Sensitivity: General

Lake Waikare Catchment Analysis

Desktop Assessment of Contributing Catchments, Ecology and Water Quality

Prepared for Watercare Services Ltd
Prepared by Beca Limited

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Executive Summary

Beca Limited (Beca) was engaged by Watercare to provide a catchment analysis of Lake Waikare to provide an overview of the existing water quality and ecological values and to provide context regarding the relative contribution of contaminants from the Te Kauwhata Wastewater Treatment Plant (WWTP) discharge compared to other catchment sources. The analysis focusses on water quality issues on a catchment scale, and how historical changes may have influenced the current state of the Lake. Ecological components of the Lake system and how they are impacted by water quality are described. Key drivers of ecological impacts and opportunities for ecological betterment have also been identified.

Lake Waikare is a shallow riverine lake with a large catchment (210km^2). The catchment comprises farmland predominantly, with patches of vegetation in steeper areas and riparian margins around Lake Waikare and other small lakes within the catchment. There are several inlets into the Lake (one of which is gate controlled) and only one outlet, which discharges to the Whangamarino Wetland. The connection between the Waikato River and Lake Waikare has resulted in extensive flooding in the past, drowning large amounts of productive farmland. The Lower Waikato/Waipa Flood Control Scheme was implemented in 1953 to mitigate flooding effects. The water level of Lake Waikare was lowered by one metre as part of the scheme.

Lake Waikare and the surrounding riparian vegetation is considered to have medium to high ecological values due to the confirmed presence of several At Risk and Threatened native fauna species. Freshwater fish populations are dominated by pest species (carp, rudd, goldfish), however, several native species including eels and galaxiids utilise the limited habitat available within the Lake. Prior to 1965, other fish species were found within the lake (lamprey, smelt, bullies) but numbers have since declined. Lake Waikare once supported a native macrophyte population, but this collapsed in about 1970, which was thought to be due to a large phytoplankton bloom. Overall, diversity in the ecosystem is hindered by the poor water quality of the Lake as well as other abiotic factors.

To provide context of the treated wastewater discharge contribution to the lake impacts relative to other catchment land uses, various sources of information were collated and analysed. Main outcomes from this analysis were:

- Agricultural practices account for 88% of the catchment land use. Cropping dominated low land areas around the lake margins, while areas of greater relief were predominantly pasture with scattered blocks of forest.
- The Lower Waikato/Waipa Flood Scheme was a key contributor to the lake’s collapse in water quality and ecosystem, due to strict hydraulic control and restriction of water exchange between the lake and river.
- A comparison between 2021 and early historic aerial photographs indicated that large swathes of riparian margin has been cleared for agricultural land use from 1943 or earlier, accompanied by slight changes in shore morphology. An increase in scour, erosion and nutrient run off due to this land use change has likely occurred.
- Previous modelling assessments undertaken have found that the treated wastewater discharge accounts for <1% of total nitrogen and phosphorus loads to the Lake.
- Additionally, because the lake is very shallow, and due to wind action, suspended settlement is largely not able to settle. This restricts the ability for macrophytes to re-establish, something that would be required to appreciable enhance the Lake’s water quality and ecosystem.

Based on the information reviewed for this report and given the significant influence of catchment land use on the Lake, the evidence concludes that water quality effects of treated wastewater discharge are likely to be localised only (e.g., influencing nutrient concentrations near the outfall rather than influencing overall lake nutrient loads and ecology).

The treated wastewater discharge has been in breach of its consent conditions for some time; however, operational improvements have been made over the last few years in response to the breaches, including the recent implementation of a Membrane Aerated Biofilm Reactor (MABR) upgrade which is expected to bring the WWTP into compliance.

The Lake's water quality is mostly influenced by catchment-related issues e.g., nutrient loss from land use, loss of riparian and wetland vegetation and related reduction in ability to attenuate and filter nutrients and sediment. This in turn, has degraded habitat quality for native flora and fauna and ecological function of the lake ecosystem. These issues are exacerbated by the lowering of the Lake level by the flood scheme.

The declining water quality, loss of macrophytes, and introduction of pest fish has resulted in a decline in the diversity and population of native fish species within the lake. Additionally, habitat changes from catchment use and a reduction in adequate food supply, has resulted in native bird life within the lake and surrounding significantly declining.

It was determined that the above factors have caused the current state of Lake Waikare and that the treated wastewater discharge is unlikely to have had a significant influence on the overall degraded state relative to the other water quality drivers. Collection of data from further locations within the Lake and its contributing catchment would support identification of key areas of nutrient inputs for the purposes of Lake management.

Ecological betterment opportunities identified include full scale pest fish removal, catchment management (e.g., revegetation and fencing tributaries), wind barriers, and re-establishment of lake macrophytes. However, none of these would likely succeed in the isolation of other measures; a holistic approach would be required with consultation with landowners to help lift the Lake out of its hypertrophic state. Solutions would be complex, given for example that it has been observed by Waikato Regional Council that macrophyte re-establishment is inhibited by suspended sediment not allowed to settle due to wave action and pest fish; and other solutions such as flushing that have been investigated to date appear to not be currently feasible due to cost and likely consenting challenges.

1 Introduction

As part of a wider resource consent project, Watercare Services Limited (Watercare) are investigating options for the future discharge of treated wastewater from the Te Kauwhata Wastewater Treatment Plant (WWTP). The discharge from the WWTP is currently to Lake Waikare. As part of this wider project, Beca Limited (Beca) was engaged by Watercare to prepare a catchment analysis, water quality and ecological baseline assessment of Lake Waikare.

The purpose of the catchment analysis is to:

- Provide an overview of the existing ecological condition and water quality of Lake Waikare and sensitive downstream receiving environments (including Whangamarino Wetland)
- Understand the relative contribution of land use activities, catchment-derived contaminants and point-source contaminants, and the influence of the flood protection scheme on the ecological functioning of the Lake.
- Assess the relative impact the WWTP discharge on the lake in terms of contaminant loads.
- Understand the changes to lake water quality over time as a product of land use change.
- Undertake an initial screen of possible ecological betterment opportunities that could be tied to a new resource consent application for the wastewater discharge (using existing catchment management plans as a basis for understanding work already being undertaken)

This assessment is limited to information provided by the client and what is publicly available.

1.1 Sources

Table 1 below summarises the information sources used in this assessment - please refer to Section 6 for a full reference list.

Table 1. List of sources used to inform assessment.

Source	Author/s	Purpose in this Investigation
Lake Waikare and Whangamarino Integrated Catchment Management Plan (ICMP) Parts 1 and 2	Waikato Regional Council	Informs much of Section 2 as background reading.
Wastewater discharge compliance/consent reporting	Watercare	Background reading to provide context to assessing treated wastewater quality of the discharge
Wastewater discharge data	Watercare	Informs the assessment on treated wastewater quality from the WWTP in context of other contributing factors
Media releases	NZ Herald, Stuff (among others)	Provides background information on key issues, history, stakeholders and public perception.
Historical Imagery	Retrolens	Provides information on historical land use change

Source	Author/s	Purpose in this Investigation
Published conference papers	Various	Technical background reading particularly in terms of water quality
Waikato Regional Council and Land, Air, Water Aotearoa (LAWA) websites	Waikato Regional Council, LAWA	Provides background information on general water quality trends and typical parameters (e.g. Secchi depth)
Technical Reporting (predominantly water quality and hydraulic modelling)	Waikato Regional Council	Conclusions are useful in understanding lake/catchment dynamic, and previously explored management strategies.

In addition to the above a high-level desk-based review of the ecological features, characteristics, and species records was completed to provide an understanding of the historic and current state of any ecologically sensitive features/species within Lake Waikare and surrounding areas in the catchment.

Ecological information was sought from several, primarily citizen science, databases including:

- eBirds (Sullivan et al., 2009);
- New Zealand Freshwater Fish Database (NZFFD) (Jowett & Richardson, 2003);
- iNaturalist Zealand Data (*INaturalist*, n.d.)
- Reports produced, and publicly available, from other consultancy providers (Wildland Consultants, Ridley Dunphy Environmental Limited).

Reference lists used within the above documents were also searched for relevant publications. However, relevant references that might provide useful information were not always publicly available, and therefore there may be information gaps within this investigation.

2 Catchment Overview

2.1 Location

Lake Waikare is located approximately 30 km north of Hamilton, with Te Kauwhata located at the north-western shoreline of the lake (Figures 1 and 2). Lake Waikare is the largest and oldest of the lakes in the Lower Waikato Valley. The lake has a total catchment size of approximately 210 km^2, has an estimated volume of over 43, 000, 000 m^3 (Wildlands Consultants Ltd, 2012) and a surface area 34.7km^2.

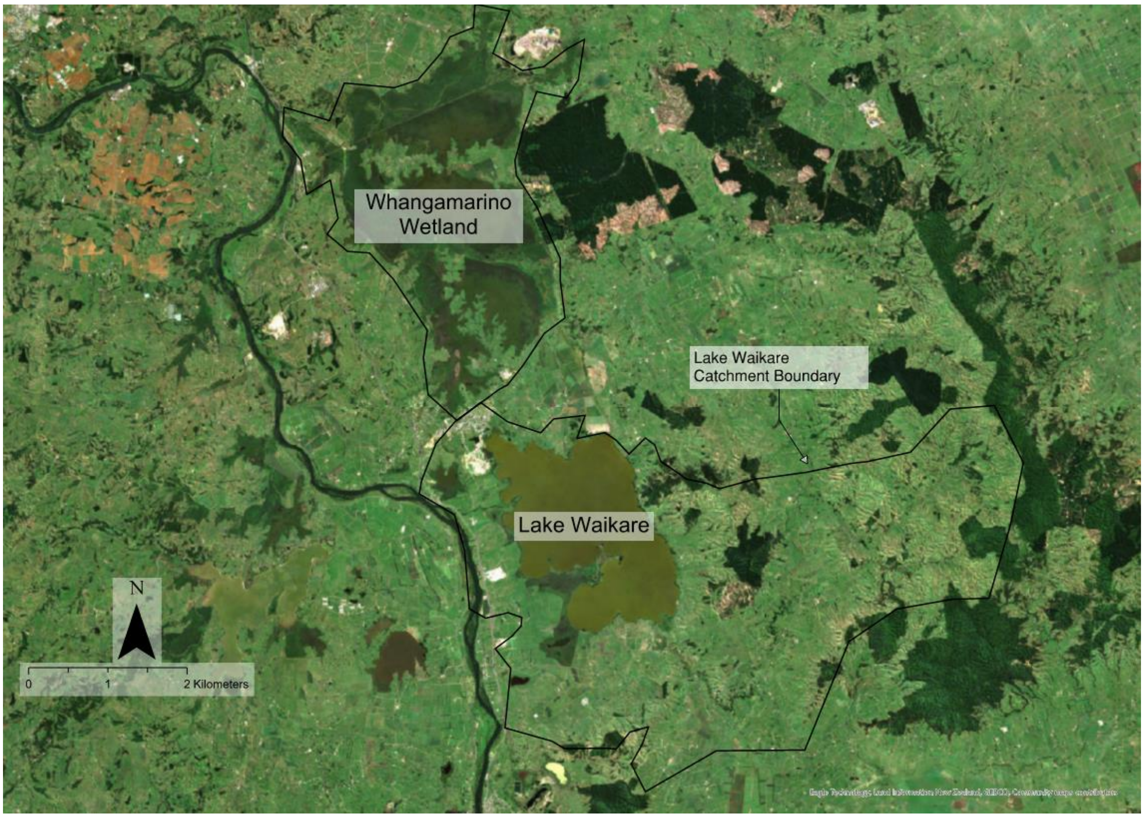

Figure 1. Lake Waikare catchment and Whangamarino wetland.

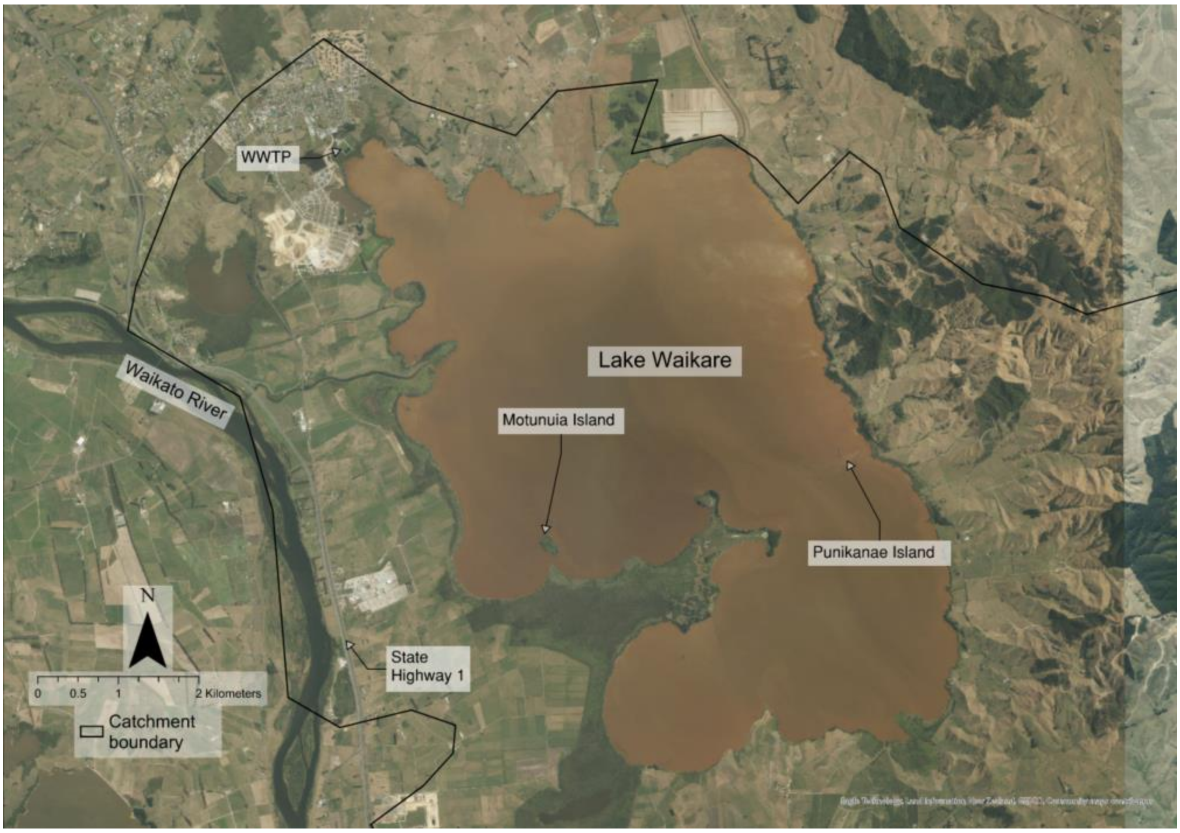

Figure 2. Features of Lake Waikare and surrounding area.

The Lake is connected to other notable freshwater features of North Waikato; the Whangamarino wetland (a Ramsar site), Whangamarino River and the Waikato River. Several smaller streams and lakes feed into Lake Waikare (see section 2.3 for additional details).

The lakebed is owned by Waikato-Tainui. Lake margins are owned by Fish & Game, local iwi, Department of Conservation (DoC), and other private owners.

2.2 Landscape

The catchment is characterised broadly by two types of topography, namely low-lying, flat floodplain transitioning to foothills of the Haupuakohe Range. The low-lying, flat flood plain areas are found all around the lake margins. Most anthropogenic activity (Te Kauwhata township, farming and otherwise) occurs within this area. This describes the catchment to the north, west and south generally, with some smaller local changes in topography. The Hapuakohe Range lies to the east and divides the Mercer-Ohinewai area from the Hauraki Plains. There is a rise of 219m between Lake Waikare and an unnamed peak within the foothills of the Hapuakohe. From aerial photography, this elevated area is partially forested and partially pasture, although the ruggedness of the area suggests it is unlikely to be intensively farmed.

2.3 Land use types

A brief analysis of land use types within Lake Waikare's catchment was completed. The graph below shows the percentage make-up of the catchment (Figure 4). Land use type was determined by visually scanning 2021 aerials (Table 2). Limitations/assumptions of this included:

- Defining specific types of cropping (e.g., horticulture, maize) was not possible. Similarly pasture for different types of farming (dry stock or dairy) could not be differentiated based on the scope of the information reviewed.

- Other agricultural area includes rural dwellings, sheds, and open grassland. Types of farming that could be included are dairy, beef and sheep farming (these are not easily distinguishable from aerial photography). The percentage of buildings and roads within this area is assumed to be 5-7%.

Much of the pasture was contained within the Hapuakohe Range, and it was clear that this area was not productive compared to flat areas nearer the lake, due to its steepness and lack of development (e.g. dwelling, and sheds). Most productive land is contained within the flat portions of the catchment, near the lake.

Table 2: Description of land use types for the purposes of this report.

Cover type	Description
Water body	All ponds and lakes other than Lake Waikare
Riparian vegetation	All vegetation fringing a water body, including that of Lake Waikare.
Industrial	Very large sheds with ancillary buildings, material storage (e.g. logs), trucks etc. Does not include small rural sheds.
Urban	Grouped housing and light commercial areas (i.e. town shops).
Cropping	Regular shaped paddocks with obvious cultivation rows and/or very green areas.
Other agricultural	All remaining area

Figure 3 below illustrates land use percentages within the catchment.

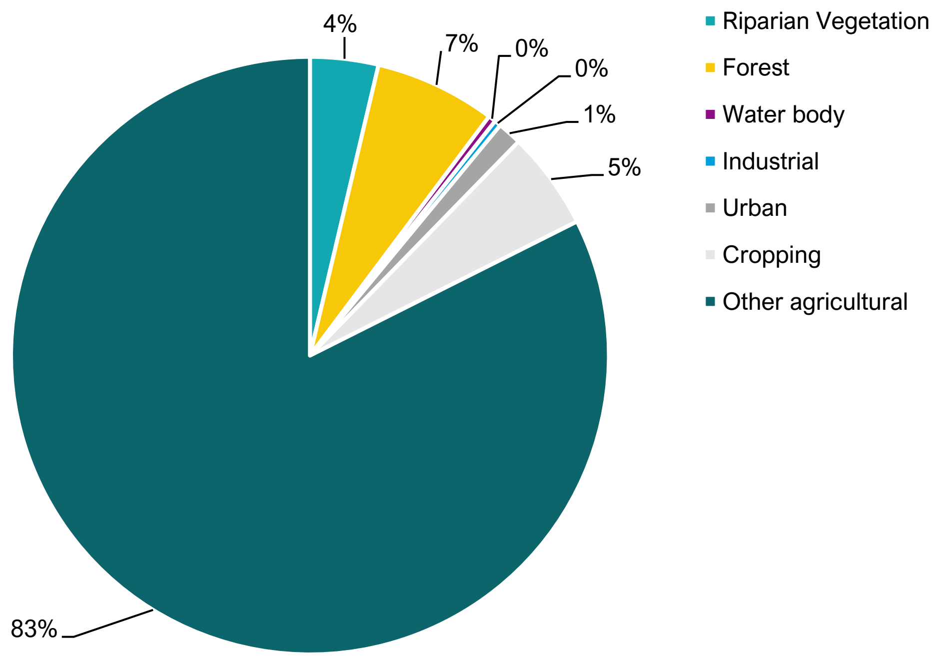

Figure 3: Pie graph indicating percentage land use type within Lake Waikare's catchment. A 0% value equals an actual percentage of less than 0.5%.

Most of the land use within the catchment is related to agricultural activities including cropping and pasture. Vegetation cover (not including pasture/grasslands) makes up a total of 13% of the catchment. Forest cover was in small blocks and was mostly restricted to areas of greater relief. Forests were generally poorly connected and broken up by large areas of grass land.

Riparian vegetation mostly comprised the large wetlands surrounding Lake Kopuera, Lake Rotokawau and the terrestrial arm that forms the south-west shores of Lake Waikare near Motunuia Island. All other riparian/wetland areas are clearly vestigial, clinging tightly to the shores of Lake Waikare to the east, south and north which coincide with the greatest areas of productive agricultural area and the bulk of the catchment.

2.4 Cultural

The cultural importance of the Lake to mana whenua is recognised and briefly covered here to acknowledge these values but recognise that further and richer information is available from local iwi. The Lake is known for the Rangiriri battle campaign fought on the shores of Lake Waikare and Lake Kopuera in 1863. Lake Waikare is tapu as the bones of those who fought are thought to lie in the Lake (as well as in Lake Kopuera).

3 Lake Waikare Overview

3.1 Geological and Hydrological Context

Lake Waikare is a shallow riverine lake, formed by material from Taupo eruptions blocking tributaries of the Waikato River forming a series of wetlands and lakes including Lake Waikare and the Whangamarino Wetland (National Wetland Trust, 2006). The Tauranga Group comprises mud, peat, pumiceous sand, and pyroclastic deposits. The Motunuia and Maurgaroa faults pass through Lake Waikare.

Lake Waikare has two small islands; one of those (Punikanae Island) that lies to the east is associated with geothermal activity. The activity comprises the only known silica depositing locations outside of the Taupō Volcanic Zone. The other (Motunia Island) lies to the south-west in the lake.

Lake Waikare has an average depth of 1.5m, and an annual fluctuation range of 0.35m since the Lower Waikato/Waipa Flood Control Scheme (LWWFCS) was introduced. The scheme was developed in response to a catastrophic flooding event in 1958; a design report was issued in 1959 and structures were completed between 1961-1982. The LWWFCS provides many benefits, including protection of State Highway 1 and the Main Trunk rail line from a 2% AEP (annual exceedance probability) flood, reduced likelihood of loss of human and livestock life, and protection of farming infrastructure (Ridley Dunphy Environmental Limited , 2018). However, implementation of the scheme drained 67% of fringe wetlands from around the Lake, due to modification of natural water level fluctuations. These wetlands were converted to pasture (Ridley Dunphy Environmental Limited , 2018).

The lake has serval inlets, described below and shown in Figure 4:

- **West**
  - Te Onetea Stream, drains from Waikato River (1.55km^2)
  - Rangiriri stream, drains Lake Kopuera (3.86km^2). During the SH1 expressway upgrades the inlet from the Waikato River was blocked and the stream now drains surface water only from the surrounding paddocks.
  - Penewaka Lagoon, drains indirectly to Lake Waikare through minor drains or through Te Onetea Stream (0.39km^2)
- **South**
  - Lake Rotokawau, drains Lake Ohinewai which in turn drains from the Waikato River (18.06km^2)
  - Matahuru Stream, drains catchments originating from ridges and valleys of the southern portion of the Hapuahoke Range (106.32km^2)
- **East**
  - Onekura Stream, drains small area of eastern ridge (5.01km^2)

The lake has only one outlet, into the Pungarehu Stream which was constructed artificially as part of the LWWFCS. The Pungharehu Steam also drains the Te Kaha Stream catchment (28.10km^2) to the north-east of Lake Waikare. The Pungarehu stream then discharges into the Whangamarino wetland, then to the Whangamarino River and back to Waikato River at the Whangamarino Redoubt, north of Meremere.

There are two hydraulic structures at the inlets/outlet of the lake:

- A control gate is present at the outlet to Pungarehu Stream. The status of the control gate (whether it is open or closed) is decided on a seasonal and lake level basis, but generally aims to keep the lake levels between RL5.4 and RL5.7m. The control gate seals were repaired in 2022, preventing a drop in lake level below RL5.4m.
- Te Onetea stream was blocked as part of the LWWFCS to prevent back flow to the Waikato River in normal conditions. A control gate was later installed at the inlet to Te Onetea stream which is opened when the level of the river is above the lake level but below RL7.0m. The Rangiriri spillway was also installed, which allows 1% annual exceedance probability (AEP) flows from the Waikato River to enter the lake as sheet flow.

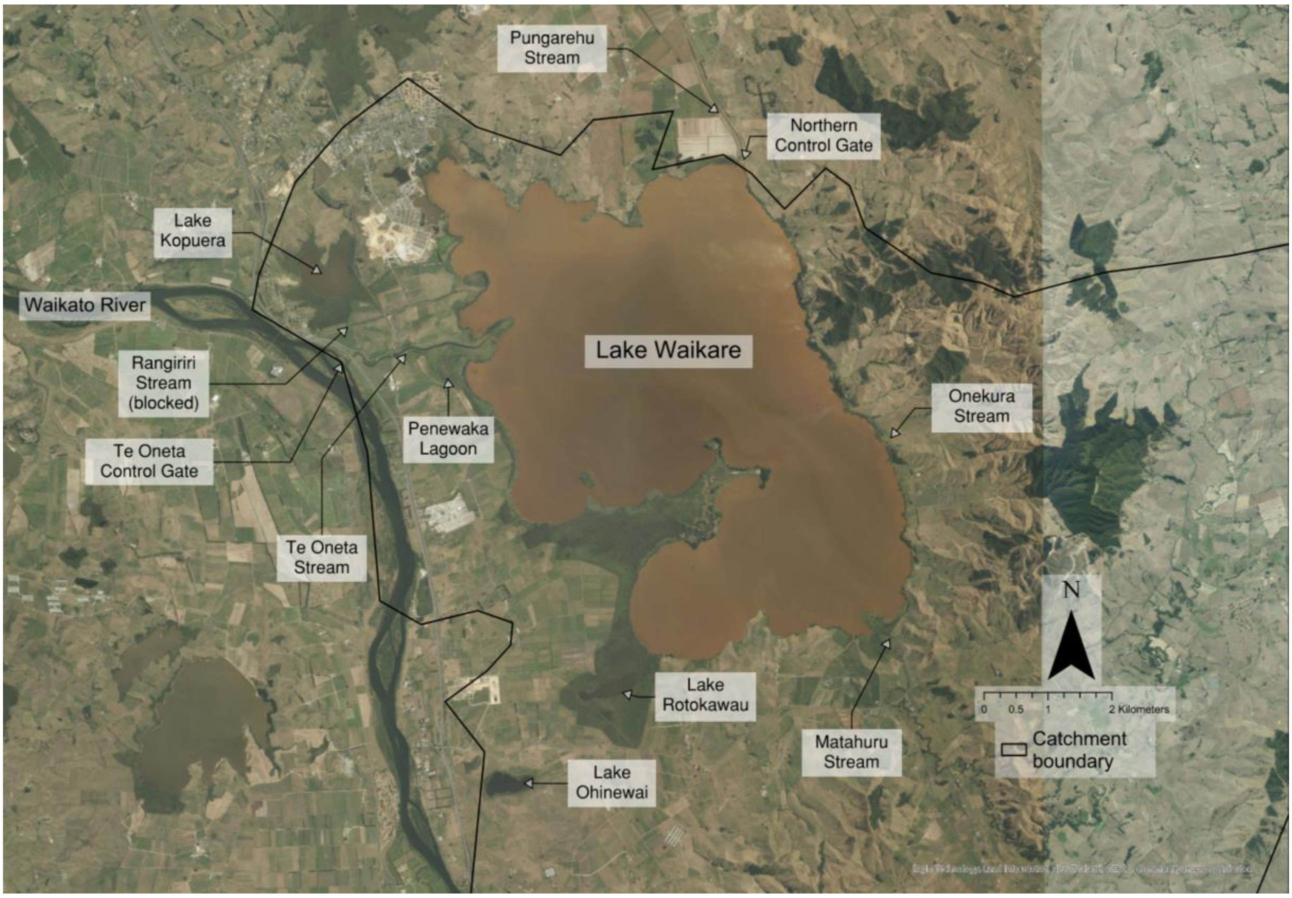

Figure 4: Hydrological and hydraulic features of the Lake Waikare catchment.

In addition to the above, there is a fish gate present at the outlet to Pungarehu Stream installed to help reduce koi carp numbers entering Lake Waikare (see Section 2.5 for additional details). The gate is only open in normal lake level ranges (above RL5.4m).

3.1.1.1 Flushing Studies

Studies have been undertaken into how the hydrological regime of the Lake could be adapted through flushing to reduce retention time. This includes a study by Cox &Cooke (Cox & Cooke, 2014), also discussed below in Section 5.5 which respect to catchment nutrient contributions. Pattle Delamore Partners Limited (PDP) assessed the feasibility of flushing strategies in 2014. This included assessment of three different channel options entering the lake from either the southern, midway or northern end of the Lake, with outflows exiting via either the Punarehu Stream or a combination of Te Onetea and Pungarehu Streams. Different flow rates were considered for these options (5 m^3/s – 50 m^3/s) on the basis of different channel widths. The flushing flows were estimated to result in a reduction of the hydraulic retention time from 100 days down to a potential minimum of 10 days. However, the report found that the large channel width expansion requirements were considered unfeasible for Te Onetea Stream and potential flow on effects to the Whangamario wetland and the Waikato River would likely result in consenting issues and impacts on a number of communities for all options. Therefore, it is understood that further investigations into a flushing regime have not yet been progressed.

The effects of the LWWFS on the hydrology and water quality of the lake are discussed in Sections 5.3.

3.2 Ecological Context Overview

Historically, the Lake Waikare catchment would have mostly comprised of secondary forest on the hills and freshwater wetland with areas of kahikatea forest (McEwen, 1987). In the mid-1940s significant forest clearance occurred within this catchment, and current land use comprises of primarily dry stock and dairy.

Despite the significant modifications that have occurred at Lake Waikare as well as change in land use, the lake retains moderate to high biodiversity values, is located adjacent to several high value wetlands, and is ranked 39th of the 96 lakes in the Waikato Region for biodiversity management (Wildlands Consultants Ltd, 2012).

Section 4 below provides further detail on the existing ecological condition of the Lake.

3.2.1.1 Whangamarino Wetland

Once water leaves Lake Waikare and the Pungarehu Canal, it enters the Whangamarino River which winds through the Whangamarino wetland. The wetland is located north of Lake Waikare and is a freshwater wetland comprising of several wetland classes including marsh, swamp, fen, and bog, and is the second largest bog and swamp complex in the North Island.

This wetland is considered internationally significant under the RAMSAR convention, with over 239 wetland species recorded, of which 60% are indigenous, with many classified as rare or vulnerable. The wetland provides habitat to a diverse range of water birds, which often utilise the wetland from autumn to late spring, including the largest population of bittern (*Botaurus poiciloptilus*) found in New Zealand. Other wetland birds utilising the site includes marsh crake (*Zapornia pusilla*), spotless crake (*Zapornia tabuensis*), Northland fern bird (*Poodytes punctatus*), and dabchick (*Poliocephalus rufopectus*), all of which are At-Risk species. During periods of floods the wetland also receives surface water from the greater Waikato River catchment via Lake Waikare (Ridley Dunphy Environmental Limited , 2018; Environmental Resources Information Network , 2002)

3.2.1.2 Lake Rotokawau

Southwest of Lake Waikare is Lake Rotokawau, also called Black Lake, and the two lakes are connected by a channel. Lake Rotokawau is unique in that it is surrounded by 145 hectares of wetland reserve, with the remainder of the catchment primarily used for dairy and dry stock farming (Ridley Dunphy Environmental Limited , 2018)

3.3 Media Coverage and Significant Events

Lake Waikare occasionally features in mainstream media, on the account of algal blooms that can change the colour of the Lake from its usual dull green to a vivid orange or red, which has been associated with an increase in intensive dairy farming over the last two generations (Vance, 2021). More recently, Lake Waikare was part of the botulism outbreak in March 2023, which killed thousands of waterfowl and was reported through both local and international media outlets (McClure, 2023).

Breaches in consented discharges from the Te Kauwhata WWTP into the lake have also been reported along with planned upgrades to the WWTP to keep flows within consented levels for nutrients and faecal coliforms (Tiffany, 2021).

The repair of the Northern control gate at the inlet to Pungarehu stream also featured in media (Waikato Herald, 2022; Ward, 2022), being a significant event to reduce contaminated water entering the Whangamarino wetland. During the blessing (karakia) of the replacement of the flood gate, iwi kaumātua lamented on the loss of kai moana from the catchment, citing the LWWFCS as a key reason why these food sources had been lost.

All media releases in recent years have cast a negative light on Lake Waikare, particularly on its status as being one of the most polluted lakes in New Zealand, the lack of biodiversity, and inputs that may have contributed to its current state.

4 Existing Ecological Condition

4.1 Trophic State

Over a century of farming and other agricultural activities, clearance of vegetation, as well as changing land use has resulted in high levels of inorganic sediment and other nutrient inputs into the lake, which has led to very poor water quality for a considerable amount of time.

It is classed as hypertrophic with a Trophic State Index (TSI) of 7.4 (LAWA, 2022).

This has led to regular and long-lasting algal blooms resulting in an algal-dominated state. By the 1970s, the macrophyte community within Lake Waikare had rapidly declined, with a phytoplankton bloom in 1977/78 believed to have precipitated the final collapse of the already stressed macrophyte community (Stephens , et al., 2004; Cox & Cooke, 2014; Ridley Dunphy Environmental Limited , 2018).

Currently, Lake Waikare has no macrophyte growth and its Lake Submerged Plant Indicator Score (LakeSPI) is 0, indicating no native or invasive macrophytes (Land Air Water Aotearoa, n.d.). This lack of growth is primarily due to wave action, shallow depth causing sediment resuspension and turbidity, and limited light penetration (Ridley Dunphy Environmental Limited, 2018). Farming practices in the catchment have also led to increased chlorophyll-a and red-pigmented algae (*Monoraphidium*) within the lake, which almost doubled between 1998/2002 and 2011 (Wildlands Consultants Ltd, 2012).

A study in 2006 attempted to reintroduce native green macro-algae called *Chara corallina*. It found that sheltered areas of the lake had higher growth due to fish exclusion. However, wave action, high algal growth, and sediment levels made light conditions inadequate for survival (Hopkins, 2006).

The establishment of aquatic vegetation to stabilise incoming sediment and nutrients is crucial to the rehabilitation of Lake Waikare (Stephens , et al., 2004; Hopkins , 2006).

4.2 Sedimentation

There are several sources of sediment input into Lake Waikare; the wider catchment/adjacent land, and through the rivers discharging directly into the lake. From here, the sediment settles, with some discharging into the Whangamarino Wetland. Due to the relatively shallow nature of Lake Waikare, as well as being a highly exposed system, it is highly prone to wind disturbance. Wind can significantly disturb the water surface, creating currents and waves that dislodge plants and re-suspend sediment. This is the case at Lake Waikare. Wind-driven wave action at Lake Waikare regularly leads to sediment re-suspension, thereby reducing water clarity and minimising the ability for any macrophyte re-establishment as noted above. The impact of the sediment resuspension with respect to restricting macrophyte re-establishment has previously been presented on to Waikato District Council by Waikato Regional Council (June 2014) and would inhibit the ability to appreciably enhance the Lake's ecosystem alongside other enhancement opportunities.

4.3 Biophysical Factors and Influence on Ecological Functioning

As discussed in Section 3.1, water levels in the Lake are controlled by the flood scheme and has had substantive influence on the ecological condition of the Lake. This includes water depth, circulation, retention time which in turns affects biophysical functioning of the lake ecosystem. Some of the related biophysical factors of the Lake are discussed below.

4.3.1 Light

Light provides the solar energy required by plants to photosynthesise, therefore, allowing for growth, reproduction, and food provisioning services. The amount of light received by a lentic lake system is impacted by the turbidity of the system and the ability for light to penetrate into the water column. Despite being a relatively shallow lake, the high concentrations of suspended matter within Lake Waikare have led to low light penetration into the water column, which is one (of several) cause for the low growing potential of macrophytes.

4.3.2 Wind

In an exposed system, wind can significantly disturb the water surface, creating currents and waves that dislodge plants and re-suspend sediment. This is the case at Lake Waikare, which is highly exposed and shallow. Wind-driven wave action at Lake Waikare regularly leads to sediment re-suspension, thereby reducing water clarity and minimising the ability for any macrophyte establishment.

4.3.3 Temperature

Despite there being no available historical data on temperature changes within Lake Waikare, assumptions can be made based on what is known about the Lake. It is known that Lake Waikare is shallow, well-mixed (no stratification), has a long retention time and regularly experiences eutrophication. Therefore, it is surmised that Lake Waikare experiences less temperature fluctuations and maintains warmer water temperatures, which supports the growth of algae (also due to nutrient input), but also allows for the survival of a range of freshwater fish (Table 3)

4.4 Native Fauna Values

Despite its degraded state, Lake Waikare has a moderate to high ecological value. This is primarily due to the available habitat provided by the lake to a range of native and At Risk freshwater fish and water birds. This is detailed further in the below sections.

4.4.1 Freshwater Fish

Data from New Zealand Freshwater Fish Database (NZFFD) confirms the presence of both native and exotic freshwater fish in Lake Waikare. The nearby Waikato River serves as an important migratory pathway and habitat for diadromous freshwater fish species. In 2001, a fish pass was installed to facilitate migration of elvers and eels from Whangamarino wetland into the lake. Subsequently, in 2011, a koi carp structure was added to mitigate their impact on water quality (Ridley Dunphy Environmental Limited, 2018).

Before 1965, Lake Waikare supported a diverse range of native freshwater fish species including eels, mullet, a range of *Galaxiids*, lamprey, brown trout, smelt, and bullies. However, changes in catchment use and declining water quality have significantly reduced their diversity over the years. Additionally, the multiple sources of nutrient and sediment input into Lake Waikare has resulted in algal blooms and increase turbidity, which has degraded water quality (Ridley Dunphy Environmental Limited, 2018).

Recent records indicate the presence of several native freshwater fish species in Lake Waikare, including some with an At Risk conservation status. However, introduced and pest fish species, such as koi carp, rudd, and catfish, are also present and thrive in the degraded environment of the Lake. Of particular concern is their disruptive feeding behaviour, which includes browsing on aquatic plants and disturbing sediment.

Table 3: Native and introduced fish species identified in Lake Waikare from the last 10 – 15 years (Allibone, et al., 2018; McDowall & Richardson , 1983).

Common Name	Scientific Name	Conservation Status
Longfin eel	*Anguilla dieffenbachii*	At Risk – Declining
Giant kōkopu	*Galaxias argenteus*	At Risk – Declining
Īnanga	*Galaxias maculatus*	At Risk – Declining

Common Name	Scientific Name	Conservation Status
Shortfin eel	*Anguilla australis*	Not Threatened
Common bully	*Gobiomorphus cotidianus*	Not Threatened
Common smelt	*Retropinna retropinna*	Not Threatened
Common carp / koi carp	*Cyprinus carpio / C. rubrofuscus*	Introduced
Gambusia/mosquito fish	*Gambusia affinis*	Introduced
Goldfish	*Carassius auratus*	Introduced
Brown bullhead catfish	Ameiurus nebulosus	Introduced

In addition to the freshwater fish species found within Lake Waikare itself, there are records of black mudfish (*Neochanna diversus*) within the Whangamarino wetland and the surrounding area of Lake Rotokawau. As black mudfish prefer wetlands and swampy areas, they are not expected, nor recorded, within Lake Waikare.

4.4.2 Native Birds

Lake Waikare is historically known to provide significant habitat for a diverse range of aquatic birds, and both the lake and Whangamarino Wetland were once referred to as the "Waikato Duck Factory," due to the high proportion of grey duck and mallard ducks present. However, due to habitat changes from catchment use and a reduction in adequate food supply, bird life within the Lake and surrounding areas has significantly declined (Ridley Dunphy Environmental Limited , 2018).

Records from eBirds and iNaturalist indicate the presence of range of introduced and native birds along the edges of Lake Waikare. Native species utilising the lake are outlined below.

Table 4. Native birds recorded within proximity to Lake Waikare (iNaturalist, n.d; New Zealand Birds Online, 2013; Ridley Dunphy Environmental Limited , 2018; Sullivan , et al., 2009).

Common Name	Scientific Name	Conservation Status
Caspian tern	*Hydroprogne caspia*	Threatened – Nationally Vulnerable
Spotless crake	*Zapornia tabuensis*	At Risk – Declining
Marsh crake	*Zapornia pusilla*	At Risk – Declining
New Zealand dabchick	*Poliocephalus rufopectus*	At Risk – Nationally Increasing
Black shag	*Phalacrocorax carbo*	At Risk – Relict
Little black shag	*Phalacrocorax sulcirostris*	At Risk – Naturally Uncommon
Royal spoonbill	*Platalea regia*	At Risk – Naturally Uncommon
Little shag	*Microcarbo melanoleucos*	At Risk – Relict
Pied shag	*Phalacrocorax varius*	At Risk – Recovering
Black swan	*Cygnus atratus*	Not Threatened
Grey teal	*Anas gracilis*	Not Threatened
Paradise shelduck	*Tadorna variegate*	Not Threatened
Pied stilt	*Himantopus himantopus*	Not Threatened
Pukeko	*Porphyrio melanotus*	Not Threatened
Sacred kingfisher	*Todiramphus sanctus*	Not Threatened
White faced heron	*Egretta novaehollandiae*	Not Threatened
Masked lapwing	*Vanellus miles*	Not Threatened

A range of At Risk and Threatened species are recorded within and within proximity to Lake Waikare, and likely utilise the lake as a feeding habitat, and the lake edges as roosting habitat. However, it is expected that some of these species regularly utilise the Whangamarino Wetland and Lake Rotokawau, both of which provide suitable roosting and feeding habit.

5 Key issues (or drivers of condition)

5.1 Historical land use change

Historical aerial photography was sourced from Retrolens to visually show and interpret changes in the replacement of lake vegetation with agriculture as an indication of land use change. The earliest photographs held are from 1943; this was before the LWWFCS was introduced, but after wetland draining had begun. The below figure illustrates how land use has changed over time.

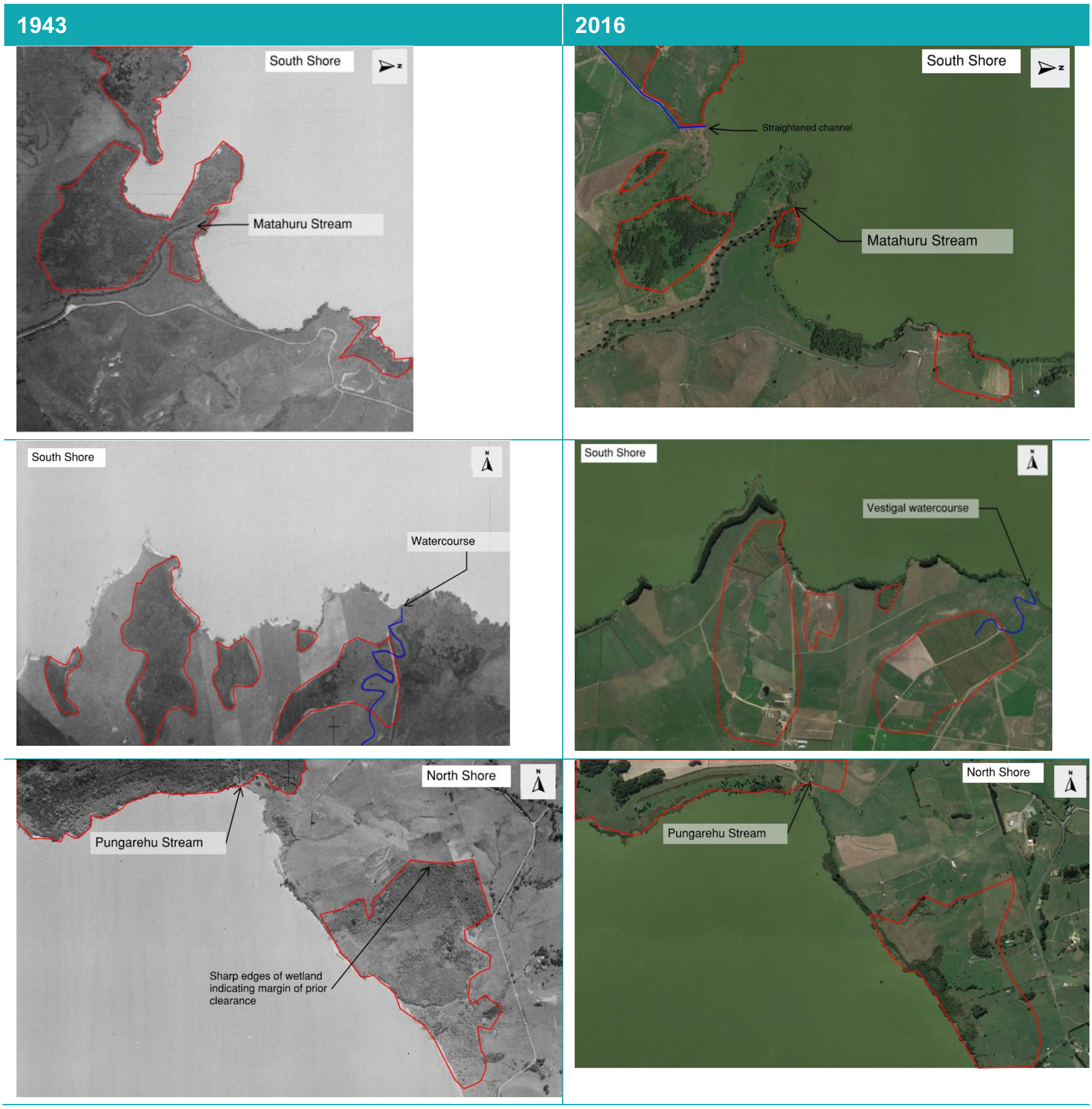

Figure 5. Land use changes at several shore locations indicated in red.

Large swathes of riparian vegetation and wetlands have been cleared/drained within the Lake Waikare catchment and replaced with farmland. Removal of these environments meant that there was likely a reduction in the amount of buffering between farms and the lake, allowing a greater degree of unmitigated runoff to occur at lake edges. This runoff was likely sediment and nutrient laden, and may be considered to be a point source of contaminants where runoff made its way to streams that feed into the lake, rather than a diffuse source controlled by fringe wetlands. Removal of vegetation also removed a certain amount of protection against scour and erosion, increasing the sediment load into the lake particularly in times of high rainfall.

It is almost certain that land use changes have had negative effects on the overall water quality of Lake Waikare. Modifications have been occurring since at least 1943, however other evidence suggests that earlier modifications have also occurred:

- 1943 photographs show that land use changes may have been occurring prior to the earliest aerial photography available. This is indicated by the straight edges and angular corners of patches of wetlands against grassed areas where vegetation has been cleared and drained to establish fenced pasture.
- Historical newspaper articles (circa 1932), sourced from PapersPast frequently discuss the drainage of 12,000 acres of Lake Waikare and adjoining catchment (Huntly Press and District Gazette, 1932) It is likely that this did result in wetland loss, although the full proposal of building a stop bank across the lake was never realised.

Therefore, Lake Waikare has experienced at least 100 years of modification within its catchment, from the drainage of wetlands through to the lowering of the lake level, as well as several flood events. The catchment is also very productive in an agricultural sense, with a high percentage of the lowland areas in either crop or pasture with low vegetation cover as noted above in Section 2.

5.2 Lower Waikato/Waipa Flood Scheme

The introduction of the LWWFCS significantly altered the natural water levels of the lake from seasonal fluctuation of 2.71m down to 0.35m of fluctuation. The scheme, which commenced in 1961 and was completed in 1982, comprises of stop banks, pump stations, floodgates and channel improvement works, which aimed to prevent flooding (and its consequences) on farmland and infrastructure (Waikato Regional Council , 2023). This resulted in the disconnection of the lower Waikato flood plain from the river, preventing the exchange and mixing of water from the river and the lake (Collier , Baker, David, Górski, & Pingram, 2017).

While hydraulic control protected people, animals, infrastructure, and livelihoods, it severely restricted the ability of the lake to be resilient against changes or continued pressure sediment and nutrient load from the wider catchment. The consequences of the flood scheme work were far reaching and irreversible and included:

- Alteration of the hydrological regime of Lake Waikare, including reducing water levels within the lake by up to 1.13 m.
- Redirecting water between Lake Waikare and the Whangamarino Wetland, with increases in the frequency and volume of discharge into the wetland. Floodwaters entering the wetland have high concentrations of suspended sediment and nutrients (Wildlands Consultants Ltd, 2012)
- The scheme resulted in unlocking swathes of flat and productive land for agricultural use, thereby facilitating development that has resulted in increased nutrient runoff.
- The control gates reduced discharge of sediment out of Lake Waikare, thereby locking it within the system which can lead to it becoming a contamination source (Yan, Cheng , Liu, Yu, & Zhou, 2022).

- Increase in turbidity by wind action that re-suspends sediment. This is exacerbated due to the lower water levels within the lake.

This has resulted in significant and irreversible ecological impacts:

- Loss of habitat for native fish
- Prevention in macrophyte growth – largely due to sedimentation and wave action.
- The loss of approximately 860 m^2 of wetland habitat at Lake Waikare, including a decline in the quality of wetland habitat with invasions of willows (*Salix fragilis* and *Salix cinerea*) (Wildlands Consultants Ltd, 2013).
- The loss of wetland habitat is anticipated to have resulted in the loss of approximately 40% of native plants and fauna.
- Increase in weed invasions with the re-direction of water providing a pathway for weeds into Lake Waikare and the Whangamarino Wetland from the Waikato River.

5.3 History of wastewater discharge quality

Discharge of human wastewater into Lake Waikare has been occurring since 1939, when untreated wastewater was directed into the Lake from Te Kauwhata township in a combined sewer with stormwater (serving the commercial area only). In the early 1970s, due to failing septic tanks in the wider residential area, sewer reticulation of the township was completed and oxidation ponds were constructed, with a subsequent discharge to Lake Waikare authorised in 1974 under the Water and Soil Conservation Act 1967.

The existing discharge consent was issued in 2013 (and expires in 2028); and the current WWTP process comprises oxidation ponds with aquamats, followed by constructed wetlands.

However, since 2013, the population of Te Kauwhata has grown significantly, increasing the amount of wastewater flow through the WWTP. The plant was not designed to treat those flows, resulting in breaches of consent conditions relating to water quality standards in the discharge.

Watercare has provided Beca with discharge quality data from 2017 to July 2023. The below figures show discharge data for *E.coli*, total nitrogen load and total phosphorus load over that timeframe compared to discharge limits specified under condition 8 of the resource consent. For the purpose of condition 8, the consent states that to determine compliance with the median limits for contaminants (excluding *E.coli*), no more than six samples in any 12 consecutive monthly samples over the period 1 July to 30 June each year shall exceed the specified limit. For the *E. Coli* median limit, no more than 13 samples in any 26 consecutive fortnightly samples shall exceed the specified limit (i.e., no more than half the samples in a monitoring year).

Figure 6 shows the calculated median concentrations of the monthly samples for each of the years 2017 to 2023 for total nitrogen and total phosphorus. Figure 7 shows the calculated annual median concentrations for *E. Coli* from 2018. These results are shown in comparison to the relevant discharge limit and the exceedances shown based on calculated values are also representative of occasions of exceedances determined based on the compliance methodology noted under condition 8 of the consent that is described above.

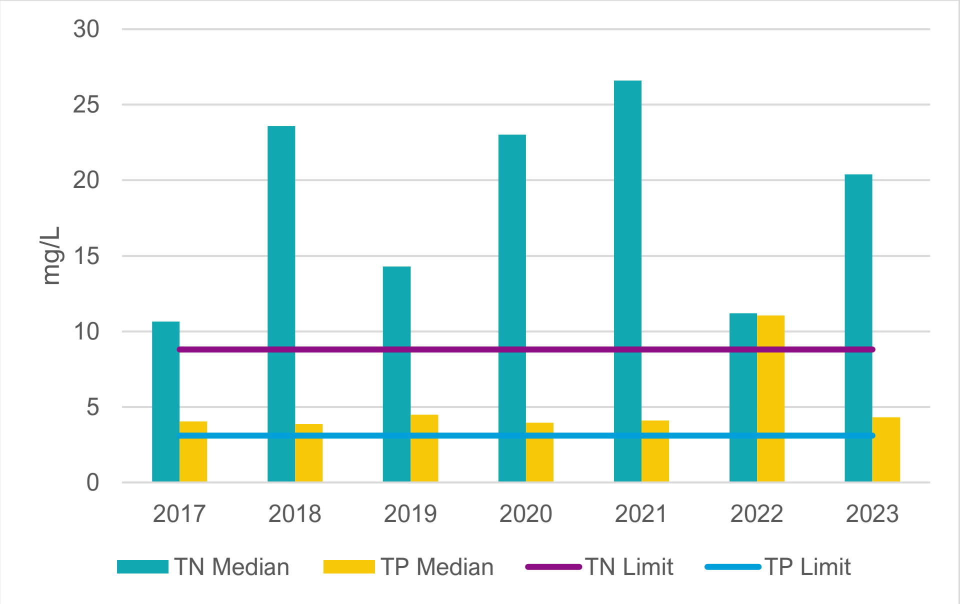

Figure 6. Total nitrogen and phosphorus load median concentrations 2017 - 2023.

Figure 7 (*E. coli*) shows that several breaches of the consent limit have also occurred over the period of data analysed. However, the most recent results have been compliant (noting the 2023 annual median was 16 cfu/100 mL), which is due to the UV system upgrade that has been implemented.

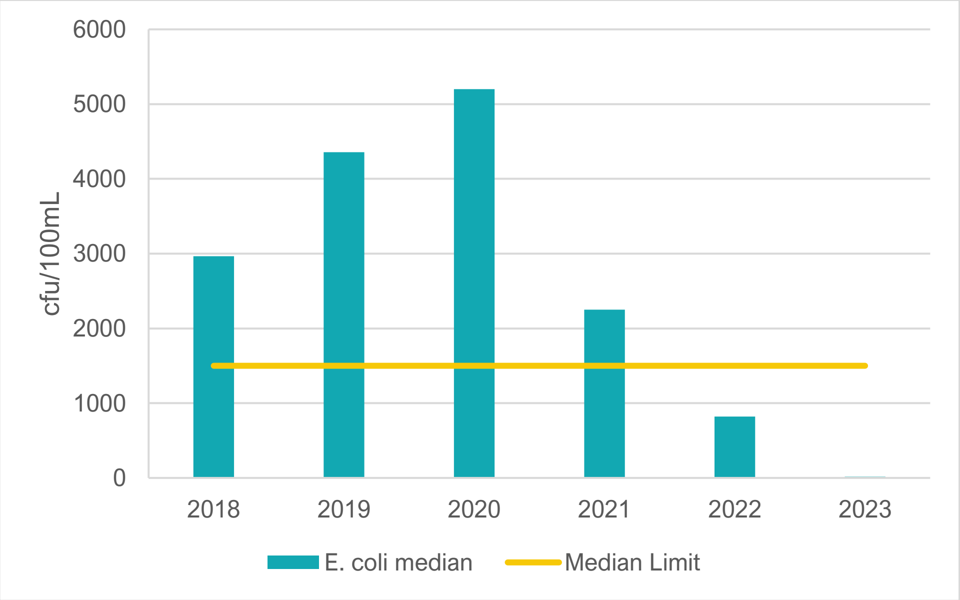

Figure 7. Median *E. coli* concentrations 2018 - 2023.

5.4 Lake Waikare and Contributing Water Quality Data

Water quality indicators are monitored monthly by Waikato Regional Council for Lake Waikare and are published on the LAWA website, analysed as state and trend. The 5-year median values for the water quality parameters published by LAWA (2014 – 2022) alongside the associated attribute states are summarised below in Table 5. The attribute states are based on those outlined in the Ministry for the Environment (MfE) National Policy Statement for Freshwater Management 2020 (NPS-FM 2020). Most of the water quality indicators are below the relevant National bottom line and therefore fall in the attribute state D band.

As noted in Section 4, the TSI for Lake Waikare is also published by LAWA and is used as an indication of the overall condition of the Lake. It is based on the concentrations of total nitrogen and total phosphorus, water clarity and algae levels. A TSI greater than 5 indicates very poor water quality and supertrohic lake conditions. The most recent TSI for Lake Waikare published by LAWA (for 2022) is 7.4 which is consistent with previous years' data that LAWA has published. Since 2008, the Lake's TSI has not been below 6.5.

Waikato Regional Council also monitors water quality at a site located on the Matahuru Stream at Waiterimu Road, which is one of the streams flowing to the Lake. Table 6 shows the 5-year median values reported by LAWA for total nitrogen, total phosphorus and *E. coli* for Matahuru Stream. The total nitrogen and total phosphorus median concentrations exceed the 'unsatisfactory' relevant limits for water quality in the Waikato Region which are 0.5mg/L and 0.04mg/L, respectively.

Table 5. Summary of water quality indicator data for Lake Waikare (2017 – 2022); Source LAWA

Water Quality Indicator	5-year median	Attribute State**
Total phosphorus (mg/L)	0.164	D
Total nitrogen (mg/L)	4.35	D
Ammoniacal nitrogen (mg NH_4-N/L)	0.01	B
Chlorophyll a (mg/L)	0.144	D
Cyanobacteria (mm^3/L)*	13.8	D
Secchi disc depth (metres)	0.15	D
E. coli (n/100 mL)	10	N/A

* Value for Cyanobacteria is based on a 3-year median.

** Attributes states reported by LAWA are based on those set out in the Ministry for the Environment National Policy Statement for Freshwater Management 2020.

Table 6. Summary of water quality indicator data for Matahuru Stream (2018 – 2023); Source LAWA

Water Quality Indicator	5-year median
Total nitrogen (mg/L)	1.35
Total phosphorus (mg/L)	0.084
E. coli (n/100mL)	900

5.5 Relative WWTP Nutrient Loading Contribution to Lake Waikare

Based on the median total nitrogen and total phosphorus concentrations from the last 5 years of WWTP compliance discharge monitoring data and median flow rate over that period, the total nitrogen load contribution from the WWTP is approximately 24.4 kg/year and total phosphorus load contribution is 4.3kg/year.

A modelling assessment of nutrient loads to Lake Waikare has previously been undertaken by Cox & Cooke (2014). The modelling inputs included water quality and daily inflow historical data for the Matahuru Stream up to 2014 and results from targeted tributary sampling undertaken by Cox & Cooke in 2014. The long-term river level record measured by Waikato Regional Council reports daily median values ranging from approximately 5.5 m to 5.7m[1]. Over the past 5 years river levels have largely been within this range with

[1] https://waikatoregion.govt.nz/environment/envirohub/environmental-maps-and-data/station/38551/WL?dt=Level

some peaks and lows outside of this range. Based on this data and that the latest 5-year median for total nitrogen and total phosphorus for the Matahuru Stream reported by LAWA are consistent with values used for the modelling inputs, the findings of the 2014 model are still considered relevant for the purpose of this report (see Table 7 for measured data used to calibrate the model).

Table 7: Measured data used to calibrate the model.

Location	Year	Data used for model calibration
Lake water (measured by Waikato Regional Council)	1996-2014 (average concentration)	TP: 0.22 mg L^{-1} TKN: 2.4 mg L^{-1}
Matahuru stream (measured by Cox & Cooke, 2014).	2014 (one monitoring occasion)	TP: 0.10 mg L^{-1} TN: 1.4 mg L^{-1}

The 2014 model assumed that the lake could be divided into three well-mixed zones, based on a qualitative assessment of the lake geography and bathymetry (reproduced figure from the 2014 modelling assessment shown in Figure 9 below). The modelling assessment noted that the Matahuru stream inflows accounted for 51% of the drainage are to the lake, influencing Zone 3.

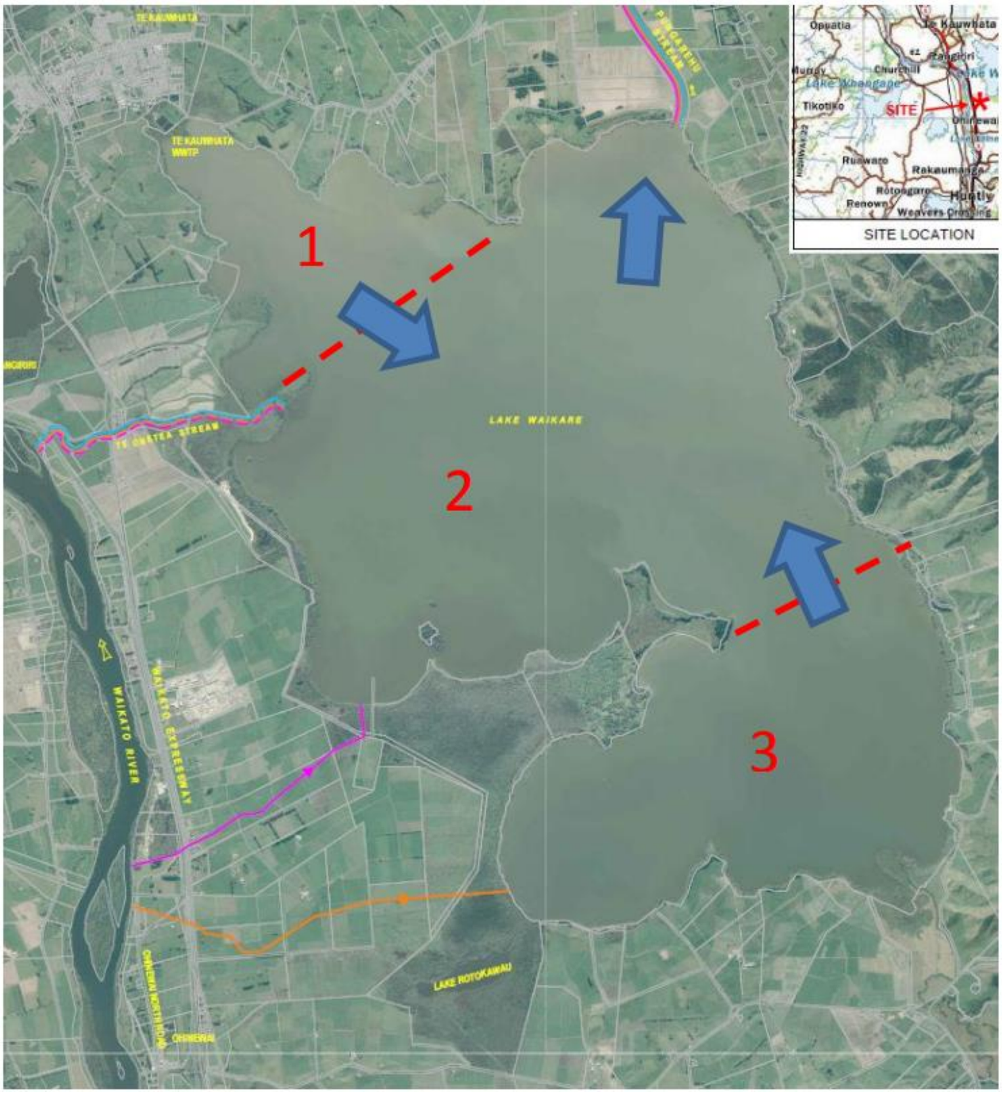

Figure 8. Excerpt from Cox & Cooke 2014 modelling study showing assumed lake mixing zones.

Most of the other half of the catchment along with Te Onetea canal flows were assumed to drain to Zone 2, with a small portion of catchment drainage along with wastewater outflows assigned to Zone 1. Nutrient loads from catchment drainage for Zones 1 and 2 were based on the local tributary sampling undertaken by Cox & Cooke in 2014 and equations were modified by applying load ratio factors to catchment inflows based on the Matahuru stream data and the local tributary data from the 2014 sampling event; along with including data from wastewater compliance flow monitoring and sampling from Te Onetea Canal in 2014. Further details of the modelling inputs and assumptions are outlined in the referenced paper.

Cox & Cooke reported that the overall lake nutrient mass balance derived from the model indicated that the predominant source of nutrients to the lake is catchment runoff. Loads from the non-Matahuru portion of the catchment comprise approximately 77% and 63% of the total annual load to the lake for phosphorus and nitrogen, respectively. The Matahuru catchment was estimated to contribute approximately 19% and 30% of the total load for the two nutrients, respectively. The WWTP was estimated to contribute only approximately 0.8% of total nitrogen and 0.2% of total phosphorus loads.

An earlier study by Vant (2008), however, estimated that contributions from the WWTP could be approximately 1% for total nitrogen and 5 % for total phosphorus.

Nevertheless, the studies both show that nutrient contributions from the WWTP are very low compared to the land use influence and catchment drainage. While there are no more recent studies, it is unlikely that the relative nutrient contributions have changed significantly since results from these studies were produced.

Based on the above modelling results, it is unlikely that the WWTP discharge is causing an effect on lake water quality in the open water further from the discharge point. Previously, a 2020 WRC compliance report provided supporting commentary from a WRC Principal Scientist:

- "*My interim conclusion from this data is that the discharge of Te Kauwhata wastewater is having only minor and localised effects on the water quality of Lake Waikare. It's undoubtedly having some effect at Location 1 [in the bay where the wastewater enters the lake], but the water quality there would probably be reasonably poor anyway, even if the discharge were not present. But it's difficult to see that the wastewater is having anything other than a small or very small effect at sites in the open water away from the north-western arm of the lake*" (Waikato Regional Council , Te Kauwhata WWTP: Site Compliance Report, 2020)

While the WWTP discharge has been in breach of its consent for a long period of time, when placed in the context of the temporal scale and complex nature of Lake Waikare's historical issues described in the above sections, it is unlikely that the discharge specifically had significant adverse effects on the current water quality for the following reasons:

- Lake Waikare has been in a supertrophic to hypertrophic state since land use change began occurring and the flood scheme was introduced.
- The discharge is occurring at a single point in the north-west arm of the Lake and previous modelling studies have shown that nutrient load contributions from the WWTP are very low compared to land use impacts and catchment drainage., Therefore, any changes in nutrient levels or sediment loads due to the WWTP discharge are likely to be very localised and have negligible effects throughout the remainder of the lake.

Further localised monitoring of contributing tributaries would be required to update previous modelling studies to increase the robustness of these conclusions and to further understand nutrient sources down to a scale that would enable more informed actions to be taken that could reduce contaminant loading to the Lake.

6 Effects on the Whangamarino Wetland

Once flows leave Lake Waikare and the Pungarehu Canal it enters the Whangamarino River which winds through the Whangamarino wetland. The river collects drainage from several smaller tributaries/overland flow paths from the wetland, equating to approximately 63.6km^2. Given the river is constantly mixing with standing water within the wetland, the whole system by nature is likely diffuse. This can make attributing changes in water quality to a particular event or source, difficult.

Specific water quality data for the Whangamarino Wetland or river is not publicly available. However, sediment depositions into the wetland have been attributed to inputs from Lake Waikare; sedimentation is strongly related to water quality, particularly as contaminants can be adsorbed/absorbed onto particles (Gibbs, 2016). Research from NIWA, commissioned by DoC, indicates that Lake Waikare definitively supplies sediment to the wetland, with confirmed samples along Pungarehu Stream and into the Whangamarino River traced back to the Lake, as far as the Raeo stream confluence located to the west of the Pungaheu/Whangamarino confluence. Large deposition areas were identified within an ~1km stretch along the Pungaheu stream, within the wetland. No investigation or modelling was carried out in the northern parts of the wetland.

As described in Section 3.2.1.1, the Whangamarino Wetland is the second largest bog and swamp complex in the North Island and is internationally significant. The wetland is deemed to have numerous significant ecological features and provides habitat to a diverse range of native water birds and freshwater fish. (Environmental Resources Information Network, 2002; Ridley Dunphy Environmental Limited, 2018).

With a limited amount of information, it is difficult to determine the actual impacts of discharge from Lake Waikare into the Whangamarino wetland and native fauna. However, given that the lake is known to have poor water quality and is almost always discharging to the wetland (dependant on gate conditions) it's more than likely that there are some adverse effects at the discharge point.

7 Summary of Key Issues

Below is a summary of the key issues that have affected Lake Waikare, causing its hypertrophic state, and have reduced its potential to support thriving ecosystems. It's important to note that while most of these issues have been catastrophic for the Lake some items – like the LWWFCS have also provided benefits to land and life.

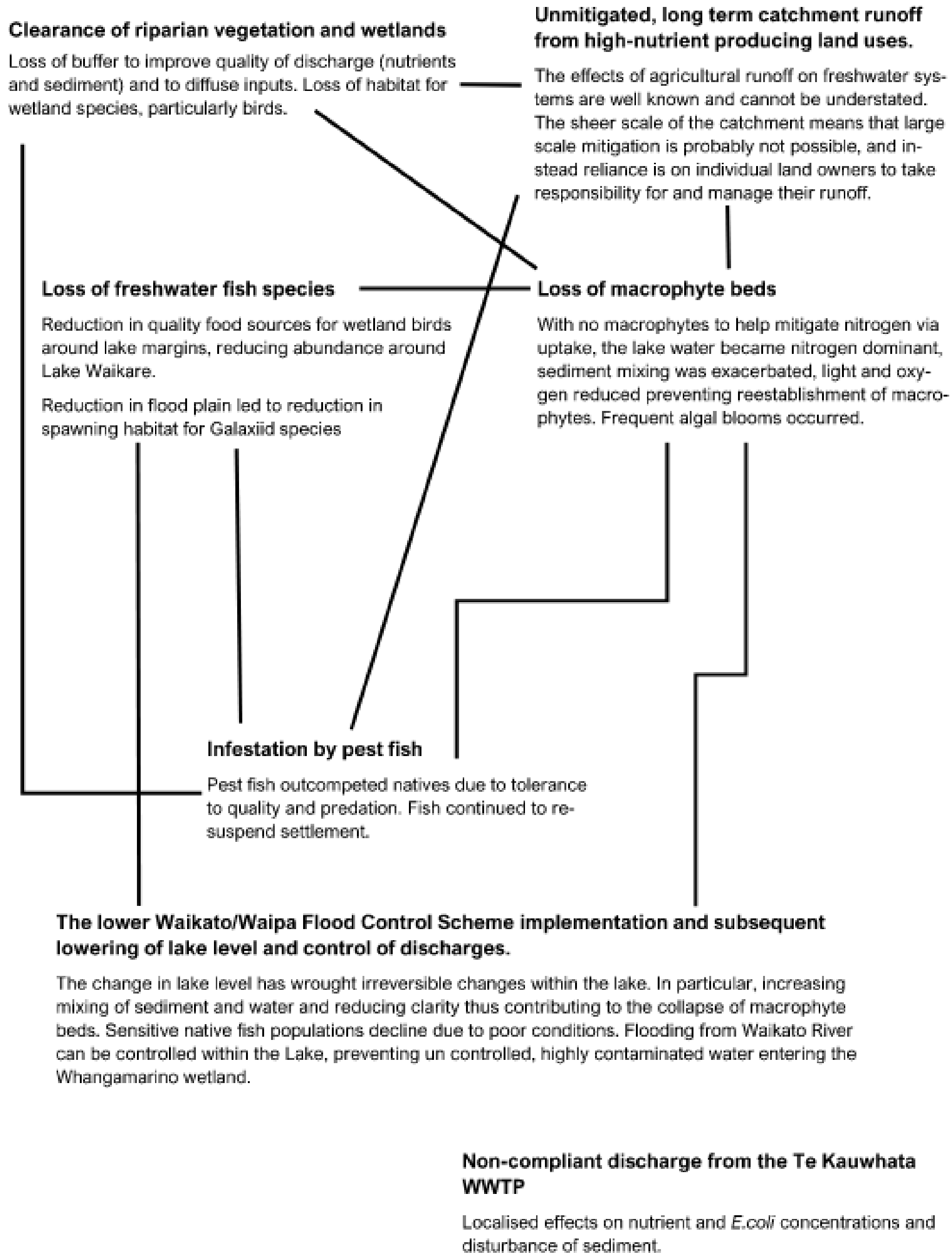

Figure 10: Linking of the key issues facing Lake Waikare (Prepared by Beca, 2023).

It's clear that not a singular issue can be blamed for the existing condition of Lake Waikare, rather all the issues are inextricably linked, aside from the discharge from the WWTP. Out of all issues, this is the only independent factor.

8 Conclusions and Recommendations

This analysis has shown that linked historical issues are the primary cause of Lake Waikare's hypertrophic state and that no one issue can be picked out as a single driver. However, the WWTP is the only issue not linked to other problems and so it can be said, with a moderate amount of confidence that the discharge has not caused Lake Waikare's existing problems to become worse. Further, previous modelling assessments undertaken have found that the treated wastewater discharge accounts for up to <1% of total nitrogen and phosphorus loads to the Lake, these nutrients being drivers of the impacted Lake ecosystem.

8.1.1 Ecology

Overall, despite the degraded water quality conditions of Lake Waikare, as well as the ongoing issues with nutrient and sediment loading from the wider catchment, Lake Waikare is considered to have moderate to high ecological value. This is primarily based on the available, albeit degraded, habitat provided by the lake to a range of native and At Risk freshwater fish and water birds.

Despite this, given the ecological features, as well as wider cultural significance of Lake Waikare, it is of high importance that reasonable effort is undertaken to improve the conditions of Lake Waikare, and a brief of opportunities previously identified is outlined in Section 7.2 below.

8.2 Recommendations

Previous investigations into the problems with Lake Waikare have been sporadic. For example several water quality modelling, hydraulic modelling and ecological investigations exist but all have a very narrow focus (Cox & Cooke, 2014; Gibbs, 2016; Sands , 2015; Lehman, et al., 2017; Wildlands Consultants Ltd, 2012). Publicly available data is old, lacking in replication and has not been targeted to comprehensively draw strong conclusions on how Lake Waikare has come to be in its current state. Instead, work thus far has focussed on methods of improving issues, and prevention of degradation of the Whangamarino Wetland from Lake discharge.

As completing this catchment analysis has been reliant on much of the information contained within the aforementioned resources, there are gaps that need to be filled by catchment wide, scientifically robust investigations to better understand the target areas for catchment improvement. Further investigations will need to examine the relationships between ecosystems and water quality; one cannot be targeted for improvement without the other, this much is clear (see Figure 7). An initial screen on possible ecological betterment opportunities is described in Section 6.2.1.

These types of investigations are especially important if the impact of wastewater discharge needs to be quantified, although the evidence examined in this analysis indicates that impacts are minimal in the context of historical issues.

8.2.1 Betterment opportunities previously identified.

The recommendations provided below include some (but not all) of the options previously presented, in the instance that any could be tied to a new resource consent application for the wastewater discharge (using existing catchment management plans as a basis for understanding work already being undertaken) should a discharge to the Lake continue into the future.

- Catchment management:

As previously stated, the primary root cause of the ongoing degradation of Lake Waikare is the wider catchment use and increasing ratings of sediment and nutrient runoff (Cox & Cooke, 2014). Therefore, catchment management is potentially the first step in the strategy to improve the water quality and ecological conditions of Lake Waikare.

The Matahuru and Waerenga catchments contribute large amounts of sediment to Lake Waikare, and managing these sediment loads is crucial to achieve rehabilitation outcomes for the Lake. Potential methods for catchment management include (but are not limited to) (Wildlands Consultants Ltd, 2012):

a) Livestock exclusion – especially around smaller tributaries in the upper catchment.
b) Re-forestation – the retirement of pastoral land and re-vegetation with native trees has the potential to reduce erosion potential of the land.
c) Creation of constructed treatment wetland between the Whangamarino Wetland and Lake Waikare – although constructed wetlands require ongoing maintenance to ensure effective treatment, they have a range of benefits. This includes reducing sediment and nutrient load entering the wider natural environment and freshwater bodies and providing flood attenuation services.

- Wind barriers to reduce wave energy:

Wind-driven wave action has been identified to disrupt any chances of rehabilitation efforts. For example, there have been methods proposed to drawdown water levels within the lake, then re-vegetate with appropriate macrophytes (Stephens , et al., 2004), however, it was concluded that the potential for success is low because of wave action preventing plant growth.

The installation of wave barriers has been previously considered by the Lake Waikare Steering Group as a potential method to reduce wave action within the Lake, thereby reducing the re-suspension of sediments. This has the potential to allow for macrophyte dispersal within the lake. Further modelling would be required to identify the optimal locations for wind barriers, as well as to calculate effects on circulation within the Lake (Wildlands Consultants Ltd, 2012).

- Removal of pest fish:

A full pest fish removal programme does not appear to have been conducted at Lake Waikare, however, has been undertaken at Lake Ohinewai, located south of Lake Waikare. At Lake Ohinewai, a koi carp pest fish barrier was installed in 2011, as well as a pest removal programme undertaken in 2016. The removal programme proved successful with over 3500 koi carp removed in a 6 day period. However, the removal of koi carp resulted in the increase in population size of catfish and goldfish, likely due to a reduction in inter-specific competition, but also an increase in shortfin eels. Additionally, the removal of koi carp did not result in any significant changes to water quality parameters in the 5 years following (Tempero & Hicks, 2017).

While this has not been trialled at Lake Waikare to date, it is surmised that the removal of pest fish is expected to increase population sizes of native fish, however, should not be considered as a sole mitigation strategy.

- Improve light conditions and establishment of aquatic vegetation:

This recommendation relies largely on sediment catchment control (point one above), and therefore is not the first mitigation measure to be employed. However, it is widely acknowledged that the re-establishment of macrophytes within Lake Waikare will improve the water quality conditions of the lake. Lake Waikare is not currently in a suitable state to re-introduce native macrophytes and attempts to do so in the past have failed (see Section 2.4.4). Light conditions within the Lake need significantly improve for aquatic vegetation to successfully re-establish and disperse. This requires reducing wave action, controlling/removing of pest fish, and reducing nutrient/sediment loads from the surrounding catchment.

The betterment options previously explored are not to be employed as sole strategies, and it is generally agreed (within the literature) that the successful rehabilitation of Lake Waikare requires a strategic approach, with multiple steps and methodologies.

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9 Limitations

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