributes.

The New Zealand trophic level index (TLI; Burns et al. 2000) aggregates phytoplankton biomass, total phosphorus, total nitrogen, and Secchi depth information into an overall estimate of trophic state, describing the level of algal productivity, nutrient enrichment, and water clarity of lakes. The levels of these attributes are often correlated among lakes, especially where the attributes are primarily influenced amounts of algae in the water column (Schallenberg & van der Zon 2020).

The TLI classifies the trophic state of lakes into classes which can be compared both within lakes over time and among lakes (Table 5).

Table 5. The New Zealand trophic state classification scheme in relation to TLI scores (Burns et al. 2000). The descriptions of the different trophic states are by M. Schallenberg (pers. obs.).

Trophic state	Description	TLI score range
Ultramicrotrophic	Extremely low productivity, suitable for all uses	0 to 1
Microtrophic	Extremely low productivity, likely suitable for all uses	1 to 2
Oligotrophic	Low productivity, attractive for recreation	2 to 3
Mesotrophic	Moderate productivity, suitable for recreation	3 to 4
Eutrophic	Algal blooms likely, not suitable for recreation at times	4 to 5
Supertrophic	Elevated algal biomass, unattractive for recreation	5 to 6
Hypertrophic	Extremely degraded, fish kills likely, unattractive for recreation	6 to 7

The water quality data collected for the Putere Lakes in 2020 allows the calculation of the trophic state of the lakes using all four attributes (TLI), whereas the data collected in 2021 are missing the Secchi depth data and were therefore used to calculate TLI_3. TLI calculations integrate water quality information over one year and are ideally calculated from monthly sampling data. For the Putere Lakes, water quality data were available from 8 samplings in 2020 and 11 samplings in 2021 (Table 6).

Table 6. The trophic state of the Putere Lakes based on water quality monitoring data. Chla is chlorophyll *a* concentration and TLc is the trophic state based on chla. TP is total phosphorus and TLp is the trophic state based on TP. TN is total nitrogen and TLn is the trophic state based on TN. SD is Secchi depth and TLs is the trophic state based on SD. TLI is the overall, integrated trophic level index score. Blue shading indicates mesotrophic state. Green shading indicates eutrophic state. Pink shading indicates supertrophic state. Red shading indicates hypertrophic state. Calculations are based on 8 samples for 2020 and 11 samples for 2021. Secchi depth was not regularly measured in 2021. TLI was calculated from January to December for each year.

Lake and year	Chla	TP	TN	SD	TLc	TLp	TLn	TLs	TLI*	Trophic state*
	µg L^{-1}	µg L^{-1}	µg L^{-1}	m						
Rotonuiahā										
2020	8.8	14	206	2.54	4.6	3.7	3.4	4.1	3.9	Mesotrophic
2021	9.1	27	211	n/a	4.7	4.4	3.4	n/a	4.1	Eutrophic
Rotoroa										
2020	18	14	250	2.64	5.4	3.6	3.6	4.1	4.2	Eutrophic
2021	20	20	263	n/a	5.5	4.0	3.7	n/a	4.4	Eutrophic
Rotongaio										
2020	62	82	1360	1.19	6.8	5.8	5.8	4.9	5.8	Supertrophic
2021	61	114	1115	n/a	6.8	6.2	5.6	n/a	6.2	Hypertrophic

* Calculated without Secchi depth (TLI_3) in 2021.

The TLI for the three lakes confirms the inferences made from analysis of the individual variables, namely that Rotonuiahā has the best water quality, ranging from mesotrophic to eutrophic, while Rotoroa is eutrophic and Rotongaio is highly degraded, ranging from supertrophic to hypertrophic. Of the different attributes, the contribution of phytoplankton biomass tends drive up the trophic state calculations more than the nutrient concentrations.

5.2.2 Macrophyte community health

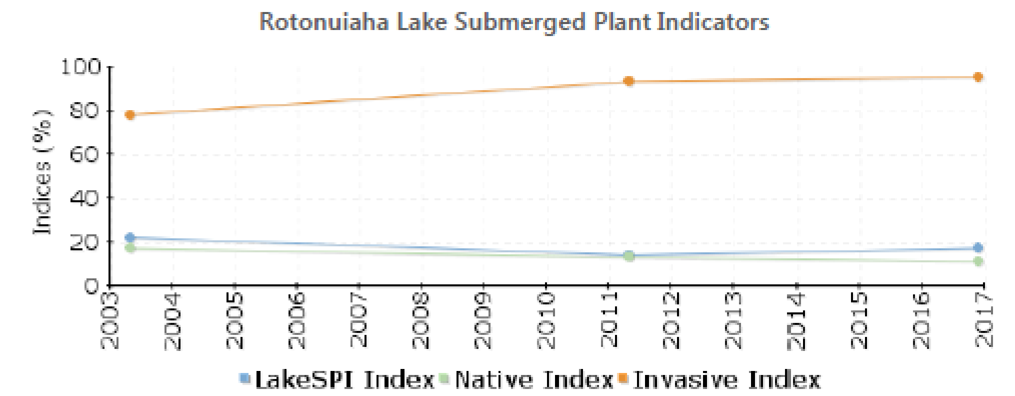
Good water quality is a key aspect of good lake health and attractiveness for recreation and mahinga kai gathering. The condition of macrophyte communities in lakes has recently been acknowledged in the NPSFM (MfE 2020a) as another important component of lake ecological health.

Burton (2017) undertook an assessment of the condition of the macrophyte communities in Hawkes Bay lakes, including all three of the Putere Lakes. Burton (2017) used the LakeSPI (lake submerged plant index) framework to assess the condition of the lakes. The framework calculates an overall index called the LakeSPI index, with aggregates information about (1.) the condition of the native plant communities (native condition index), (2.) the impact of invasive plant species (invasive impact index), and (3.) the water clarity of lakes.

The LakeSPI assessment places strong emphasis on the influence of native vs invasive plant species, while assessing both the ecosystem services of submerged plants as well as their contribution to native biodiversity and nuisance plant proliferations (Schallenberg & van der Zon 2020). While invasive macrophytes may negatively impact native macrophyte biodiversity, the presence of invasive macrophytes in a lake may be more desirable than the absence of any macrophytes, due to positive effects of macrophytes on water clarity and water quality. The LakeSPI framework rates devegetated or unvegetated lakes as being in the poorest LakeSPI condition, lakes with proliferations of invasive macrophytes also rate very low, even though the water quality of the latter may benefit from the presence of these macrophytes.

Burton (2017) rated the macrophyte communities of the Putere Lakes as poor. Rotonuiahā and Rotoroa received the poor rating mainly due to the proliferation of hornwort in these lakes. However, Rotongaio received a poor rating mainly due to the very limited cover and extent of macrophytes. This is likely due to the low water clarity of the lake and Burton (2017) suggested that the lake may be on the cusp of becoming devegetated. So, while the lakes were all rated as poor, their macrophyte status differed markedly.

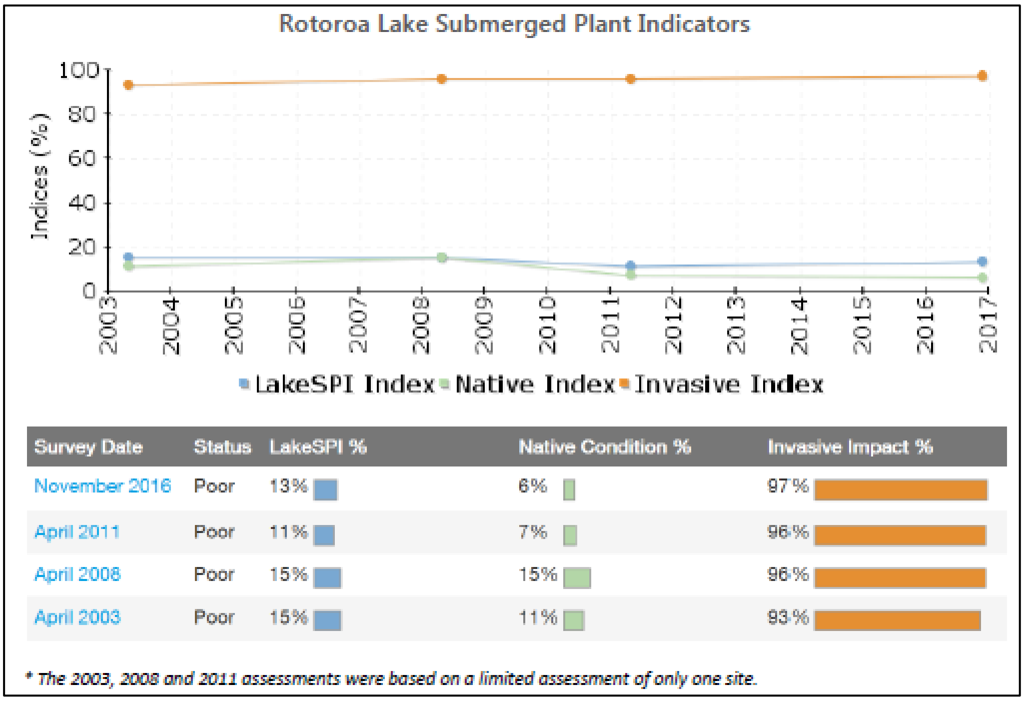
Burton (2017) also summarised the trends in the macrophyte health of the lakes by comparing their current condition to their conditions during previous investigations and assessments of macrophytes (Figs 9 to 11).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
November 2016	Poor	17%	11%	95%
April 2011	Poor	14%	13%	93%
April 2003	Moderate	22%	17%	78%

** The 2003 and 2011 surveys were based on a limited assessment of only one site.*

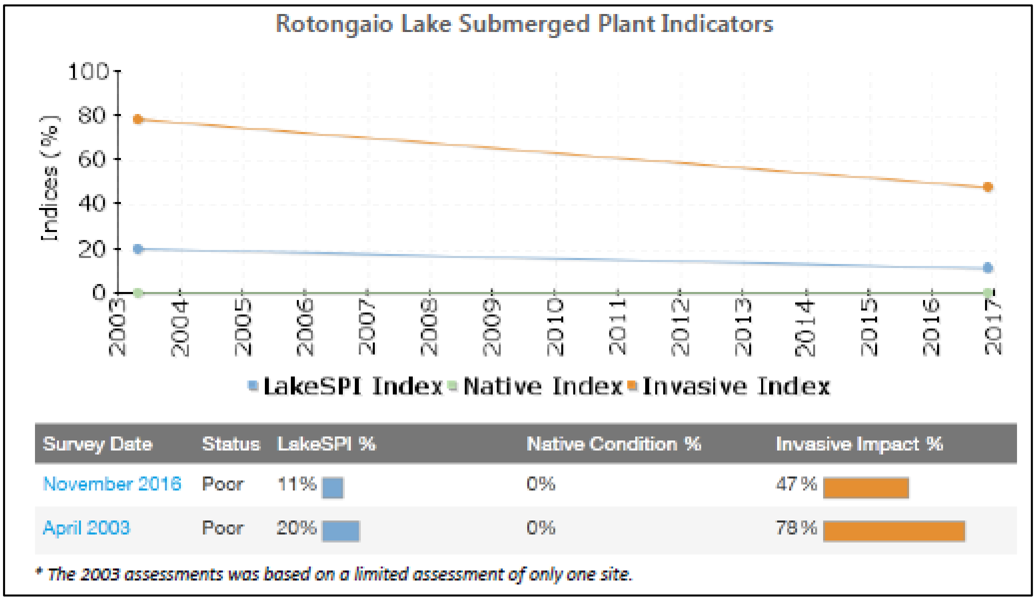
Figure 9. Trends in LakeSPI indicators of Rotonuiahā from Burton (2017).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
November 2016	Poor	13%	6%	97%
April 2011	Poor	11%	7%	96%
April 2008	Poor	15%	15%	96%
April 2003	Poor	15%	11%	93%

* *The 2003, 2008 and 2011 assessments were based on a limited assessment of only one site.*

Figure 10. Trends in LakeSPI indicators of Rotoroa from Burton (2017).



Survey Date	Status	LakeSPI %	Native Condition %	Invasive Impact %
November 2016	Poor	11%	0%	47%
April 2003	Poor	20%	0%	78%

* *The 2003 assessments was based on a limited assessment of only one site.*

Figure 11. Trends in LakeSPI indicators of Rotongaio from Burton (2017).

It's apparent from these assessments that LakeSPI indicators in Rotonuiahā and Rotoroa have been relatively stable since 2003 with very high invasive impact scores since 2011, whereas the invasive impact score for Rotongaio declined markedly from 2003 to 2016 with no sign of recovery of the native macrophytes. Burton's (2017) concern that Rotongaio appeared to be on a trajectory towards devegetation is likely due to conditions water quality conditions in that lake being too challenging for macrophytes - even for elodea.

5.2.3 Summary of current condition and trends

Although scientific information on the Putere Lakes is sparse, the lakes have been severely impacted first by eutrophication related to agricultural intensification of the catchments and then by the invasion of the lakes by invasive macrophytes. Rotonuiahā and Rotoroa were substantially more eutrophic in 1983, while they were unimpacted by invasive macrophytes, than they are today. While elodea colonised these lake between 1983 and 2003, hornwort appears to have colonised them between 2003 and 2008, and it seems likely that the proliferation of these invasive macrophytes has contributed to an improvement in water quality, while negatively impacting native biodiversity.

Less is known about the historical trajectory of Rotongaio, but the lake has recently exhibited much poorer water quality than the other two lakes, while exhibiting very restricted macrophyte cover. Although based on sparse data, it appears that this lake may be on the cusp of becoming devegetated (Burton 2017), at which point any ecosystem services provided by the sparse macrophyte community will be lost.

6 A STRESSOR-RESPONSE FRAMEWORK FOR LAKE MANAGEMENT AND RESTORATION

Lakes are ecosystems and such complex systems tend to behave in complex ways due to multiple interactions and system feedbacks operating within the system. For example, historical nutrient and sediment inputs to lakes can persist in affecting the water quality of the lakes for decades. Phosphorus bound to sediment particles in the lakebed can continuing being recycled into the water column, for example when water turbulence generated by winds resuspends bottom sediments into the water column or when historical phosphorus inputs bound to lakebed sediments are released into the water column due to water becoming anoxic or developing a high pH. Such changes can result in tipping points in the system, where a relatively small change in a stressor level can exceed a chemical threshold, thereby resulting in major changes to the system, such as a phytoplankton blooms and the collapse of macrophyte beds. Eutrophication tipping points have been frequently reported for lakes (Scheffer 2004). Some lakes can exhibit a flipping behaviour, where they alternate between a macrophyte-dominated clear water state and a phytoplankton-dominated, turbid state (Mitchell et al. 1988; Scheffer 2004; Schallenberg & Sorrell 2009), while others may remain fixed in a degraded state for long periods of time, resisting restoration attempts (Schallenberg & Sorrell 2009; Schallenberg et al. 2010).

Figure 12 is based on alternative stable state theory. It shows how the water quality of a lake can change from pristine (i.e., high water clarity, no algal blooms) to highly degraded (i.e., eutrophic with algal blooms) by passing through tipping points of nutrient availability. The straight, dashed line shows how a simplified system (e.g., an aquarium with algae growing in it) would be expected to respond to increasing nutrient additions. However, lakes are much more complex and often show non-linear behaviour. For example, in the early stages of increasing nutrient availability, the lake may absorb nutrients without much change in water quality, thanks to the effect of grazers, denitrification, or macrophytes which absorb nutrients and may secrete anti-phytoplankton chemicals, preventing the build-up of phytoplankton (e.g., Körner & Nicklish 2002).

The line **a1**-**b1** shows how the Putere Lakes probably responded to increasing land use intensification. The lakes probably showed a moderate degree of ecological resistance provided by their native macrophyte communities until Tipping Point 1 was approached – a point in the nutrient availability gradient where the risk of the lakes becoming highly eutrophic and losing their macrophyte communities becomes great. The point **a1** might represent where the Rotonuiahā and Rotoroa were in 1983, exhibiting significant degradation in water quality, while still retaining some native macrophyte biomass. We don't know anything about the state of Rotongaio at that time, but since that lake seems to have much higher nutrient concentrations, it is possible that the lake was already largely devegetated and in a highly degraded state at that time (**b1**). The line **a2**-**b2** shows how the water quality of the lakes likely responded the invasion of hornwort. Hornwort grows faster and reaches higher biomass than the native macrophytes. Therefore, hornwort provides enhanced ecological resistance against eutrophication by absorbing more nutrient and suppressing phytoplankton more than the native macrophyte communities were capable of doing. Thus, that a2-b2 line shows a eutrophication trajectory with greater ecological resistance to eutrophication.

There is no hornwort in Rotongaio, no data on when elodea invaded that lake, nor is there any historical water quality data for that lake. So, how this lake responded to eutrophication and macrophyte invasion is unknown. However, recent macrophyte and water quality surveys suggest that the lake is at a tipping point and macrophytes may soon disappear from this lake. Without hornwort, the increased resistance to eutrophication afforded by that highly invasive species is not a seen in Rotongaio. Elodea is less invasive and generally doesn't grow as tall or achieve as high biomasses as hornwort does (Champion et al. 2019). So, according to the theoretical framework in Figure 12, Rotongaio is likely to be currently somewhere in the vicinity of **b1** and **b2** – with degraded water quality and poor macrophyte condition. Once a lake is devegetated, the resistance to eutrophication that an abundant macrophyte community provides is gone and lake generally enter a highly degraded state exhibiting severe algal blooms. The loss of macrophytes allows wind and bioturbation to facilitate the resuspension of lakebed sediment, making the water very turbid, further reducing light penetration to the lakebed and making it even more unlikely that the lake will recover macrophytes without the assistance of major restoration actions. Such devegetated lakes often remain in a highly degraded state, even resisting attempts to restore them through reductions in external nutrient loads (Scheffer 2004; Søndergaard et al. 2003).

This theoretical framework appears to be relevant to the Putere Lakes, which provide examples of interesting historical and current degradation trajectories, in which macrophytes undoubtedly played, and continue to play, a key role. This framework suggests that, although hornwort has negative impacts on biodiversity, food webs, and recreation, it does provide some resistance to the effects of eutrophication such as algal blooms and high turbidity (e.g., Körner & Nicklish 2002; Scheffer 2004). Such eutrophication effects also negatively impact biodiversity, food webs and recreation as is reflected in the current state of Rotongaio.

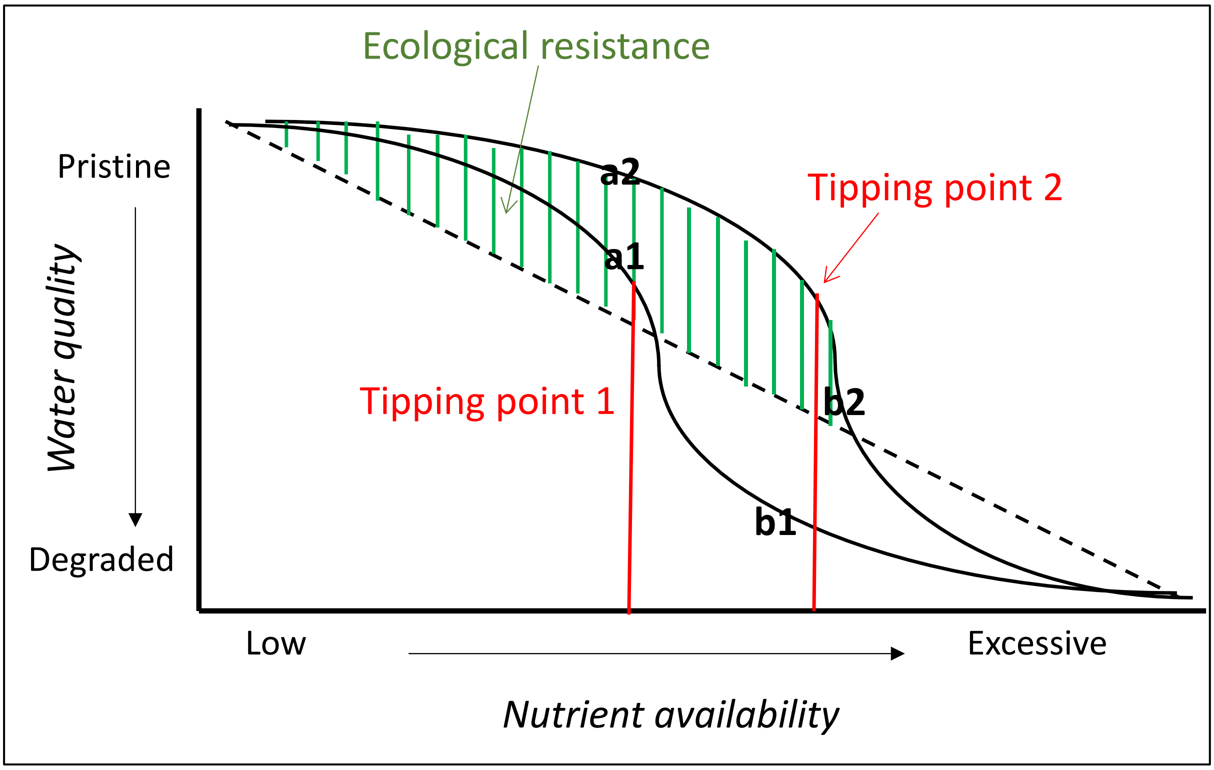


Figure 12. Degradation (left-to-right) and recovery (right-to-left) trajectories of a hypothetical lake eutrophication framework based on alternative stable state theory (e.g., Scheffer 2004; Larned & Schallenberg 2018). As eutrophication proceeds due to increasing nutrient availability, lakes pass through tipping points separating a macrophyte-dominated clear water state and a phytoplankton-dominated turbid state. Line **a1-b1** shows a trajectory with moderate ecological resistance to the effects of eutrophication while line **a2-b2** illustrates a trajectory with enhanced ecological resistance to eutrophication, as could be expected due to high macrophyte cover and biomass. The red vertical lines indicate the levels of nutrient availability that cause the lakes to tip into a persistent degraded state. The difference between the two tipping points is due to the effect of increased ecological resistance to eutrophication hypothetically due to invasion by hornwort.

Research has been carried out on the factors that facilitate New Zealand lakes crossing a eutrophication tipping points (Table 7). Schallenberg & Sorrell (2009) identified several characteristics associated with lakes which had crossed these tipping points into degradation: (1.) the percentage of catchment in agriculture, (2.) the presence of certain pest fish species and (3.) the presence of the invasive macrophyte, *Egeria densa*. The precise percentages of the catchments of the Putere Lakes that are in agriculture are unknown, but Figure 3 suggests that it is > 50% for all the lakes. Schallenberg & Sorrell (2009) found an increased risk of lake flipping for lakes with >30 % agriculture in their catchments (Table 7). The Putere lakes don't contain the pest fish species that were found to be associated with lake flipping. This highlights the importance of excluding the pest fish species from the Putere Lakes that are implicated in causing lakes to cross tipping points. The Putere Lakes also don't contain the invasive macrophyte, *E. densa*, which is also fortuitous because this species can form beds so dense beds that they can collapse and cause a rapid shift to a degraded state of water quality.

Studies by Schallenberg & Schallenberg (2012) and Kelly et al. (2013) also identified summer total nitrogen and total phosphorus tipping points. Rotonuiahā and Rotoroa are well below these nutrient thresholds, whereas Rotongaio exceeds the nitrogen threshold for macrophyte collapse and the phosphorus threshold for severe decline in macrophyte cover.

The empirical tipping points identified from other lakes are consistent with the conditions observed in the Putere Lakes. They help understand the extent of restoration actions needed to reduce nutrient availability in Rotongaio to levels whereby one might expect to see improvement in water quality and restoration of macrophytes.

The final sections of this report discuss options for restoring the Putere Lakes considering the values identified in Section 1. We currently understand the key values and lake conditions that are desired by the community and those that are mandated by statutory guidelines. We also have some understanding of the stressors and the invasive species that can affect, or mediate, the relationship between stressor levels and lake conditions. However, we don't have a good understanding of current stressor levels (e.g., current sediment and nutrient loads) or of the influence today of historical sediment and nutrient inputs to the lakes on lake conditions. Due to a lack of long-term monitoring data, we also aren't able to identify the precise stressor levels for these lakes which cause these lakes to cross their tipping points. Therefore, most of the restoration actions discussed below require further analyses, additional information, and feasibility studies to be conducted before they should be undertaken at a lake-wide, or catchment-wide, scale.

Table 4. Summary of research on tipping points in New Zealand shallow lakes and intermittently closed and open lake-lagoons (ICOLLs). The grey columns show estimates for the Putere Lakes.

Stressor	Response	Tipping point	Type of system	Reference	Rotonuiahā	Rotoroa	Rotongaio
% catchment in agriculture	Probability of flipping	*P* ≈ 0.40 for 30 to 70% agriculture	95 shallow lakes and ICOLLS across New Zealand	Schallenberg & Sorrell (2009)	Mostly agricultural, but with upstream lake	Mostly agricultural	Mostly agricultural
Presence of either *Ameiurus nebulosus* (catfish), *Carassius auratus* (goldfish), *Scardinius erythrophthalmus* (rudd), *Tinca tinca* (tench), *Cyprinus carpio* (koi carp)	Probability of flipping (1 species present): Probability of flipping (2 species present): Probability of flipping (3 species present):	………*P* = 0.26 ………*P* = 0.80 ………*P* = 0.90			None present	None present	None present
Presence of *Egeria densa*	Probability of flipping	*P* = 0.53			Not present	Not present	Not present
Total nitrogen (summer concentration)	Severe decline in macrophyte cover	700 µg L^{-1}	10 South Island brackish lakes and ICOLLs	Schallenberg & Schallenberg (2012)	234 µg L^{-1}	178 µg L^{-1}	1168 µg L^{-1}
Total nitrogen (summer concentration)	Severe algal blooms	1500 µg L^{-1}			234 µg L^{-1}	178 µg L^{-1}	1168 µg L^{-1}
Total phosphorus (mean summer concentration)	Severe decline in macrophyte cover	50 µg L^{-1}	19 South Island shallow lakes	Kelly et al. (2013)	9 µg L^{-1}	9 µg L^{-1}	164 µg L^{-1}

7 TOWARDS A PUTERE LAKES MANAGEMENT/RESTORATION PLAN

The above sections of this report assembled available information to help inform a management/restoration plan for the Putere Lakes. Section 1 reported on community consultations in which the main values of the lakes for the local community discussed. Section 4 discussed the water quality and ecosystem health guidelines in the NPSFM that the lakes must be assessed against, including the national bottom lines for the various attributes. Section 5 assessed the current and historical conditions of the lakes based on available data, which are, unfortunately, sparse. Section 6 proposed using a theoretical stressor-response framework for developing a management/restoration plan that ties together (1.) ecological indicators of the values to be protected, 2. the stressors that affect the values and 3. the ecological components of lake ecosystems which can influence the relationship between stressor levels and the condition of valued lake attributes.

While there is some information concerning the main stressors to the lakes (e.g., sediment and nutrient inputs) and mediators of the stressor-response relationship (e.g., invasive macrophytes, kākahi densities, etc.), little information on the historical and current stressor levels exists. This means that there is considerable uncertainty around stressor levels that define ecological tipping points in these lakes.

Clearly, Rotongaio is at a critical stage in its trajectory towards severe eutrophication because the lake is nearly in a devegetated state, exhibiting very poor water quality. On the other hand, Rotonuiahā and Rotoroa still generally exhibit acceptable water quality, which has improved in relation to conditions reported for these lakes in 1983. However, the improvement in water quality is likely to be at least partly due to proliferations of hornwort in these lakes, which suppresses sediment resuspension and algal proliferation, but threatens native biodiversity and cultural and recreational values.

Currently the situation in Rotongaio is that unacceptably poor water quality is driven by high nutrient concentrations. The lake's macrophytes beds dominated by moderately invasive *Elodea canadensis* cover a very low proportion of the lakebed and, therefore, can not substantially compete with phytoplankton for nutrients. The key problem in this lake is high nutrient concentrations which probably result from high loads from the catchment (external nutrient loading) and/or from the lakebed (internal nutrient loading). However, this is speculative because we currently have no information on external or internal nutrient loads to the lake. However, the nutrient and phytoplankton concentrations of the lake are consistent with that of a highly eutrophic lake, with high nutrient inputs.

In contrast, the most obvious management issue in Rotonuiahā and Rotoroa is the proliferation of hornwort and its impacts on lake values. However, the presence of high densities of macrophytes, covering a substantial proportion of the lake beds probably hides a eutrophication problem in these lakes. The macrophytes, and the periphyton that grows on them, take up and retain substantial amounts of nutrients from the water column, while hornwort has also been reported to produce chemicals which inhibit photosystem II in phytoplankton, suppressing phytoplankton growth rates (Körner & Nicklish 2002). If the lakes did not have these macrophytes, conditions would be more favourable to phytoplankton. Therefore, the nuisance macrophytes in these lakes provide an ecosystem service by suppressing phytoplankton blooms, which would be worse if macrophytes weren't so dominant in the lakes.

Given the situation of the three lakes, recommended management/restoration strategies fall into three categories: (1.) control of macrophytes, (2.) control of nutrient and sediment inputs from the catchments, and (3.) control of nutrient availability in the lakes.

7.1 CONTROL OF MACROPHYTES

Hornwort is considered an "unwanted organism" in the National Pest Plant Accord and is listed as an "environmental weed" by the Department of Conservation (Champion et al. 2019). It is considered one of the most invasive aquatic plants to have established in New Zealand, receiving an AWRAM (Aquatic Weed Risk Assessment Model) score of 67 out of 100 (Champion & Clayton 2000). Although it is recognised as an "organism of interest", it is not considered to be a pest organism in the Hawkes Bay Regional Pest Management Plan 2018 -2038 (HBRC 2019). Local Ngāti Pāhauwera consider it to be a weed that "chokes waterways, smothers native plants, impacts biodiversity, swimming and recreation" in the Rotonuiahā and Rotoroa (Hape, 2019). Therefore, a management/restoration plan for the Putere Lakes should address the nuisance factor of hornwort in Rotonuiahā and Rotoroa.

In contrast, elodea has a much lower AWRAM invasiveness score of 46 and is not included in the National Pest Plant Accord and has no management status under the Hawkes Bay Regional Pest Management Plan 2018 – 2038, althought it is considered by the Department of Conservation to be an "environmental weed" (Champion et al. 2019). This macrophyte is struggling to persist in Rotongaio, where it is perhaps the only remaining macrophyte present in the lake and may be on a path to extirpation due to the poor water quality of the lake (Burton 2017).

In an analysis of pest aquatic macrophyte occurences in New Zealand lakes, De Winton et al. (2009) reported that hornwort had successfully colonised lakes across the trophic state gradient from oligotrophic to super/hypertrophic lakes, showing that hornwort is a species that can tolerate a wide range of conditions from nutrient-poor, clear water conditions to highly polluted, turbid conditions. Hornwort doesn't produce roots and, therefore, obtains its nutrients entirely from the water column. Its inability to utilise nutrients in lake bed sediments may explain why it produces chemicals which inhibit the growth of some phytoplankton and periphyton algae, thereby reducing competition for nutrients in the water column. Macrophyte assessments show that current conditions in Rotonuiahā and Rotoroa are favourable to its growth, competitiveness and persistence in these lakes (Burton 2017; Hussain & Jones 2022a, b).

Methods for control of nuisance aquatic macrophytes have been extensively studied because of the adverse effects of macrophyte proliferations on aquatic ecology, recreation and aquatic infrastructure. NIWA produced a a detailed framework for aquatic macrophyte management, which outlines many approaches to controlling macrophyte proliferations (Champion et al. 2019). The approaches they describe fall into three general categories: (1.) physical, (2.) chemical, and (3.) biological (Table 5). It is beyond the scope of this report to delve into the details of each of these methods, their advantages, disadvantages, and costs because these are already well-described in Champion et al. (2019). Because most of these control methods would require substantial resourcing in order to succeed in a long-term substantial reductions in macrophyte biomass in these lakes, detailed feasibility studies should first be undertaken before deciding to move ahead with any of the macrophyte control methods.

Table 5. Macrophyte control methods described in Champion et al. (2019).

1.Physical
• Hand weeding
• Raking, netting
• Suction dredge, excavator
• Mowing, cutting, harvesting
• Benthic barriers
• Water level drawdown
2.Chemical
• Available herbicides
• Restricted herbicides
3.Biological
• Insects
• Grass carp
• Snails

Lake-wide erradication of hornwort from these lakes is probably not feasible. Furthermore, removal of a large proportion of the macrophyte biomass in the lakes without first reducting nutrient availability could result in a sudden increase in trophic state characterised by persistent cyanobacterial blooms, potentially producing cyanotoxins. For example, this type of response was observed in Lake Ōmāpere, Northland, in response to devegetation of the lake using grass carp (Gray 2012). Any sudden, substantial change to a lake ecosystem has the potential to produce unexpected consequences due to the complexity of lake ecosystems. Tipping points can suddenly be exceeded due to the release of nutrients and the development of, or exacerbation of, bottom water anoxia resulting in increased internal nutrient loading (Closs et al. 2004; Gray 2012). Therefore, careful planning is required, especially when restoration actions are likely to disrupt an established equilibrium in the lake ecosystem. A feasibility study regarding the potential use of grass carp to remove hornwort from Rotonuiahā and Rotoroa should consider the outcomes of grass carp use to control lake weeds in other Hawkes Bay lakes including Lakes Eland, Tutira, Waikopiro and Opuahi.

Given the potential for unintended consequences of whole lake devegetation by biological control agents, it would be more prudent to attempt localised removal and control at key sites in the lakes. Such sites would probably include access ways and swimming areas as well as habitats where valued organisms like kākahi and native macrophytes are present (e.g., Hussain & Jones 2022b discuss locations of kākahi beds). However, if hornwort remains in the lakes, localised control methods will have to be employed indefinitely because the ceasing of macrophyte control will allow rapid recolonisation.

7.2 Controlling nutrient and sediment loads from the catchments

For successful long-term restoration of lakes, it is usually necessary to reduce external nutrient loading because this is usually the fundamental, long-term driver of eutrophication in lakes (Larned et al. 2018). In dealing with diffuse sources of discharges, the reduction of external nutrient and sediment loads can be achieved by (1.) mitigations via changes in land cover and land use intensity which change the rates of nutrient and sediment loss from soils and by (2.) catchment interventions, which are designed to intercept the transfer of sediment and nutrients from land into the lake (McDowell et al. 2018).

7.2.1 Land cover/land use

Land use and land cover play pivotal roles in sediment and nutrient delivery to aquatic systems (Larned et al. 2018) especially in steep, highly erodible landscapes and where wet and stormy climates facilitate rapid water movement through the landscape. The presence of wetlands in the landscape slows water flow, facilitating denitrification, nutrient uptake by wetland plants and microbes, and sediment retention. Unfortunately, typical historical farming systems tended to place low value on wetlands, leading to their drainage and conversion to pasture, speeding the flow of water through the landscape into aquatic receiving environments.

There are many mitigations which can be utilised to reduce nutrient and sediment losses from farm soils. Where such mitigations are not available or are insufficient to help restore the lakes, reductions in stocking rates or changes in land use may reduce nutrient and sediment losses from farmland. The National Environmental Standard for Freshwater Management (NESFW; MfE 2020b) and the National Environmental Standard for Plantation Forestry (NESPF; MfE 2017) provide guidance on mitigating some of farming and forestry practices which are most polluting to freshwater ecosystems. Regional Councils and industry advisory bodies such as DairyNZ and New Zealand Beef & Lamb also have guidance on minimising impacts to water of land use practices. The Essential Freshwater package of reforms will soon mandate farm environment plans to be developed in conjunction with Regional Councils and the use of these plans will provide an opportunity for farmers in the catchments of the Putere Lakes to upgrade their farming practices to minimise sediment and nutrient losses from land to water (https://environment.govt.nz/acts-and-regulations/freshwater-implementation-guidance/freshwater-farm-plans/).

7.2.2 Intercepting contaminants before they reach the lakes

Other sources of sediment runoff to waterways include roading (especially non-metalled roads) and earthworks. It is challenging to reduce sediment loads from these sources, even when good management practices are put into place. Ultimately, sediments and nutrient mobilised from the catchment may need to be intercepted before reaching the lakes and streams flowing into the lakes. Contaminants in both overland flow and in shallow groundwater can be intercepted by riparian buffer strips along the banks of streams and on the shores of lakes. These not only prevent stock from accessing waterways, but also slow the flow of water from land into receiving environments, allowing for some sediment and nutrient retention by plants and microbes. The NESFM and NESPF provide useful guidance on the use of riparian buffer strips to intercept contaminants flowing from land to water.

Where riparian buffer strips cannot be effectively employed, sediment traps may be helpful in reducing high suspended sediment and nutrients loads in flooded streams. For example, swales and other types of temporary impoundments can be constructed such that, at high stream flows, some or all the flow is diverted into the sediment trap, which retains suspended sediments that sink out of the water while the water velocity is reduced within the sediment trap. Such traps tend to preferentially retain coarser sediment particles, which occasionally need to be removed from the sediment trap as it fills up over time. This material is ideally taken away from waterways and distributed in a way so that it doesn't find its way back into aquatic receiving environments. As a large proportion of phosphorus in streams is generally bound to sediment particles, any mitigations that reduce sediment loads will also substantially reduce phosphorus loads.

7.2.3 The ecosystem services value of historical wetlands

Of all ecosystem types in the world, wetlands are among the ones that provide the highest valued ecosystem services (Patterson & Cole 1999). In terms of improving water quality, they not only trap sediments and nutrients but they also remove nitrate via denitrification. Wetlands are, therefore, ideal habitats for "treating" water before it reaches lakes and streams.

Examination of the low-lying areas in the catchments of the Putere Lakes indicates that, historically, numerous wetlands existed in the vicinity of the lakes, which have subsequently been drained and converted to pasture (Fig. 13). The areas in Figure 13 that are shaded blue are areas inferred to have originally been wetlands that are now pasture. These are generally areas that the main inflow tributaries flow through. Today, instead of being wetlands that attenuate sediment and nutrients flows to the lakes, these pasture areas are likely to be sources of nutrients and sediments to the lakes during high flow events.

Although these areas are also likely to be the most valuable farmland in the catchments, the loss of ecosystem services from converting the wetlands to pasture was likely substantial. An assessment of the ecosystem services provided by different ecosystems in the Waikato Region placed the total (direct and indirect) ecosystem services value (in 1997 dollars) of Waikato wetlands at $39,777 per ha, whereas the ecosystem services of Waikato agricultural land were valued at $1,017 per ha (Patterson & Cole 1999).

The satellite image of the catchment of Rotongaio in Figure 13 appears to show that the inflow stream has been diverted away from the lake, removing the main inflow and source of water and dissolved oxygen to the lake. If this is the case, the potential for flushing of nutrients out of the lake has been greatly reduced, in effect making the lake a stagnant water body, dependent on little more than direct rainfall to generate flows out of the lake. While this would have lowered the nutrient and sediment loads to the lake, it also reduced the flushing rate of the lake, which could potentially exacerbate its trophic state. Without further field-based investigations, it is difficult to definitively assess the importance of this diversion to the health of the lake.

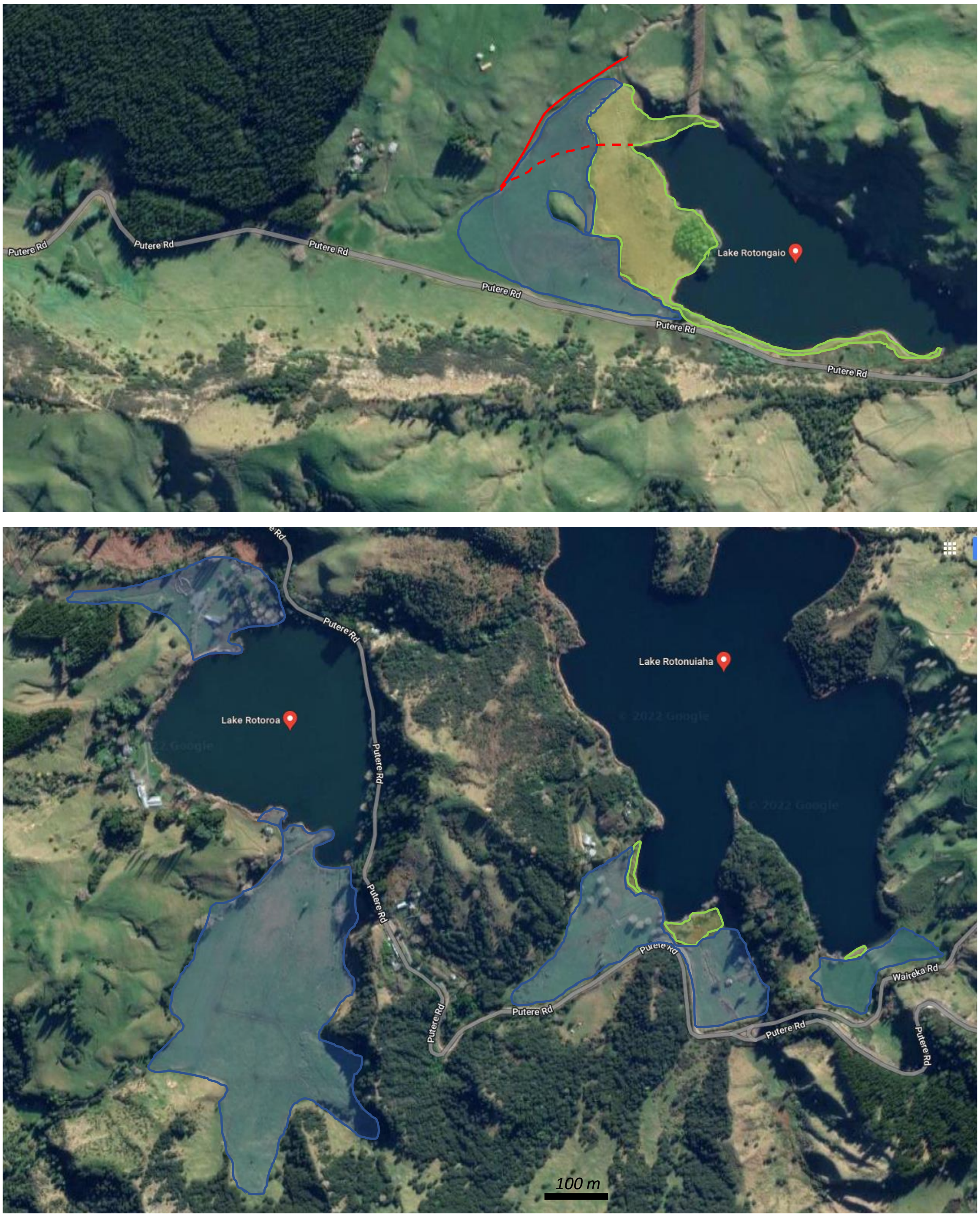


Figure 13. Potential for restoration of lake-shore wetlands. Areas with bright green shading are areas of current wetland vegetation. Areas with blue shading appear to be former wetland areas converted to agriculture through drainage and hydrological alteration. The solid red line in the upper panel is the current tributary stream bypass of Rotongaio. The dashed red line is the likely historical trajectory of the tributary stream, which historically increased the hydrological flow through the lake.

7.3 CONTROLLING NUTRIENT AVAILABILITY IN THE LAKE

Once mitigations and interventions are in place to minimise external nutrient and sediment loads, in-lake interventions can contribute to reducing eutrophication. Such in-lake interventions may target (1.) the internal phosphorus load and the conditions that cause it, (2.) the flow, cycling and distribution of nutrients among various desirable and undesirable components of the lake food web, and (3.) aspects of the hydrological regime of the lake which may contribute to eutrophication.

7.3.1 Limiting the internal phosphorus load

The problem of internal phosphorus loading in lakes has been well studied because this problem has been identified as a significant impediment to restoration from eutrophication in many lakes (Verburg et al. 2018). The internal P load is often a result of historically high P inputs to lakes through means such as sewage discharges, high rates of superphosphate fertiliser usage, etc. This is known as legacy phosphorus, which can repeatedly recycle in eutrophic lakes by alternating between being bound to lakebed sediments and dissolving and diffusing into overlying waters under conditions of anoxia and high pH. A useful decision support and risk assessment framework for managing internal phosphorus loads was developed by Hickey & Gibbs (2009). Various approaches include (1.) the use of phosphorus binding and flocculating agents, (2.) the use of sediment phosphorus capping agents, (3.) the aeration of bottom waters, (4.) the oxygenation of bottom waters, and (5.) the mixing of lake waters to prevent thermal stratification. The costs benefits of these methods are described in Hickey & Gibbs (2009).

In general, these methods should be used in conjunction with restoration actions aimed at reducing external nutrient loading. If external nutrient loads remain high, then multiple applications or long-term use of in-lake methods will be required to produce a sustained improvement in water quality. Methods to control internal phosphorus loads would be particularly beneficial in conjunction with external load reduction and macrophyte control because macrophyte control methods will likely increase phosphorus availability to phytoplankton. Therefore, the use of P binding agents, or of methods to prevent bottom water anoxia from occurring because of increased amounts of dead macrophyte detritus in the lake, will to some extent reduce the spike in phosphorus availability that could occur when macrophytes are controlled.

7.3.2 Biomanipulation

Biomanipulation of food web components can facilitate lake restoration from eutrophication (Burns et al. 2013). Often the aim of food web biomanipulation is to enhance the biomass of grazers, which should in theory reduce phytoplankton biomass (Burns et al. 2014). In the Putere Lakes, biomanipulation to restore the lakes from eutrophication could aim to increase the biomass of the grazing zooplankter, *Daphnia*, if it occurs in the lakes. This could potentially be facilitated by reducing the number of planktivorous fish in the lakes, such as smelt and larval bullies. A robust assessment of whether biomanipulation could help reduce phytoplankton biomass or not would require an assessment of the fish and zooplankton communities of the lakes.

Another biomanipulation approach was suggested by Hussein and Jones (2022b), who described the use of floating rafts containing kākahi, which would remain suspended in the water column where they could filter the lake water. Kākahi have been shown to be effective grazers of phytoplankton in shallow lakes (Ogilive & Mitchell 1995; Phillips 2007). However, it is not known whether the use of kākahi rafts has been successfully trialled anywhere. Therefore, a feasibility study would have to be undertaken, which would have to include an assessment of whether enough kākahi could be sourced for this approach to be successful.

7.3.3 Hydrological regime

The Putere Lakes have relatively small catchments and, therefore, may have long water residence times with slow rates of flushing. Slow flushing can result in slow recovery from historically high nutrient loads. After reductions in external nutrient loads, legacy phosphorus loads in lakebed sediments can typically take around 15 years to be sufficiently reduced to allow lakes to achieve a new nutrient equilibrium in relation to reduced external loads (Søndergaard et al. 2003). One way to speed this process is to provide augmentation inflows of relatively clean water to accelerate the flushing process. In Rotongaio, this could potentially be achieved by diverting the main inflow back into the lake (Fig. 13). For Rotonuiahā, a potential source of augmented flows could be the Waiau River, from which water could be pumped into the lake. This would likely be a costly restoration activity and a thorough feasibility study would need to be undertaken to determine the likely benefit of such a restoration action.

Finally, lakes that regularly flood surrounding pasture soils may receive pulses of phosphorus and nitrogen as high water levels recede and the flooded land is drained into the lake. Soils high in phosphorus and nitrogen may then contribute these nutrients directly to the lake ecosystem. If the Putere Lakes regularly undergo substantial water level fluctuations, then modifications to the lake outlet may help reduce high water level variations and associated nutrient loads to the lakes.

8 KNOWLEDGE GAPS

8.1 ROUTINE MONITORING

The water quality monitoring programme for the Putere Lakes is a joint endeavour between the Ngāti Pāhauwera Development Trust and Hawkes Bay Regional Council. The expansion of lake monitoring as discussed below provides numerous further opportunities for co-development and co-management of the monitoring plan for the lakes as well as providing opportunities for citizen science initiatives, public education, and the weaving of science and local mātauranga.

8.1.1 Water quality

The development and implementation of lake management/restoration plans requires substantial resources. Thus, such plans should be underpinned by robust data, ecological understanding, and feasibility studies. In the case of the Putere Lakes, a monthly water quality monitoring programme was initiated in January 2020 and the data from this programme have been instrumental in determining the current state of water quality in the lakes. As part of the water quality sampling, it would be useful to collect the following additional information to help understand the suitability of the lakes in relation to key values expressed by the community:

- Depth profiles of temperature, dissolved oxygen, and chlorophyll *a* at the deepest site in each lake
- Hypolimnetic total phosphorus concentrations during the stratified period
- *E. coli* and cyanobacteria biovolume concentrations at recreational/swimming sites during the swimming season

8.1.2 Macrophyte assessments

LakeSPI surveys have provided valuable information on the condition of the macrophyte communities in the lakes. However, the LakeSPI protocol recommends at least 5-yearly frequency for LakeSPI assessments (Clayton & Edwards 2006) and this higher, more regular frequency of assessment would be helpful, particularly in relation to any macrophyte control work that is undertaken as part of a restoration programme. It is important to regularly assess the condition of the macrophyte community in Rotongaio because it appears as though this lake may be on the cusp of becoming devegetated. In addition, hornwort is apparently absent from Rotongaio and the proximity of this lake to the other two hornwort-infested Putere Lakes makes it vulnerable to hornwort invasion. So, regular LakeSPI assessments would provide some surveillance of the presence/absence of hornwort in that lake. All monitoring surveys must ensure that macrophytes (or any other pest species) are not transferred between lakes. Furthermore, if the invasive macrophyte, *Egeria densa*, were to become established in the lakes and displace hornwort, it could cause the lakes to undergo periodic collapses in macrophyte biomass and shifts to highly eutrophic conditions (Schallenberg & Sorell 2009). Therefore, careful cleaning of boats and equipment when moving between lakes is highly recommended and regular, 5-yearly surveillance for the presence of this species in the lakes would also be useful.

8.1.3 Fish and kākahi surveys

Surveys assessing the catch per unit effort of the fish species in the lakes would clarify the state of taonga species and mahinga kai resources. Work with local iwi could also identify other mahinga kai indicators that could be incorporated into a monitoring programme for the lakes. It is fortunate that pest fish species such as koi carp, catfish, goldfish (although see hui notes), rudd, etc. have not been recorded from the Putere Lakes, because these species have the potential to impair the water quality and ecological condition of lakes (Schallenberg & Sorrell 2009). Fish surveys would also help determine whether species are present that could suppress the densities of zooplankton grazers, such as *Daphnia* sp., in the lake. Thus, fish surveys could provide guidance on whether biomanipulation might be an option for helping to improve the water quality of the lakes.

When present in high densities, filter-feeding kākahi can improve water clarity of lakes (Ogilvie & Mitchell 1995; Phillips 2007). Therefore, understanding the current densities, spatial distributions and size distributions of kākahi can help inform the current states and trends of these valued organisms in the lakes. A preliminary assessment of kākahi densities and size distributions was undertaken in two locations in Rotonuiahā, which reported low densities of 2 to 4 individuals per m^2 (Hussain & Jones 2022b). More information on kākahi in this, and the other two lakes, would help determine the current health of kākahi populations in the lakes.

8.1.4 Zooplankton and phytoplankton

Daphnia are strong grazers of phytoplankton. Collection of zooplankton using vertical hauls with a 300 µm mesh size net would confirm whether *Daphnia* are a component of the zooplankton communities of these lakes. When algal blooms occur in the lakes, samples of phytoplankton can help identify which species of phytoplankter are responsible for the blooms. This can provide insights as to why the blooms occur. For example, the dominant algae may be types that are inedible to grazers, or they may be able to fix nitrogen, or they may be mobile species that can move up and down in the water column at different times of day. Knowing which species develop nuisance phytoplankton blooms in the lakes can provide insights as to why and how they proliferate in the lakes.

8.2 OTHER KNOWLEDGE GAPS

8.2.1 Bathymetry

Information on the bathymetry of the lakes is lacking. Bathymetric surveys would allow the calculation of mean depth, lake volume and flushing rate (and its inverse – the water residence time) of the lakes. This information is important for determining nutrient standing stocks and budgets as well as for determining appropriate regions within the lakes for targeted restoration interventions and monitoring.

8.2.2 Nutrient and sediment loads and budgets

Nutrient and sediment management of lakes is greatly facilitated by having lake nutrient and sediment budgets, which comprise estimates of loads, standing stocks, and exports (Verburg et al. 2018). Loads can be crudely estimated by use of catchment models, such as NIWA's CLUES models for total phosphorus, total nitrogen, and suspended sediment. However, loads can also be measured by monitoring water discharge and nutrient and sediment concentrations at the main inflow tributaries to the lakes. The lake outflows can be similarly monitored enabling the calculation of nutrient and sediment export from the lakes. These calculations enable the estimation of rates of net nutrient and sediment retention in the lakes. From this information, the magnitude of internal phosphorus loads can also be inferred.

Nutrient and sediment budgets are useful for setting nutrient and sediment reduction targets and, if updated regularly, can inform as to whether the lakes are accumulating or shedding nutrients over time and whether the management of both internal and external loads is important for management/restoration purposes.

8.2.3 Sediment phosphorus content and mobility

The Putere Lakes likely experience historical high phosphorus loads – phosphorus which today is likely bound to lakebed sediments. Depending on sediment geochemistry, bound phosphorus may be released into overlying water, where it can act as an internal phosphorus load to the lake. In this way, the lakes' phosphorus load legacy can continue to cause eutrophication problems for decades after external loads have been reduced (Søndergaard et al. 2003).

Lakebed sediment collected by sediment coring can be analysed to determine the phosphorus content and the solubility of bound phosphorus under conditions of low dissolved oxygen concentrations and high pH. Dr Sean Waters at the Cawthron Institute does these analyses, which can be used to identify the potential influence of phosphorus in lakebed sediments on phytoplankton blooms and eutrophication (Waters et al. 2020). This information, together with nutrient budgets, can help identify the importance of internal phosphorus loading to the trophic state of lakes, which can help prioritise and optimise potential lake restoration actions.

8.2.4 Catchment inflows to Rotongaio

Satellite images appear to show that the main inflow tributary to Rotongaio was diverted so that it is now bypassing the lake. If true, sediment and nutrient loads to the lake may be highly curtailed. Study of the catchment inflows to the lake would help confirm whether the main historical tributary to the lake now largely bypasses the lake or not. This knowledge would help understand the current magnitude and sources of nutrient and sediment inputs to the lake.

9 SUMMARY AND RECOMMENDATIONS

The Putere Lakes are of high value to local iwi as reservoirs of native aquatic biodiversity, as sites of mahinga kai gathering, and for recreation. The water quality of Rotongaio is very poor and the lake appears to be on the cusp of losing its submerged macrophyte community. This would likely exacerbate the shift of the lake to a persistent, highly eutrophic state in which nuisance cyanobacterial blooms will be common. In contrast, the water quality of Rotonuiahā and Rotoroa has improved substantially since 1983, but this has at least partly been due to the proliferation of invasive hornwort, which negatively impacts biodiversity, recreation and mahinga kai gathering.

Due to these differences, recommended approaches for restoring Rotongaio differ to some extent from those for restoring Rotonuiahā and Rotoroa. Reducing external nutrient and sediment inputs should benefit all three of the lakes, however the focus in restoring Rotonuiahā and Rotoroa should be hornwort control. Caution will have to be exercised when attempting to reduce hornwort cover and biomass so that this does not result in increased nutrient availability to phytoplankton.

Various restoration actions are available to control macrophytes, to reduce external nutrient and sediment loading to the lake, and to reduce internal phosphorus loading from the lakebed sediments. Currently, there is a lack of information regarding the sediment and nutrient inputs to the lakes and it is not clear whether external loads are more influential than internal loads. Any attempts to reduce macrophyte cover and biomass should strive to avoid increasing nutrient availability to phytoplankton in the lakes.

While some scientific information and data exists with which to assess the current health of the lakes, some significant knowledge gaps also exist, which hinder the identification of a set of restoration actions that will deliver desired and cost-effective restoration outcomes. However, the undertaking of some feasibility studies, together with the collection of more data and information will allow for the co-development of a robust restoration/management plan for the lakes. The recommendations in Table 6 are provided to help focus efforts to develop an effective and cost-effective management/restoration plan for the Putere Lakes.

Table 6. Recommendations toward the development of an effective and cost-effective management/restoration plan for the Putere Lakes.

Recommendation	Relevant sections in this report	Timing
11. Estimate catchment contaminant loads	7.2, 8.8.2, 8.2.4	Immediate
12. Undertake a feasibility study for hornwort control in high-value, localised areas of Rotonuiahā	7.1, 8.1.2	Immediate
13. Undertake a feasibility study to determine whether lake-side wetland areas could be re-established to remove contaminants from tributary inflows	7.2.3, 8.2.4	Immediate
14. Expand monitoring programme	8.1	Immediate
15. Determine lake bathymetry, volumes, and water residence times	7.3.3, 8.2.1	Immediate
16. Develop a riparian planting programme to protect streams and lake shores from stock access and from overland flows	7.2.2	Immediate
17. Calculate nutrient and sediment budgets for lakes	8.2.2	Contingent on recommendations 1, 4, and 5
18. If internal phosphorus loading is determined to be substantial, undertake a feasibility study to assess the potential to reduce internal phosphorus loading	7.3.1, 8.2.2, 8.2.3	Contingent on recommendation 7

After the information in this report is considered, it could be useful to hold a wānanga together with some experts in lake restoration science and mātauranga as a way to help bring a restoration plan for the lakes into focus. At that stage, it would also be helpful to have an indication of a budget that would be available to invest into restoration actions as well as an indication of the desired time frame within which to achieve the restoration targets that are set for the lakes.

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