Ayrburn Road and Rezoning: Mill Creek - Assessment of Aquatic Ecology Effects

SO2388 – Waterfall – T14 – Goldsmith R - Evidence

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Ayrburn Road and Rezoning: Mill Creek - Assessment of Aquatic Ecology Effects

Prepared for Waterfall Park Developments Limited by Ryder Environmental Limited

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1. INTRODUCTION

1.1. My full name is Ruth Johanna Goldsmith.

1.2. I am an environmental scientist and hold a BSc. (Zoology, 1998), a Postgraduate Diploma (Wildlife Management, 2000), and a PhD (Zoology, 2004) from the University of Otago. I am a member of the New Zealand Freshwater Sciences Society.

1.3. I have been an employee of Ryder Environmental Limited (formerly Ryder Consulting Limited), an environmental consulting business based in Dunedin, for 14 years.

1.4. During this time I have been involved in a wide variety of studies on aquatic ecology throughout New Zealand, examining the effects of human activities on freshwater ecosystems, including channel maintenance works, gravel abstraction, hydro and wind generation, industrial discharges, and water abstraction and augmentation.

1.5. I have complied with the Code of Conduct for Expert Witnesses contained in the Environment Court Consolidated Practice Note 2014. This evidence is within my area of expertise, except where I state that I am relying on another person, and I have not omitted to consider any material facts known to me that might alter or detract from the opinions I express.

1.1 Background

1.1.1 Waterfall Park Developments Limited (WPDL) is proposing to construct a residential development on Ayrburn Farm, approximately 3 km southwest of Arrowtown. This requires rezoning of the land to allow residential activities. The proposed development, which also includes an access road, is located on land adjacent to Mill Creek (Figure 1), and some modifications to the creek channel are planned as part of the development, included in these are extensive revegetation and enhancement of the riparian zone.

1.1.2 Ryder Consulting was engaged by WPDL to provide an assessment of aquatic ecological effects (AEE) of the development on Mill Creek. The assessment included the following components:

- Assessment of the existing aquatic ecology values of Mill Creek.
- Identification of potential adverse aquatic ecological effects associated with the proposed development.
- Recommendations to avoid, remedy or mitigate any adverse effects.
- Identification of potential positive effects.

1.1.3 In completing my assessment I have read and considered the following reports:

- Baxter Design. 2017. Landscape Assessment Report. Waterfall Park Resort Zone – Access Road, November 2017.
- Fluent Solutions. 2017. Waterfall Park Access Road – Flood and Stormwater Management Proposal and Effects Assessment. Prepared for Waterfall Park Developments Limited by Fluent Solutions, October 2017.
- Fluent Solutions. 2018. Waterfall Park Developments Ltd: Ayrburn Rezoning – Water, Wastewater and Stormwater Infrastructure Assessment. Prepared for Waterfall Park Developments Limited by Fluent Solutions, June 2018.
- Paterson Pitts Group. 2017. DRAFT Earthworks Management Plan. Waterfall Park, Access Road. Prepared for Waterfall Park Developments Limited by Paterson Pitts Group, October 2017.
- Waterfall Park. 2018. DRAFT Construction Management Plan.
- Submission 2388 lodged by WPDL which seeks to rezone parts of the Ayrburn Valley floor for residential or rural lifestyle use in place of the current stock farming use.

1.2 Executive summary

1.2.1 The aquatic ecology assessment found that the existing water quality in Mill Creek is generally good. However inputs of groundwater elevate nitrogen concentrations, and faecal bacteria concentrations are also high at times. This probably reflects the primary catchment land use of beef and sheep grazing on exotic pasture, and golf course maintenance, which often involves the application of potential water contaminants (including fertilisers, herbicides and pesticides). The invasive algae *Didymosphenia geminata* (Didymo) is also present in the creek.

1.2.2 Benthic macroinvertebrate communities found in Mill Creek are as expected for the type of habitat present, and the taxa found are both common and widespread in similar habitats throughout New Zealand. There are four fish species in the Lake Hayes and Mill Creek catchment; brown trout and perch (introduced species), and common bully and koaro (native species). Mill Creek provides spawning habitat for koaro, and spawning and rearing habitat for brown trout (which can be observed in the creek).

1.2.3 Potential adverse aquatic ecological effects associated with the proposed development are:

- Sediment and other contaminant discharges entering the creek during construction in association with earthworks adjacent to Mill Creek, earthworks generally which could result in sediment discharge into Mill Creek and instream works required for bridge construction.
- Bridge installation disrupting fish passage.
- Stormwater discharges post-development.

1.2.4 Measures to address these potential effects include the adoption of 'best-practice' guidelines for the management of sediment and erosion during building construction, which will be implemented through an Earthworks Management Plan. Instream works will also not be undertaken during the period from the 1st of May to the 7th of January to avoid potential disruption to koaro and trout spawning activity. Proposed mitigation measures, consistent with meeting the anticipated QLDC and ORC requirements for flood management and attenuation and treatment of stormwater prior to discharge to Mill Creek, will be adopted. On that basis, it is confirmed that requirements for no adverse effects on aquatic life will also be met.

1.2.5 Potential positive aquatic ecological effects associated with the proposed development are:

- The change in land use from a working sheep farm to residential housing will reduce nutrient loss to water. In particular nitrogen loss will reduce by approximately 15%, which is a positive effect as water quality limits for nitrogen are exceeded at times in Mill Creek.
- Riparian planting providing cover and shade to the creek channel, which will increase the diversity of fish and macroinvertebrate habitat and reduce the potential for nuisance algae growth (including Didymo).
- Riparian planting reducing nutrient and sediment run-off from the surrounding land, which will reduce the input of these potential contaminants to the creek.
- Fencing and other measures to exclude stock from the creek.

1.2.6 The proposed development will contribute to achieving the restoration of Lake Hayes through extensive riparian enhancement (stock exclusion/change in land use and planting), which will reduce nutrient and sediment run-off to Mill Creek.

2. EXISTING INFORMATION

2.1 Field assessment

2.1.1 A field assessment of Mill Creek tributary was undertaken on 10th of March 2017 to assist with describing the existing aquatic ecology values within the vicinity of the proposed access road. Weather conditions at the time were settled and the flow in the creek was approximately 0.3 m^3/s, which is close to the median flow for the creek of 0.35 m^3/s (measured downstream near Lake Hayes by ORC).

2.1.2 The entire length of Mill Creek within the boundaries of Ayrburn Farm and Waterfall Park (an approximately 1 km long reach) was visually assessed. The creek enters Waterfall Park via an approximately 40 m high waterfall.

Continuing downstream the creek flows through an incised valley, with a relatively steep channel gradient. The channel here is unfenced and the riparian vegetation dominated by rank pasture grasses and occasional trees. From near the site of the historic Ayrburn Farm woolshed to the downstream boundary the valley widens and the channel becomes less steep and more meandering. The channel here is also unfenced, or fenced on one side only. Pasture grasses (largely grazed) and willow trees dominate the riparian vegetation.

2.1.3 At three sites aquatic community samples were collected (Figures 1 to 4). Sampling methods are described in Appendix One. The first site ('Upstream boundary') was located immediately downstream of the waterfall at the upstream boundary of the farm and outside of the proposed development area (Figures 1 and 2). The second site ('Mid-way') was located approximately mid-way between the upstream and downstream boundary of the farm and inside of the proposed development area (Figures 1 and 3), and the third site ('Downstream boundary') was located at the downstream boundary of the farm and the development area (Figures 1 and 4).

Figure 1a *Topographical map showing the location of the three sampling sites in Mill Creek at Ayrburn Farm. The reach of Mill Creek within the proposed development area is highlighted with a blue line.*

Figure 1b *Waterfall Park proposed access road (dashed black line) and rezoning area (dashed red outline) (provided by WPDL).*

Figure 2 *Mill Creek at Ayrburn Farm upstream boundary sampling site.*

Figure 3 *Mill Creek Ayrburn Farm mid-way sampling site.*

Figure 4 *Mill Creek at Ayrburn Farm downstream boundary sampling site.*

2.2 Water quality

2.2.1 Water quality at all three Mill Creek sites at Ayrburn Farm was similar on the day of the field assessment in March 2017 (Table 1), indicating that there are no major existing inputs entering within the site that impact water quality in the creek.

Table 1 *Water quality at Mill Creek Ayrburn Farm sites, 10th of March 2017.*

Parameter	Upstream boundary	Mid-way	Downstream boundary
Time of measurement	1500	1530	1400
Temperature (°C)	13.9	14.5	13.1
Dissolved oxygen (%)	101.4	102.5	103.0
Dissolved oxygen (mg/L)	10.48	10.43	10.84
Conductivity (µS/cm)	115.0	116.7	112.4
pH	7.91	8.02	7.88
Turbidity (NTU)	-	3.5	-
Clarity (m)	-	2.3	-

2.2.2 The Otago Regional Council (ORC) carries out monthly State of the Environment (SOE) water quality measurements at a site in Mill Creek (Mill Creek at Fish Trap) approximately 1.5 km downstream of Ayrburn Farm. ORC monitoring results from this site, and also for Lake Hayes, for the period February 2007 to December 2016 are shown in Figures 5 to 10 (with dashed lines showing the relevant Schedule 15 water quality limits from the Regional Plan: Water for Otago). Figure 11 shows the flow in Mill Creek over this same period.

2.2.3 Mill Creek consistently exceeded the water quality limits for nitrogen (Figure 5), and occasionally exceeded limits for phosphorus (Figure 7), faecal bacteria (Figure 9) and turbidity (Figure 10). As expected, turbidity levels were elevated during high flows (Figures 10 and 11). In Lake Hayes, limits for phosphorus were regularly exceeded (Figure 8), and limits for nitrogen (Figure 6), faecal bacteria (Figure 9) and turbidity (Figure 10) were occasionally exceeded.

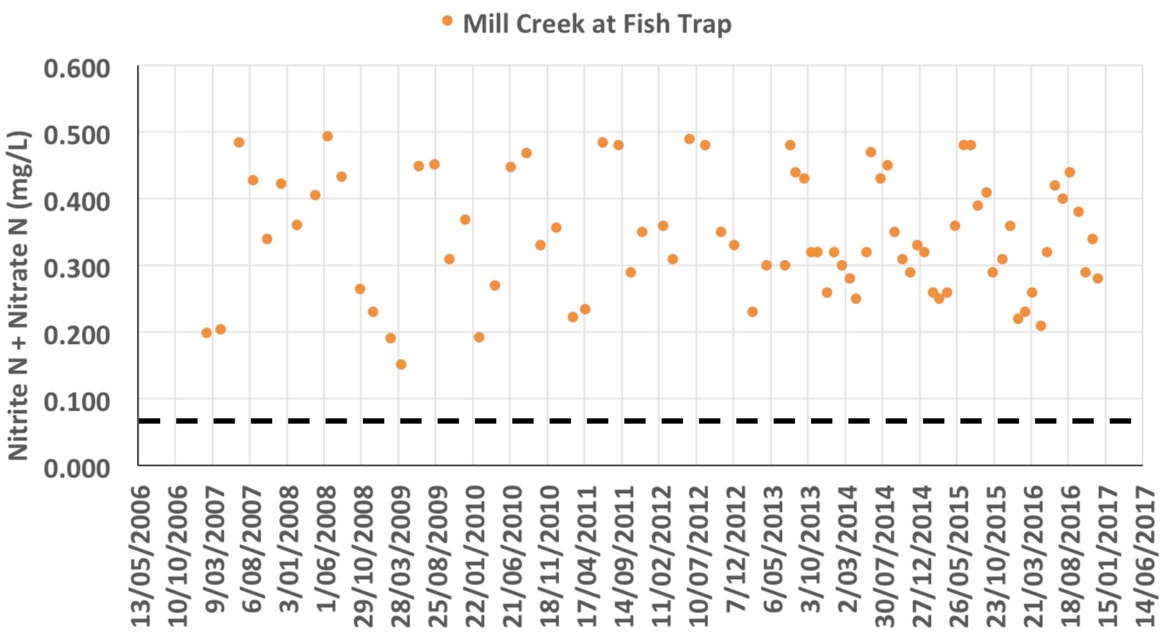

Figure 5 *Nitrite nitrogen + nitrate nitrogen concentration (mg/L) at ORC Mill Creek at Fish Trap site. The dashed line shows the relevant water plan limit for Mill Creek (0.075 mg/L).*

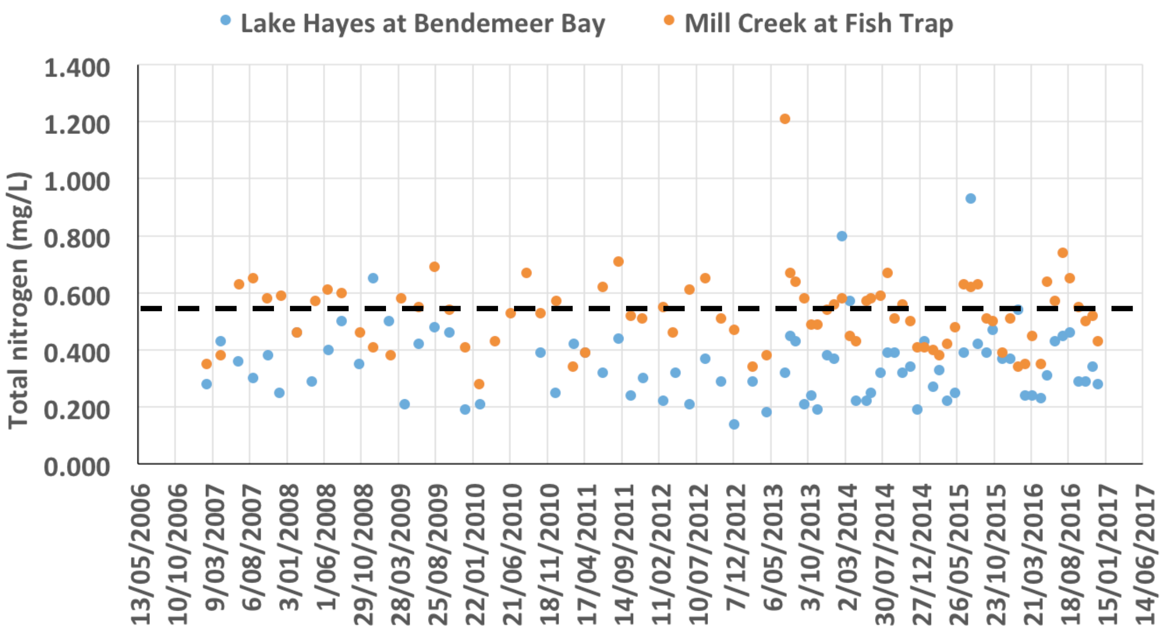

Figure 6 *Total nitrogen concentrations (mg/L) at ORC Lakes Hayes at Bendemeer Bay and Mill Creek at Fish Trap sites. The dashed line shows the relevant water plan limit for Lake Hayes (0.55 mg/L).*

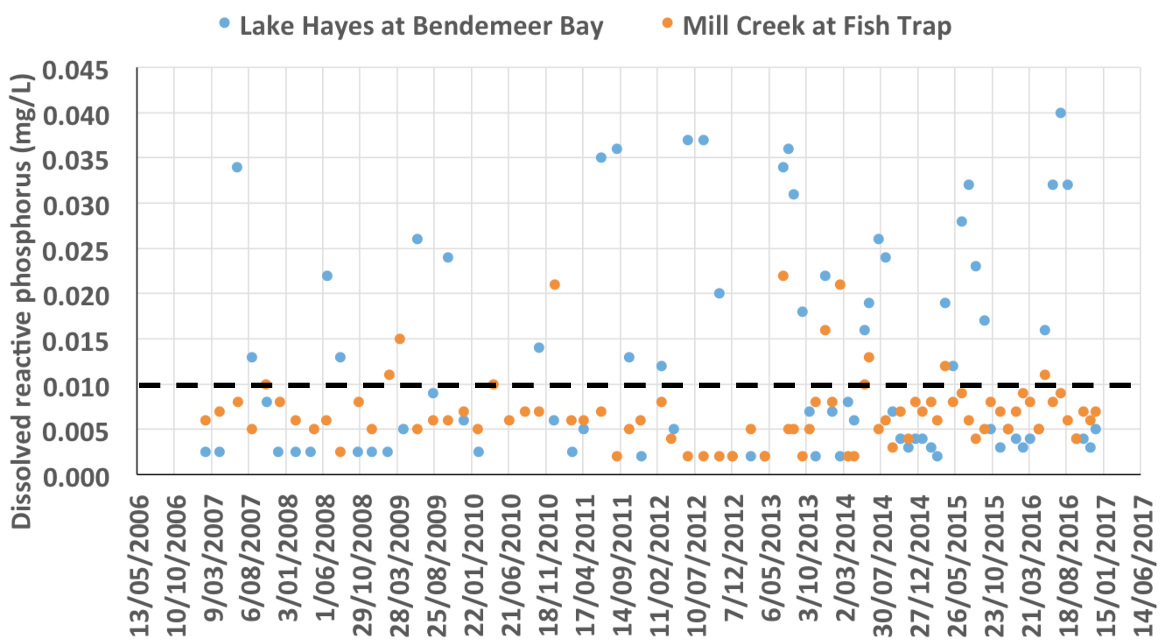

Figure 7 *Dissolved reactive phosphorus concentrations (mg/L) at ORC Mill Creek at Fish Trap and Lakes Hayes at Bendemeer Bay sites. The dashed line shows the relevant water plan limit for Mill Creek (0.010 mg/L).*

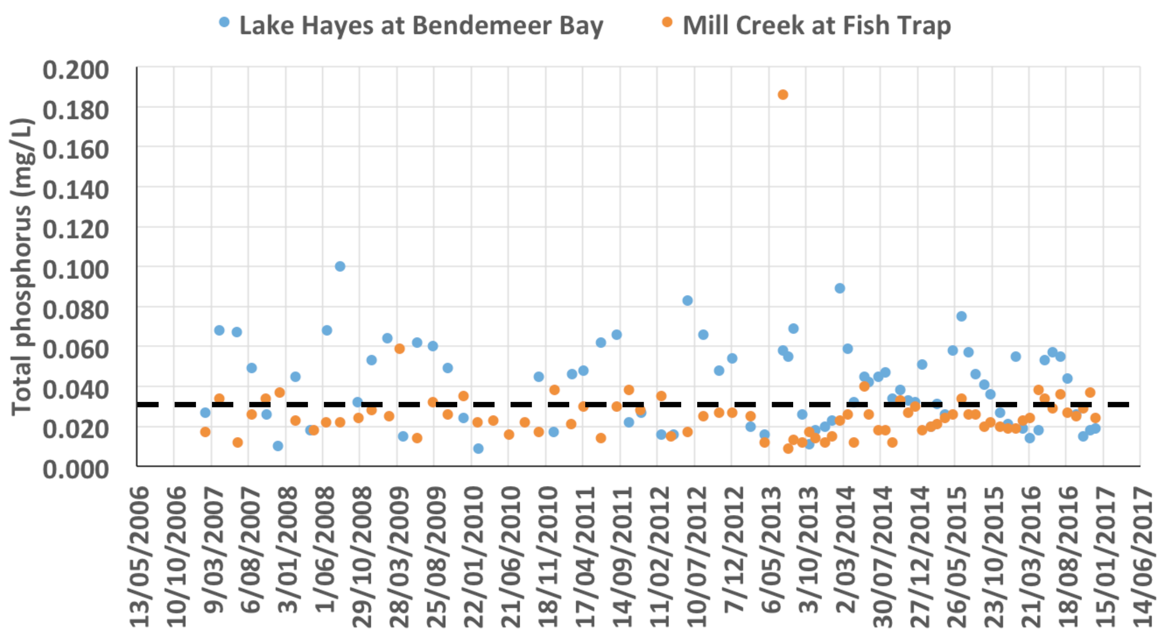

Figure 8 *Total phosphorus concentrations (mg/L) at ORC Lakes Hayes at Bendemeer Bay and Mill Creek at Fish Trap sites. The dashed line shows the relevant water plan limit for Lake Hayes (0.033 mg/L).*

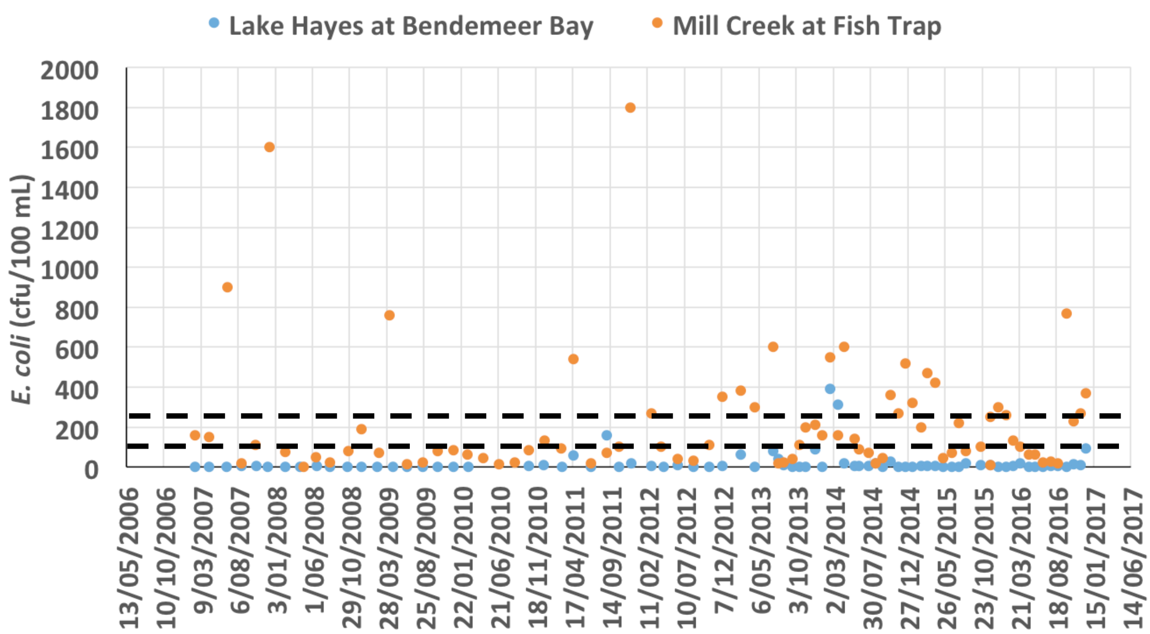

Figure 9 *E. coli concentrations (cfu/100 mL) at ORC Lakes Hayes at Bendemeer Bay and Mill Creek at Fish Trap sites. The dashed line shows the relevant water plan limit for Lake Hayes (126 cfu/100 mL) and Mill Creek (260 cfu/100 mL).*

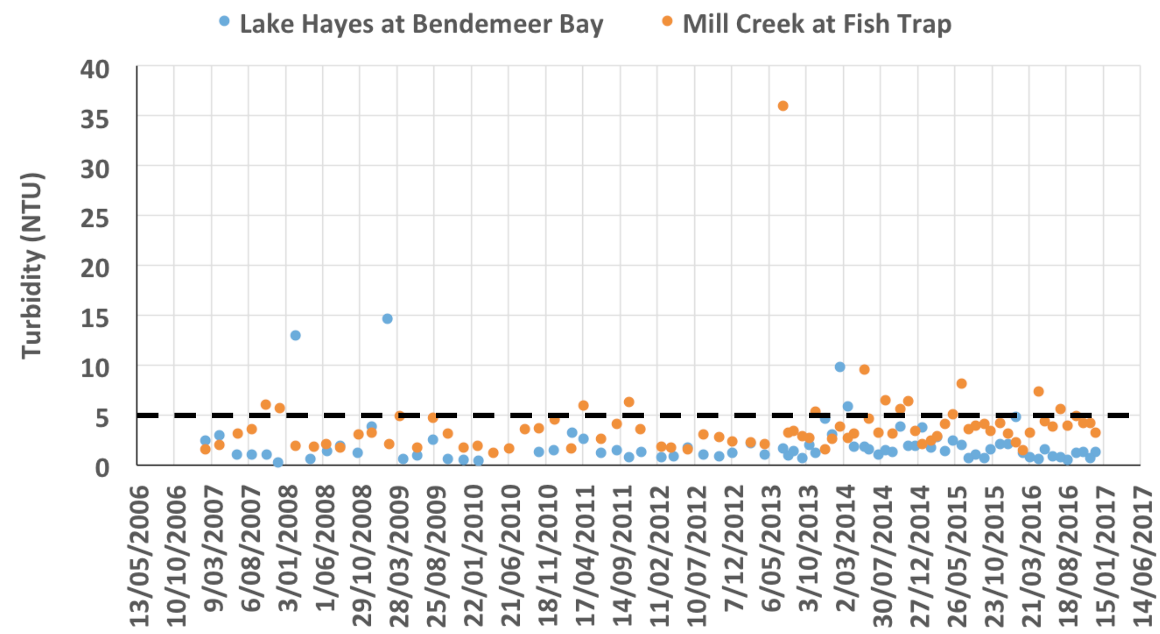

Figure 10 *Turbidity level (NTU) at ORC Lakes Hayes at Bendemeer Bay and Mill Creek at Fish Trap sites. The dashed line shows the relevant water plan limit for Lake Hayes and Mill Creek (5 NTU).*

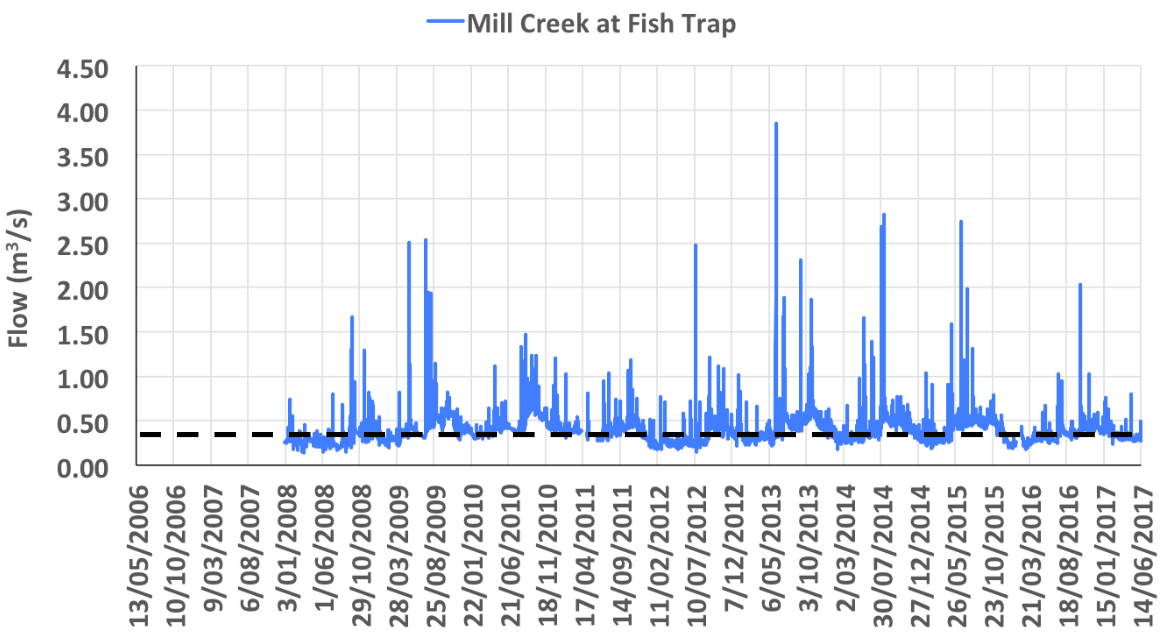

Figure 11 *Flow (m^3/s) at ORC Mill Creek at Fish Trap flow site. The dashed line shows the median flow for the site (0.35 m^3/s) (data provided by ORC).*

2.2.4 Table 2 presents the Land and Water Aotearoa (LAWA) median water quality values at the Mill Creek and Lake Hayes sites in 2016, and interprets these values in relation to the National Objectives Framework (NOF) bands. LAWA five year trend analysis results are also shown. In Mill Creek nitrogen and faecal bacteria concentrations fall within NOF band A, indicating that the existing nitrogen concentration is unlikely to have an effect on even sensitive species (A), and for faecal bacteria (*E. coli*) that people are exposed to a very low risk of infection from contact with water during activities with occasional immersion. Trend analysis indicates 'indeterminate' or 'improving' water quality in Mill Creek, with the exception of turbidity, which has a 'degrading' trend (Table 3). In Lake Hayes nitrogen and chloropyhll *a* concentrations fall within NOF band B indicating that lake ecological communities are slightly impacted by additional algal and plant growth arising from nutrients levels that are elevated above natural conditions. Phosphorus concentrations fall within NOF band C indicating that lake ecological communities are moderately impacted by additional algal and plant growth arising from nutrients levels that are elevated well above natural reference conditions.

Summary

2.2.5 Overall, the water quality in Mill Creek is generally good. However, inputs of groundwater elevate nitrogen concentrations, and faecal bacteria concentrations are also high at times. This probably reflects the primary catchment land use of beef and sheep grazing on exotic pasture and golf course maintenance, which often involves the application of potential water contaminants (including fertilisers, herbicides and pesticides). Phosphorus limits were only occasionally exceeded in Mill Creek, however in Lake Hayes, they were regularly exceeded.

Table 2 *Median water quality data for Mill Creek and Lake Hayes monitoring, 2016. 5-year trends (2011 to 2016) are reported as either indicating 'improving' or 'degrading' water quality. Where appropriate the relevant National Objectives Framework (NOF) Bands are also reported ('A', 'B', and 'C' indicates that water quality is considered suitable for the designated use, and 'D' indicates water quality is not considered suitable for the designated use). Data and interpretation sourced from the Land Air Water Aotearoa (LAWA) website.*

Parameter	Value	Mill Creek	Lake Hayes
Total phosphorus (g/m^3)	Median	0.024	0.023
	Trend	Indeterminate	Indeterminate
	NOF annual median	-	C
Dissolved reactive phosphorus (g/m^3)	Median	0.006	-
	Trend	Indeterminate	-
Total nitrogen (g/m^3)	Median	0.51	0.30
	Trend	Improving	Degrading
	NOF annual median	-	B
Total oxidised nitrogen (g/m^3)	Median	0.32	-
	Trend	Improving	-
	NOF annual median	A	-
	NOF 95th percentile	A	-
Ammoniacal nitrogen (g/m^3)	Median	0.008	-
	Trend	-	-
Turbidity (NTU)	Median	3.4	-
	Trend	Degrading	-
E. coli (per 100 mL)	Median	160	-
	Trend	Indeterminate	Indeterminate
	NOF annual median	A	-
Chlorophyll *a* (mg/m^3)	Median	-	4.15
	Trend	-	Indeterminate
	NOF annual median	-	B

2.3 Periphyton

2.3.1 During the field assessment in March 2017 there was minimal periphyton (algae) growth in Mill Creek with generally clean bed substrates observed (Figures 3 and 4). There were however some patches of filamentous and mat algae growths on the margin of the stream in the vicinity of the upstream boundary sampling site and also mid-channel between the upstream boundary and mid-way sampling sites (Figure 12).

2.3.2 Samples of the periphyton were collected and taxa were identified in the laboratory, with several filamentous and diatom taxa identified. Filamentous algae was dominated by *Oedogonium*, with *Mougeotia* also present. *Oedogonium* may be abundant in slow flowing waters (Moore 2000), which is the type of habitat that was observed in Mill Creek (i.e., low velocity areas on the margins of the channel). Mat algae growths were dominated by the diatom *Fragilaria*. *Fragilaria* forms dense growths along the margins of slow flowing, often nutrient enriched waters (Moore 2000). Other diatom taxa present included *Synedra*, *Gomphonema* and *Surirella*. The invasive algae *Didymosphenia geminata* (Didymo) was also common within the samples.

Figure 12 ***Top:*** *Periphyton at Mill Creek upstream boundary sampling site.*
Bottom: *Periphyton in Mill Creek between upstream boundary and mid-way sampling sites.*

2.4 Benthic macroinvertebrate communities

2.4.1 A total of 28 benthic macroinvertebrate taxa were identified from Mill Creek, with the highest number of taxa recorded at the furthest upstream site (20 taxa) closely followed by the other two sites downstream (19 taxa each) (Table 3). *Potamopyrgus* snails numerically dominated the community at all sites. *Pycnocentria* caddisflies were also 'very very abundant' at the mid-way and downstream boundary sites. At all three sites the number of taxa was higher than the national median of 18 taxa per site, as determined by Scarsbrook *et al.* (2000) from samples collected from 66 sites located throughout New Zealand.

2.4.2 The number and percent of Ephemeroptera (mayflies), Plecoptera (stoneflies) and Trichoptera (caddisflies) (EPT) taxa[1] were similar at all sites. *Deleatidium* mayflies were 'rare' at the upstream boundary site, in contrast to being 'very abundant' at the other two sites downstream. The national median level for EPT taxa is eight taxa per site (Scarsbrook *et al.* 2000), and between six and seven taxa were identified at the Mill Creek sites.

2.4.3 Macroinvertebrate community index (MCI) scores were indicative of 'poor' to 'fair' habitat quality (Tables 3 and A1.1). Semi-quantitative MCI scores were indicative of 'poor' habitat quality at the upstream boundary site and 'good' quality at the other two sites downstream.

2.4.4 Monitoring of benthic macroinvertebrate communities is undertaken annually by the ORC at a site in Mill Creek (Mill Creek at Fish Trap) approximately 1.5 km downstream of Ayrburn Farm. ORC MCI data from this site for 2011 to 2015 indicates 'poor' to 'fair' habitat quality (data sourced from the LAWA website), which is comparable to the results of the current monitoring.

Summary

2.4.5 Benthic macroinvertebrate communities found in Mill Creek were as expected for the type of habitat present, and the taxa found are both common and widespread in similar habitats throughout New Zealand.

[1] These insect groups are generally dominated by invertebrates that are indicative of higher quality conditions. In stony bed rivers, the number of EPT taxa usually increases with improved water quality and increased habitat diversity.

Table 3 *Benthic macroinvertebrate communities at three sites in Mill Creek at Ayrburn Farm.*

TAXON	MCI score	Upstream boundary	Mid-way	Downstream boundary
COLEOPTERA				
Elmidae	6	R	C	A
COLLEMBOLA	6		R	
CRUSTACEA				
Ostracoda	3	C	C	C
DIPTERA				
Chironomus species	1		C	
Empididae	3	C	A	R
Maoridiamesa species	3	VA	VA	R
Mischoderus species	4			R
Muscidae	3	C	C	
Orthocladiinae	2	VA	C	R
Paralimnophila skusei	6			R
Tanytarsini	3	C	A	
EPHEMEROPTERA				
Deleatidium species	8	R	VA	VA
HIRUDINEA	3			R
MOLLUSCA				
Gyraulus species	3	A	R	A
Physa / Physella species	3	R		
Potamopyrgus antipodarum	4	VVA	VVA	VVA
Sphaeriidae	3		R	
NEMATODA	3	C		R
OLIGOCHAETA	1	VA	A	C
PLATYHELMINTHES	3	R		
TRICHOPTERA				
Costachorema species	7		R	R
Hudsonema amabile	6	R	A	C
Hydrobiosis umbripennis group	5	C	A	R
Oxyethira albiceps	2	C		
Paroxyethira species	2	R		
Psilochorema species	8	R	C	C
Pycnocentria species	7	VA	VVA	VVA
Pycnocentrodes species	5			A
Number of taxa		20	19	19
Number of EPT taxa		7	6	7
Percent EPT taxa		35	32	37
MCI score		78	86	92
SQMCI score		3.6	5.3	5.6

2.5 Fish communities

2.5.1 New Zealand Freshwater Fish Database records indicate that there are four fish species in the Lake Hayes and Mill Creek catchment; brown trout, common bully, perch, and koaro (koaro are classified as 'at risk' (Goodman *et al.* 2014) (Table 4). Mill Creek provides spawning habitat for koaro, and spawning and rearing habitat for brown trout. Another sports fish, perch, are also found in Lake Hayes. Several brown trout were observed in Mill Creek during the field assessment in March 2017 (at locations from the downstream boundary to near the waterfall at the upstream boundary due to the good water clarity and shallow-moderate water depth). The waterfall restricts fish passage further upstream, although native fish that are good climbers may be able to pass.

2.5.2 The margins of Lake Hayes, including the area at the mouth of Mill Creek, are identified as a 'regionally significant' wetland in the Otago Regional Council

Regional Water Plan: Water for Otago (2016). This recognizes the lake and margins as providing habitat for nationally or internationally rare or threatened species or communities, and a high diversity of indigenous wetland flora and fauna.

Table 4 *Native and introduced freshwater fish species identified as present in the Lake Hayes and Mill Creek catchment (NZFFD records accessed March 2018).*

Common name	Scientific name	DOC threat classification status (Goodman *et al.* 2014)	Diadromous/ migratory	Number of NZFFD records
Common bully	*Gobiomorphus cotidanus*	Not threatened	Yes	8
Perch	*Perca fluviatilis*	Introduced and naturalised	No	4
Brown trout	*Salmo trutta*	Introduced and naturalised	Yes	2
Koaro	*Galaxias brevipinnis*	At risk	Yes	2
Trout	*Salmo* species	-	-	3

Summary

2.5.3 There are four fish species in the Lake Hayes and Mill Creek catchment; brown trout and perch (introduced species), and common bully and koaro (native species). Mill Creek provides spawning habitat for koaro, and spawning and rearing habitat for brown trout (which can be observed in the creek).

2.6 Natural values

2.6.1 The ORC Water Plan: Water for Otago (2016) identifies several natural values of Mill Creek relating to aquatic ecology including sand and gravel bed composition, significant areas for fish spawning and juvenile fish habitat and the presence of rare fish (Table 5). Mill Creek is identified in the plan for providing significant habitat for roundhead galaxiids (*Galaxias anomalus*), which have a threat classification of 'nationally endangered'. This species is however unlikely to be present in Mill Creek within Ayrburn Farm.

Table 5 *Natural values for Mill Creek relating to aquatic ecology. Schedule 1A, Otago Regional Council Regional Plan: Water for Otago (2016).*

Ecosystem values	Significant indigenous vegetation and significant habitat of indigenous fauna
Pgravel, Psand, Hspawn, Hjuve, Weedfree, Rarefish	*Significant habitat* for roundhead galaxiid.

3. ASSESSMENT OF EFFECTS AND RECOMMENDED MITIGATION

3.1 Sediment discharges during construction

3.1.1 The proposed development requires earthworks to undertake access road, subdivision and building construction, and the establishment of a new vehicle and pedestrian crossing bridge (Figure 1b). Narrowing of the existing Mill Creek channel is necessary to install the bridge and this will result in disturbance to the banks and bed of the creek. In the wider area soil will be exposed during development earthworks and there will be deposition of material to raise the access road above floodplain level. Without adequate measures to control erosion the discharge of sediment to Mill Creek is therefore possible, especially through surface runoff during periods of high rainfall.

3.1.2 Depending upon the level of sediment discharge, water quality and fish and macroinvertebrate communities downstream of the works area may be impacted. In general, the effects of increased suspended sediment levels on benthic macroinvertebrates and fish can occur both directly and indirectly, through impacts on the chemical and physical properties of the water and periphyton (a food source for invertebrates). The degree of the impact is dependent on the sensitivity of each species to elevated turbidity, which is related to their habitat requirements and the magnitude and duration of the change. Brown trout spawning habitats can be particularly vulnerable to increased sediment inputs with deposited sediments potentially smothering redds and therefore preventing egg or larval development. Adult fish are likely to respond to increased sediment levels by moving out of the affected area, returning when water quality and food resources return to normal conditions. Adult koaro are much less sensitive to suspended sediment than trout, however koaro spawning habitat can be smothered by deposited sediments.

3.1.3 The discharge of sediment to a river is a prohibited activity under the ORC Water Plan: Plan Change 6A Rule 12.C.0.3 if nothing has been done to control sediment. Sediment control measures therefore need to be adopted during construction and should ensure that any sediment discharges to Mill Creek do not result in a conspicuous change to colour or visual clarity, nor noticeable local sedimentation. This is particularly important given the value of the creek as a spawning and juvenile rearing habitat for trout.

3.1.4 Construction of a single span bridge is permitted under the ORC Water Plan provided that the bed disturbance rules are met (Rule 13.5.1.1, below) and that:

- *it doesn't cause flooding or impede flood flows; does not impede the movement of bed material; and is secure against bed erosion, floodwaters, and debris;*
- *it doesn't cause erosion of the bed or banks of a lake, river, or Regionally Significant Wetland, or property damage;*
- *measures are included that avoid animal waste entering water from the structure;*
- *any public access is maintained and it complies with the rules below.*
- *there can be no more than 20 metres of crossing over any 250 metre stretch of any lake or river;*
- *the bridge soffit cannot be lower than the top of the higher river bank*.

3.1.5 Rule 13.5.1.1, which relates to construction work that disturbs the bed of a waterway requires that:

Any activity that involves disturbance to the bed of any river, lake, or Regionally Significant Wetland is permitted, provided the structure is legal and:

- *the Department of Conservation and Fish and Game are notified in advance if work is carried out between 1 May and 30 September;*
- *the disturbance does not cause any flooding or erosion;*
- *the disturbance is limited to the extent needed to carry out the work;*
- *the time of the work within the wetted bed does not exceed 10 hours;*
- *reasonable steps are taken to minimise the release of sediment to the waterway;*
- *there is no conspicuous plume or change in colour or visual clarity beyond 200 metres downstream of the disturbance;*

- *there is no damage to fauna or native flora in or on a Regionally Significant Wetland;*
- *there is no change in water levels and the site is left tidy upon completion of the work and,*
- *no take of water is adversely affected.*

3.1.6 Construction of the new bridge, including narrowing of the existing creek channel, will require machinery to access the creek bed to drive piles and establish concrete abutments. This work needs to occur in the dry and consequently a coffer dam will need to be established to divert the Mill Creek flow away from the works area. The duration of the works is estimated to be six weeks to allow for piling, construction of the abutments and reinstatement of the bed and banks (Gary Dent, Fluent Solutions, pers. comm.). The estimated channel length that would be affected by the construction works is approximately 35 m (Gary Dent, Fluent Solutions, pers. comm.).

3.1.7 Given the potential for sediment release downstream during the six week instream works period, and the potential disruption to fish passage associated with temporary diversion of a section of the creek, it is recommended that the bridge installation works do not occur from the 1st of May to the 7th of January. This will minimize potential disruption to koaro and trout spawning activity. Recovery of any fish present within the section of the channel that will be dewatered when the coffer dam is installed will be necessary. Additionally, the creek diversions will be constructed in accordance with the Auckland Regional Council's (2016) Erosion and Sediment Control Guide GD05 ('Temporary watercourse diversions', section G4.2.3), which are considered 'best-practice'.

3.1.8 The 'best-practice' guidelines (ARC 2016) will also be applied to the management of sediment and erosion during building construction.

3.2 Other potential construction related effects

3.2.1 The presence of construction machinery and ablution facilities for personnel on site present a risk of contaminants (e.g. diesel, lubricants, sewage effluent) entering watercourses, with the potential to harm aquatic life. Machinery brought to the site from elsewhere may also bring in new pest species (e.g. aquatic weeds), although it is noted that Didymo is already present in Mill Creek. The discharge of any contaminant to water that produces a nasty odour, or an obvious oil or grease film, scum, or foam is a prohibited activity under ORC Water Plan: Plan Change 6A Rule 12.C.0.1.

3.2.2 It is understood that an Earthworks Management Plan will be provided and a condition of consent offered for approval by QLDC and ORC. This should detail how potential contaminant run off will be controlled to ensure that the requirements of Rule 12.C.0.1 are met during construction. This includes:

- Storage of contaminants (e.g. diesel, lubricants) and the refuelling of machinery away from watercourses.
- Use of 'portaloos' to manage sewage with the removal of all waste from site.
- Inspection and (if necessary) cleaning of machinery at the site entrance to minimise the risk of introducing weed species.

3.3 Stormwater discharges post-development

3.3.1 The proposed development will increase stormwater discharges to Mill Creek. Stormwater runoff can contain contaminants (suspended sediments, oxygen demanding substances, toxicants and elevated nutrient levels) and is likely to have different water quality attribute values (e.g. temperature, conductivity) than that which currently enters the creek. As a result of stormwater runoff flows in Mill Creek may also increase.

3.3.2 Fluent Solutions (2018) have considered the management of Waterfall Park stormwater and concluded that there are multiple design options available to remove potential contaminants. Assessment of these options and sizing and specific location of the stormwater management elements would be confirmed during the detailed design phase.

3.3.3 A flood mitigation strategy for the proposed development is detailed in Fluent Solutions (2017). This strategy will ensure that at the southern boundary of the development there is no increase above pre-development peak flood flows in Mill Creek. A 'Mill Creek Floodway Maintenance Plan' is proposed to monitor the condition of the Mill Creek waterway and provide a mechanism for identifying channel conditions that could adversely affect flood levels and channel stability. Where significant debris deposition is identified upstream of the bridge, maintenance requirements would be flagged in the course of the inspections and corrective action would be planned and implemented to reinstate the required channel state (Fluent Solutions 2018b). Any works that are required in Mill Creek as part of this maintenance will comply with the relevant QLDC and ORC requirements for instream works.

3.3.4 Fluent Solutions (2017 and 2018) have concluded that the development, with its proposed mitigation measures, is consistent with meeting the anticipated QLDC and ORC requirements for flood management and attenuation and treatment of stormwater prior to discharge to Mill Creek. On that basis, it is confirmed that requirements for no adverse effects on aquatic life will also be met.

3.4 Positive effects

3.4.1 The proposed development will result in a change of land use for Ayrburn Farm, from a working sheep farm to residential housing. Associated with this land use change will be a reduction in nutrient loss to water. To quantify the amount of existing nutrient loss OVERSEER® modelling was undertaken by Irricon Resource Solutions. The OVERSEER® model predicted that the existing nitrogen loss to water is 27 kg/ha/yr, which equates to a total loss of 278.71 kg over the area of the proposed development (10.1092 hectares). This nitrogen loss is predicted to reduce to 23 kg/ha/yr or 237.42 kg over the development area[2]. It should be noted that this is a conservative calculation of the reduction (as the OVERSEER® model is not designed to model residential development) and the actual reduction is likely to be higher. In any case, this approximately 15% reduction is a positive effect as water quality limits for nitrogen are exceeded at times in Mill Creek.

[2] Based on the assumption of four people per section, connection to town sewage and that 15% of the section will be cultivated garden (e.g. flowers) excluding grass.

3.4.2 Extensive riparian enhancement of Mill Creek is proposed as part of the road development. A landscape plan has been developed by Baxter Design that includes a 2-4 m wide riparian planting strip on both banks of the creek. Mill Creek and the riparian planting will be protected from stock access (for example through fencing).

3.4.3 Riparian planting and the restriction of stock from the water's edge have the potential for many environmental benefits to Mill Creek:

- The exclusion of stock can improve the condition of the channel and banks by reducing erosion, slumping and trampling. Stock exclusion will reduce the direct input of animal waste into waterways as well as reducing the run-off of some nutrients, sediment and microbes from the riparian area.
- Riparian planting can further stabilise the stream channel and banks. Vegetation within the riparian zone, if ungrazed, can reduce nutrient, sediment and microbial loads by filtering overland flow. It can reduce nutrient loads in sub-surface water, as well as maintaining or promoting conditions suitable for denitrification. Riparian vegetation can provide cover for fish and can also increase the shading of the stream channel. Shading can reduce algal growth, which can reduce the risk and severity of "blooms" as well as reducing water temperatures.

3.4.4 In order to achieve the benefits of the riparian enhancement outlined above for Mill Creek, it is recommended that riparian planting and stock exclusion for the proposed development follow the guidelines provided within the DairyNZ document "Getting riparian planting right in Otago" (which includes advice from industry and regional council experts). Key points relevant to Mill Creek are:

- Riparian planting of 2-4 m width, including the upper and lower bank zones, will further improve water quality.
- Grass strips will also help to filter out sediment, phosphorus and faecal bacteria from runoff. A minimum of 1 m is recommended between the riparian planting and any fencing.
- Maintenance of the riparian plantings to control weeds and pests is crucial in the first five years for a healthy riparian zone to become established.

4. LAKE HAYES

4.1 Mill Creek is the major inflow to Lake Hayes, a small relatively shallow lake (maximum depth of 33 m and surface area 2.76 km^2, LAWA website). The lake has likely undergone progressive eutrophication (nutrient enrichment) since development and intensification (e.g. cultivation and wetland drainage, dairy shed and cheese factory discharges, fertiliser and herbicide application) began in the catchment, resulting in algal blooms and a decline in lake health and fishing. Consequently, the ORC developed the 'Lake Hayes Management Strategy' (ORC 1995) to improve the water quality of the lake, and more recently the Friends of Lake Hayes Society have had the 'Lake Hayes Restoration and Monitoring Plan' prepared (Hydrosphere Research 2017).

4.2 The 'Lake Hayes Management Strategy' (ORC 1995) was developed by the ORC and QLDC (with community input) in response to the increase in eutrophication (nutrient enrichment) in the lake over the previous approximately 30 years (the first algal bloom in the lake being recorded in 1969). The eutrophic state of the lake was linked to the movement of phosphorus bound to soil from land to the lake, where it contributes to an already massive phosphorus load (ORC 1995). Phosphorus is released from lake bed sediments in autumn when bottom waters lose all oxygen (i.e., become anoxic), favouring the rapid growth of algae and associated problems. The strategy recognized that to reduce eutrophication the amount of nutrients entering the lake must be reduced, and secondly the nutrients already in the lake must be immobilised or removed (ORC 1995).

4.3 The first can be achieved by controlling phosphorus inputs to the lake, by reducing erosion of phosphorus-rich soils and collecting as much silt as possible as it moves down the catchment (ORC 1995). The transfer of soils to waterways can occur by direct movement of overland flow, the erosion of streams by flood flows, degradation of streambanks due to livestock influences, and by animal faeces entering water. The establishment of riparian margins along Mill Creek was recognized as a means of reducing these phosphorus sources by reducing stock access, trapping sediment, and helping to stabilise banks (ORC 1995).

4.4 Locking up the phosphorus that is already in the lake is more difficult and requires stopping the anoxic release of phosphorus for at least one year by artificial means (ORC 1995). The strategy considered various methods that could be employed to achieve this, including piping to remove nutrient rich lake bottom waters, chemical methods of in-lake control (e.g. herbicides, flocculants), and artificial circulation to aerate the water. After considering these methods, it was concluded that the best option was to first substantially decrease the external phosphorus inputs into the lake, and only after this has been achieved, consider internal lake treatment methods (ORC 1995).

4.5 The 'Lake Hayes Management Strategy' therefore prioritised methods to address external nutrient inputs to the lake (ORC 1995). In addition to the establishment of riparian margins, recommended methods to achieve this were the control and mitigation of point source discharges of contaminants (e.g. septic tank overflows, stormwater) and efficient and effective management of water quality in the catchment (ORC 1995).

4.6 The 'Lake Hayes Restoration and Monitoring Plan' (Hydrosphere Research 2017) also recognizes the decline that has occurred in the health of Lake Hayes, noting that algal blooms have worsened since 2006. However, it is noted that this has occurred when both external inputs of nutrients and internal nutrient loads in the lake have been stable or reducing. The algal blooms that have occurred are therefore not related to increased nutrient inputs to the lake. Instead, there has been a change in the dominant algae in the lake to a species (*Ceratium hirundinella*) that has a competitive advantage over other algae when nutrient levels are low (Hydrosphere Research 2017).

4.7 Based on this understanding of the current cause of algal blooms in the lake, a restoration strategy to accelerate the recovery of the lake has been developed (Hydrosphere Research 2017). This included the evaluation of various restoration activities and from this a restoration strategy was developed, including potential timelines to achieve implementation and targets by which to measure success. The four key recommended strategies are: (1) food web bio-manipulation, (2) enhanced flushing by using surplus irrigation water from the Arrow River, (3) alum dosing to flocculate and bind phosphorus to the lake bed, and (4) a focus on land use activities in the catchment to further reduce nutrient and sediment losses from land to water (Hydrosphere Research 2017).

4.8 Both the 'Lake Hayes Management Strategy' (ORC 1995) and the 'Lake Hayes Restoration and Monitoring Plan' (Hydrosphere Research 2017) therefore identify that a key restoration strategy for the lake is to reduce the nutrient and loading to the lake from Mill Creek, which can be achieved by:

- Reducing nitrate concentrations in Mill Creek.
- Reducing suspended sediment (turbidity) and total phosphorus concentrations in Mill Creek during high flow events.
- Developing a catchment management plan to ensure improved land management practices are adopted throughout the catchment.

4.9 The proposed development will contribute to achieving the restoration of Lake Hayes through extensive riparian enhancement and change in landuse activities, which will reduce nutrient and sediment run-off to Mill Creek.

5. FURTHER INFORMATION – REZONING SUBMISSION

5.1 Paragraphs 61.1 and 61.2 of Mr Langman's statement of evidence (dated 30 May 2018) notes that, in relation to the rezoning of a 'wedge' located between two areas of land zoned Waterfall Park Zone, insufficient information has been provided with the submission on the potential impacts of the rezoning on ecology. I can confirm that I have viewed this 'wedge' of land and observed that it has similar vegetation cover to the adjacent area and is not densely vegetated. The rezoning of this land will have no adverse effects on the aquatic ecology of Mill Creek.

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Appendix One: Sampling methodology

Water quality

Measurements of water physico-chemistry (conductivity (μS/cm), dissolved oxygen (saturation (%) and concentration (mg/L)), pH and temperature (°C)) were taken at each site using either a calibrated handheld YSI Professional Plus multi-probe field meter. In addition, water clarity (m) and turbidity (NTU) were measured at the mid-way site using a transmissometer and a Hach 2100Q turbidimeter, respectively.

Benthic macroinvertebrate communities

One macroinvertebrate sample was collected at each site following protocol C1 of the Ministry for the Environment's protocols for sampling macroinvertebrates in wadeable streams (Stark *et al.* 2001) (kick-net sampling). Samples were preserved and later processed in the Ryder Consulting laboratory.

Laboratory analysis

Samples were processed in the laboratory following protocol P3 (Full count). This protocol is summarised briefly below.

Samples were passed through a 500 μm sieve to remove fine material. Contents of the sieve were then placed in a white tray and macroinvertebrates were identified under a dissecting microscope (10-40X) using criteria from Winterbourn *et al.* (2006). When more than 500 individuals of one taxa were present, the number of individuals from a fixed fraction (between 10% and 50%) were counted and the number scaled up to the total number in each sample using a weighting factor based on the fraction of the sample that was counted.

Data summaries and metric calculations

For each site, benthic macroinvertebrate community health was assessed by determining the following characteristics:

Taxonomic richness: A measurement of the number of taxa present.

Number and percentage of Ephemeroptera, Plecoptera and Trichoptera (EPT) taxa: These insect groups are generally dominated by pollution sensitive taxa. In stony bed rivers, this index usually increases with better water quality and increased habitat diversity.

Macroinvertebrate Community Index (MCI) (Stark 1993): The MCI uses the occurrence of specific macroinvertebrate taxa to determine the level of organic enrichment in a stream. Taxon scores are between 1 and 10, 1 representing species highly tolerant to organic pollution (e.g., worms and some dipteran species) and 10 representing species highly sensitive to organic pollution (e.g., most mayflies and stoneflies). A site score is obtained by summing the scores of individual taxa and dividing this total by the number of taxa present at the site. These scores can be interpreted in comparison with national standards (Table 1), for example, a low site score (e.g., 40) represents 'probable severe pollution' and a high score (e.g., 140) represents very 'clean' conditions.

$$\text{MCI} = \left(\frac{\text{Sum of taxa scores}}{\text{Number of scoring taxa}}\right) \times 20$$

Semi-quantitative MCI (SQMCI) (Stark 1998): The SQMCI uses the same approach as the MCI but weights each taxa score based on how abundant the taxa is within the community. Abundance of all taxa is recorded using a five-point scale (i.e., rare = 1-4 animals per sample, common = 5-19, abundant = 20-99, very abundant = 100-499, very very abundant = >500). As for MCI, SQMCI scores can be interpreted in the context of national standards (Table 1).

$$\text{SQMCI} = \frac{\text{Sum of (Taxa coded abundance x Taxa score)}}{\text{Sum of coded abundances for sample}}$$

Table A1.1 *Interpretation of macroinvertebrate community index values from Boothroyd and Stark (2000) (Quality class A) and Stark and Maxted (2007) (Quality class B).*

Quality Class A	Quality Class B	MCI	SQMCI
Clean water	Excellent	> 120	> 6.00
Doubtful quality	Good	100 – 119	5.00 – 5.99
Probable moderate pollution	Fair	80 – 99	4.00 – 4.99
Probable severe pollution	Poor	< 80	< 4.00

Lake Hayes Management Strategy

Otago Regional Council/
Queenstown Lakes District Council
September 1995

ISBN: 0-908922-26-4

Foreword

The Otago Regional Council and the Queenstown Lakes District Council are pleased to present this Management Strategy for Lake Hayes. It reflects the concerns that both Councils and the community have about the continuing water quality problems of the lake, and the need to take action to address the resultant decline in recreational, fishery and scenic values.

This strategy details the objectives and policies for future sustainable management of the lake and catchment. The strategy outlines the actions the Otago Regional Council proposes to carry out in the catchment and regulatory matters recommended for consideration in the forthcoming *Regional Plan: Water* (prepared by the Otago Regional Council) and the Queenstown Lakes District Plan. This separate but coordinated and consistent response recognises the different functions afforded to District and Regional Councils under the Resource Management Act 1991.

Tourism has grown rapidly over recent decades in the Wakatipu basin with Lake Hayes being an important component of those scenic resources which attract tourists to the area. The conservation of the Lake Hayes resource is of regional and national importance both economically, recreationally and for its intrinsic and scenic values.

The effects of poor water quality in Lake Hayes have been noticeable to the general public since the first algal bloom in 1969. The lake supports a recreational fishery of Brown Trout and Perch and native fish species including Upland Bully, Koaro and the long-finned eel. People enjoy swimming, boating and fishing in the lake, however recreation and habitat values are restricted at times of the year due to the poor water quality.

The Councils wish to thank the community for their comments received on the draft strategy. These have been important in shaping this finalised form of the strategy which will direct the future management of this important regional and national asset.

Thank you for your interest and support.

Chairperson,
Otago Regional Council

Mayor,
Queenstown Lakes District Council

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1. Introduction

1.1 Why is a strategy needed?

Over approximately the last thirty years Lake Hayes has become increasingly eutrophic (nutrient rich), this being characterised by anoxic water, poor water clarity, frequent algal scums, fish deaths and insect pests. This state of eutrophication has been found to be due to the movement of phosphorus bound to soil from the land to the lake, where it contributes to an already massive phosphorus load. Phosphorus is released from lake bed sediments in autumn when bottom waters lose all oxygen, favouring the rapid growth of algae and associated problems. Numerous reports have been written on the lake's water quality, its causes and possible solutions.

The most comprehensive scientific study to be carried out on the lake and catchment was done by Barry Robertson of the Otago Catchment Board in 1983-84 (Robertson, 1988).

This report described a phosphorus budget and seasonal cycle for Lake Hayes. These were related to past and present uses of the catchment. The report identified several possible management options to address these problems. It is intended that this strategy in association with the Queenstown Lakes District Plan and the Otago Regional Council's *Regional Plan: Water* will be the instruments used to implement methods for improving water quality in Lake Hayes.

The overall goal of this strategy is:

To improve the water quality of Lake Hayes, to achieve a standard suitable for contact recreation year round and to prevent further algal blooms.

1.2 Implementation of the strategy

This strategy is a non statutory document which has been developed by the Otago Regional Council and the Queenstown Lakes District Council and finalised following community comment. It proposes methods to be used by the Otago Regional Council (subject to the Annual Planning Process under the Local Government Act), and regulatory matters to be considered in the *Regional Plan: Water* and the Queenstown Lakes District Plan. These matters will be coordinated to ensure all resource issues are dealt with by the agency responsible for such functions. The Otago Regional Council is currently preparing a *Regional Plan: Water*, which will address all water issues in Otago. Regulatory mechanisms required to address the resource issues surrounding Lake Hayes will be considered within the proposed *Regional Plan: Water*. Regulatory mechanisms associated with land use will be included in the Queenstown Lakes District Plan and any associated District Plan changes. Consultation between the Otago Regional and Queenstown Lakes District Councils will be ongoing to ensure the goal of this management strategy is achieved.

Discussions will be held with affected land owners over the implementation of this strategy. Agreement will be a necessity on the proposed actions such as riparian margin enhancement, wetland creation and fencing of areas. The priority will be on:

- Riparian margins and fencing
- Bank stabilisation
- Wetland protection and recreation.

It is expected that over the next three to five years, the implementation of the strategy will result in a reduction in phosphorus inputs.

1.3 What is eutrophication?

Lake Hayes is eutrophic. This means there are excess levels of nutrients in the lake, with the lake ecosystem suffering as a result. Eutrophication is the term normally used to describe the natural "aging" process of a lake. While the lake may begin as a pool of clear fresh water, it slowly begins to accumulate silt and plant nutrients, resulting in an increase in the growth of water plants and a decrease in the depth of water. Ultimately the lake can reduce to a wetland ecosystem. Normally this will take thousands of years to occur.

Unfortunately, human activities in lake catchments can speed up this process. Construction of roads and houses, cultivation, livestock, eroded soils, drainage of wetlands, effluent discharge, fertiliser use and streambank erosion all contribute to phosphorus being washed downstream to the lake.

One of the first noticeable signs of eutrophication, is the periodic rapid growth of small floating water plants, or algae. If the water is warm enough, and has enough nutrients, a "bloom" of algae may occur, resulting in the water taking on red, yellow or green colours. However these algae soon out-grow the supply of plant nutrients and the "bloom" begins to die. The rotting of the algae uses up the available oxygen in the water and the lake begins to smell.

This is the state in which we now find Lake Hayes. The value of the lake as a recreational facility and as a wildlife and fishery habitat is affected by periodic algal blooms.

The vast majority of nutrients enter the lake from the Mill Creek catchment in the form of phosphorus attached to soil particles, as well as some dissolved phosphorus and nitrates. Phosphorus has been found to be the nutrient responsible for the eutrophication in Lake Hayes. While the phosphorus is not immediately available to the algae, their later release to the water controls the algal blooms.

When the phosphorus-loaded sediments enter the lake, they sink to the bottom. The surface water warms up over summer and being lighter than the cold water below, does not mix with underlying cooler layers. Plants which die in the lake fall to the bottom and, as they decay, use up the oxygen in the cooler lower layers of water. Under these low-oxygen conditions the phosphorus may be released from the silt particles into the water.

While there is now a nutrient-rich layer of water, there will not be an algal bloom as there is not enough warmth or light at the bottom of the lake. However, during winter the surface water cools and the layers of water mix quite easily. In spring, with warmth and light, the surface water is nutrient-rich and conditions are right for an algal bloom. This results in conditions which are less than desirable for the fish, angler, swimmer and sailor.

1.4 What can be done about eutrophication?

Firstly the amount of nutrients entering the lake must be reduced, and secondly the nutrients already in the lake must be immobilised or removed. The amount of phosphorus entering the lake may be minimised by controlling phosphorus inputs to streams and by controlling phosphorus inputs into the lake. The actions proposed in this strategy have been developed in order to achieve these controls. They include such actions as reducing erosion of phosphorus-rich soil in the catchment and on the stream banks and collecting as much silt as possible as it moves down the catchment.

Locking up the phosphorus already in the lake is more difficult. Mechanisms which can help achieve this do so by stopping the anoxic release of phosphorus for at least one year by artificial means. This approach is explained in the section on nutrient inactivation in Appendix 1.

1.5 Alternative methods for improving water quality

With technological changes, investigations and monitoring, the Council may become aware of more suitable techniques for dealing with the issues surrounding Lake Hayes. This will be assessed as the strategy is reviewed and at any other time when additional information becomes available and, if appropriate, Council will modify this strategy.

Before deciding on the mechanisms to be used in this strategy, the possible alternative methods of improving the water quality of Lake Hayes were explored. They are summarised in Appendix 1.

1.6 Reducing external phosphorus inputs and lake recovery

With reduction of external inflows of phosphorus there will still be a large pool of sediment phosphorus in the upper sediment layer of the lake. This will be released at a relatively constant rate during anoxic conditions, until such time as the pool begins to deplete or anoxia becomes less intense. It is not clear from studies in other lakes how long this will take. In some lakes a measurable decline occurred in 5-10 years and in other lakes there was no change after 10 years or more. Recovery time will depend on how quickly internally released phosphorus can be flushed from the lake, how much is added to the sediment from the external load and the initial extent of the pool available for release.

After consideration of these methods, the best option for addressing lake eutrophication from the point of view of long term sustainability is considered to be by treating the cause of eutrophication, prior to treating those symptoms associated with it. For this reason the Otago Regional and Queenstown Lakes District Councils, in consultation with the Lake Hayes community have chosen to firstly address the external phosphorus inputs into the lake by way of a number of phosphorus control methods. Other studies have found that internal lake treatment methods are effective only after external lake phosphorus inputs have been substantially decreased. Hence the methods in this strategy are prioritised to address external nutrient input.

1.7 Matters taken into account in formulating this strategy

- Kawarau Water Conservation Notice. Evidence presented in support of the application by the Otago Regional Council
- Proposed Regional Policy Statement for Otago
- Department of Lands and Survey, 1982: *Lake Hayes Reserves Management Plan*, Management Plan series number RR20. Department of Lands and Survey, Dunedin
- Robertson B M, 1988: *Lake Hayes Eutrophication and Options for Management, Technical Report.* Otago Catchment and Regional Water Board, Dunedin
- Robertson B M and Associates Environmental Consultants and Royds Garden Ltd, 1989: *Lake Hayes Eutrophication and Options for Management, Internal Treatment Evaluation and Preliminary Design.* Otago Catchment and Regional Water Board, Dunedin
- Mitchell *et al: Eutrophication of Lake Hayes and Lake Johnson.* Report to Ministry of Works
- Queenstown Lakes District Plan (in preparation)

1.8 Monitoring the strategy

Monitoring to determine the degree to which the strategy is achieving its objectives will be required. That monitoring will assess the degree to which the eutrophication of the lake is decreased, over time, and will be used in the review of the strategy. The parameters that will need to be monitored include:

- Water quality in Mill Creek and Lake Hayes
- Mill Creek flow information
- Lake levels
- Land use.

1.9 Strategy review

A review of this strategy will take place at five yearly intervals or sooner if required.

It will assess the changes to the quantity of external phosphorus entering Lake Hayes, and chemical composition of the lake and any change to trophic status. When a 20% reduction in the total annual phosphorus load to Lake Hayes has been achieved, from 1994 figures, and/or in-lake phosphorus concentration achieves that of the water quality class, the Otago Regional Council will, in association with the Community consider the need for in-lake treatment methods including piping nutrient rich waters from the bottom of the lake.

This may be required if the lake is still experiencing algal blooms and the community wants an alterative option to external load reduction.

2. Description of the Catchment

2.1 Topography

Lake Hayes is believed to have been formed following the scouring of the bed by the Wakatipu glacier and subsequent separation from the ancestral Lake Wakatipu by outwash from the Shotover River. The catchment itself reflects its glacial origins in its topography having steep to moderately steep mountain lands, with a highest point of 1600m at Coronet Peak. There are also broad fans and terraces over the flood plain, moderately steep hills and associated rolling hills around the perimeters of the catchment.

2.2 Geology

The dominant geology is Palaeozoic metamorphic schist, with lesser areas of quaternary outwash gravels, till and morainic deposits and late glacial lake beds.

2.3 Vegetation

The original vegetation in the catchment was native tussock, which has been cultivated on the lowlands into pasture and crops. Sward grass predominates on the poorer soils in the valley and on the low altitude steep faces. Also present on these faces is native matagouri and exotic briar. Above these species are found sward grass and short tussocks. Some oversowing with white clover has occurred at these altitudes. Above approximately 1000m snow tussock *(Chionochloa rigida)*, blue tussock *(Poa colensoi)* and *Festuca mathewsii* are present.

2.4 Soils

Two broad soil types have developed, the yellow grey earths or loess soils on the valley floor, and the yellow brown earths on the steeply sloping faces of Coronet Peak. Nutrient status is generally medium to high on the valley floors and low on the faces. Perhaps the over-riding consideration in terms of phosphorus transport to the lake, is the ease with which these soil types are picked up and carried in suspension by moving water (Robertson 1988).

2.5 Erosion

Some erosion in the catchment is found within the streams. This can be through bank collapse from stock pressure and high energy stream flows or slip erosion on the steep faces of water bodies on the lower slopes of Coronet Peak. Robertson identified in 1989 that slight to moderate sheet and wind erosion has occurred on all slopes in the catchment. A more recent 1994 inspection by the Otago Regional Council found a healthier stream channel with beds and banks generally in a very well vegetated and stable state.

2.6 Catchment water quality

The major inflow into Lake Hayes is Mill Creek. Its water quality is characterised by high sediment and nutrient loads, particularly phosphorus. This is due to the soil and rock types in the catchment as well as the effects of land use. Limestone is also present in high concentrations, and this is thought to have exacerbated the release of phosphorus from sediment.

Appendix 2 summarises the characteristics for Lake Hayes from recent trend analysis of water quality monitoring data.

2.7 Land use and tenure

Pastoral farming with some mixed cropping are the predominant land uses in the Lake Hayes catchment. The area has undergone extensive changes in recent times with the subdivision of some of the larger runs into small blocks. Land in the valley and on the rolling hills is freehold with many separate titles, while Coronet Peak is Crown land in pastoral lease.

2.8 Social descriptors

The Queenstown Lakes District has experienced extensive growth over the last decade. The resident population figure has increased by 21.5% since 1986. The Lake Hayes catchment and Wakatipu Basin is consistent with this growth trend. Retailing, a major industry in the Queenstown area is also experiencing strong growth. With such growth comes the requirement for housing and subdivision. Lake Hayes has traditionally been a popular holiday location, while in recent times more permanent residents have been developed. It is well located for both work in Queenstown and Arrowtown and will most likely develop further with the Queenstown Lakes District Plan's proposing the settlement of satellite communities.

2.9 Iwi values associated with the Lake Hayes area

The association Kai Tahu whanui have with Lake Hayes and the wider area of the Lakes District is of ancient origin. In tradition and mythology the relationship stems from the time of creation, the source of mauri and wairua, elements that connect Manawhenua with the environment, and constitute mana.

In tradition it was the journey of discovery south through the centre of the island by Rakaihautu and his people of the Uruao canoe, the Waitaha, that marks the first human contact with the Lakes District of "Te Waka Aoraki" (South Island).

Lake Hayes is known to Kai Tahu as "Te Whaka-ata a Haki-te-kura", a name that refers to the mirror image of Haki-te-kura a famous ancestress noted for her exploits, whose image was reflected in the lake.

The Wakatipu Basin was occupied for many centuries by sections of first the Waitaha followed by the Kati Mamoe and latterly the Kai Tahu, an amalgam of people who over time merged in whakapapa into a single entity known collectively as Kai Tahu whanui.

The Wakatipu basin was important for the resources that it provided to the mobile units of Maori who regularly travelled inland to gather pounamu (greenstone) from the source, to gather mahika kai, and to reside at selected places around the edge of the lakes over the summer months. Trading of resources with neighbouring hapu was a prime activity.

Water
Kai Tahu advocate the respect and protection of all water resources. In traditional times classifications existed for many of the water resources of Otago. Water bodies fed from the interior mountains were regarded particularly highly. Waters that provided food resources were treasured. Protocols existed to ensure that appropriate conduct of people occurred in, on and by water so as not to offend or desecrate the natural balance that existed between land, water and the people dependent on it.

Modification
Kai Tahu consider that the breakdown of the ecosystem of Lake Hayes and the extensive modification of the catchment to the lake is symptomatic of other areas in the Otago region. It is hoped that the exercise that is jointly being undertaken to mitigate the effects of land and water modification of the last 150 years on Te Whaka-ata (Lake Hayes) and its catchment area will be adopted elsewhere in Otago.

Taoka
The lake is still regarded as a taoka. The customary practice of gathering mahika kai in and around Te Whaka-ata (Lake Hayes) has long since disappeared, although Kai Tahu people do fish there in a recreational capacity. The halting of customary practice can be linked to historical events that hindered and fragmented the traditional communities of Kai Tahu, limiting a people who were once mobile hunter gatherers to confined spaces and resources. Contributing factors include drainage of wetlands, pollution of mahika kai resources and reduced access.

The fact remains however that Kai Tahu still retain the rangatiratanga or customary authority over Te Whaka-ata (Lake Hayes) and the waters that feed the lake.

Consultation
Initial consultation on Te Whaka-ata (Lake Hayes) with Kai Tahu runanga has occurred at a hui held at Kaka Point in December 1993. Runanga from Otago and Southland were present at this hui. Discussion focused on the modification issues affecting the catchment area and the effect of this on the waters of Te Whaka-ata (Lake Hayes).

Archaeological
Sites of cultural occupation or cooking places may be disturbed or unearthed in the catchment area of Te Whaka-ata (Lake Hayes) through development, catchment works or natural erosion.

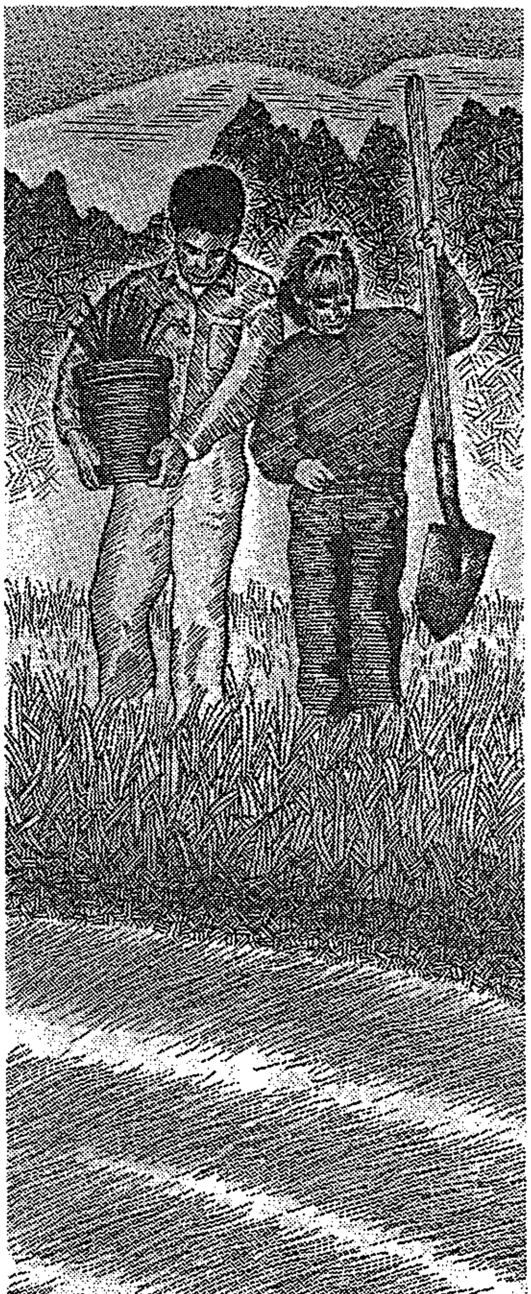
Where and if earth works are proposed as part of the management strategy for Te Whaka-ata (Lake Hayes) it may be necessary to consult Kai Tahu over possible disturbance of archaeological sites. In a situation where possible cultural archaeological sites may exist Iwi prefer that a site survey (visual) be carried out prior to any work commencing.

Native fishery
While the Te Whaka-ata (Lake Hayes) native fishery is no longer part of the seasonal mahika kai resource of Kai Tahu, the Iwi have a responsibility as kaitiaki of the native fishery to seek the improvement of the native habitat.

2.10 Recreational use

Lake Hayes is used for a variety of recreational pursuits. These include on-water activities such as swimming, fishing, rowing, and sailing and land based activities associated with the general use of the reserves around the lake.

3. Erosion and Land use Practices



3.1 Introduction

The degradation of Lake Hayes water quality is related to land use practices, and the associated runoff of phosphorus. With the growth of agriculture and other industries in this catchment since 1910, waters in the Lake Hayes catchment have been subjected to dairy shed effluent, cheese factory discharge, outlet restrictions, irrigation race discharge, the application of superphosphate fertiliser, increasing livestock numbers and land cultivation, drainage of wetlands and soil erosion. In combination these practices have the effect we see today on Lake Hayes' water quality. Some of these practices no longer occur, and the effects of others can be mitigated.

The transfer of phosphorus from pasture into the streams is linked to the transfer of sediment. This transfer may be by the direct movement of overland flow, the erosion of streams by flood flows, degradation of streambanks due to livestock influences, and by animal dung entering water bodies. Streambank riparian margins are advantageous in reducing these phosphorus sources. The establishment of riparian margins along the length of Mill Creek will primarily reduce stock access, trap sediment that would otherwise get into the stream, and help stabilise banks.

Streambank erosion occurs along sections of Mill Creek and this also contributes to phosphorus loading on the lake. General soil erosion throughout the catchment, in combination with the soil types present, also contributes to lake sediment and phosphorus. Many of the mechanisms needed to reduce the further flow of phosphorus into Lake Hayes amount to what would be done in any area for the purposes of soil conservation and sustainable land management.

3.2 Issues

3.2.1 Land use practices in the Lake Hayes catchment contribute to the eutrophication of Lake Hayes.

Explanation

The process of lake eutrophication has been accelerated in Lake Hayes due to natural geology, and the effects of human land use which result in the transfer of phosphorus into water bodies. This results from:

(i) Runoff of nutrients from farms due to fertiliser application and animal wastes.

It is estimated that superphosphate losses in the order of 0.5-2.0% of the fertiliser applied can occur into nearby water bodies. Subsequent losses of phosphorus varies depending on soil phosphorus retention, the land and climatic condition at the time of, and immediately following application, stock management and erosion characteristics.

Animals are also responsible for large amounts of phosphorus entering waters. They do this through runoff, by the addition of phosphorus through dung, by changing the soil-grass system, and in the decomposition of their bodies.

(ii) Loss of vegetation on and adjacent to river banks.

Vegetation adjacent to water bodies acts as a nutrient sieve, capturing and utilising nutrient before it enters the water body. When vegetation is lost from a river, lake or streambank, the soil surface is more susceptible to erosion and the battering of water flows. Closely grazed grass cannot sieve particulate matter efficiently and animal trampling lowers the infiltration capacity of the soil and increases the likelihood of soil runoff.

(iii) Drainage of wetlands.

Wetlands can take up large quantities of nutrients through their plants and the deposition of sediment. Drainage of wetlands in the Lake Hayes catchment removed a natural nutrient trap. As a result the lake has become the predominant nutrient sink.

3.2.2 Erosion in the catchment adversely affects water quality.

Explanation
Studies have shown that the majority of phosphorus entering Lake Hayes is bound to sediment. Minimising erosion throughout the catchment therefore becomes an important factor in lake rehabilitation. The primary sources of sediment are the erosion of stream banks, hill slopes and to a lesser extent sediment within the stream channel.

3.3 Objectives

3.3.1 To avoid the adverse effects of land use on water in order to improve water quality in Lake Hayes and its catchment.

Explanation
The relationship between land use practices and water quality are well established. In association with other factors, these practices represent the overriding causes of lake eutrophication. Addressing the cause of the problems associated with Lake Hayes is the method most closely related to the principles of sustainable management. Situations must be avoided where runoff potentially containing contaminants could enter water without firstly being treated or buffered involving sediment or nutrient entrapment. This objective is intended to promote mechanisms to limit the adverse effects of land use activities.

3.3.2 To minimise erosion in the Lake Hayes catchment.

Explanation
A decline in soil and streambank erosion in the Lake Hayes catchment will be accompanied by a decline in the amount of sediment-bound phosphorus entering Lake Hayes. As the sediment in the bed of Lake Hayes is primarily responsible for the continual release of phosphorus into the lake water at lake turnover, a decline in the amount of sediment and the associated concentration of bound phosphorus is expected to aid lake recovery. This is because, as time goes on, phosphorus gradually gets leached out of the sediments and/or becomes buried by fresh sediment containing less phosphorus.

3.4 Policies

3.4.1 To avoid the contribution that phosphorus and sediment from non-point source pollution makes to phosphorus loading on Lake Hayes.

Explanation
In 1984 an estimate of the total annual phosphorus load to Lake Hayes from all sources was 2400 +/- 480 kg per year. For the period of 1990-93, this was estimated to be in the order of 400-1000 kg per year. The intent of this policy is to control the contribution from non-point source discharges in the Lake Hayes catchment, to ensure a decline in the total annual phosphorus loading rates. In 1994 a re-estimate of the contribution of phosphorus to Lake Hayes from the Mill Creek catchment alone was estimated to be 80% of the annual external phosphorus load.

Non-point source pollution is the predominant source of phosphorus input into Lake Hayes. The ease of transport of phosphorus into water bodies is a result of the fine-textured (rock-flour) soils present, as soil particles are easily picked up and carried in suspension by moving water. Soils in the area have relatively high natural phosphorus levels, and as a result will contribute phosphorus wherever erosion occurs. A reduction in the amount and concentration of phosphorus entering Lake Hayes will eventually result in a lower overall nutrient status in the lake, thereby slowing the eutrophication process and aiding lake recovery.

3.4.2 To protect existing wetlands, ponds and other nutrient sinks, and to establish new ones by land owner agreement, in the Lake Hayes catchment.

Explanation
Wetlands, ponds and other nutrient sinks act as valves or sinks to regulate or trap the flow of nutrients and sediments from surrounding terrestrial systems. Wetland macrophytes, phytoplankton and emergent vegetation are capable of taking up large amounts of phosphorus, especially during the first few years of addition. The loss of wetlands can result in increased sediments and nutrients entering water bodies. Because of their benefits in entrapping nutrients the protection of existing wetlands, ponds and other nutrient traps, and the establishment of new ones will be encouraged, wherever possible.

3.4.3 To ensure the retention of current riparian margins, and the development of new riparian margins throughout the Lake Hayes catchment.

Explanation
In order to reduce the transfer of nutrients from pasture to surface water, the Otago Regional Council needs to promote the future development of riparian margins throughout the catchment and protect current riparian margins. Riparian margins are accepted as being the best management practice for the control of non-point source pollution. Riparian margins act to reduce the contribution of nutrients, entering as both particulate and dissolved phosphorus. They do this by processes of infiltration, deposition, filtration, adsorption and absorption. Phosphorus loads to water bodies have been shown to reduce by 24% with riparian retirement.

3.4.4 To ensure that land use activities are considered in terms of their effect on the water quality of the receiving waters.

Explanation
This strategy proposes that water quality classes for Mill Creek and Lake Hayes be established in the proposed *Regional Plan: Water* (see 4.4.3). Classification aims to advance water quality improvements. The intent of this policy is to encourage the consideration of the future use of land, within the context of improving water quality in the Lake Hayes catchment. As land and soil qualities and land use are the predominant causes of poor water quality in the Lake Hayes catchment, improvement will only be achieved when the adverse effects of land use are avoided, remedied or mitigated.

3.5 Proposed Otago Regional Council actions

3.5.1 The Otago Regional Council will negotiate with land owners adjacent to Mill Creek and Lake Hayes for the establishment of riparian margins.

Explanation
Riparian margins are the best management practice for the control of non-point source pollution, providing benefits to water quality. Fenced riparian margins are also beneficial to farming as they prevent stock losses into the river channel, and with planting, contribute to river bank stability.

3.5.2 Where the Otago Regional Council provides for works to be carried out on lands adjacent to water bodies in the Lake Hayes catchment, the Council will consider entering into an appropriate agreement with the land owner to protect these works.

Explanation
Under Section 30 of the Soil Conservation and Rivers Control Act 1941, the Council can have the maintenance of works which they have fully or partially funded attached to the title of a property. This will ensure the works carried out for the purpose of soil conservation and water quality protection are safeguarded in the event of future changes in land ownership and management practices.

3.5.3 The Otago Regional Council will consider providing assistance to fence off the water body from areas of high phosphorus input.

Explanation
The areas which are found to be priority areas requiring fencing due to the contribution of high phosphorus levels as a result of current erosion occurring at these sites will be agreed through individual negotiation with land owners. Because the fencing off of all water bodies in the Lake Hayes catchment will be a costly exercise, work will have to take place over several years. The Otago Regional Council does not intend purchasing land, but rather working towards an agreement with land owners on the cost of fencing, the provision of alternative water supplies, and stock and vehicular access across water bodies where necessary.

3.5.4 The Otago Regional Council will consider carrying out stream bank stabilisation works in areas contributing high phosphorus levels.

Explanation

Some of the phosphorus inputs are derived from the erosion of water courses. The sites contributing the highest phosphorus inputs will be considered as priority intervention areas. Erosion can be alleviated by depositing rock at bank erosion sites.

3.5.5 The Otago Regional Council will advocate and provide assistance towards the protection and re-establishment of wetlands in the Lake Hayes catchment.

Explanation

Wetlands play an important role in water quality improvement by slowing the flow of water through catchments and acting as nutrient sieves. The peaks of flood flows are also diminished through the catchment as a consequence of wetlands. Negotiation and providing assistance to land owners to protect and re-create wetlands are considered the most effective mechanism for achieving the establishment of wetlands. Although there is insufficient land available in the catchment for one large wetland that will achieve major reductions in phosphorus loadings, it is still considered beneficial that small scale ponds and wetlands be developed.

3.5.6 The Otago Regional Council will provide technical advice and assistance to land owners wishing to establish riparian margins.

Explanation

The provision of technical advice and assistance to the community, is considered to be an important mechanism for assisting in the establishment of riparian margins.

3.5.7 The Otago Regional Council will provide advice and assistance to the community, as a means of encouraging sustainable land use practices in the Lake Hayes catchment.

Explanation

Community groups including Landcare groups are an important focus for locally driven initiatives aimed at cooperation between land owners to help achieve sustainable land management. Community groups have shown success in addressing, supporting and encouraging solutions to problems that can occur in land use practices. Being community driven they are seen to be preferable mechanisms to address problems rather than the use of regulation.

The form of advice and assistance provided could be educational material, updated land use practices and other information which encourages sustainable land uses.

3.6 Regulatory matters recommended for consideration in the *Regional Plan: Water*

3.6.1 Controlling the modification of wetlands.

Explanation
All wetlands in the Lake Hayes catchment play a role in slowing the rate of flow of water through the catchment, and acting as sediment traps. These functions are highly beneficial for improving water quality. The requirement to obtain a consent when wishing to modify wetlands would ensure that adverse effects can be addressed. In most cases modification of a wetland will require the taking, use, damming or diversion of water.

3.6.2 Controlling berm management practices.

Explanation
The contribution stock make to the phosphorus loadings of Lake Hayes is well established. Because of the potential effects stock can have on water bodies, consideration should be given to establishing rules with the proposed *Regional Plan: Water* to regulate the proximity of grazing near water bodies.

Because non-point source pollution is the major source of contamination in the catchment, the preservation of current riparian margins is an important factor in maintaining water quality. Due to the current deteriorated state of Lake Hayes regulatory control needs to be considered as a way of avoiding further adverse effects to the water quality in those area where erosion is most severe. Education, and advocacy, are however also appropriate mechanisms to achieve the increase in riparian margins throughout the catchment

3.7 Regulatory matters recommended for consideration in the Queenstown Lakes District Plan

3.7.1 The allocation of the maximum size of esplanade reserve possible in new land subdivisions, or esplanade strips or access strips and the requirement for the fencing and planting of such areas by the developer as part of the subdivision consent.

Explanation

District Councils are required to set aside esplanade reserves when land is subdivided. The Queenstown Lakes District Council may take and if necessary pay compensation for land subdivided in the Lake Hayes catchment, in recognition of the need to provide riparian margins to improve water quality. It is also possible under Section 235 of the Resource Management Act to create esplanade strips for maintaining and enhancing water quality. This mechanism may be costly to the Queenstown Lakes District Council and will not be used until the success of negotiated establishment of riparian margins can be ascertained. The provision of access strips may also lead to improved riparian management.

3.7.2 The protection of existing and future riparian margins in the catchment.

Explanation

District Councils are often the first point of contact for the prospective land developer, and hence are an important linking mechanism in ensuring current and future riparian margins are recognised and protected from future development.

3.7.3 The inclusion of a land disturbance strategy to control the potential effects of land disturbance adjacent to water bodies in the Lake Hayes catchment as part of any resource consent issued.

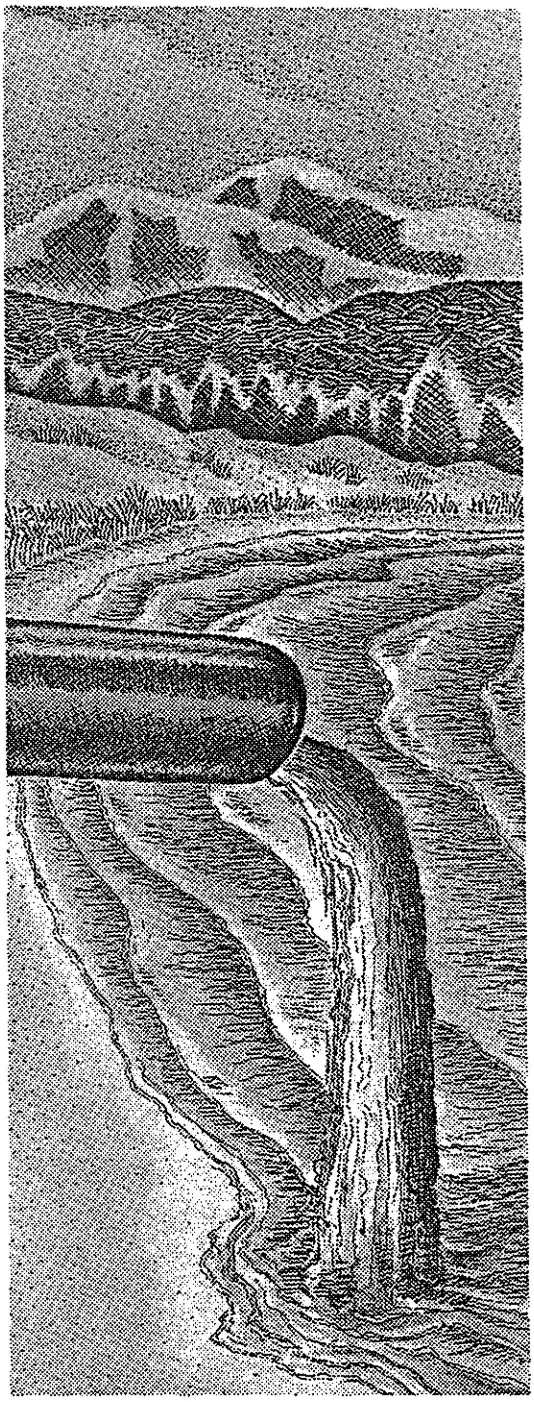
Explanation

District Councils have functions under the Resource Management Act to control the use, development and protection of land and the subdivision of land. Disturbance to the land, as occurs with most development, has the capacity to increase sediment loadings on water bodies. Recent work on Coronet Peak in forming new tracks and development works associated with improving the area as a ski-field have highlighted the change in sediment loadings that can occur as a result of land disturbance. In circumstances where the use of water is not directly related to the development, the District Council may be the only authority involved in the granting of consents. In these situations, it is important that the Queenstown Lakes District Council consider how land disturbance will take place, and whether there is likely to be any runoff into a water body.

3.7.4 The future land uses in the catchment with regard to their impact on water quality and soil conservation.

Explanation
Future land use planning has the capacity to consider and provide for mechanisms that will prevent the future deterioration of Lake Hayes water quality.

4. Point Source Discharges to Land, Water



4.1 Introduction

Point source discharges refer to the discharge of a contaminant from a specific and identifiable source, onto or into land, air or water. The discharge of a contaminant into a water body from a identifiable point can have effects which occur far beyond that point of discharge. In combination with the surrounding water quality present, a point source discharge can contribute to further degradation of the water quality. Because of their easily identifiable location and mechanism of release, it is easier to control and mitigate adverse effects from point source discharges than from the corresponding diffuse pollution source.

There is also a greater amount of technology available to treat contaminants which are traditionally discharged from an identifiable outlet. In the Lake Hayes catchment point source discharges tend to emanate from sewage disposal, ponds, and irrigation supply. The effects of such activities can be avoided, remedied and mitigated with adequate planning and design. With growth expected in both the tourism industry and residential settlement in this catchment, it is important that the associated issues of waste disposal and land management do not exacerbate the current poor standard of water quality. The intent of this section of the strategy is to establish a framework to ensure current and future point source discharges do not continue to contribute phosphorus to the Lake Hayes catchment.

4.2 Issues

4.2.1 Point source discharges within the Lake Hayes catchment contribute to the phosphorus loads entering Lake Hayes.

Explanation

Wastes from industries which have high nutrient content such as that from dairy farms and cheese factories has increased the nutrient loading of Lake Hayes in the past. Other point source discharges still occur today which contribute phosphorus to the lake.

4.2.2 Leaching of septic tanks contributes to the phosphorus loading of Lake Hayes.

Explanation

Septic tanks may have an adverse effect on catchment water quality where their location, maintenance or surrounding soils structure is inadequate for the nutrient loads they are carrying. Past studies in the catchment have indicated that septic tanks do contribute to the overall nutrient loading of the lake.

4.3 Objectives

4.3.1 To ensure that point source discharges in the Lake Hayes catchment do not contribute to the phosphorus loading in the lake.

Explanation
Point source discharges are usually able to be controlled and treated to ensure the discharge does not contain nutrients in levels that will adversely affect Lake Hayes. Current and future point source discharges will be required to show that their discharge to water will not contravene any water quality standard proposed for the water body.

4.4 Policies

4.4.1 To restrict the phosphorus and nutrient levels in point source discharges in the Lake Hayes catchment to ensure a decline in the total annual phosphorus loading rates of Lake Hayes.

Explanation
A decline in the phosphorus input into the lake from point source discharges will further assist lake recovery. To achieve long term lake recovery the high nutrient loading to the lake needs to be addressed. The impact of leaf litter on the phosphorus loadings of Lake Hayes is to be investigated.

4.4.2 Through the proposed *Regional Plan: Water*, current septic tank discharges which do not meet the proposed standards outlined in Appendix 3 will be required to meet that standard. All new on-site disposal systems will be required to operate to the standard outlined in Appendix 3.

Explanation
Some of the current septic tanks in the Lake Hayes catchment result in poor treatment of effluent and adverse effects on the ground and surface water resource. This policy requires those systems to be upgraded so that after treatment the effluent conforms to the standard specified in Appendix 3. All new systems must be designed to achieve the standard specified in Appendix 3.

4.4.3 Through the proposed *Regional Plan: Water*, water quality classes will be adopted for Lake Hayes and its tributaries, and Mill Creek.

Explanation
This policy aims to provide for the management of the lake and tributaries that reflects what the lake is used for, and provide for the improvement of the lake water quality.

4.4.4 To encourage the connection of subdivisions and areas of development to reticulated sewerage systems.

Explanation
Many of the houses and developed areas in the Lake Hayes catchment use septic tank systems. Encouraging the connection to reticulated sewerage systems recognises the potential contamination source of those septic tanks and their effect on phosphorus levels in the lake.

4.5 Regulatory matters recommended for consideration in the *Regional Plan: Water*

4.5.1 Establishing water quality classes for Mill Creek and Lake Hayes.

Explanation
The development of water quality classes for Mill Creek and Lake Hayes will be considered within the regulatory framework of the proposed *Regional Plan: Water.*

4.5.2 The control of the discharge of contaminants including stormwater and sewage.

Explanation
Regulation in the form of water quality standards will give direction and certainty to water users and provide for cumulative effects to be considered in order to address the water quality of Lake Hayes. Consideration will also need to be given to Appendix 3, which promotes an effluent standard for on-site sewage disposal (for example septic tanks).

4.5.3 Provision for the review of conditions on current resource consents issued under the Resource Management Act to ensure they meet any prescribed standards.

Explanation
This mechanism may be necessary given the current level of phosphorus loading into Lake Hayes.

4.5.4 The control of the use of fertilisers, pesticides and herbicides.

Explanation
There is a need to ensure that vegetated margins, which are performing a role in trapping nutrients are not affected by accidental or intended use of herbicide. If pesticides and herbicides are used according to manufactures directions then human safety is assured. Provisions exist under the Pesticides Regulations for prosecution if spray damages non target plants, and if negligent use can be demonstrated. These controls may be sufficient without the need for further regulation. To improve the trophic status of Lake Hayes phosphorus inputs into the lake must be reduced. It is particularly important that riparian margins do not receive fertiliser application, as their close proximity to water bodies and likely saturated soils will aid the flow of phosphorus into both surface and groundwater.

4.6 Regulatory matters recommended for consideration in the Queenstown Lakes District Plan

4.6.1 Consideration of the on-site disposal guidelines and standards outlined in Appendix 3, consistent with any regional plan.

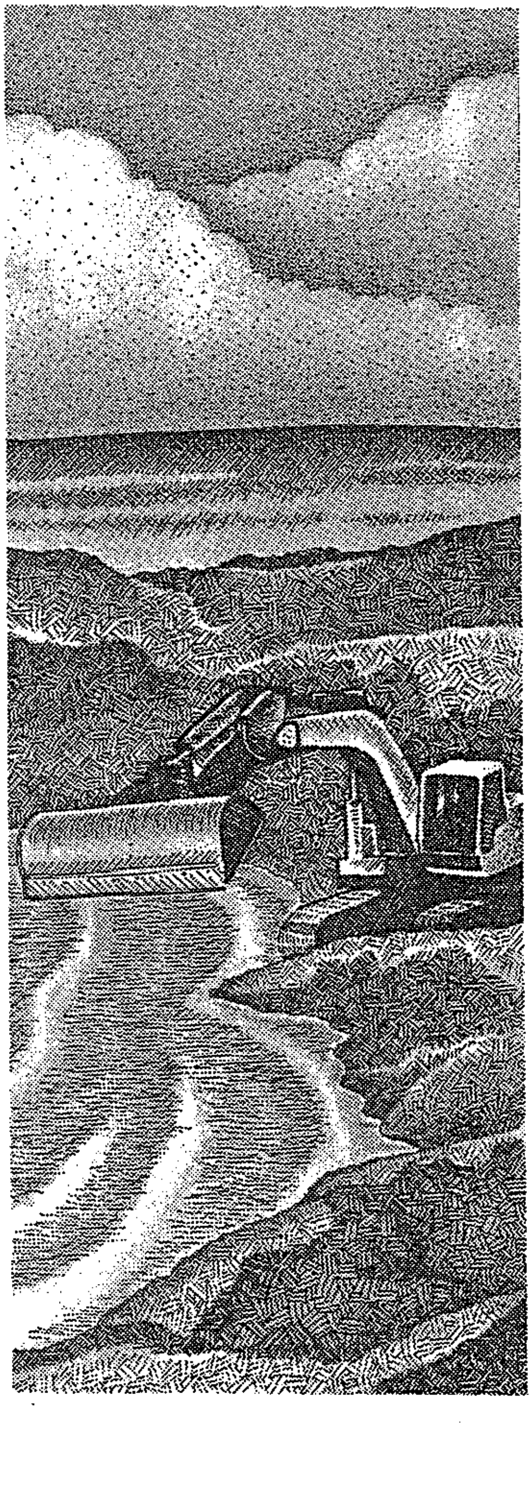
Explanation
On-site disposal guidelines for effluent quality are shown in Appendix 3. This mechanism is considered the most effective as the installation of the septic tank and its operating requirements can be dealt with in conjunction with the building consent. Where septic tanks currently do not meet the standard of effluent discharge required, the land holder is given the option of upgrading, or having the septic tank emptied regularly through a service agreement. This may be the best mechanism for households which are not regularly occupied, but where the septic tank system is currently inadequate.

4.6.2 Requiring the connection of new subdivision areas and areas of development into reticulated sewerage systems.

Explanation

New subdivision proposals, unless adequate provisions are made to deal with associated sewage discharges, could result in increased phosphorus loadings into Lake Hayes. Requiring the connection to a reticulated sewerage system, at the time of considering the subdivision application, will ensure that the potential impact of increased sewage discharges on the eutrophic state of the lake is taken into account.

5. The Taking, Use, Damming and Diversion of Water



5.1 Introduction

Water is used for a wide variety of functions in the Lake Hayes catchment. Some of these uses include fish ponds, snow making, public water supply, wildlife and tourism ventures, mining and irrigation. Pressure on the water resource is likely to increase with the expected growth in the area. The catchment can experience water shortages, in both summer and winter months, making the efficient and effective management of water quantity in the catchment extremely important. Water quantity will also affect water quality in tributaries and Lake Hayes. Lake Hayes itself is favoured for recreational use and the tributaries have important wildlife and fishery values.

Management of water use is necessary to sustain the potential of the lake to meet the needs of future generations. The need for further drinking water supply, irrigation, recreational use and fishing of the water resource in the Lake Hayes catchment can be foreseen.

Large scale drainage works and willow clearance were carried out in the Lake Hayes catchment in 1961. Between 80 and 120 hectares of land was drained in the upper half of Mill Creek resulting in an increase in productive land, but with the associated loss of wetlands. To improve the water quality of Lake Hayes, the benefits and methods of clearing drainage channels and the rate of flow of water through the catchment needs to be reassessed. This section of the strategy deals with how the taking, use, damming and diversion of water should be managed to achieve the objective to improve the water quality of Lake Hayes.

5.2 Issues

5.2.1 The quantity of water flowing in Mill Creek affects the quantity of nutrient entering the lake and the lake's rate of flushing.

Explanation

Continuous low flow of Mill Creek will affect the rate of flushing of Lake Hayes and hence potentially lead to a higher concentration of phosphorus in the lake. However since most of the nutrient entering the lake is bound to sediment, flood flows tend to carry more phosphorus. High flows also result in more erosion of the banks and movement of sediment downstream.

There are both water takes and discharges into Mill Creek, mostly for the purposes of land irrigation during the summer months. With an increase in viticulture in the catchment, demands for water from groundwater sources Lake Hayes and Mill Creek may increase. Groundwater takes from the catchment may also affect the amount of surface water available to the area.

5.2.2 The culverts at the outlet of the lake may be of insufficient size to manage high lake levels without causing flooding of adjacent land.

Explanation

It is normal for lake levels to rise at times of high rainfall. However when this occurs nutrients from the surrounding farmland is washed into the lake. It would be of benefit to lake recovery and lake flushing rates to ensure the culverts do not pose an excessive restriction on lake flushing and level control.

5.2.3 Lack of information on the groundwater resource in the Lake Hayes catchment impedes sustainable management of the use of water in the catchment.

Explanation

Groundwater recharges Mill Creek, the lake and the spring at the head of the lake. Increasing pressure to take water in the catchment, including the public water supply the spring provides, requires management agencies to have a better understanding of the capacity of the groundwater resource. In the Wakatipu Basin away from the main rivers, recharge of the groundwater aquifers is very limited and there is a possibility of aquifers giving low yields or becoming exhausted. The ability of the ground to sustain effluent disposal without contaminating ground or surface water is partially dependent on the geology. In coarse gravels, where there are few fine particles to act as a filter, soakage can allow effluent through the ground easily with little treatment. In the Lake Hayes basin the rural residents are mainly obtaining their domestic water supply from aquifers within the same ground deposits which are taking their effluent.

5.2.4 Drainage and flood protection works carried out in the past and their maintenance, increase the rate of flow of water through the Lake Hayes catchment and contribute high phosphorus content sediment to Lake Hayes.

Explanation

Increased rates of flow result in less sediment being able to settle out of the water column, and disturbs highly nutrient enriched sediment, sending it downstream into Lake Hayes.

5.3 Objectives

5.3.1 To ensure that the taking, use, damming and diversion of water in the Lake Hayes catchment does not adversely affect catchment water quantity and quality.

Explanation
The taking, use, damming and diversion of water has the potential to either increase or decrease sediment and nutrient flows into Lake Hayes, depending on how it is carried out and the mitigation mechanisms employed.

5.3.2 To manage drainage channels and flood protection works so they no longer contribute phosphorus and sediment to Lake Hayes.

Explanation
The use and maintenance of drainage channels have been found to contribute approximately 10% of the phosphorus loads to Lake Hayes per year. To improve the water quality of Lake Hayes it is necessary to reduce this form of phosphorus contribution.

5.4 Policies

5.4.1 To minimise obstructions to lake flushing and efficiently manage high lake levels.

Explanation
Structures which restrict the rate at which the lake can clear itself of high inflows are inconsistent with water quality improvement as they exacerbate flooding of adjacent land and increase water residence time.

Obstruction to the outflow of the lake results in higher than normal lake levels over the whole year, and flooding of shoreline margins at times of high rainfall. When shoreline margins are flooded, phosphorus from the land is made available to the lake. Obstruction to outflow also increases lake residence time, which will extend the time it takes the lake to recover under the mechanism of reducing phosphorus inputs.

5.4.2 Through the proposed *Regional Plan: Water,* minimum flows for Mill Creek will be established.

Explanation
Where the Otago Regional Council has a role in managing the use of water in the Lake Hayes catchment, it will ensure that use of water will not result in the lowering of Mill Creek to below its minimum flow.

Minimum flow regimes are mechanisms whereby the needs of instream values are considered alongside the water needs of the community, and the minimum flow is set which reflects a balance between the two.

5.4.3 To ensure the efficient use of water in the catchment.

Explanation
The Queenstown Lakes District including the Lake Hayes catchment is experiencing rapid population growth and rural/urban development. With these changes to land use, crops such as grapes, which require irrigation, are currently and will in the foreseeable future put further pressure on the catchment's water supply. Along with this, there is little information on the capacity of the groundwater resource in the catchment. These factors culminate to requiring a conservative approach to water use.

5.4.4 To adopt a cautious approach to the quantity of groundwater taken in the catchment and to ensure that use of groundwater will not significantly adversely affect the flow rate in tributaries, lake levels, or result in a decline in water quality.

Explanation
Lack of information on the groundwater resource in the Lake Hayes catchment means there is the potential for unsustainable use of groundwater. Since groundwater recharges surface water there is a potential impact on dilution and concentration of phosphorus entering Lake Hayes with over use of groundwater. The spring at the head of Lake Hayes is a groundwater site which is used for a public water supply. The availability of that water source is required for the predicted growth of households in the area, however it should not significantly impact on water available to Lake Hayes. In-lake factors such as residency time (the time a particle of water spends in the lake system) and the requirements of aquatic ecosystems also need to be considered when water is allocated between users.

5.4.5 To reduce water flow rates, and the movement of sediment in catchment tributaries and Mill Creek.

Explanation
High flow rates carry more sediment in the streams and creeks of the catchment and are more likely to cause streambank erosion. When water is slow moving, suspended solids have the chance to settle out through the water column. This is what happens in a wetland. The sediment in the beds of water bodies is disturbed during high flow and released into the lake, making phosphorus available to the lake and for future algal blooms.

5.5 Proposed Otago Regional Council actions

5.5.1 The Otago Regional Council will commission an independent engineering report into the functioning of the culverts at the outlet of Lake Hayes and the functioning of Hayes Creek itself.

Explanation
Past investigations have found that base levels in the outlet channel could be lowered, and this would provide some buffering capacity between the normal lake level and that at which significant flooding occurs. A reduction in lake levels in the order of 20-30cm is considered appropriate. It is estimated that a 1600mm culvert, properly installed under SH6 would reduce persistent high lake levels. Such a culvert would prove slightly less efficient at low lake levels, hence further investigation is required to ascertain how peaks can be reduced, while residence time decreases or remains the same. The gradient of Hayes Creek at the outlet may also be responsible for restrictions to flushing. Obstruction from willow colonisation suggests works on Hayes Creek itself may also be required.

5.5.2 The Otago Regional Council will promote water efficiency mechanisms.

Explanation
The Council will actively promote the efficient and effective use of water in the Lake Hayes catchment, a potentially water short catchment.

5.5.3 The Otago Regional Council will provide for an investigation into groundwater resources in the Lake Hayes catchment.

Explanation
This investigation is needed to obtain information on the quantity and quality of the groundwater resources in the Lake Hayes catchment and

Wakatipu Basin, so that management of the groundwater resource is based on sound technical information and knowledge.

5.5.4 The Otago Regional Council will provide advice on the management and maintenance of stream and drainage channels to ensure any work undertaken is in a way that minimises phosphorus and sediment inputs into the Lakes Hayes catchment.

Explanation
Drainage works carried out in the 1960s increased the amount of production land available and removed the natural nutrient sinks. The works included drainage and stream channels which now form part of the existing system of carrying nutrients to Lake Hayes. Maintenance of the channels needs to be carried out in such a way that phosphorus and sediment inputs into water bodies is minimised. Any maintenance undertaken shall recognise any conditions contained on a consent that has been granted.

Works that are required following a flood can be undertaken provided they meet the requirements of the emergency provisions of the Resource Management Act.

Consultation and advice to land owners will need to be carried out to ensure that the best approach is adopted.

5.5.5 The Otago Regional Council will provide where necessary for a programme of shaping, spreading, grassing and fencing around channels.

Explanation
Spoil created from the clearance of drainage channels has previously been placed on the bank above the water body. This spoil has a high nutrient content, and with rainfall this is displaced back into the water course. Spreading and grassing of the spoil will reduce the likelihood of sediment re-entering the water body.

5.5.6 The Otago Regional Council will investigate the re-establishment of Mill Creek to a meandering form in the sites currently channelled.

Explanation
Mill Creek's natural character was more meandering than its current form. Meandering streams are better for water quality as the flow rate is slower and there is greater provision for sediment deposition. Where possible it would be beneficial from both a water quality and fisheries perspective for Mill Creek to return to its meandering form through the valley. The impact on sedimentation of works required to

recreate a meandering form, and the potential for the meandering form of the creek to contribute greater amounts of phosphorus as a result of increased erosion on the creek bends need to be considered.

5.5.7 To establish a wetland or sediment pond on land occupied by Millbrook Country Club.

Explanation
Millbrook Country Club are in agreement with the establishment of a wetland or sediment pond on part of their land which is being developed as a resort hotel and golf course.

5.6 Regulatory matters recommended for consideration in the *Regional Plan: Water*

5.6.1 Establishing minimum flows for Mill Creek.

Explanation
The development of minimum flows for Mill Creek will be considered within the regulatory framework of the proposed *Regional Plan: Water*.

5.6.2 Controlling the taking and use of water in the Lake Hayes catchment.

Explanation
Section 14 of the Resource Management Act already establishes restrictions relating to the taking, use, damming and diversion of water. In a catchment such as Lake Hayes where rapid growth and land use changes are taking place some form of regulatory control provides the ability to consider and mitigate current and potential adverse effects, so that sustainable management may be achieved. Controlling the use of water in this catchment is also needed to ensure there are adequate quantities of water flowing into the lake to maintain the lakes rate of flushing, dilution of phosphorus and the aquatic ecosystem.

Non utilised irrigation water can have high sediment and nutrient loads where it has flowed over pasture, crops or exposed ground. It is also wasteful to apply irrigation in quantities larger than the assimilative capacity of the crop and soils present. The use of regulation will need to be considered further in the proposed *Regional Plan: Water*.

5.6.3 Controlling the damming and diversion of water.

Explanation

Dams can assist in augmenting natural flows and levels, retaining water during periods of high flows to be released at periods of low flow. They are also required for the creation of wetlands and ponds, which this strategy supports. The damming and diversion of water also needs to consider the potential impact on fish passage.

5.6.4 Controlling the disturbance of bed and banks of Lake Hayes and its tributaries.

Explanation

Section 13 of the Resource Management Act restricts the disturbance, deposition, reclamation and introduction of plants, to the beds of rivers and lakes. In relation to the Lake Hayes catchment, the primary concern of disturbance of the beds and banks of water bodies, is the effect that disturbance may have on sedimentation and channel destabilisation.

6. Appendices

6.1 Appendix 1: Alternative Methods for Improving Water Quality

6.1.1 Diversion of Mill Creek.

The feasibility of this method was explored in 1985. It was found that proposals to divert flows of up to 10m³/s from Mill Creek during times of flood were impractical and very costly. Mechanisms investigated included the channelling of flood flows around the lake into Hayes Creek, diverting flows from Dan O'Connell, Station and McMullens Creeks (tributaries to Mill Creek) into the Shotover River, and channelling flood flows from Mill Creek into the Arrow River catchment. For any of these works it was found that costs would prove high and in two of the cases the works would be highly visually obtrusive.

6.1.2 Clearing the outlet and decreased lake levels.

A preliminary investigation on the fluctuation of Lake Hayes' level and the effect the culvert at the outlet to Lake Hayes may have on this was undertaken in response to long term residents' concern that the level of Lake Hayes had risen between 300 and 500mm since the replacement of the SH6 bridge over Lake Hayes Creek with twin 900mm diameter culverts in the 1960s.

It was found (based on 15 years of once monthly observations) that the range in lake levels fell between RL 327.6 - 328.5m. (RL = reduced level, measured as height above Mean Sea Level.) A desirable range of lake levels from the point of view of farm drainage, from the lakes was considered to be RL 327.6 - 328.1m. It was also estimated that one 1600mm diameter culvert would reduce persistently high lake levels, although it may be slightly less efficient at low lake levels. From the point of lake nutrient reduction, it is detrimental to lake recovery to have adjacent farm land flooded, as with the return of flood water to the lake comes nutrients from the farmland.

Further exploration is needed into this issue of the functioning of the lake outlet, and hence lake flushing and residence time.

6.1.3 Piping of nutrient rich bottom waters.

This involves selectively withdrawing hypolimnetic (bottom) waters, which tend to be the richest at times of lake stratification. This method decreases the residence time (the time a particle of water spends in the lake system) of the hypolimnion. It has been shown to be effective in lakes that are smaller than Lake Hayes and show different stratification patterns. Application of Nurnberg's conclusions to Lake Hayes suggest hypolimnetic withdraw could be used to enhance the rate of depletion of the sediment pool of phosphorus during the anoxic release period (Nurnberg, 1984). Such an approach would gradually reduce hypolimnetic phosphorus concentrations and the sediment pool of available phosphorus for subsequent release. It could not be considered as a technique to achieve immediate cessation of internal phosphorus release and immediate lake recovery. In a programme with external load reduction and hypolimnetic withdrawal, evidence suggests lake recovery would eventually occur more rapidly than with external load reduction alone.

6.1.4 Use of barley straw.

The use of barley straw to clear waters of algae was investigated following suggestions of this method from members of the public. Barley straw does have some application in shallow lakes where it can act in a sieve-like fashion, to capture floating algae. However, following consultation with organisations employing this technology, it was considered to be an ineffective method for a lake the size and depth of Lake Hayes.

6.1.5 Chemical methods of in-lake control.

There are three broad groups of chemical methods available to treat eutrophic lakes. They are herbicides, algal flocculation and nutrient inactivation.

6.1.5.1 Herbicide

Copper sulphate has been the most widely used algicide in New Zealand as it is effective against blue green algae. Its application however is most relevant to water reservoirs for drinking water supplies. Copper sulphate can be toxic to freshwater vertebrates and invertebrates, hence for a lake the size and depth of Lake Hayes the risk of toxicity to the important fishery and wildlife values of the lake is considered too great a risk.

Other herbicides which have been used in New Zealand in the past include Diquat and triazines. Herbicides of this nature tend to be most effective against higher plants than the blue-green algae which is present in Lake Hayes towards the end of summer. New Zealand regulations only permit the use of triazines in irrigation ditches.

6.1.5.2 Algal Flocculation

Flocculation is the process of precipitating out suspended solids from the water column. This is done by dosing the water with a surface spray of chemical compounds. In this way phytoplankton are directly precipitated with the chemical floc, and phosphorus is precipitated from the water column. However, this method is only successful for small lakes, up to 0.6km². Lake Hayes at 2.76km² and with a maximum depth of 33m is too large for this method of treatment.

6.1.5.3 Nutrient Inactivation

Where phosphorus is shown to be the limiting nutrient in phytoplankton growth, lake treatment with alum (aluminium sulphate) to precipitate the phosphorus can produce a reduction in phytoplankton biomass. Application of alum to intermittently stratified lakes such as Lake Hayes has not been as successful as with shallow or constantly stratified lakes. Studies on nutrient inactivation have shown that lake recovery from in-lake controls alone has not been sufficient if phosphorus inputs were not previously reduced.

A full investigation of the use of alum in Lake Hayes was undertaken by Robertson and Royds Garden in 1989. Alum was found to be the preferable method of in-lake controls for Lake Hayes. That document should be referred to for an explanation of the proposed costs and benefits to Lake Hayes of alum technology.

6.1.6 Flushing Lake Hayes with water from the Arrow River.

Flushing a nutrient rich lake with water of lower nutrient concentration will improve the water quality. However, in the case of Lake Hayes it is not certain whether this option could possibly aggravate the situation by upsetting the natural thermal balance of the lake and encouraging mixing of high phosphorus hypolimnetic water with low phosphorus surface water during summer. This method, like that of diverting Mill Creek (see 6.1.1 above) is likely to have high capital costs. The problem of high nutrient loads entering the lake from the Mill Creek catchment would still remain under this method.

6.1.7 Introduction of carp

MAF Fisheries investigated the potential benefits of using silver carp to control eutrophication in Lake Hayes in 1989. It was found that, in terms of long term control, silver carp would not be of benefit, as total nutrient loading to the lake would not change unless the fish were harvested. It was also considered that the amount of phosphorus bound up in fish flesh would be insignificant. It is suggested that silver carp may in fact increase algal biomass by eating the zooplankton which is currently the only control on the algal population. Given the uncertainties of the benefits and evidence that the carp may be a hindrance to improving lake water quality, this option will not form part of the rehabilitation plan.

6.1.8 Hypolimnetic aeration.

An investigation into the viability of hypolimnetic aeration in Lake Hayes was carried out by Robertson and Royds Garden in 1989. The major objective of hypolimnetic aeration is to raise the oxygen content of the hypolimnion without destratifying thermal stratification. Review of hypolimnetic aeration results concluded that the technique is not accepted as a technique with demonstrated effectiveness to substantially reduce internal loading of phosphorus. Although phosphorus in the hypolimnion during aeration can be reduced, the effect is not as great nor as permanent as other techniques such as alum addition, hypolimnetic withdraw (siphoning) or dredging. Investigations of this method in 1989 concluded operating costs would be in the order of an initial cost for materials of $380,000 and a yearly operating cost of $55,000.

6.1.9 Artificial circulation.

The objective of artificial circulation is to aerate the volume of water that is normally the hypolimnion and oxidise substances in the entire water column. In so doing the lake is destratified. Destratification of Lake Hayes should result in a permanently oxic lake, with lowered iron, manganese and ammonium concentrations. The most extensive and recent review of the effectiveness of this technique to date considers artificial circulation to be a technique requiring more research and demonstration. It does not currently appear effective at substantially reducing internal loading of phosphorus. This method was reviewed by Robertson and Royds Garden in 1989 and that review should be referred to for additional information.

6.1.10 Sediment traps and wetlands.

The feasibility of constructing a sediment trap was briefly explored by the Otago Catchment Board in 1985. Initial costings of $100,000 were made for a 4 hectare sediment trap. Wetlands were identified in the Robertson report as possible mechanisms for achieving phosphorus removal by the settling out of sediment. It has been claimed that prior to the draining of the major wetland in the Lake Hayes catchment, dirty Mill Creek floodwaters were not seen in Lake Hayes, implying the wetland was performing a role in settling out sediment. Initial costing of this option was $500,000.

A full investigation into the feasibility of wetlands to achieve improved water quality in Lake Hayes was undertaken by the Otago Regional Council in 1994. The Council commissioned Royds Consulting Limited to undertake the investigation. They found that wetlands store phosphorus in sediment on their beds and did not consider that wetlands could achieve a net removal of phosphorus under this mechanism. Royds found that a water retention time of 15 days would be required to achieve sedimentation of phosphorus. This would give an 80% phosphorus removal rate. Royds also stated that in order to maintain these rates of removal, wetland sediment would need to be periodically dredged and dispersed onto land. The amount of land required to achieve the required retention time was found to be 345 hectares. A total of only 149 hectares was potentially available, and this area was dispersed over 4 sites.

To achieve a 50% removal would have required 138 hectares, which is still more area than was available at any one of the potential sites. The largest site was 93 hectares.

Royds found that constructing wetlands at each of the potential sites would not be satisfactory because even though the total area may be sufficient, it was the flow velocity (retention time) at each site that was important for effective phosphorus removal.

Wetlands as defined in the Royds report required excavation of 1 metre depth to achieve the desirable water depth. Such a design is expensive due to the construction requirements.

Royds therefore found that there were no suitable sites within the Mill Creek catchment for a wetland of sufficient area to ensure a high degree of phosphorus removal. All potential sites were said to require a compromise between the extent of phosphorus removal achievable and the area of wetland physically available. The largest area of land that might be available to form a wetland had the disadvantage of being furthest up the catchment away from Lake Hayes and hence could only intercept up to 40% of the phosphorus load to Lake Hayes.

Royds found that the likely cost of constructing a surface flow wetland, including land purchase, was $155,000/ha. Based on this, the cost of the largest wetland that could be built in the catchment, would be $17 million.

6.1.11 Mill Creek erosion.

In June 1994 the Otago Regional Council re-investigated Mill Creek to identify sources of sediment and identify the cost measures that might prevent or reduce the flow of sediment from Mill Creek into Lake Hayes. The report identified measures to reduce the runoff into water of non-sediment, phosphorus bearing material, particularly dung. The report identified areas within the creek where erosion is currently occurring and where some stabilising of the creek would reduce erosion. It also identified areas which would benefit from the exclusion of stock, and fencing was recommended. The fencing and associated works were costed out at $95,000, including the provision of alternative stock water supply.

6.1.12 Altering land use practices, reducing external phosphorus inputs.

Changes in land use and land use practices correlate highly with the movement of phosphorus off the land and into water bodies in the Lake Hayes catchment. Major estimated inputs of phosphorus into the Lake Hayes catchment were shown in Robertson's 1988 report. This report identified various methods of phosphorus control. In terms of land use practices he identified: reduction in fertiliser application and runoff, reduction in runoff from animal stocking, wetland re-establishment, erosion prevention, and changes in land use, as being necessary to alleviate lake eutrophication. Each of these options is explored in more detail in Robertson's report.

6.2 Appendix 2: Trends From Water Quality Monitoring Data 1983-1994

In relation to Mill Creek:

(1) Mill Creek provides about 80% of the annual external load of phosphorus to Lake Hayes. The proportion has not changed significantly since 1983.

(2) The suspended solids phosphorus content (about 0.2%) is similar under all flow conditions and has not changed significantly since 1983.

(3) The annual phosphorus load is variable and was much higher in 1983-84 than in 1990-94 because of a high incidence of flood events, an above average base flow rate and elevated concentrations of sediment-bound phosphorus.

(4) Base flow annual phosphorus load, and to a lesser degree total annual phosphorus load, correlates well with the annual median total phosphorus and sediment-bound phosphorus concentrations.

(5) pH levels were lower in 1983 than in 1984 and 1990-94, possibly because of an above average mean flow rate and incidence of flood events.

(6) Conductivity, turbidity and inorganic nitrogen levels have not changed significantly since 1983.

In relation to Lake Hayes:

(1) The recent yield of total phosphorus for the Lake Hayes catchment is in the range 10-20kg/km^2/yr making it a low-average exporter of phosphorus.

(2) The annual external load of phosphorus in 1983-84 (2400kg) was much higher than in 1990-93 (400-1000kg), whereas the output in 1983-84 (580kg) was similar to that in 1990-93 (550-700kg). The data support the view that the cycling of phosphorus in the lake is being driven primarily by the internal release of sediment-bound phosphorus.

(3) Phosphorus concentrations in the lake are seasonal and depth dependent. Winter surface phosphorus concentrations and summer reactive phosphorus concentrations in the hypolimnion were significantly lower in 1983-85 than in 1970-71 and 1990-94. During the 1990-94 period total and dissolved reactive phosphorus concentrations remained relatively constant at all depths. It is hypothesised that in 1983 flow rates in Mill Creek were above average, throughput in the lake was elevated and lake residence time lower than normal. This resulted in lower lake phosphorus concentrations following autumn mixing. At stratification the subsequent rate of oxygen depletion would be lower because of a phosphorus concentration related fall in biological activity, the onset of anoxia

delayed, the amount of sediment-bound phosphorus released into the hypolimnion would be reduced, and the resulting phosphorus concentration in the hypolimnion would be lower.

(4) Median dissolved oxygen concentrations in the hypolimnion during summer were <1 g/m^3 in each of the three study periods. There is insufficient information to determine whether the date of onset of anoxia has changed, but it is clear that the hypolimnion is still anoxic during the summer stratification period.

(5) The pH of the lake is seasonal and depth related. The winter pH was about 7.5 in 1983-84 and 8.0 since 1988. During spring and summer the epilimnion becomes increasingly alkaline and the hypolimnion more acidic, probably in response to increased rates of photosynthesis and respiration. Since 1989 the pH of the epilimnion during the summer period has been around 9.0.

(6) The present water quality survey suggests that the water quality of the lake has probably not changed significantly since 1983. Under normal input flow conditions elevated lake phosphorus concentrations continue to provide a nutrient rich environment for algal growth, whilst the absence of any improvement in the anoxic condition of the hypolimnion, combined with high pH levels in the epilimnion during summer stratification constitutes a poor fishery environment.

6.3 Appendix 3: On-Site Disposal Effluent Standard

Because of the soil and drainage characteristics of the Lake Hayes catchment and the location of groundwater and drinking water sources, it is important that future on-site disposal mechanisms achieve an effluent standard that will protect the groundwater resources from phosphorus.

Prior to the granting of a consent for on-site disposal, evidence must be supplied that the engineering of the system will achieve reliable uniform loading of effluent to the full design infiltration surface and in general this will be achieved by pressurised distribution systems incorporating sound principles of hydraulic design.

The effluent discharge from the land disposal field as determined by monitoring should conform with the following criteria, until such time when a regional plan rules otherwise:

(1) Biological Oxygen Demand (BOD) shall not exceed $10g/m^3$ and annual average shall not exceed $5g/m^3$.

(2) Total Suspended Solids shall not exceed $5g/m^3$ and annual average shall not exceed $2g/m^3$.

(3) Total Phosphorus shall not exceed $5g/m^3$ and annual average shall not exceed $1g/m^3$.

(4) Total Nitrogen shall not exceed $20g/m^3$ and annual average shall not exceed $10g/m^3$.

(5) Faecal coliforms shall not exceed 200 per 100mls and annual average shall not exceed 10 per 100mls.

6.4 Appendix 4: Suggested Species for Riparian Management Plantings

Sedges and Grasses

Species		Fringe	Mid	High bank	Characteristics	Soils
Tussock sedges	*Carex* spp	Yes	Yes	No	Excellent for cool conditions and poorly drained sites.	Low fertility, acid soils.
Tussocks (native)	*Chionochloa* spp	Yes	Yes	Yes	Use locally grown stock. *C. rubra* (red tussock) can become the dominant species in poorly drained soils, frost hardy.	Low fertility, moist soils but can withstand drought.
Tussocks (other native)	*Festuca novae-zelandiae*	No	Yes	Yes	Planted at close spacings provides a micro climate for other plantings. Frost hardy and drought tolerant.	Most dry soils.
Toetoe	*Cortaderia* spp	Yes	Yes	Yes	Large coarse grasses up to 5m in height. Frost hardy, mildly drought resistant, ideal nurse crop for establishing native plants. The exotic *C. selloana* and *C. jubata* should be avoided.	Low fertility, moist soils providing an abundant water supply exists.

Appendix 4 (continued): Shrubs and trees

Species		Fringe	Mid	High bank	Characteristics	Soils
Wine-berry	*Aristotelia serrata*	Yes	Yes	No	Suitable for low to mid tier shelter (but not as a windbreak) for more permanent species. Provides rapid canopy, frost hardy.	Most soils except very poorly drained or drought prone.
Flaxes	*Phormium* spp	Yes	Yes	Yes	Excellent stream bank stabiliser and water shade provider. Very tolerant of frost, drought and wind. Provides good shelter for other plantings.	All soils from waterlogged to drought prone. Use locally grown stock.
Olearia	*Olearia* spp (32 species)	No	Yes	Yes	Extremely hardy, easily propagated, will tolerate dry and exposed positions. Ideal nurse crop.	Most soils except poorly drained.
Senecio	*Senecio* spp (23 species of shrub)	No	Yes	Yes	Hardy shrub, easily propagated, ideal for use in soil conservation or revegetation in botanically sensitive areas ie, scenic reserves.	Most soils including peaty and sandy soils.
Koro-miko	*Hebe stricta* and *H salicifolia*	Yes	Yes	No	Shrub to 4-5m ideal for stream side and wet gullies. Fine fibrous root system.	Most soils, not very drought tolerant.
Pitto-sporum	*Pittosporum* spp	No	Yes	Yes	Shrub or small tree. Ideal for understorey plant or nurse crop for taller species. Protect from direct wind.	Well drained, but not drought prone.
Copros-ma	*Coprosma* spp	Yes	Yes	Yes	Up to 5m *C. parviflora* most suited. Frost tolerant but not drought hardy. Ideal understorey for taller species. Plant from locally grown stocks.	Tolerates heavy, wet and infertile soils very well. Most soils and clay.

Broadleaf	*Griselinia littoralis*	No	Yes	Yes	Up to 15m with stout branches, frost tolerant, withstands strong wind except when young. Will not tolerate prolonged drought. Glassy foliage.	Grows well on all but very infertile or gravelly soils.
Cabbage tree	*Cordyline australis*	Yes	Yes	Yes	Up to 12m, sparingly branched, leaf cluster at top, strong tap root.	All soils, from wet swampy ground to dry windy hill slopes.
Kowhai	*Sophora microphylla*	No	Yes	Yes	Attractive hardy small tree.	Well drained fertile soils.
Corokia	*Corokia cotoneaster*	No	Yes	Yes	Shrub up to 3m, extremely frost and drought tolerant and withstands exposure well. Excellent hedging or windbreak plant.	Most soil conditions.

NB: Slow maturing native trees such as Beeches, Kahikatea, Rimu, Matai, Totara etc, and the numerous exotic species are all suitable for interspersed plantings and the long term plan. Existing natives ie, Matagouri, *Carmichaelia* etc, should remain *in situ*.

6.5 Glossary

Terms marked with an * are terms defined by Section 2 of the Resource Management Act 1991.

Access strip Is a strip of land created by the registration of an easement in accordance with Section 237B for the purpose of allowing public access to or along any river, or lake, or the coast, or to any esplanade reserve, esplanade strip, other reserve, or land owned by the local authority or by the Crown (but excluding all land held for a public work except land held, administered, or managed under the Conservation Act 1987 and the Acts named in the First Schedule to that Act).

Aesthetic Value A value associated with the visual quality or the appreciation of the inherent visual quality of an element in the built or natural environment.

Anoxia (and anoxic) A state of being oxygen poor, (cf. oxic state).

BOD Biochemical Oxygen Demand. Used as a measure of organic pollution. The measured amount of oxygen required by micro-organisms to biologically degrade the organic matter in water.

Catchment The total area from which a single water body collects surface and subsurface runoff.

Conditions* In relation to plans and resource consents, includes terms, standards, restrictions, and prohibitions.

Consultation The communication of a genuine invitation to give advice and a genuine consideration of that advice.

Contaminant* Includes any substance (including gases, liquids, solids and micro-organisms) or energy (excluding noise) or heat, that either by itself or in combination with the same, similar, or other substances, energy or heat:

(a) When discharged into water, changes or is likely to change the physical, chemical or biological condition of water; or
(b) When discharged onto or into land or into air, changes or is likely to change the physical, chemical, or biological condition of the land or air onto or into which it is discharged.

Dam — A structure used or to be used for the damming of any natural water, river, or stream but does not include a flood bank or channel training work.

Discharge* — Includes emit, deposit and allow to escape.

Divert — The act of deflecting or moving a stream or river to another area.

Ecosystem — A dynamic complex of plant, animal and micro-organism communities and their non-living environment interacting as a functional unit.

Effect — Section 3 of the Resource Management Act defines the term effect as including:

(a) Any positive or adverse effect; and
(b) Any temporary or permanent effect; and
(c) Any past, present, or future effect; and
(d) Any cumulative effect which arises over time or in combination with other effects - regardless of the scale, intensity, duration or frequency of the effect; and also includes -
(e) Any potential effect of high probability; and
(f) Any potential effect of low probability which has a high potential impact.

Environment* — Includes:

(a) Ecosystems and their constituent parts, including people and communities; and
(b) All natural and physical resources; and
(c) Amenity values; and
(d) The social, economic, aesthetic, and cultural conditions which affect the matters stated in paragraphs (a) to (c) of this definition or which are affected by those matters.

Epilimnion (and epilimnetic) — The highest stratum (layer) of a stratified lake.

Erosion — The processes of the wearing away of the land surface by natural agents and the transport of the material that results.

Esplanade reserve*	A reserve within the meaning of the Reserves Act 1977 - (a) Which is either - (i) A local purpose reserve within the meaning of Section 23 of that Act, if vested in the territorial authority under Section 239 of the Act; or (ii) A reserve vested in the Crown or a regional council under Section 237D; and (b) Which is vested in the territorial authority, regional council, or the Crown for a purpose set out in Section 229 of the Act.
Esplanade strip*	A strip of land created by the registration of an instrument in accordance with Section 232 of the Act for a purpose or purposes set out in Section 229 of the Act.
Eutrophication	Process by which water (usually freshwater) becomes rich in nutrients, causing excessive plant growth which kills animal life by deprivation of oxygen.
Fauna	All the animal life of a given place or time.
Flora	All the plant life of a given place or time.
Flushing Rate	The rate at which a body of water completely replenishes itself.
Fresh Water*	All water except coastal water and geothermal water.
Groundwater	Water that occupies or moves through pores, cavities, cracks and other spaces in crustal rocks.
Habitat	The place or type of site where an organism or ecological community naturally occurs.
Hydrology	The science of the properties and laws of water, especially its movement on, under and above the land.
Hypolimnion (and hypolimnetic)	The lowest stratum (layer) of a stratified lake.
Indigenous Species	A native species of New Zealand.

Instream Values	Those uses or values of rivers and streams that are derived from within the river system itself and include those associated with freshwater ecology and recreational, scenic, aesthetic, intrinsic and educational uses.
Intrinsic Values*	In relation to ecosystems, means those aspects of ecosystems and their constituent parts which have value in their own right, including: (a) Their biological and genetic diversity; and (b) The essential characteristics that determine an ecosystem's integrity, form, functioning, and resilience.
Issue	A matter of concern to an area's community regarding activities affecting some aspect of natural and physical resources and the environment of the area.
Kaitiakitanga*	The exercise of guardianship; and, in relation to a resource, includes the ethic of stewardship based on the nature of the resource itself.
Lake*	A body of fresh water which is entirely or nearly surrounded by land.
Land*	Includes land covered by water and the air space above land.
Land Drainage	The act of taking off or diverting water from the land by artificial channels, pipes or other means.
Loess	A homogenous deposit of wind-blown silt.
Mitigate	To make or become less severe or harsh. To moderate.
Natural and Physical Resources*	Includes land, water, air, soil, minerals and energy, all forms of plants and animals (whether native to New Zealand or introduced), and all structures.
Non-point Source Discharge	Runoff or leachate from land, onto or into land, air, a water body or the sea.
Oxia (and oxic)	A situation with oxygen present (cf. an anoxic state).
Phytoplankton	Planktonic plant life, mainly microscopic algae, existing in the water column.
Point Source Discharge	A discharge from a specific and identifiable source, onto or into land, air, a water body or the sea.

Policy	The course of action to achieve the objective.
Resource Consents	A consent to do something which would otherwise contravene any of Sections 9 to 13 of the Resource Management Act 1991. It includes Land Use Consent, Coastal Permit, Subdivision Consent, Water Permit, Discharge Permit.
Riparian Margins	A strip of land adjacent to a water body which is frequently moist, and which generally extends from the perceived change in contour of the flood plain to the water body itself.
River*	A continually or intermittently flowing body of fresh water; and includes a stream and modified watercourse; but does not include any artificial watercourse (including an irrigation canal, water supply race, canal for the supply of water for electricity power generation, and farm drainage canal).
Tributary	A stream or river that flows into a water body.
Turbidity	The relative tendency of a water to scatter light. Informally taken as synonymous with "cloudiness" (lack of visual clarity).
Water Body*	Fresh water or geothermal water in a river, lake, stream, pond, wetland, or aquifer, or any part thereof, that is not located within the coastal marine area.
Wetland*	Includes permanently or intermittently wet areas, shallow water, and land margins that support a natural ecosystem of plants and animals that are adapted to wet conditions.

6.6 Maori terms and phrases

Hapu	Subtribe, extended whanau
Hui	Consultative meeting
Iwi	Tribe
Kai Tahu	Descendants of Tahu, the tribe
Kai Tahu whanui	The large family of Kai Tahu
Kaitiaki	Guardians
Kaitiakitanga	Guardianship
Mahika kai	Places where food is procured or produced
Mana	Authority or influence or prestige
Manawhenua	Those with rangatiratanga for a particular area of land or district
Mauri	Life force
Rangatiratanga	Chieftainship or authority
Runanga	Local representative groups or community system of organisation
Taoka	All things highly prized, including treasures, property, a resource or resources or even a person (same as taonga)
Wai	Water
Wairua	Life principal
Whakapapa	Genealogy or family tree
Whanau	Family
Whanui	Large or extended

6.7 Bibliography

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Queenstown Lakes District Plan *(in preparation)*

Lake Hayes Restoration and Monitoring Plan

Photo: David Hamilton

Prepared for the Friend of Lake Hayes Society Inc.

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Executive summary

Lake Hayes is a highly-valued lake that has suffered from algal blooms for many decades. Since 2006, the blooms have worsened and lake health and fishing has deteriorated markedly. This report provides relevant historical background to the Lake Hayes water quality story, analyses water quality and ecological data and information, and proposes a restoration strategy for lake recovery.

The worsening of algal blooms since 2006 has occurred when both external and internal nutrient loads to the lake had been either declining or stabilising. So, the reason for the blooms was not related to increased nutrient inputs to the water column. Rather, a change in the dominant algae species occurred and the new nuisance alga, a dinoflagellate called *Ceratium hirundinella*, possesses some particular adaptations that allow it to supplement its nutrition in unusual ways. So, the development of *Ceratium* blooms appears to have been facilitated by a decline in nutrient loads, which gave it a competitive advantage over other algae. The scientific literature contains reports of *Ceratium* and other dinoflagellates sometimes becoming dominant during a recovery from high nutrient loads.

While *Ceratium* seemed to have had a hold on Lake Hayes, two recent summers (2009/10 and 2016/17) have seen the lake exhibit extremely clear waters with very little algae biomass. This could indicate that the lake is approaching a recovery tipping point. How long it will take the lake to achieve consistently high water clarity is unknown. However, observations indicate that high densities of zooplankton (grazers of algae) in summer have been associated with high summer water clarity, suggesting that dynamics of the pelagic food web may play an important role in the lake's recovery.

This report evaluates the potential for many various restoration activities to accelerate the recovery of the lake. Four of these strategies have been selected to be the most promising and cost-effective. These are: (1) food web biomanipulation, (2) enhanced flushing by using surplus irrigation water from the Arrow River, (3) alum dosing to flocculate and bind phosphorus in the lake bed, and (4) a focus on land use activities in the catchment to further reduce nutrient and sediment losses from land to water. These strategies were scrutinised using the available data and some costing were determined. This allowed the development of a restoration strategy proposing the most promising strategies to use, potential timelines to achieve implementation, and suggesting a range of restoration targets by which to measure success. This report also discusses lake monitoring options to help track recovery of the lake and demonstrate effectiveness and cost-effectiveness of the strategies.

Contents

Scope

Lake Hayes is a treasured asset to Tangata Whenua, locals and tourists alike. Located within the Arrow Basin between Queenstown and Arrowtown, the lake is highly visible by road and frequented by lake users and campers year-round. Since the late 1960's the lake has been subject to severe algal blooms, initially as a result of increased nutrients entering through Mill Creek and from springs at the northern end of the lake, which are high in nitrate concentration (Bayer & Schallenberg 2009). From the 1960's through to 2010, lake water quality had steadily decreased to a eutrophic state with blooms of blue-green algae/cyanobacteria, green algae and dinoflagellates occurring in stages throughout that time. Currently the lake suffers from severe blooms of the dinoflagellate alga *Ceratium hirundinella* blooms almost yearly, prompting the Friends of Lake Hayes Society to investigate and instigate restoration measures with the aim of returning the lake to a healthier state.

Multiple reports have described the main issues affecting Lake Hayes as well as a range of potential lake restoration options for consideration. However, with the changeable nature of the lake's algal blooms and the fast-increasing trend towards further eutrophication, this restoration plan was commissioned by the Friends of Lake Hayes Society. The restoration plan aims to describe the current state of the lake, summarise the major issues affecting water quality, recommend and discuss realistic restoration options, provide a restoration strategy with timelines, and recommend useful monitoring strategies for monitoring lake status and recovery to a stable water quality state which aligns with community, stakeholder and tourism values.

1 Background

1.1 Community values, uses and importance

Lake Hayes has been described as one of the most scenically attractive landscapes of its type in New Zealand and it holds significant importance for recreation and tourism (Cromarty & Scott 1995). Surrounding the lake is a vegetated margin with patches of wetland areas supporting a high diversity of endemic, rare or threatened fauna including the koaro, longfin eel and breeding birds such as paradise ducks, New Zealand shovellers, marsh grebes, Australian coots and great crested grebes (Cromarty & Scott 1995). A popular shared-use trail navigates these margins. Parts of the lake surroundings have been granted recreational and wildlife management reserve status as well as belonging to a wider wildlife refuge area covering 354 ha, including the lakebed. The lake and its immediate surrounds are used by locals and tourists alike for a range of recreational activities including rowing, boating, fishing, swimming, running, biking, walking and picnicking.

The Lake is culturally important for its food gathering which has led to the lakes recognition as a treasured resource (Waahitaoka) (ORC 2009) and the Lake Hayes Management Strategy states that "the conservation of the Lake Hayes resource is of regional and national importance both economically, recreationally and for its intrinsic and scenic values" (ORC 1995).

1.2 Historical catchment development

Extending far to the north-west of the lake along Mill Creek, the Lake Hayes catchment (Fig. 1) was likely forested with kahikatea prior to 1740 and a large wetland extended through the western reaches of Mill Creek in the mid-catchment. A number of smaller wetland swamps also existed in the catchment to the west and north of the lake as well as extensive riverine marshes on the banks of Mill Creek and smaller streams (Robertson 1988).

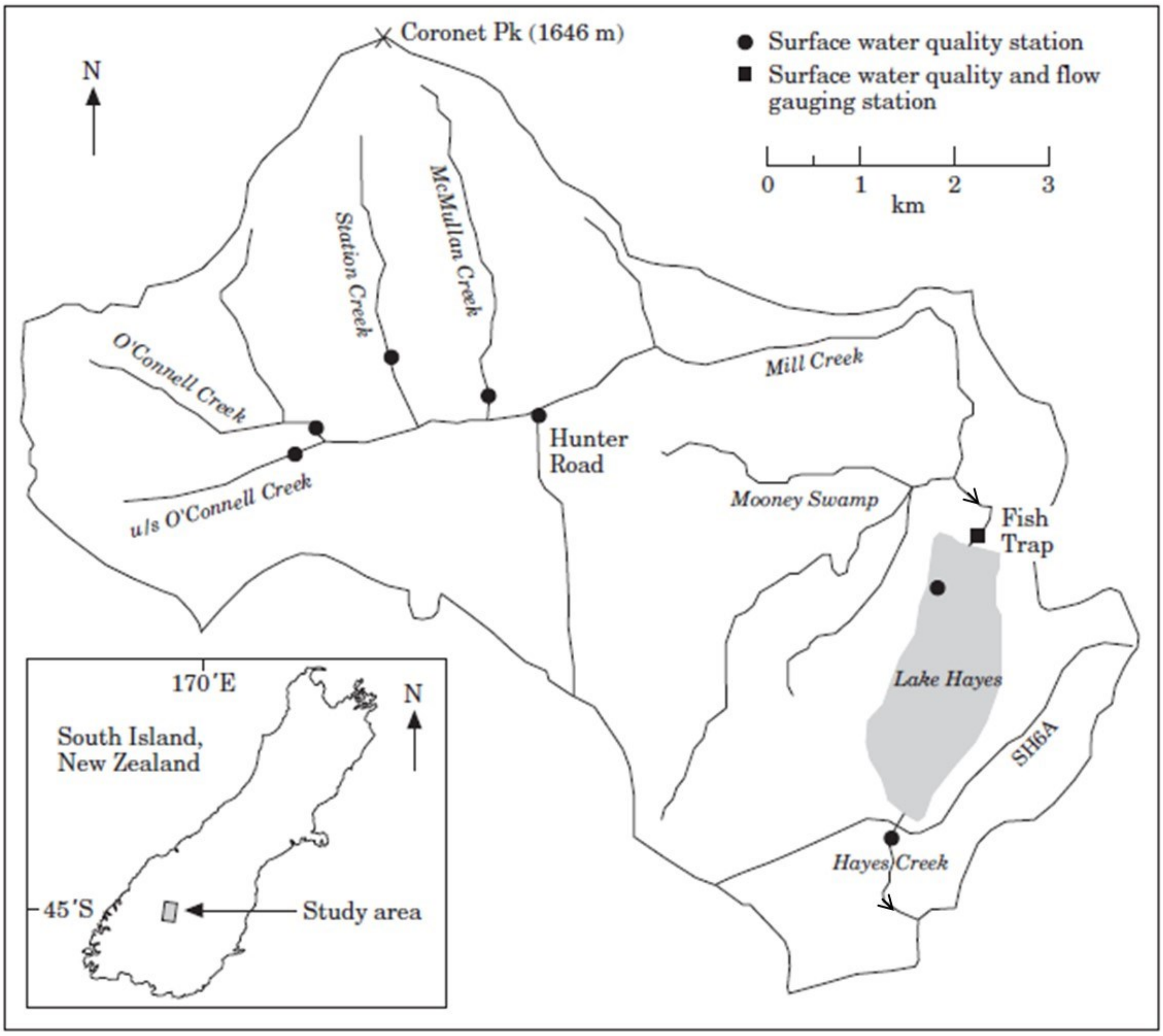

Figure 1. The Lake Hayes catchment (adapted from Caruso 2001)

Deforestation in the catchment began around 1740 when the Kahikatea forest was largely destroyed by fire, and further deforestation likely occurred through the late 1800's as miners and settlers harvested trees for shelter and firewood (Robertson 1988). After the deforestation of the Kahikatea forest, the Lake Hayes catchment comprised mostly native tussock grassland in the high country with swamps and wetlands dominating the lowland areas including the Arrow Basin (Robertson 1988). Mill Creek is the major tributary in the catchment, fed by a number of high country streams including O'Connell Creek, Station Creek and McMullan Creek, sediment and nutrients from which were once immobilised in the wetland before continuing on down Mill Creek towards Lake Hayes. Smaller wetland areas also existed adjacent to the mid-reaches of Mill Creek including Mooney Swamp, which acted as wildlife habitat, flood mitigation and a sediment and nutrient sink. Relatively low concentrations of nutrients are expected to have been transported by Mill Creek and its tributaries through the early 1900's.

The early-to-mid 1900's saw land converted to sheep pasture and further conversions from sheep to cattle and dairy. Superphosphate fertilizer was introduced in the 1950's allowing cattle and dairy to intensify in the catchment and aerial topdressing was common on farms, particularly around the lake, within which a topdressing plane was lost in 1953 (Robertson 1988). From approximately 1912-1955 a local cheese factory operated to the north of the lake where it released whey effluent with a phosphorus (P) load of approximately 1000kg/yr (roughly equivalent to the annual effluent of 2000 cows) directly into Mill Creek (Robertson 1988). Remaining whey was fed to pigs which also contributed further effluent to the creek.

The Otago Catchment Board began major drainage and channeling works in 1961-62, which saw wetlands drained and artificial channelization through what was soon to be high producing exotic grasslands. The initial channel and drainage works in 1961 cut through 80-120ha of wetland in the upper catchment, bringing a significant amount of sediment through Mill Creek and into Lake Hayes (Robertson 1988). Locals recorded the first sighting of brown water flowing into the lake in 1961 which continued sporadically throughout the remainder of the drainage and channelisation works over the next few decades (Robertson 1988). This significant land conversion and sediment immobilization has been touted as a major turning point for lake ecosystem health.

With the conversion of wetlands into pastoral grasslands, the water quality buffering capacity of the catchment decreased. It is estimated that 80% of the P load in Mill Creek came from the tributaries above the large wetland (Robertson 1988) and when in its natural wetland state, sediment and sediment-bound nutrients such as P were trapped and nitrate was denitrified. Nutrient loads from the catchment to the lake via Mill Creek and the springs at the northern end of the lake are likely to have been very low. Robertson (1988) also notes the operation of the Arrow River irrigation scheme which at the time of writing in 1988, was taking 1.75m^3/s of water from the Arrow River and irrigating 1100ha in the middle of the Lake Hayes catchment. Through the 70's, 80's and the early 90's, multiple catchment stressors continued to affect lake water quality including the loss of wetland buffering capacity, the application of superphosphate fertilizers on new pastoral land, and continued catchment cutting and drainage works which delivered further pulses of sediments and nutrients to the lake.

1.3 Fisheries

1.3.1 Trout fishery

Brown Trout were introduced to Lake Hayes in 1870 and the fishery flourished from the late 1800's through the 1930's with fish up to 25lb caught (Fig. 2). In the 1940's, the Wildlife Service set up fisheries operations including the collection of brown trout ova (Robertson 1988; H. Trotter, Otago Fish & Game, pers. comm.) and the construction of a fish trap on Mill Creek near the inflow to Lake Hayes. From 1940-1960, 1000-4000 adult trout passed through the fish trap annually with up to 2 million ova collected annually for national and international fish stocking (Otago Fish & Game, unpublished data). Fish trapping operations slowed through the 1960's and 70's before ceasing in the late 1970's as demand for ova stock decreased and the water quality in Mill Creek declined (Robertson 1988; H. Trotter, Otago Fish & Game, pers. comm.).

Figure 2. Lake Hayes trout fishery, 147 brown trout, 1 October 1897.

1.3.2 Perch fishery

Perch were introduced shortly after trout, in the late 1870's, and quickly established, being the most commonly caught fish species by 1900. The perch population grew and in 1988 the Percy Perch Classic fishing competition was established, running until 1990. The event attracted over 1000 anglers to the lake and more than 13,000 perch were landed over two days in 1989; however around 97% of those adults caught were less than 20cm long, indicating a highly-stunted population (H. Trotter, Otago Fish & Game, pers. comm.). Such stunting can be a result of unrestrained population growth controlled only by competition within the species for food resources as opposed to predatory 'top down' population controls. The lack of predation on Perch continues to result in a high proportion of stunted adults confirmed by a survey in 2016 where 70 Perch were caught in one hour and 97% of adults were stunted (<20cm). (Otago Fish & Game, unpublished data).

The Lake Hayes trout fishery has long been recognized as a regionally important fishery and is highly regarded by anglers for both its recreational and amenity values (H. Trotter, Otago Fish & Game, pers. comm.), however its popularity among anglers has decreased rapidly since the mid 2000's. Annual angler days (a measure of angler effort) were at around 1500 days in the mid 1990's and early 2000's (Fig. 3) but dropped dramatically in 2006/2007 (Otago Fish & Game, unpublished data). Fish & Game received numerous complaints from anglers regarding the "muddy, brown colour" of the lake water and the poor condition and scarcity of trout during the 2006/2007 season, followed by two fish kills observed in March and April 2007 (Otago Fish & Game, unpublished data). In March, Mill Creek was running high and carrying brown sediment into the lake where few trout were seen, which were all in very poor condition and 6 dead trout were found around the creek mouth. In April, emaciated trout were observed in the lower reaches of Mill Creek and there were reports of around 30 dead trout floating near the mouth of Mill Creek. Lake Hayes itself had a bloom of the dinoflagellate *Ceratium hirundinella* during this time and all remaining trout observed were described as emaciated and in very poor condition.

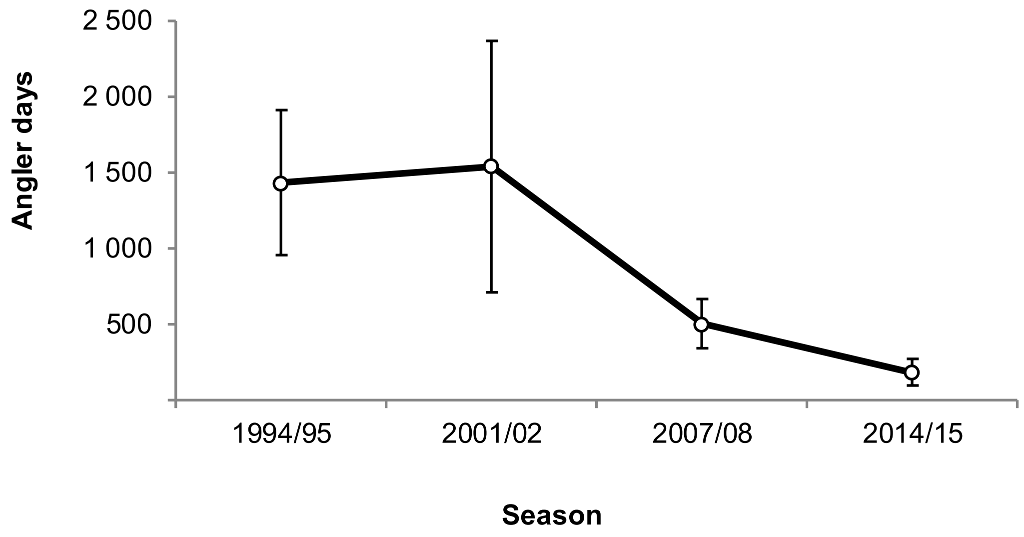

Figure 3. Annual total angler effort estimates for Lake Hayes taken from the National Angling Survey (Otago Fish & Game, unpublished data).

Due to increasingly poor fishing conditions, angler days dropped to around 500 in the 2007/2008 season (Fig. 3) and although no further fish kills have been reported, angler effort continued to decline to a record low of 180 angler days in the 2014/15 season. Over this time, public concerns arose again regarding the low numbers of poor quality trout spawning in Mill Creek, however a Fish & Game monitoring programme set up in response found the condition of trout in Mill Creek had improved over 2013-2015 compared with those found in 2007. While there have been reports of trout in good condition being caught in recent years (H. Trotter, Otago Fish & Game, pers. comm.), anglers remain concerned about the lower numbers of fish caught and the degraded water quality of the lake.

2 Water Quality

2.1 Background

The information presented above describes the situation, whereby Lake Hayes has become a eutrophic lake, with generally relatively low water clarity, poor water quality and frequent algal blooms. Since 2006, the trophic level index (indicating nutrient enrichment) has deteriorated markedly, and in 2015 the water quality of the lake was very poor (supertrophic) (Fig. 4).

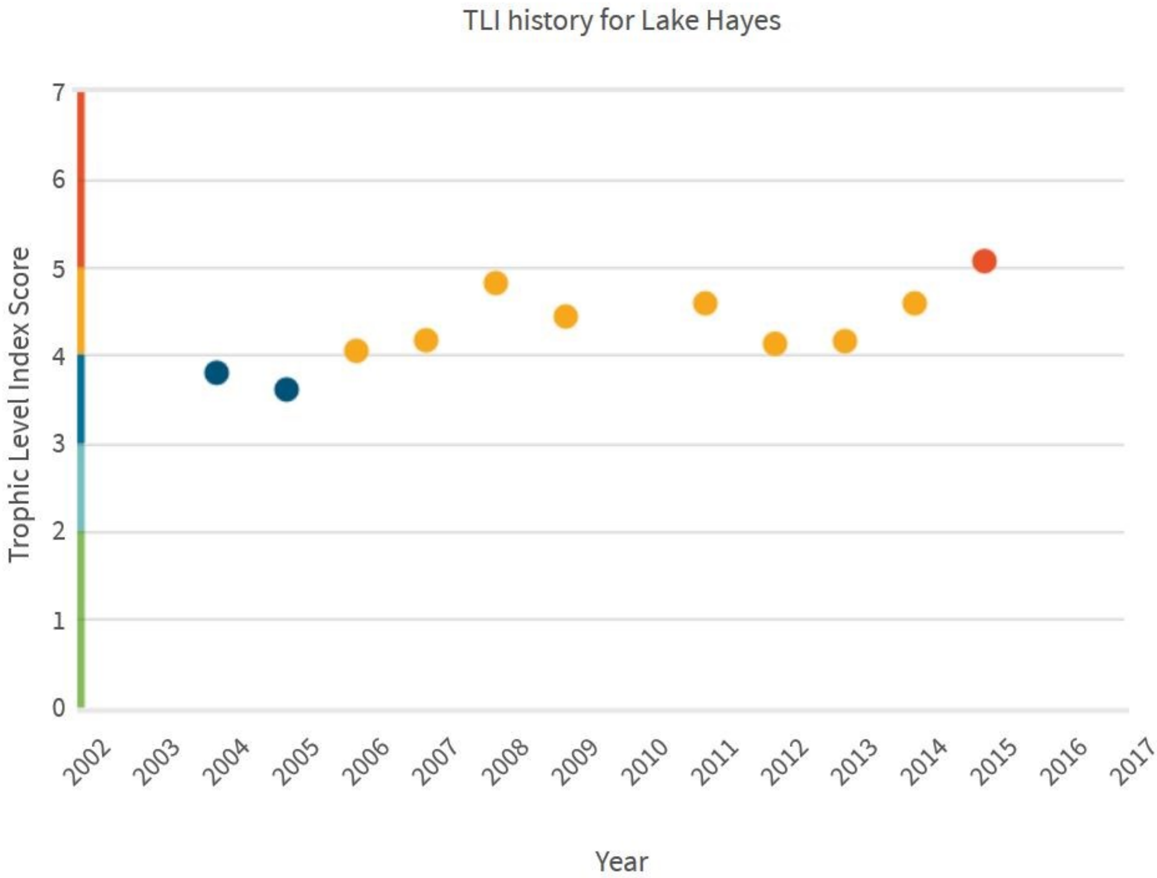

Figure 4. The trophic level index (TLI) score for Lake Hayes from 2004 to 2015. The TLI aggregates total phosphorus, total nitrogen, chlorophyll *a* (an indicator of phytoplankton biomass) and Secchi disk depth (a measure of water clarity) data. TLI between 3 and 4 is mesotrophic (good water quality). TLI between 4 and 5 is eutrophic (poor water quality). TLI between 5 and 6 is supertrophic (very poor water quality). Data and graph are from the LAWA website.

Publicly available data from the LAWA website (Land Air Water Aotearoa; https://www.lawa.org.nz/explore-data/otago-region/lakes/lake-hayes/) only go back to 2004. However, Lake Hayes has been studied since the late 1940s, beginning with the work of Jolly (Jolly 1959). Comparing lake data back as far as Jolly's time provides a useful context for our analysis of the historical and current condition of Lake Hayes.

Figure 5 presents the Lake Hayes Secchi disk depth data, showing how water clarity in the lake has changed over time. Since the 1950s, when the lake's bottom waters were oxygenated in summer (Jolly 1959), water clarity has been variable, but has often been quite poor (e.g., eutrophic or water clarity below 3.6 m) due to algal blooms.

From 1970 onward, nitrogen-fixing cyanobacteria (e.g., *Anabaena* sp.) have often been part of the phytoplankton community, sometimes occurring as the dominant species of phytoplankton (Burns & Mitchell 1974; ORC 1995). Nitrogen-fixing cyanobacteria may outcompete other phytoplankton when excess phosphorus is available because the cyanobacteria are able to harvest nitrogen from the atmosphere (from air dissolved in the lake water). The bottom waters of Lake Hayes have become anaerobic (with a complete loss of dissolved oxygen) since at least 1970 (Burns & Mitchell 1974) and summer deoxygenation of the bottom waters has been recorded, whenever it has been measured, since that time (Robertson 1988; ORC 1995; Bayer et al. 2008; Bayer & Schallenberg 2009; M. Schallenberg, unpublished data; ORC, unpublished data). The loss of dissolved oxygen from the bottom waters not only excludes trout, zooplankton and many invertebrates from the cooler bottom waters of the lake, but it also causes biogeochemical changes in the lake sediments, releasing sediment-bound phosphorus into the water column (Bayer et al. 2008). When the surface of the sediment is oxygenated, the oxygenated minerals (e.g., iron and manganese oxyhydroxides) in the sediments bind a large proportion of sediment phosphorus, preventing its release back into the water column. Deoxygenation of the water and sediment converts the sediments from P sink to a P source. Since at least 1970, the summer bottom waters have been releasing significant amounts of phosphorus into the lake water (Mitchell & Burns 1981; Robertson 1988; Bayer et al. 2008; Bayer & Schallenberg 2009; M. Schallenberg, unpublished data; ORC, unpublished data), recycling historically accumulated and immobilised P back into the lake ecosystem and further fuelling algal and cyanobacterial blooms. Severe blooms eventually settle to the lake bed delivering more P to the sediments as dead phytoplankton cells, where they decompose and consume oxygen, contributing to the next year's summer deoxygenation. This internal anoxia-phosphorus-algae feedback cycle has contributed to maintaining Lake Hayes in a eutrophic state since at least 1970 despite the fact that external nitrogen and phosphorus loading from Mill Creek and the springs at the northern end of the lake decreased into the 1990s and early 2000s (Caruso 2000; Bayer et al. 2008; Bayer & Schallenberg 2009).

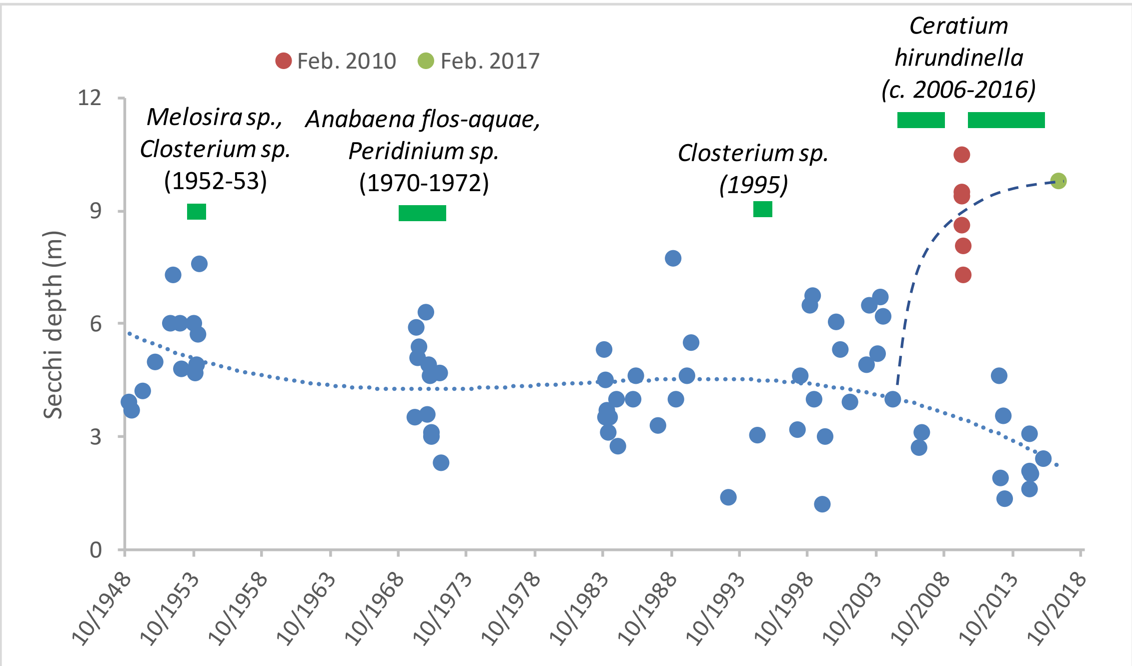

Figure 5. Historical summer (November to April) water clarity (Secchi disk depth) measurements in the open waters of Lake Hayes. The dominant phytoplankton species causing summer blooms are shown, if reported. Phytoplankton information and data from 1952/53 are from H. Jolly (1959) and Burns & Mitchell (1974), from 1970-72 are from Burns & Mitchell (1974), and from 1995 are from C.W. Burns, unpublished data. Blue dot Secchi data from 1984-2015 are from unpublished Otago Regional Council data, M. Schallenberg unpublished data, and Caruso (2001). Red dots are from M. Schallenberg, unpublished data. Green dot is a datum from the Otago Regional Council.

The average water clarity of the lake was rather stable from 1970 to 2006 (Fig. 5), until the brown-coloured dinoflagellate alga, *Ceratium hirundinella*, began to form dense blooms in the lake (Bayer et al. 2008). These blooms were more severe than most previous blooms, further reducing summer water clarity (Fig. 5). *Ceratium* blooms were also associated with fish kills and decreased angler interest in the lake, as discussed in Section 1.3, and began to cause skin and mucous-membrane irritation in at least one long-term local resident who regularly swam in the lake (M. Schallenberg, pers. comm.). Curiously, the severe *Ceratium* blooms were not associated with increased external nutrient loading from Mill Creek or the springs (Bayer & Schallenberg 2009; LAWA website) or with increases in internal nutrient recycling during the summer anoxic period. In fact, phosphorus concentrations in the anoxic deep (25m) summer waters appeared to have been decreasing from around the year 2000 and ammoniacal N concentrations were also low during the *Ceratium* bloom period compared to in the 1980s and 1990s (Fig. 6).

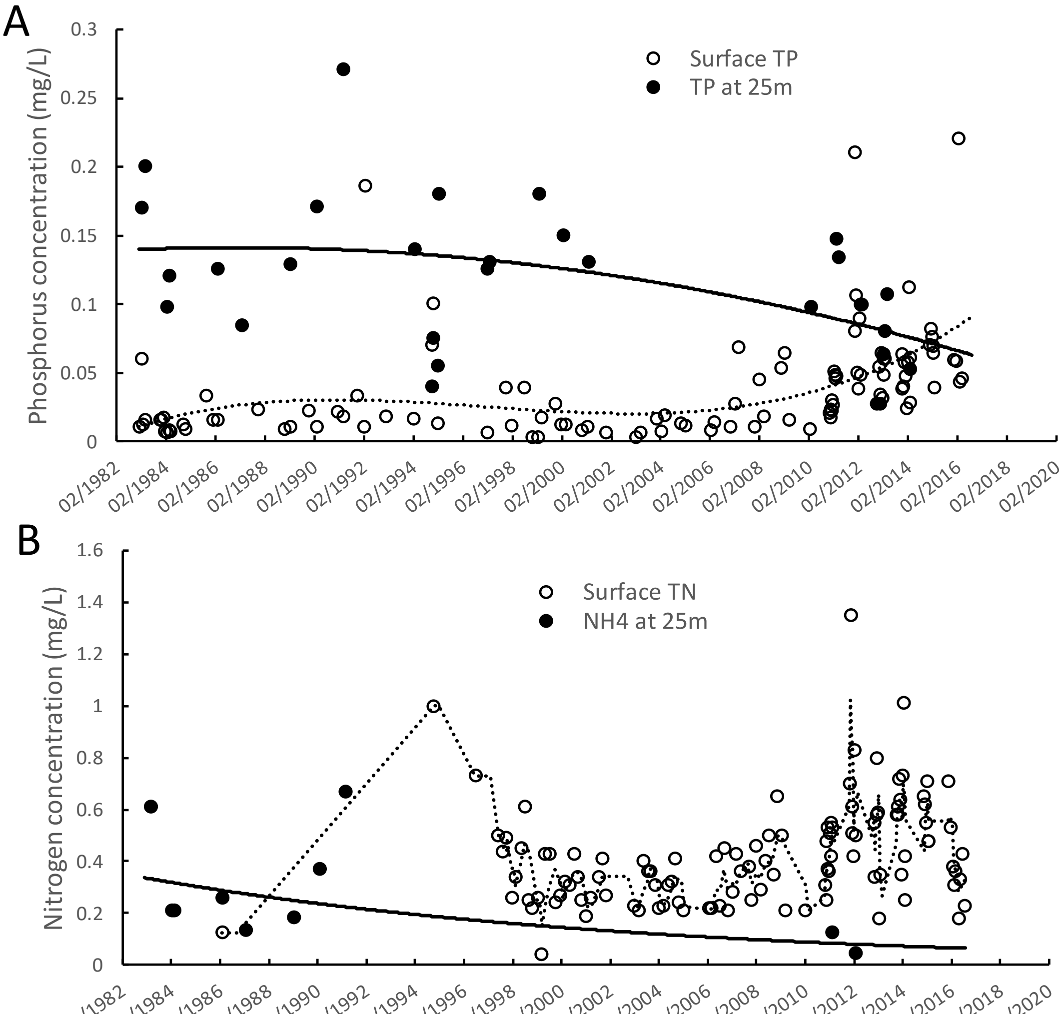

Figure 6. Trends in the concentrations of phosphorus and nitrogen concentrations in Lake Hayes during the stratified period (Nov-April inclusive) from 1983 to 2016. A. Total phosphorus at the lake surface and at 25 m depth (anoxic bottom waters). B. Total nitrogen at the lake surface and ammoniacal nitrogen at 25 m depth (anoxic bottom waters). Data are from the Otago Regional Council.

This intriguing situation of worsening algal blooms while internal and external nutrient loads had not measurably increased was frustrating for locals and recreational users of the lake. However, this apparent enigma can be explained by ecological peculiarities of the *Ceratium* alga, shown in Figure 7. This dinoflagellate is a large, spikey, motile (swimming) alga that is mixotrophic, meaning that it can gain energy both via photosynthesis (as plants do) and also by feeding on bacteria (as some protozoans and zooplankers do).

Figure 7. *Ceratium hirundinella* showing one of the two flagella used for locomotion/swimming. Total length of the cell is typically 150 µm to 200 µm. Photo: https://why.gr.

Mixotrophic dinoflagellates including *Ceratium* have been reported to become abundant and dominant in the phytoplankton communities of lakes during periods of lake recovery from eutrophication (Jeppesen et al. 2003; Gerdeaux & Perga 2006, Mehner et al 2008), partly due to their ability to supplement their nutrient requirements by feeding on bacteria (Gerdeaux & Perga 2006). *Ceratium* is also able to migrate vertically in the water column on a daily basis, enabling it to access recycled nutrients in the deep waters of lakes at night while also enabling high rates of photosynthesis in the upper water column during the day (James et al. 1992). In Lake Hayes, as in other lakes, these strategies probably enabled *Ceratium* to become highly competitive by nocturnally migrating and accessing nutrient-rich bottom waters at night and by feeding on bacteria when nitrate, ammonium and phosphate concentrations in the surface waters of the lake are scarce (i.e. during summer).

2.2 A *Ceratium* nutrient pump hypothesis

If *Ceratium* in Lake Hayes undertakes a day-night migration to harvest recycled N and P from the bottom waters during summer, then it is expected that *Ceratium* would transfer significant amounts of phosphorus from the bottom waters into the mixed layer during daytime, when it migrates to the surface layer to photosynthesise. The accumulation of recycled phosphorus in the bottom waters of Lake Hayes has been a major component of the P budget of the lake; however, Figure 6A shows that the recycled P contribution from summer bottom waters has decreased while the summer surface water phosphorus concentration has increased since the time that *Ceratium* began to bloom, in 2006. This raises the possibility that *Ceratium* may translocate P from the bottom waters to the surface waters of the lake during summer (Fig. 6A). We see a similar pattern over time for N (Fig. 6B), but, unlike for P, recycled ammoniacal N is only a small part of the N budget of the surface waters of the lake.

Because *Ceratium* blooms have been associated with increases in surface water P concentrations in summer (Fig. 6A), the apparent *Ceratium*-mediated transfer of P from the bottom waters to the surface waters in summer is expected to enhance the flushing of P out of the lake via Hayes Creek. This water flowing out of the lake is surface water and, therefore, the transfer of P from bottom waters to surface waters increases the flushing of P out of the lake. This hypothesis is consistent with the increasing concentrations of total phosphorus at the Hayes Creek outflow between 1993 and 2008 reported by Bayer & Schallenberg (2009). This enhanced P flushing should accelerate the recovery of Lake Hayes by eventually breaking the summer anoxia-phosphorus-algae feedback cycle that had been delaying recovery of the lake.

As the flushing of P from the lake progresses, it is expected that *Ceratium* blooms will eventually become self-limiting due to this apparent translocation and enhanced flushing of P from the lake. Currently, the declining levels of P available in the summer deep waters of the lake may already be reducing the competitive advantage that *Ceratium* has over other algae in the lake. A further reduction in *Ceratium's* competitive advantage could occur if the density of bacteria in the lake, which may supplement *Ceratium's* energy requirements, were also to decline.

2.3 Is Lake Hayes approaching a recovery tipping point?

We have shown that the bottom water nutrient concentrations which reflect internal recycling of legacy nutrients, have been decreasing in recent years. The apparent *Ceratium*-mediated transfer of P to the surface layers has probably increased the flushing of P out of the lake via Hayes Creek by increasing surface water nutrient concentrations in summer. Since 2006, *Ceratium* blooms have plagued the lake, where *Ceratium* has outcompeted other algae and cyanobacteria probably by harvesting phosphorus from deeper waters in summer and by grazing on bacteria to supplement its nutrition. While the lake has suffered severe *Ceratium* blooms in most summers since 2006, the developments described above suggest that the lake is on a trajectory toward recovery from historically high nutrient loads.

Further evidence of this is the fact that in the summer of 2009/10 and 2016/17, the lake experienced unprecedented water clarity (Fig. 5) and very low *Ceratium* biomass. The *Ceratium* hiatus in 2009/10 lasted only one summer, but the reduction in algal biomass in the surface waters (Fig. 8) and the increase in water clarity (Fig. 5) was striking. While the reduced internal P recycling probably contributed to these clear water summers, another interesting feature of these summers was the persistence of the water flea, *Daphnia pulex*, in the lake over the summer period. *D. pulex* is an intense grazer of algae (Burns 2013) and our sampling of zooplankton in the summers of 2009/10, 2012/13 and 2015/16 indicate that during summers when *Ceratium* bloomed, *D. pulex* was absent from the lake. Thus, we believe that food web interactions related to summer *Daphnia* presence in the lake also contributed to the sudden shift of Lake Hayes from a eutrophic condition with severe summer *Ceratium* blooms to summers with very low *Ceratium* biomass (Figure 9).

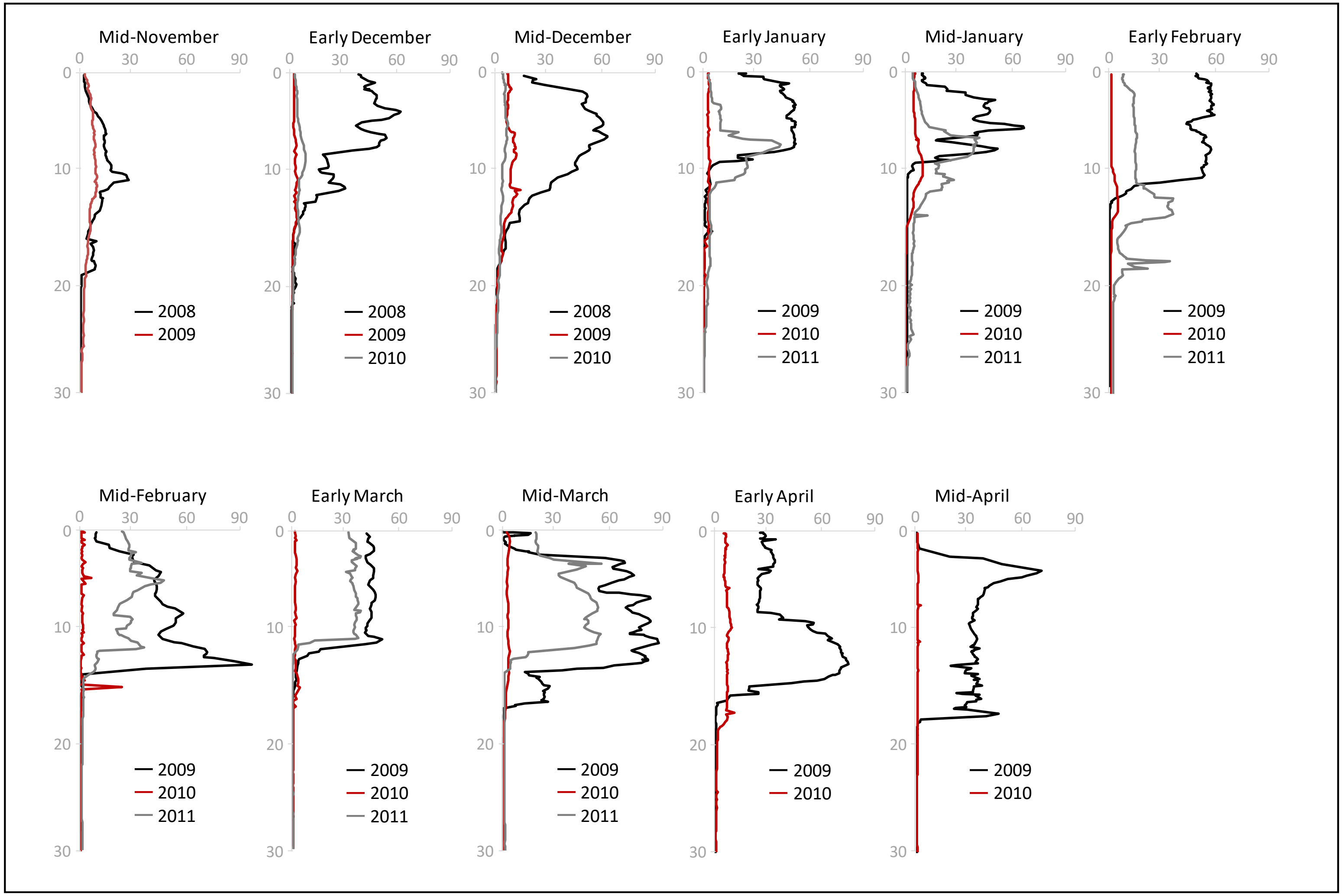

Figure 8. Vertical profiles of chlorophyll *a* in the summers of 2008/09, 2009/10 and 2010/11. Profiles were measured by the Otago Regional Council. Chlorophyll *a* data are *in vivo* fluorescence measurements from an uncalibrated datasonde and are, therefore, approximate concentrations in µg/L.

Rapid changes in trophic state are common in shallow lakes, which can fluctuate markedly in water clarity from year-to-year (Mitchell 1988; Scheffer 2004; Schallenberg & Sorrell 2010), when nutrient loading approaches a tipping point. However, such behaviour is not as common in deep, seasonally stratifying lakes, but has been reported in relation to species invasions (e.g., Lakes Erie and Ontario due to zebra mussel invasion) and to the dynamics of algal pathogens (e.g., pathogenic fungi controlling *Ceratium* spp.; Heaney et al. 1988). Circumstantial evidence described here suggests that Lake Hayes has entered a phase of recovery whereby nutrient availability is approaching a recovery tipping point and that food web interactions in some years may have tipped the lake into a temporary recovery from eutrophication (Fig. 9). These food web interactions are discussed in more detail in Appendix 1.

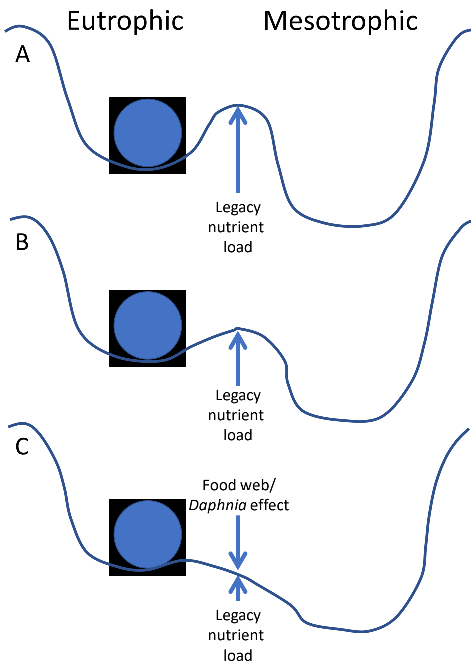

Figure 9. A conceptual model showing alternative stable states for Lake Hayes. The lake is represented by the ball, which is held in the eutrophic state by intensely recycled phosphorus (A). Recent reductions in P recycling have weakened the resistance to recovery (B). In the summers of 2009/10 and possibly 2016/17 (to be confirmed), the combination of reduced P recycling and food web effects reduced resistance to recovery further, allowing a temporary shift to a clear water state (C). In summer 2010/11, the *Ceratium* bloom returned and the lake shifted back to a eutrophic state (Fig. 8).

Experiments done on the Lake Hayes phytoplankton community in 2006 (Bayer et al. 2008) indicated that the phytoplankton community in the lake (dominated by *Ceratium* at the time) was stimulated by additions of N and the trace elements boron and zinc. In the four experiments conducted, phosphorus additions did not stimulate phytoplankton production. This result supported an analysis of N:P ratios in the lake, which also suggested that P was often in surplus in the lake water relative to N (in relation to the nutrient demands of phytoplankton) (Bayer et al. 2008). It would be interesting to now re-examine the nutrient supplies in the lake to test whether a decade of *Ceratium* dominance in the system has reduced phosphorus levels in the lake to the point where they can again begin to restrict phytoplankton blooms. The re-establishment of P-limitation of phytoplankton growth would have the added benefit of removing the competitive advantage of N-fixation, which historically dominant bloom-forming phytoplankters such as *Anabaena sp.* are capable of.

Our analysis of water quality data has yielded some insights into the drivers of phytoplankton blooms in Lake Hayes and it highlights the importance of having a detailed understanding of the nutrient budgets of lakes affected by nutrient enrichment. The combination of Otago Regional Council State of the Environment monitoring data and the University of Otago's occasional research projects on the lake provides a useful perspective on the factors driving large changes in water quality of the lake over time. Although the available data are patchy and many knowledge gaps would need to be filled to confirm the hypothesis presented here, the combined use of lake data, information on overseas lakes and expert experience and deduction provide a compelling hypothesis concerning the recent condition of the lake and what could be done to speed its recovery.

2.3 Key points on water quality analysis

The key points from our analysis of water quality data are as follows:

- The internal recycling of phosphorus during summer, which has been a large source of P to the lake at winter turnover, has been decreasing in recent years such that it is now so reduced so as to have little effect on the surface water concentrations of P.
- *Ceratium* blooms began in response to reduced internal nutrient recycling and external nutrient loading and its proliferation has probably been due to the fact that it can harness nutrient resources unavailable to most other algae.
- The *Ceratium* blooms have probably transferred recycled P from bottom waters to the surface waters, enhancing flushing of legacy P from the lake.
- Since *Ceratium* can't add P or N to the lake, it's apparent translocation of P (and maybe N) to the surface waters probably increases the flushing of these nutrients out of the lake and will eventually reduce nutrient availability to the point where Ceratium may become limited by low nutrient availability.
- Lake Hayes appears to be approaching a recovery tipping point, where nutrient availability and food web factors prevent the development of significant algal biomass in occasional summers.
- At this point, the food web factors assisting the temporary recovery seem to involve *Daphnia* persistence over the summer months.
- The current situation suggests that appropriate restoration measures could result stable in improvements in summer water clarity, reductions in *Ceratium* summer biomass, and the re-oxygenation of the bottom waters of the lake. These factors appear to be facilitated by maintaining a low nutrient availability and a high summer *Daphnia* density.

3 Lake Hayes historical timeline of events

The information presented in Sections 1 and 2 can be summarised in a timeline describing the trajectory of Lake Hayes and its catchment, as related to the health of the lake. The significant historical events in Figure 10 show how complex the Lake Hayes system is and how a combination of historical factors (e.g., fish introductions, fertiliser overuse, dairying, wetland drainage, etc.) and current factors (e.g., *Ceratium* blooms, *Daphnia* dynamics, decreasing nutrient loads, etc.) affect the current conditions and trajectory of the lake. The complexity of the Lake Hayes system highlights that management of the lake must consider a comprehensive range of factors that operate on a range of time scales and that often interact with each other to affect lake health.

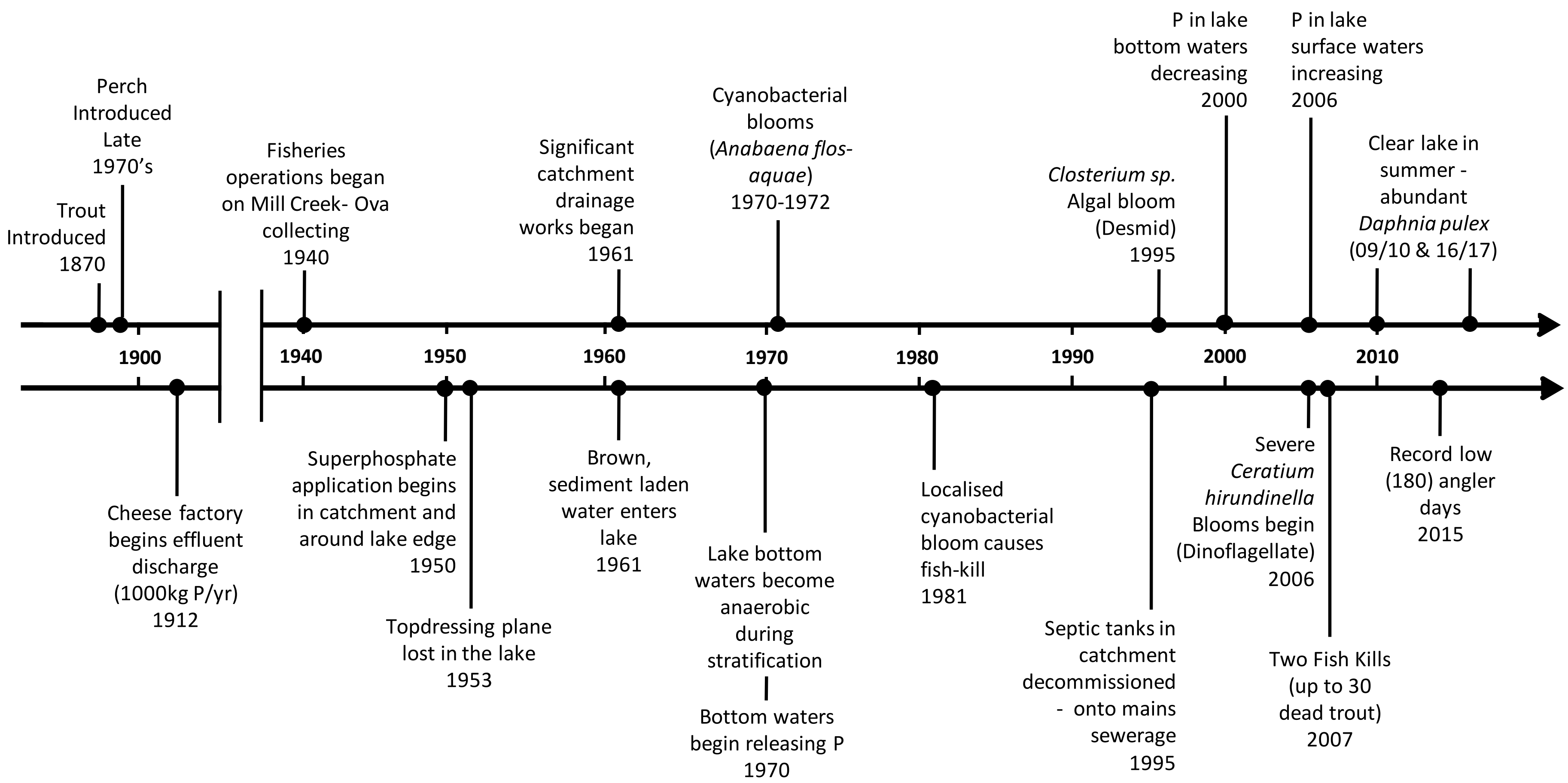

Figure 10. Historical timeline of major events impacting Lake Hayes and its catchment.

4 A restoration strategy for Lake Hayes

Restoration options for Lake Hayes have been discussed since the early 1970s, soon after the lake experienced its first severe algal blooms (Mitchell & Burns 1972) and have been revisited numerous times since then (Robertson 1988; Bayer & Schallenberg 2009; Ozanne 2014). Numerous strategies have been considered in terms of effectiveness and cost-effectiveness. The strategies fall into five main types: 1. catchment rehabilitation to reduce external nutrient loads to the lake, 2. reduction of internal nutrient loads/recycling, 3. food web manipulation, 4. flushing of water through the lake, and 5. other in-lake actions (Table 1).

Mitchell & Burns (1972) discussed and costed options including diversion of inflows away from the lake, flushing the lake with irrigation water and oxygenation of the bottom waters. Robertson (1988) placed much emphasis on catchment mitigation strategies, while subsequent reports have focused more on controlling in-lake P loading/recycling from the hypolimnion. The focus on internal P loading was sensible when the lake was releasing large legacy amounts of P into the water from the anoxic bottom waters on an annual basis and when the growth of the dominant phytoplankers was limited by P availability. However, our analysis of water quality data show that nowadays, the P concentration in the deep bottom waters (25 m) is similar to the P concentration in the surface waters during summer. In addition, the concentration of P in the Hayes Creek outflow had been rising at least up to 2009 (Bayer & Schallenberg 2009), indicating that while external P loads had reduced (Bayer & Schallenberg 2009) more P was being flushed from the lake. Our analysis suggests that *Ceratium* blooms that have plagued the lake since the mid-2000s have transferred bottom water P to the surface of the lake, enhancing the flushing of legacy P out of the lake.

Lake Hayes has a water residence time of around 1.8 years (Caruso 2000). Flushing of the lake could potentially be enhanced by augmenting Mill Creek with cleaner water from the Arrow River Irrigation Scheme, as was suggested by Mitchell & Burns (1972). When surplus water from the scheme is available (November to June – see Appendix 2), it could be used to augment the flushing of the lake. Augmented flushing of the lake could enhance the flushing of algae and P out of the surface waters of the lake. It could also add dissolved oxygen if the augmented flow were to plunge into the bottom waters during the stratified period. Total P concentrations are currently almost uniform in the surface and bottom waters in summer (Fig. 6A) and algae are concentrated in the surface layer in summer (Fig. 8). According to the surplus irrigation water that would be available, the augmentation flow available from the Arrow River would flush an additional 7% of the lake volume if the full surplus were used from September to June (Appendix 2). The relative temperatures (and therefore densities) of Mill Creek and lake water during this period suggests that Mill Creek (including any augmentation flow), is not likely to plunge into the bottom waters of the lake (Appendix 2). Therefore, while flow augmentation would enhance flushing of the lake by 7% per annum, it is unlikely to significantly alter the oxygen concentration or dynamics in the bottom waters of the lake. Thus, according to the analysis, the main benefits of flow augmentation to the recovery of the lake would not occur immediately, but would accrue over time, as long as the nutrient concentrations in Mill Creek don't increase.

We have no data showing that *Ceratium* in Lake Hayes migrates vertically in the water column, drawing recycled nutrients from the bottom waters to the surface waters. However, this nutritional strategy, along with the ability to feed on bacteria, potentially allows Ceratium to persist and outcompete other algae when dissolved, inorganic plant nutrients (i.e., nitrate, phosphate, ammonium) are scares. Thus, studies have shown that dinoflagellates such a *Ceratium* may be indicators of reducing inorganic nutrient availability in lakes (Jeppesen et al. 2003; Gerdeaux & Perga 2006; Mehner et al. 2008).

If our hypothesis is correct and internal nutrient recycling is playing a diminishing role in fuelling algal blooms in the lake, then restoration actions aimed at reducing internal P loading/cycling will provide diminishing benefits into the future. Previous reports have recommended strategies to reduce internal P loading/recycling in the lake. However, in light of the information provided here, the restoration benefits of such actions into the future should be carefully scrutinised in terms of their costs and potential benefits. An analysis of the cost of alum treatment for Lake Hayes was carried out by John Quinn and Max Gibbs of NIWA in 2015 (Appendix 3), based on a maximum accumulation of dissolved reactive phosphorus in the bottom waters of 300 mg/m^3 of P, which was estimated based on previous measurements of P made in 1994/95 and 2012/13 (M. Schallenberg, unpublished data). However, more recent data and the analysis presented in Section 2 suggest that this may be an overestimate of the current maximum accumulated P by a factor of two. So, their estimated cost for an alum treatment of $535,000 (Appendix 3) may also be an overestimate by a factor of around two. Otago Regional Council samples being collected this summer will confirm whether or not the cost estimate in Appendix 3 can be substantially reduced.

While gains have been made in reducing nutrient loads to the lake from septic tanks, and nutrients in Mill Creek and the springs (Bayer & Schallenberg 2009), the condition of Mill Creek has stabilised since around 2005 (LAWA website; Appendix 4) and there are indications that summer nitrogen concentrations in Mill Creek may be increasing, although not yet statistically significant (LAWA website; Appendix 4). In comparison to other upland streams, Mill Creek is higher than average in nitrogen and *E. coli* (faecal bacteria) concentrations and in turbidity, while it is lower than average in phosphorus concentrations (LAWA website). Because Lake Hayes is an important and sensitive receiving environment, we suggest that the concentrations of contaminants flowing into Lake Hayes from all sources should be better than average. We, therefore, recommend that attention be refocused on land practices and nutrient, *E. coli* and sediment losses from the Lake Hayes catchment in order to further improve water quality in the lake (Appendix 4). The rapid rate of land development and the diversity of land uses in the catchment both highlight the importance of the use of best management practices and suggest that land/nutrient management mechanisms might be appropriate to protect the lake from future degradation. These should focus on phosphorus and nitrogen and should also account for fluxes during flood flows.

In the summers of 2009/10 and 2016/17 the lake did not experience algal blooms. This suggests that the lake's condition is destabilising and has begun to flip between algal blooms and clear water summer conditions. This kind of behaviour is a characteristic of complex systems as they approach pressure-response tipping points or thresholds. We hypothesise that the recovery from external and internal nutrient loading is creating instability in the lake and that the clear water summers are evidence that a stable recovery is attainable.

Table 1. Lake Hayes restoration actions discussed and recommended in four reports. Actions recommended in each report are shaded green.

Mitchell & Burns (1972)	Robertson (1988)	Bayer & Schallenberg (2009)	Ozanne (2014)	This report
Reducing external nutrient loading				
	• Wetland re-establishment • Reduce fertilizer application and runoff • Establish streambank buffer • Control channel clearance and drainage operations in catchment • Manage future development P load			**Collaborative catchment management plan** • Wetland re-establishment • Reduce fertilizer application and runoff • Establish streambank buffer • Control channel clearance and drainage operations in catchment • Manage future development P load
Change in catchment land use	Change in catchment land use			
Divert high P water out of the lake	Divert high P water out of lake		Divert high P water out of lake	
	Reduce runoff from animal stocking			
Reducing internal nutrient loading				
	Chemical P precipitation/inactivation	Chemical P precipitation/inactivation	Chemical P precipitation/inactivation	Chemical P precipitation/inactivation
	Hypolimnetic withdrawal	Hypolimnetic withdrawal	Hypolimnetic withdrawal	
Hypolimnetic aeration	Hypolimnetic aeration	Hypolimnetic aeration	Hypolimnetic aeration	
		Dredging	Dredging	
			Sediment oxidation	
			De-stratification	
Food web biomanipulation				
		Daphnia enhancement	*Daphnia* enhancement	*Daphnia* enhancement
Flushing				
Enhance flushing	Enhance flushing, remove flushing restriction at the outlet	Enhance flushing	Enhance flushing	Enhance flushing
Other in-lake strategies				
			Use of floating wetlands, algicides, pathogenic bacteria and ultrasound	

Why did the water clarity of the lake suddenly improve in these summers of 2009/10 and 2016/17? Data and observations suggest that the summer persistence of *Daphnia* in the lake was associated with the clear water phases. Current studies by the University of Otago Zoology Department and collaborators are examining the potential of perch recruitment to regulate *Daphnia* density via predation by juvenile perch on *Daphnia.* Preliminary evidence suggests that the perch life cycle and spawning time in the lake may be associated with crashes in *Daphnia* densities during the summers when algal blooms were severe (Appendix 1). The data in Appendix 1 outline compelling evidence that food web biomanipulation to reduce juvenile perch numbers and increase summer *Daphnia* densities could push the lake into a more stable clearwater phase. While research is ongoing, a key component of the research will be completed by the end of 2017 and we have begun to consider various approaches that could be used to reduce the numbers of young perch in the lake (see Appendix 1 for examples).

4.1 Restoration plan and timeline

Table 2 and Figure 11 outline a proposed restoration plan and timeline for accelerating the recovery of Lake Hayes to a stable desirable state and for controlling catchment development to prevent potential future increases in nutrient and sediment loading from the catchment to the lake. Table 3 sets out potential restoration targets for the recovery. These are suggested targets only because interested members of the community, iwi and stakeholders together with the Otago Regional Council would need to vet any final targets. We present the draft targets in Table 3 to help initiate a collaborative community project to set final restoration targets.

Table 2. Proposed restoration plan for Lake Hayes.

Action - in order of priority	Reasons/benefits	Time	Likely effectiveness	Cost	Cost effectiveness
Catchment management plan and actions	• High population growth rate • Diverse land uses • Valuable and sensitive receiving environment • Community education, collaboration and buy-in • Holistic improvement	• Start the process immediately • In 2017/18 undertake a management plan feasibility study • Continuing development and refinement over time	• Large number of diffuse and long term benefits including education, stakeholder involvement, and improvement in water quality • Effectiveness in improving water quality will depend on feasibility to be determined in catchment management plan	• Unknown, but some costs can be covered under normal Regional and District Council business	• Likely to be highly cost-effective in the long term
Biomanipulation	• Potentially restore eels to the lake • Potentially increase native bully and koaro densities in the lake • Reduce the density of non-native perch	• Immediately begin looking into options • In early 2018, undertake a feasibility study in light of information in Helen Trotter's MSc thesis (end of year) • Carry out biomanipulations in 2018	• Likely to be effective, but to what extent depends on feasibility study • Some techniques may require follow up or ongoing biomanipulations	• Unknown. Depends on techniques used • Unlikely to be expensive	• Potentially highly cost-effective • Some techniques may require ongoing biomanipulations to keep perch recruitment down

Table 2. Proposed restoration plan for Lake Hayes, continued.

Action - in order of priority	Reasons/benefits	Time	Likely effectiveness	Cost	Cost effectiveness
Flushing	• Increase flushing rate but requires upfront connection cost and continual water purchase	• Can be carried out immediately if cost-benefit is favourable	• Potentially helpful in the long-term	• $22,000 hook-up cost plus $35,000 p.a. for 200 L/s capacity	• Moderate long-term cost-effectiveness
Alum dosing	• Expensive, but likely to reduce internal P loading further	• Reassess costs in light of declining P concentrations in bottom water • If sufficiently cost-effective, could be carried out in summer 2017/18	• Effective immediately upon use • May require follow up treatments after 5 years	• Between $250,000 and $500,000, depending on reassessment using 2017 lake phosphorus data	• Low to moderate immediate cost-effectiveness

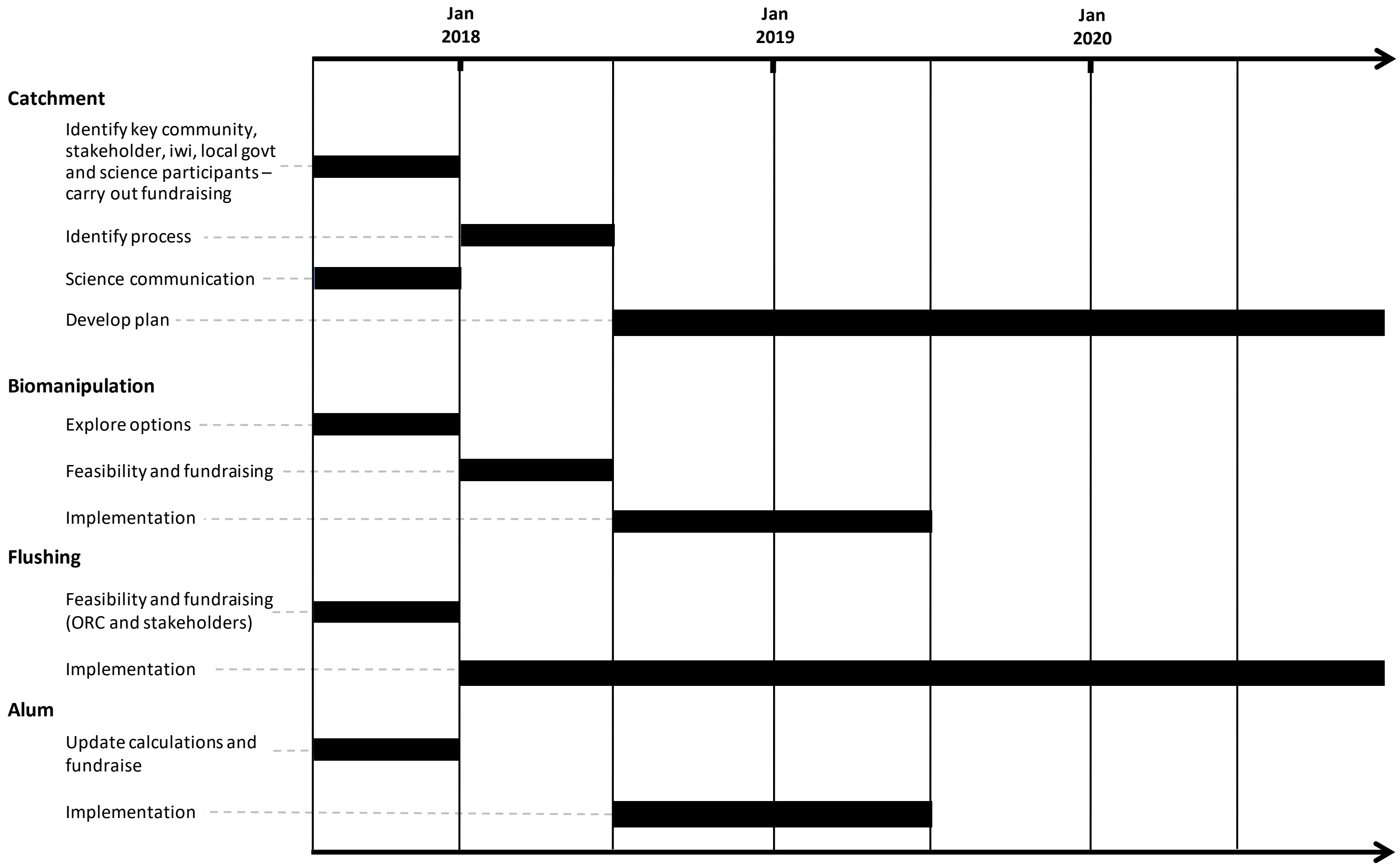

Figure 11. Proposed timeline for planning and implementation of lake restoration strategies.

Table 3. Suggested restoration targets for Lake Hayes. A successful restoration should achieve these targets consistently, from year to year.

Lake condition desired	**Measurable targets to meet condition**	**Parties to help develop final targets**
Lack of summer algal blooms and clear water which encourages recreational activities including swimming/bathing	• Trophic lake index during summer months < 4 • Secchi disk depth in summer months > 4 m	Otago Regional Council, locals, Fish & Game, rowing clubs, etc.
Inhibition of internal nutrient loading	• Improving oxygen content of the summer bottom waters to eventually achieve a condition where oxygen is never fully depleted • Nutrient budget shows a net loss of P from the lake on an annual basis, eventually stabilising at an ecologically sustainable level of P accumulation (permanent burial)	Otago Regional Council, University of Otago
Improved trout fishery	• Increase angler hours to 1995 levels • Reduce turbidity and temperature in Mill Creek • Maintain or increase Mill Creek flow rates	Fish & Game
Reduce nutrient loading to the lake from Mill Creek and the springs	• Reduce nitrate concentrations in Mill Creek • Reduce suspended sediment (turbidity) and total phosphorus concentrations in Mill Creek during high flow events • Develop a catchment management plan to ensure improved land management practices are adopted throughout the catchment	Otago Regional Council, Fish & Game and catchment land owners
Restore longfin eels to the lake	Achieve an eel trap and transfer target	Iwi, Contact Energy, DoC, Fish and Game
Maintain or enhance native biodiversity	Develop a strategy to prevent the incursion of invasive non-native species	Ministry of Primary Industries, DoC, Otago Regional Council

5 Water quality and lake health monitoring for Lake Hayes

Lake Hayes is one of the most thoroughly monitored and studied lakes in New Zealand. A combination of interest from university academics since the 1940s coupled with the Otago Catchment Board/Otago Regional Council monitoring of the lake which began in the early 1980s, provides one of the best datasets from which to interpret and understand lake conditions and trends in the country. Despite the scientific interest it has attracted and the relatively good lake monitoring dataset that exists, the cumulative data assembled on the lake are barely enough to allow for a good understanding of the lake's changes over time.

5.1 The importance of regular and consistent monitoring

Lake Hayes and its catchment constitute a complex, linked terrestrial and aquatic ecosystem, which is highly valued by the local community. The water quality monitoring of the lake by the Otago Catchment Board/Otago Regional Council has been sporadic. Therefore, the dataset for the lake has many gaps and changes in sites and lake depths sampled, making it difficult to extract robust long-term data and to derive clear interpretations of how the lake has responded. The pitfalls of intermittent sampling can be seen in the dataset, where Secchi disk and trophic level indicators were not sampled in the summer of 2009/10, when the lake experienced a highly unusual and dramatic shift to what was likely an oligotrophic condition. This illustrates the potential for the lake to undergo rapid changes from year-to-year. Such dynamics are important to understanding the condition of the lake and its trajectory over time. Variability over time is an important indicator of lake condition, and trend and variability can best be assessed based on regular, long-term sampling of the lake's state.

5.2 The importance of nutrient budgets

Lake Hayes has undergone major changes in water quality as a result of major changes in nutrient loads over time. It's resistance to improvement from the 1980s to 2000s was in part due to the legacy of phosphorus loading that occurred in the 1960s and 1970s, which had been held in the lake bed sediments and recycled on an annual basis for decades. This illustrates the effect of legacies and time lags, which can affect lake condition. Consequently, the lake has probably rarely been in a nutrient equilibrium or steady state, where nutrient loads are balanced with nutrient concentrations and nutrient losses (via sedimentation and outflow).

Nutrient budgets involve the simultaneous intensive sampling of nutrient inputs (surface water and groundwater), nutrient concentrations (vertically resolved in a stratified lake) and nutrient losses. In the absence of such a nutrient budget (calculated at least on an annual basis), understanding of whether the lake is becoming cleaner or more polluted is only inferable via careful inference based on incomplete water quality data.

Nutrient budgets are a standard approach to understanding the nutrient sink/source dynamics of a lake in relation to nutrient loads from the catchment. To fully understand the condition and trajectory of a lake, it helps to understand if the lake is absorbing or shedding nutrients in relation to its nutrient inputs. Robertson (1988) calculated a P budget for the lake over a two-year period, which showed that the lake was retaining P. The current condition of *Ceratium* blooms is probably helping speed the shedding of legacy phosphorus from the lake bed to the outflow of the lake. Therefore, although the lake appears to be degrading, it is probably improving (flushing P), although only a current or recent nutrient budget can confirm this.

5.3 The importance of long term datasets

As described above, Lake Hayes and its catchment have probably rarely been in nutrient equilibrium over the past 50 years. The Secchi disk depth data, reaching back to the late 1940s show how water clarity has degraded, has been highly variable with a stable average for over 30 years, has further declined and has recently begun to swing sharply and intermittently from very low to extremely high clarity. This long-term information is very helpful in understanding many important characteristics of the lake such as its pre-degradation condition, how far the lake has departed from that condition, the time scales of change (which can indicate resistance to change), where the lake's tipping points might be, how close it might be to recovery, and so on.

Furthermore, long term data provide the best chance of identifying small and slow but important changes in the lake such as climate change impacts or depletion of the recycled phosphorus pool. The longer the dataset, the easier it is to distinguish ecological signal from stochastic noise in the dataset.

5.4 The importance of monitoring factors beyond simple water quality variables

Water quality (e.g., nutrients, water clarity, algal biomass) relates directly to the appeal of the lake for recreational activities like boating, fishing and swimming. So, it is understandable that statutory obligations for monitoring lakes focus mainly on water quality. However, to understand how and why changes to water quality occur in lakes, it is important to have information on supporting factors of the lake, which either drive or help explain changes in water quality. These could be related to climate change (temperature, mixing, etc.), which councils routinely monitor. However, key secondary factors often relate to components of the food web, such as the dominant phytoplankton species, zooplankton density, aquatic plant distributions, the presence of invasive species, etc. Early warning indicators of change in lakes are most likely to be changes in community composition of biological communities such as algae or zooplankton (Schindler 1987). For example, our interpretation of the data from Lake Hayes suggests that the development of *Ceratium* blooms in the mid-2000s both indicated an improvement in nutrient conditions and facilitated further improvement in nutrient status. One could not come to this conclusion based on water quality information alone.

5.5 The importance of monitoring change on different time scales

Regular monthly sampling of a lake allows for the analysis of lake changes on three important time scales: monthly, annual, and inter-annual. However, sometimes monthly sampling is too coarse a time scale to understand key drivers and processes. For example, climate warming should increase the period of time that a lake is thermally stratified. Changes in the timing and period of stratification can affect the ecology of the lake ecosystem and water quality (e.g., Winder & Schindler 2004). Unfortunately, monthly sampling will not reveal the exact timing of lake turnover or when the first day of seasonal thermal stratification occurs. So, monthly temperature profiles don’t help identify some key climate change-related effects that could affect the state of the lake. Other important factors, such as: i) when the lake’s temperature reaches a threshold for perch spawning or ii) when temperature becomes stressful to brown trout or iii) how rapidly dissolved oxygen in the bottom waters is depleted, can best be determined from high frequency measurements using *in situ* lake monitoring sensors.

5.6 The importance of monitoring at different places in the lake

In a lake with a simple basin shape and bathymetry, like that of Lake Hayes, it is tempting to think that monitoring only at the deepest site will be adequate. While one site can provide very useful data, water quality factors can vary substantially across Lake Hayes and with depth in the lake. For example, *Ceratium*, a motile alga, is often observed in distinct brown patches from the surface of the lake (Fig. 12). If the distribution of the dominant alga is patchy in the lake, sampling at a single site won’t give an accurate estimate of the biomass of algae in the lake.

Figure 12. Brown-coloured, patchy *Ceratium* bloom in Lake Hayes, summer 2006/07. Photo: Otago Fish & Game.

Jolly (1952) indicated that there was high spatial variation in the densities of zooplankton due to the effect of winds and currents. We have also observed high spatial variability in zooplankton distributions in the lake.

Ceratium has the ability to migrate vertically in the water column and is often seen to intensify in biomass from early morning to midday while zooplankton species also migrate vertically in the lake from day to night (Jolly 1952; James et al. 1992). So, monitoring of the lake should take into account such vertical movements of algae and zooplankton so that better estimates of biomass of these can be monitored.

5.7 Suggested monitoring for Lake Hayes

While the historical Otago Catchment Board/Otago Regional Council data has been valuable for explaining changes in water quality and nutrient dynamics, lake monitoring could be improved along the lines discussed above. Comprehensive and good quality lake monitoring data are especially important in the context of lake restoration because the effectiveness and cost-effectiveness of restoration actions can only be ascertained by careful monitoring of changes in the lake. Furthermore, year-to-year variation in factors such as temperature, mixing depth, timing of stratification, zooplankton dynamics, fungal pathogen dynamics and the effect of floods can impact on expected recovery and such dynamic behaviour needs to factored into assessments of restoration success.

Below, we present some options for improving the monitoring of the water quality and health of Lake Hayes to support restoration actions.

Table 3. Suggested lake monitoring approaches in order of priority.

Priority	Type of monitoring	Frequency and technology
1a.	Sampling by boat at 2 deep water sites (31m and c. 26m) 1. CTD datasonde casts (Temp, DO, Chl *a*, phycocyanin) 2. Samples at 5m, 10m, 15m, 20m 25m, 30m for: • Total, dissolved inorganic N and P • Chlorophyll *a* and pH (only at 5m) 3. Samples at 5m, 10m and 15m for phytoplankton species 4. Vertical zooplankton hauls for species and density of Daphnia 5. Secchi depth	Monthly; various standard methods
1b.	P budget Measure total P and flow rate (where relevant) in: • Mill Creek (plus flow) • Spring (plus flow) • 6 depths in the lake at 31m site (1a.) • Hayes Creek outflow (plus flow)	Monthly; standard wet chemistry methods
2.	Profiling lake monitoring buoy at 31m site • Temp • DO • Chl *a* • Phycocyanin (cyanobacteria)	Hourly; Limnotrack monitoring buoy
3.	Survey aquatic plants using divers (e.g., LakeSPI) At 4 fixed transects record: • Maximum depth of plants • Native species distributions and % cover • Presence and cover of non-native species • Health of plants	Every 5 years; Scuba divers (e.g. LakeSPI methodology)

Priority 1a. monitoring covers the basic water quality parameters at 2 sites and 6 depths on a monthly basis. This protocol accounts for spatial variation in the lake by sampling 2 sites and for vertical variation by sampling 6 constant depths and obtaining some more detailed information using a profiling CTD datasonde. It recommends sampling the phytoplankton and zooplankton communities, which provides valuable information on subtle changes in biological communities that can be related to subtle environmental changes. Currently the Otago Regional Council is using a monitoring programme similar to this, but at a single site. The Otago Regional Council monitoring effort has not been consistent on an annual basis, instead involving a cyclical monitoring rotation in which the lake is monitored for three years and then not monitored for a number of years. A regular, annual and long-term monitoring commitment for lakes yields better datasets and leads to a better understanding of lake behaviour and management requirements.

Adding priority 1b. measurements of total P in the inflows and outflows of the lake would provide the data required to calculate a phosphorus budget for the lake. This would indicate the internal and external P loads to the water column and the amounts of P lost via the outflow and via permanent burial in the sediments. With this information, it would be possible calculate a P budget (e.g., Robertson 1988) to determine whether the lake is a sink or source of P in a particular year, enabling the tracking of how the lake is responding to historical and current P loads.

Priority 2 monitoring provides high frequency vertical profiles of selected variables. This would allow the timing of various important events such as stratification/destratification to be identified. In addition, the timing and position in the water column where temperature and DO thresholds are exceeded can also be identified and compared across years. This would provide valuable background information for interpreting various stressors and drivers of changes in the lake.

Priority 3 monitoring focuses on the important littoral (submerged plant) zone of the lake, which is the primary habitat for many important aquatic organisms. It would allow for the determination of the health and biodiversity of the aquatic plant community, the distribution of plants in relation to water depth (indicating whether the plant community is shallowing, stable or deepening in the lake), as well as the status of non-native aquatic plants in the lake. The Otago Regional Council has had such aquatic plant surveys carried out in 1992 and 2001, but to our knowledge, these have not been carried out since. As a result, we have little understanding of how *Ceratium* blooms have affected plant distributions and associated fish habitat in the lake.

The comprehensive monitoring programme described here would provide information on lake health at different spatial and time scales, enabling the careful monitoring of changes in algal blooms, dissolved oxygen, trophic state (nutrient status), climate-related effects, phytoplankton, zooplankton, aquatic plant communities and invasive species within these communities. It would also provide data required to calculate nutrient budgets for the lake at monthly, annual and longer time scales. Together these monitoring strategies would be capable of sensitively tracking changes in the lake and would also provide valuable background information for targeted research on lake ecology. Finally, long term data are extremely valuable in understanding lake functioning and trends and. Therefore, there should be a commitment to continue regular monitoring over the long term, without hiatuses.

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Appendix 1: Food web biomanipulation as a restoration tool for Lake Hayes

Food web cascades in lakes

Studies overseas and in New Zealand lakes have found that lakes can undergo rapid changes in water quality if nutrient loading is pushed beyond certain tipping points and when invasions by non-native fish and aquatic plant species cause major changes in lake food webs and nutrient cycles (Scheffer 2004; Schallenberg & Sorrell 2010). Once in a degraded, eutrophic state, lakes can exhibit inertia and resistance to restoration by nutrient reduction alone (Fig. 1).

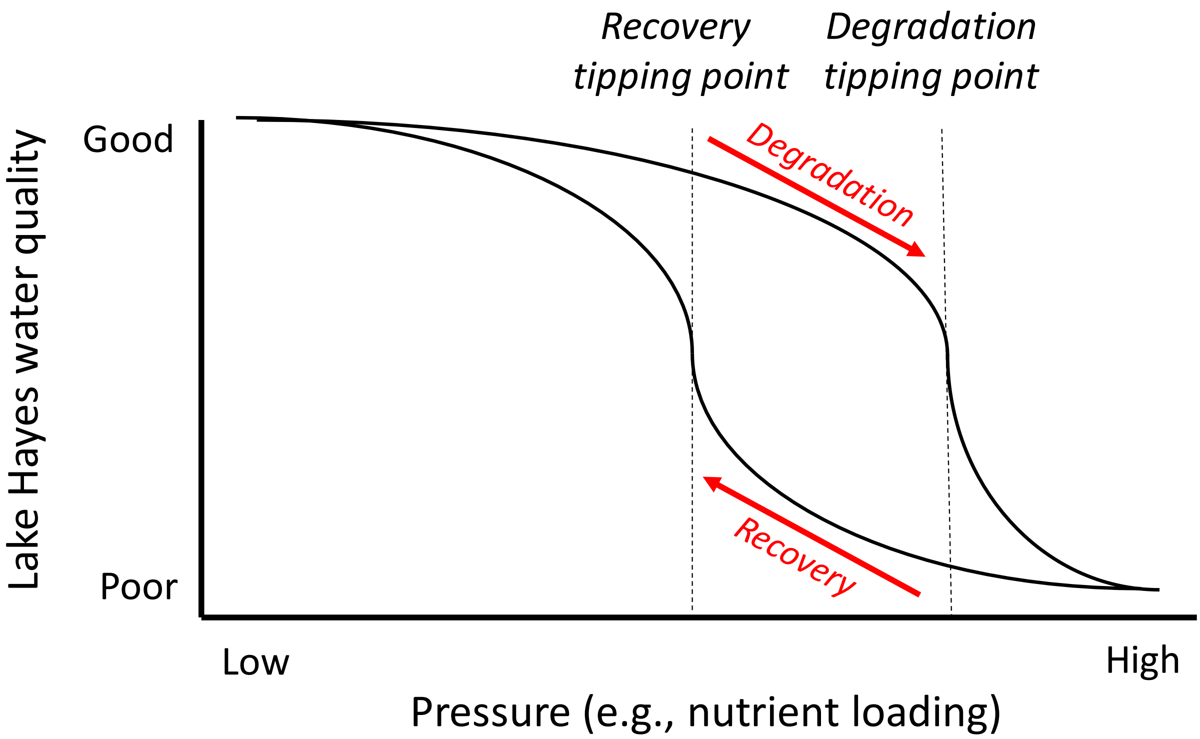

Figure 1. Idealised, non-linear relationship between water quality and environmental pressures in lakes, showing tipping points and inertia to degradation and to recovery that are typical of many shallow lakes.

However, in concert with nutrient load reduction, food web manipulations (fish stocking/removal) have been shown to successfully assist a return to a clear water state, usually by releasing zooplankton (which graze on algae) from predation pressure by fish (Søndergaard et al. 2007). Such food web biomanipulation aims to initiate, or strengthen, a top-down trophic (food chain) cascade by reducing zooplanktivory, resulting in an increase in the abundance and size of zooplankton (Shapiro 1980; Burns et al. 2014). If the zooplankton is dominated by large species (e.g. *Daphnia* sp.), increased grazing pressure on phytoplankton and ultimately increased water clarity result from a successful biomanipulation of the lake food web (Reynolds 1994) (Fig. 2). A cascade to reduce algae biomass may focus on increasing piscivorous fish density and/or decreasing zooplanktivorous fish density.

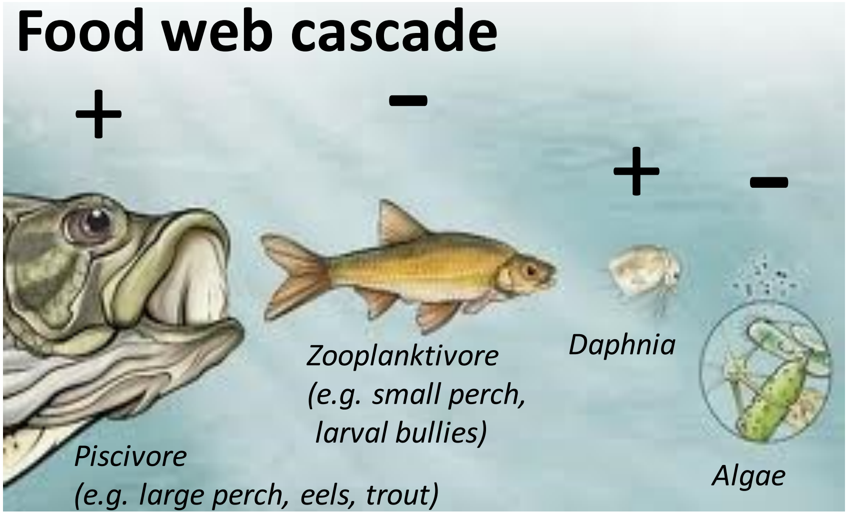

Figure 2. Example of a food web cascade showing how increasing the density of piscivorous fish can cascade (left to right) to reduce densities of algae.

Evidence for a link between *Daphnia* persistence in summer and the inhibition of *Ceratium* blooms in Lake Hayes

In the summers of 2009/10 and 2016/17, Lake Hayes exhibited unexpected, rapid improvements in water clarity and quality. Studies by the University of Otago Zoology Department revealed that the invasive zooplankter, *Daphnia 'pulex'* (Fig. 3), had colonised the lake, probably in the mid-2000s, and was attaining higher densities than had been previously recorded when the native *Daphnia thomsoni* was the sole *Daphnia* species in the lake (Fig. 3). Work by Professor Carolyn Burns of the Zoology Department has shown that *Daphnia 'pulex'* has higher temperature preferences than *Daphnia thomsoni* (called *D. carinata* in her study) and reaches higher densities than the native species (Burns 2013).

Figure 3. *Daphnia 'pulex'* from Lake Hayes, February 2010. Photo: Ciska Overbeek.

High *Daphnia* densities in 2010 occurred at the time when Lake Hayes attained and sustained unusually high water clarity throughout the summer (Fig. 4; Main Report - Fig. 5), suggesting a link between *Daphnia* summer density and summer algal biomass in the lake. In support of this apparent link between high *Daphnia* density and clear water in summer, we have observed that in the summers of 2012/13 and 2015/16, when *Ceratium* blooms occurred, *Daphnia* were absent in the lake during summer. In addition, zooplankton samples collected during the summer of 2016/17 (another summer with unusually high water clarity in the lake, Main Report – Fig 5), *Daphnia* continued (densities not yet determined).

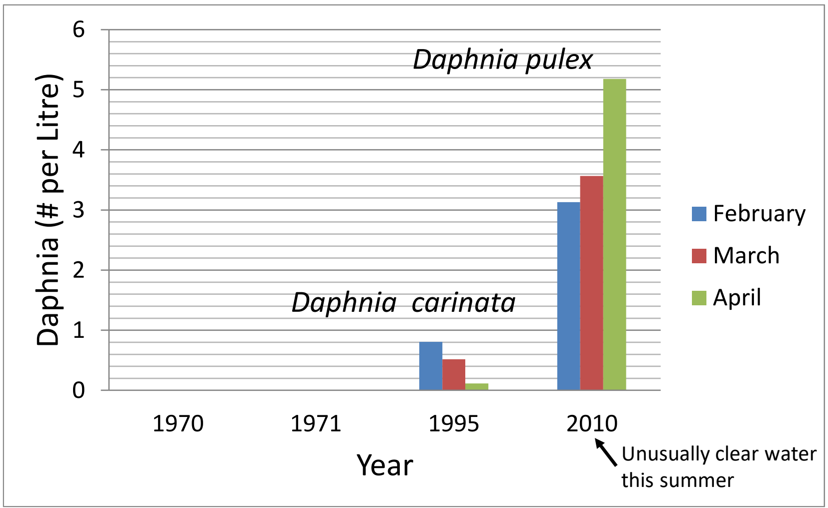

Figure 4. *Daphnia* densities in summer months in Lake Hayes in 1970 and 1971 (no *Daphnia* present in summer), 1995 (low densities present in summer), and 2010 (high densities present in summer).

The potential role of small perch in determining water quality

The clear water summer of 2009/10 did not persist into the summer of 2010/11. Observations of high juvenile perch numbers in 2010/11, suggest that perch recruitment increased in response to the plentiful *Daphnia*, and it is hypothesised that *Daphnia ‘pulex’* density (and grazing on phytoplankton) was suppressed by predation on *Daphnia* by juvenile perch. These findings have prompted further investigations into the potential of biomanipulation as an approach to improve the water quality of Lake Hayes.

To test this hypothesis and to confirm that biomanipulation of *Daphnia* densities could facilitate a switch to a clear water state, studies by the University of Otago Zoology Department and collaborators from other research institutes and universities are underway to determine the strength of food web interactions between fish, zooplankton and phytoplankton in Lake Hayes. The relative importance of nutrients versus the food web structure in controlling phytoplankton abundance is being examined in order to evaluate the potential for food web manipulation to facilitate a shift back to a stable clear water state in Lake Hayes.

While declining water quality in New Zealand has attracted many millions of dollars of clean up funds for lake restoration, biomanipulation of the pelagic food web has only been attempted in one other New Zealand lake, the Lower Karori Reservoir, Wellington (Smith & Lester 2007). In this very small reservoir, the removal of perch resulted in enhanced zooplankton densities, reduction in algal biomass, and improved water quality (Burns et al. 2014), suggesting that reducing predation of small perch on *Daphnia* in Lake Hayes may help improve water quality in the lake.

Ideally, the lake food web models produced from this research will provide confidence in applying a biomanipulation approach in the lake. Key information needed to develop a successful biomanipulation approach includes:

1. Which fish species in the lake are responsible for reducing summer *Daphnia* densities, and at what size and life stage does predation on *Daphnia* occur?
2. How might *Daphnia* reduce *Ceratium* biomass? The large size of *Ceratium* in relation to *Daphnia* food size preference suggests that the interaction between *Ceratium* and *Daphnia* is not a direct grazing effect of the zooplankter on the algae. Rather *Daphnia* grazing on bacteria may reduce bacterial prey available for *Ceratium*. Alternatively, strong *Daphnia* grazing on other algae may increase light penetration and oxygen production in the deeper waters of the lake, restricting the upward flux of phosphorus toward the thermocline. There are other possible interactions.
3. What are cost-effective approaches for reducing zooplanktivorous fish densities (i.e., young perch) in spring and early summer?

Helen Trotter is currently doing an MSc thesis study to answer some of these questions. Her preliminary data from 2015/16, show that the recruitment of perch in early summer coincided with a sharp decline and eventual disappearance of *Daphnia* from the lake by January (Fig. 5). When her study is completed (end of 2017), sufficient information will be available to help produce a feasibility study for a biomanipulation intervention to cause a favourable food web cascade in Lake Hayes.

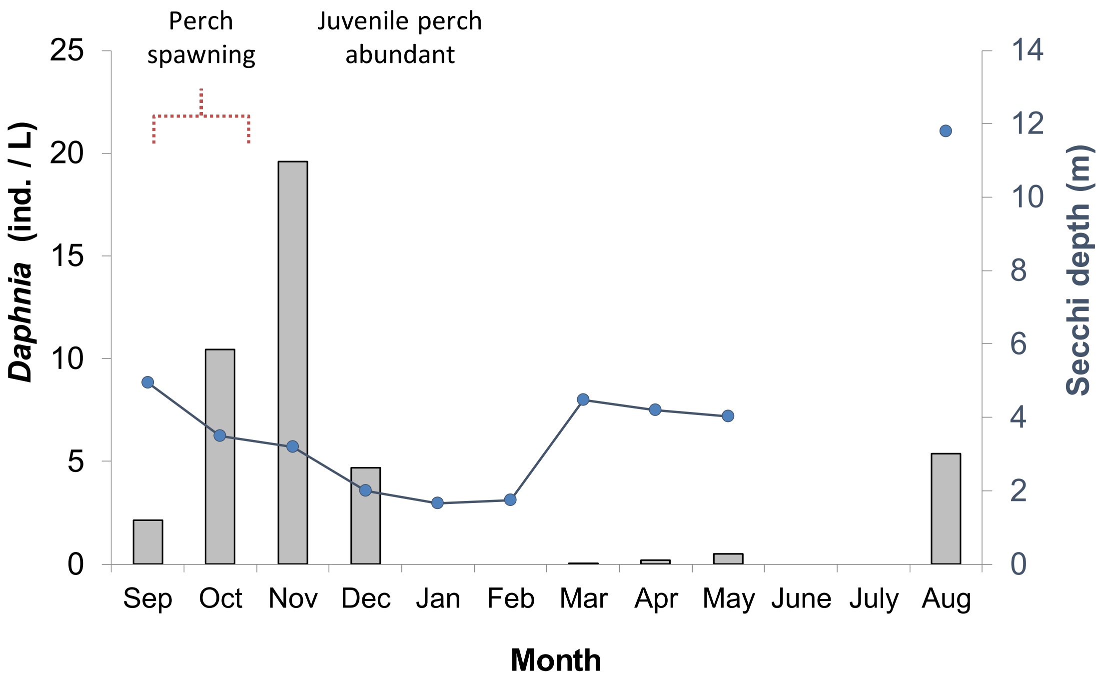

Figure 5. *Daphnia* density (bars) and Secchi disk depth (line) during the period September 2015 to August 2016. Note that when juvenile perch become abundant in December and January, the *Daphnia* decline and disappear from the lake, resulting in a decrease in water clarity to around 2 m. Data from Helen Trotter, University of Otago.

Potential ways to stimulate an effective food web cascade

Below we briefly introduce some potential approaches that could be used to induce a favourable food web cascade in Lake Hayes. These approaches could be further tested with respect to cost-effectiveness once Helen Trotter's study is complete.

1. **Adding *Daphnia* to the lake**. This is not seen as a practical option because of the large numbers of *Daphnia* that would be needed and the size of the facility that would be required to breed up such high numbers of *Daphnia*. *Daphnia* are intense grazers and require large amounts of food, further challenging the ability to produce the numbers that would be needed to affect algae in the lake. Furthermore, unless controls were also placed on planktivorous fish in the lake, the addition of large numbers of *Daphnia* would simply provide more food for planktivorous fish.
2. **Removal of juvenile perch**. This is not seen as practical because of the large size of the lake and because of the presence of aquatic plants in the shallow zones of the lake, which would make large-scale netting ineffective.
3. **Stocking of piscivorous trout and eels**. This may be a cost-effective and practical option. Fish to be stocked should be large enough to no longer feed on *Daphnia*, but instead feed on small fish (zooplanktivores). Fish & Game Otago may be able to raise hatchery brown trout to contribute to such a project. Longfin eels would have recruited into Lake Hayes prior to the construction of the Roxburgh Dam (1957). Subsequent to the dam, recruitment of eels, and eel biomass will have been severely or even completely reduced. Working with Contact Energy to trap and transfer returning eels from the Roxburgh Dam to Lake Hayes may have some merit because eels are effective piscivores capable of preying on young perch.
4. **Rearing and stocking of large, piscivorous sterile perch**. Perch longer than c. 150mm are known to be piscivorous. In some fish species (and possibly also in perch), it is possible to induce sterility by managing temperature of the developing ova (eggs). It may be possible to rear sterile perch to a large enough size so that they shift from zooplanktivory to piscivory. Stocking sterile piscivorous perch into Lake Hayes could reduce juvenile perch numbers through cannibalism, which is common in perch.
5. **Removing perch ova (eggs) from the lake**. Artificial perch spawning substrates could be built and deployed in the lake to attract perch spawn. Once spawning time is over but before egg hatching, the substrates could be removed, reducing perch recruitment. This strategy could complement strategy 4, by providing perch eggs for rearing into piscivorous perch.
6. **Encouraging fishing of perch**. Encouraging the catching of perch could possibly reduce perch numbers in the lake. If spawning perch could be targeted, this could potentially reduce perch recruitment. However, removing large perch from the lake could induce stunting in the population, which could increase predation pressure on *Daphnia* (see section 1.3.2. of the main report).

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Appendix 2: A preliminary assessment of the potential for augmentation of the inflows of Lake Hayes with Arrow River irrigation water to speed the recovery of the lake

This Appendix is updated from: Schallenberg M. (2015) A preliminary assessment of the potential for augmentation of the inflows of Lake Hayes with Arrow River irrigation water to speed the recovery of the lake. University of Otago Limnology Report No. 18, prepared for the Friends of Lake Hayes. Oct. 30, 2015.

Background

Lake Hayes usually undergoes thermal stratification from September to May or June. During this period, the warmer surface water is separated from the denser, colder water at the bottom of the lake. Due to the breakdown of algal material which settles to the bottom, the oxygen content of the bottom water declines during the stratified period, with the lake bed beginning to become anoxic in December to January (Fig. 1).

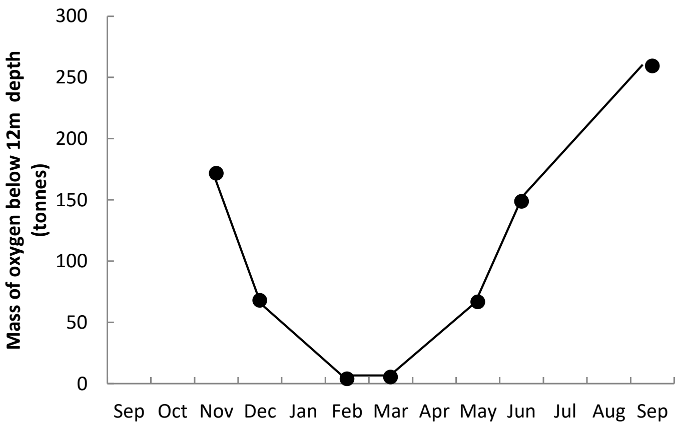

Figure 1. Mass of oxygen in the bottom waters (below 12m) of Lake Hayes, summer 2012/13.

As this occurs, phosphorus, which is bound to the sediments when oxygen is present, becomes liberated from the sediment and diffuses into the bottom waters and accumulating there until the end of the stratified period (Fig. 2).

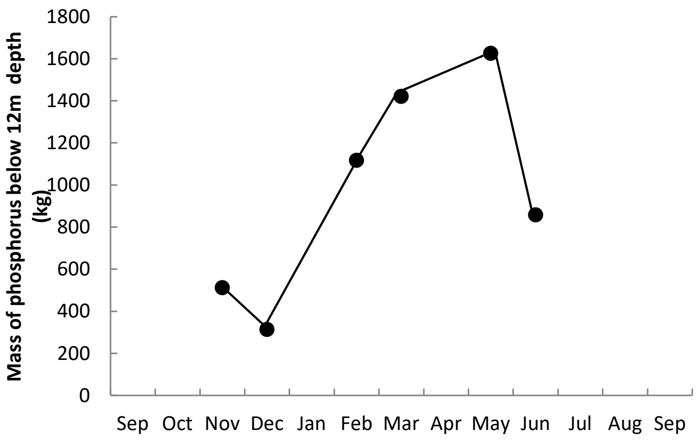

Figure 2. Mass of phosphorus in the bottom waters (below 12m) of Lake Hayes, summer 2012/13.

Stratification usually breaks down in June when the lake again mixes from top to bottom and phosphorus is diluted and also re-bound to particles in the water column.

The Friends of Lake Hayes have been examining potential methods for restoring Lake Hayes. A proposal has been put forward to help speed the recovery of Lake Hayes by augmenting the inflow to the lake at Mill Creek with water from the Arrow River Irrigation Scheme, sourced from the Arrow River near Macetown (Fig. 3).

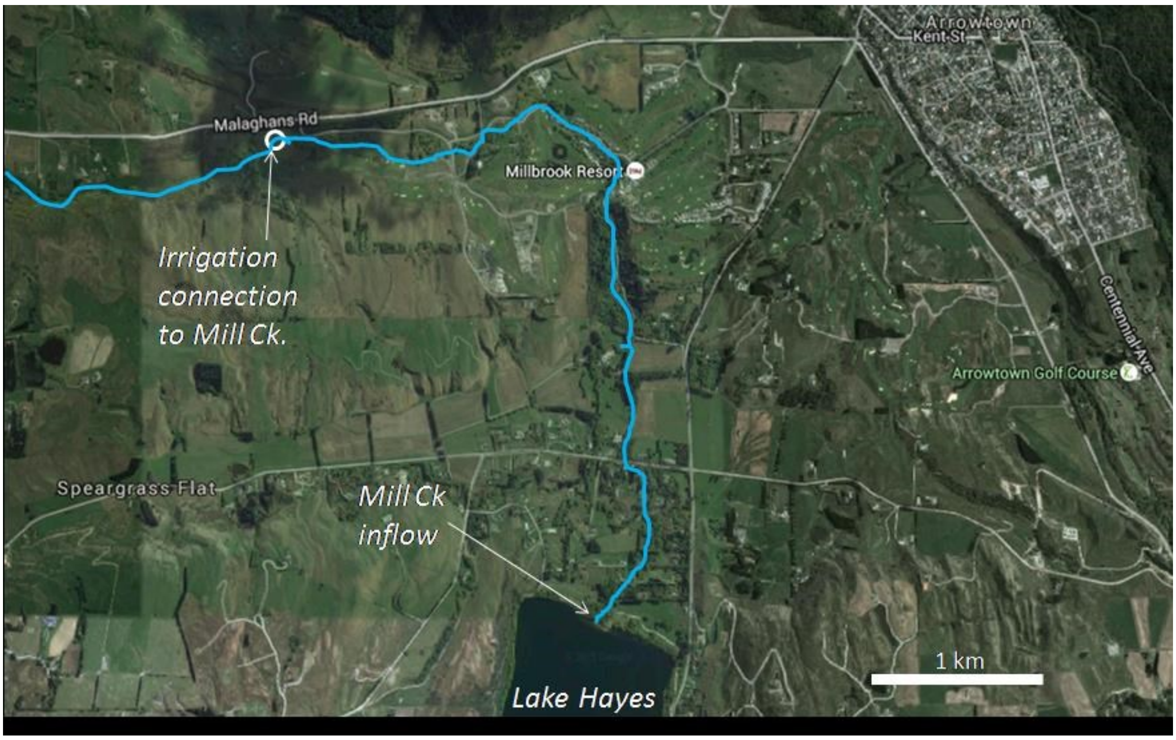

Figure 3. Map of the Lake Hayes area, showing Mill Creek and the potential connection point of the Arrow River Irrigation Scheme.

In this preliminary report, I use available data to try to answer four key questions regarding this potential restoration idea: 1. Could the augmented inflow flush displace substantial amounts of water from the lake? 2. Would the augmentation flow displace bottom water? 3. Could the augmented inflow supply enough dissolved oxygen to the bottom water to prevent its deoxygenation and, thereby, prevent P release from the sediments? 4. How much P and chlorophyll *a* could the augmented flow flush from the lake and what effect would this have on trophic state?

1. Could the augmented inflow displace substantial amounts of water from the lake?

This proposal would increase the flushing of the lake, which currently replaces its water roughly every 1.8 years (Caruso 2000). If the Arrow River water is more dilute than the lake water (with respect to phosphorus), then the flushing effect could remove some of the recycled phosphorus from the lake by displacement. The magnitude of the enhanced flushing effect would be proportional to: 1. the difference in nutrient concentrations between the Arrow River and the lake water that it displaces and 2. the amount of water available for flushing.

Recent ORC data show little difference in TP in surface and bottom waters (see main report, Fig. 8). Below, I have examined how beneficial the augmented flow could be for flushing phosphorus from the lake.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Arrow river phosphorus concentrations (Otago Regional Council data; Table 2)

3. Lake temperature profiles (University of Otago; Fig. 4)

4. Lake phosphorus concentrations from summer 2012/13 (University of Otago)

Table 1: Available water from the Arrow River Irrigation Scheme (info provided by Rob Hay).

Month	Cubic m per day	Cubic m per month	Cumulative irrigation inflow
Sept	18000	540000	540000
Oct	18000	540000	1080000
Nov	9000	270000	1620000
Dec	9000	270000	1890000
Jan	9000	270000	2160000
Feb	9000	270000	2430000
March	9000	270000	2700000
Apr	18000	540000	2970000
May	18000	540000	3510000
June	18000	540000	4050000

Table 2. Typical phosphorus concentrations of the waters of Lake Hayes (University of Otago) and the Arrow River (Otago Regional Council data from site at Morven Ferry Rd.).

Month	Lake Hayes surface water TP (μg/L)	Arrow River TP (μg/L; ORC data*)
Nov	27	14
Dec	52	9
Feb	47	7
March	116	8
May	43	9
June	69	5

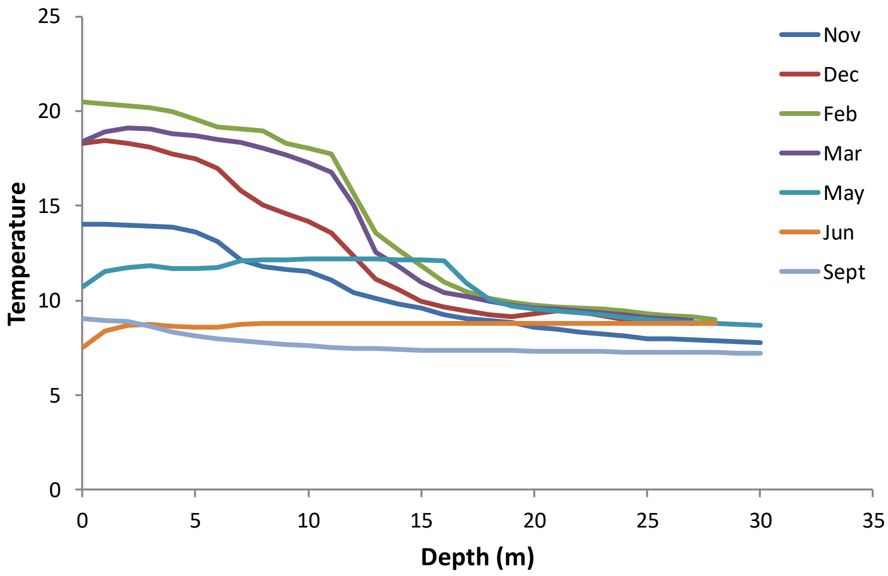

Figure 4. Lake temperature profiles from the summer of 2012/13.

Table 3 shows that the P concentration in the Arrow River is much lower than the lake P concentration of the lake, indicating that the Arrow River water would be suitable for the dilution and displacement of P-rich lake water.

Using the above information, I calculated the cumulative input of Arrow River water from September to June and compared that with the lake volume. I calculated this cumulative flushing volume as a percent of the whole lake volume.

The calculations show that the flushing effect of the Arrow River augmented inflow would displace a small percentage of the lake volume – only approximately 7% of the whole lake volume by the end of the stratified period (Fig. 5).

While these flushing effects are not substantial, they are not insignificant and could, over many years help reduce lake P concentrations and recycling. However, the addition of Arrow River water to Mill Creek could increase the loading rate of dissolved inorganic nutrients to Lake Hayes during the summer months (DSIR 1973), when these are often in very low concentrations in the surface water of the lake. Therefore, even though the concentrations of added nutrients from the proposed augmentation might be small, and the net P and N balance might be negative, it is possible that the addition of small amounts of available N and P could have a somewhat stimulatory effect on the lake's phytoplankton during summer. Therefore, before this restoration method is employed, further thought should be given to this potential stimulatory effect.

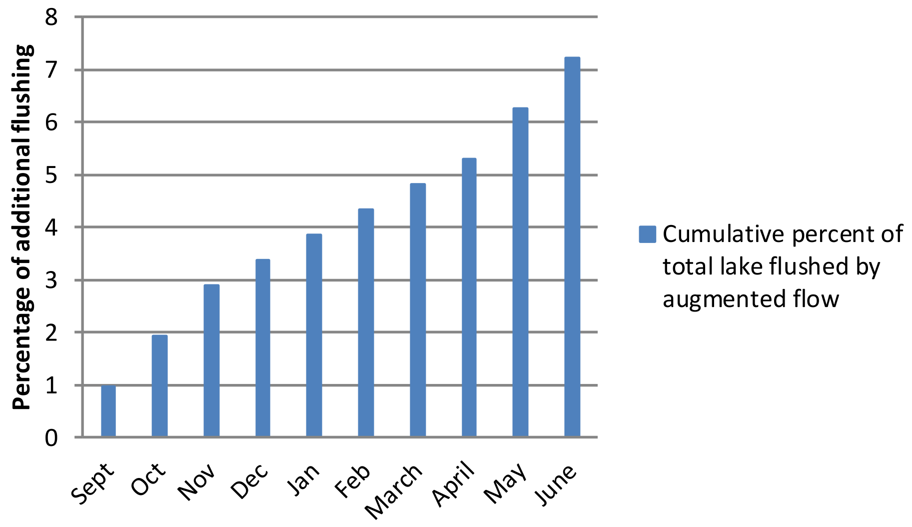

Figure 5. Cumulative proportion of the total lake water that could be flushed by Arrow River water, using the maximum amount of augmentation water available (200 L/s in shoulder seasons and 100 L/s in summer).

2. Would the augmentation water displace bottom water?

The colder the water, the denser it is (this is true down to 4°C). So, to displace the colder bottom water of Lake Hayes, the combined Mill Creek/Arrow River inflow would have to be colder than the surface layer of the lake and, ideally, it should be as cold/dense as the bottom water of the lake.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Lake temperature profiles (University of Otago; Fig. 4)

3. Mill Creek temperatures (Otago Regional Council data; Fig. 6).

I have assumed the following for these calculations:

1. The combined Mill Creek/Arrow River inflow would be the same temperature as the current Mill Creek inflow.

To test whether the inflow would be likely to plunge to the bottom layer of Lake Hayes, I compared the temperatures of Mill Creek with the temperatures of the lake, over the stratified period (Fig. 6). The data show that only toward the very end of the stratified period (in May), does the temperature of Mill Creek. approach that of the bottom water of the lake. Prior to that time, the inflow would either flow into the warm surface water or would flow between the layers (but not enter the bottom water layer).

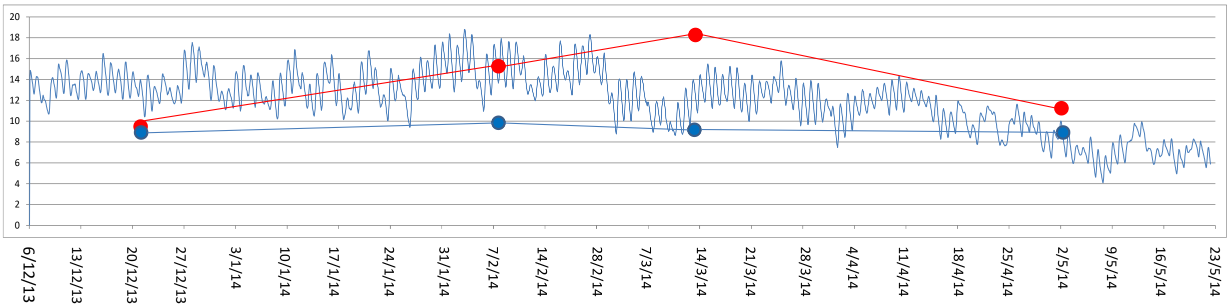

Figure 6. Temperature data for Mill Creek (blue line; 2013/14) and Lake Hayes (blue and red lines with dots; 2012/13). The blue dots show the lake bottom water temperatures and the red dots show the lake surface water temperatures. Mill Creek data were supplied by the Otago Regional Council.

Addressing the above assumption, is it possible that the temperature of the Arrow River augmented flow might lower the temperature of Mill Creek enough to allow both volumes of water to plunge into the bottom of Lake Hayes? Unfortunately, we don't have temperature data for the Arrow River at the offtake site or at the site where the irrigation water would connect to Mill Creek. This connection site is 4 km upstream from where Mill Creek enters Lake Hayes (Fig. 3), so even if the Arrow River water were substantially colder than Mill Creek, by the time it was transported from near Macetown to the Mill Creek connection site, diluted by Mill Creek and then transported 4 km downstream, any temperature benefit from the Arrow River is likely to have been lost. However, I have not been able to confirm this with data or modelling.

3. Could the augmented inflow supply enough dissolved oxygen to the bottom water of Lake Hayes to prevent its deoxygenation?

Another potential benefit of the injection of Arrow River water into the bottom waters of Lake Hayes is that the addition of oxygenated Arrow River water to the bottom waters of the lake might prevent deoxygenation of the bottom waters, maintaining P binding in the sediment of the lake.

For these calculations, I have used the following information:

1. Available Arrow River flows: 200 litres per second for September, October, April, May and June. 100 litres per second for November to March (inclusive) (Table 1)

2. Lake temperature profiles (University of Otago; Fig. 4)

3. Estimates of the volume of 1 m-thick slices of Lake Hayes (calculated from the NZ Oceanographic Institute bathymetric chart)

I have assumed the following for these calculations:

1. The combined Mill Creek/Arrow River inflow would discharge into the bottom waters of Lake Hayes
2. That the combined Mill Creek/Arrow River inflow would have an oxygen content approximating 100% air saturation (i.e., equilibration with the atmosphere).

For these calculations, I cumulatively added the mass of oxygen that would exist in the Arrow River augmented flow over the period for which water would be available. This mass of oxygen was then compared to the mass of oxygen in the bottom waters of Lake Hayes during the same period (the stratified period). Figure 7 shows that the cumulative input of oxygen is only relatively minor compared to the oxygen holding capacity of the bottom waters of Lake Hayes (indicated by the September value, when the bottom waters were mostly oxygenated). The rate of oxygen supply to the bottom waters (the slope of the line = 0.0888 tonnes of oxygen supplied per day) is also small compared with the rate of oxygen loss from the bottom waters in spring and summer (from November-February; 1.93 tonnes of oxygen consumed per day). Thus, the rate of oxygen consumption in the bottom water is 22 times greater than the rate of oxygen supply which could be contributed to the Arrow River augmentation, if it were injected directly into the bottom waters. This indicates that injecting the Arrow River augmentation flow directly into the bottom waters would not overcome deoxygenation in this lake.

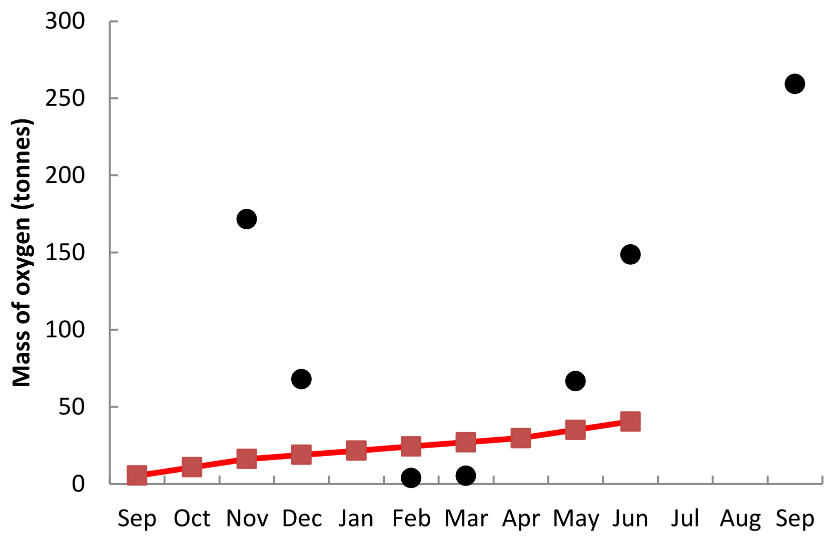

Figure 7. The mass of oxygen in the bottom water of Lake Hayes (2012/13; black dots) and the cumulative mass of oxygen estimated to be in the proposed augmented Arrow River inflow (red squares).

3. How much P and chlorophyll a could the augmented flow flush from the lake and what effect would this have on trophic state?

Displacement of surface water:

It appears from the above analysis in Section 2 that the augmented flow from the Arrow River would largely flow into the upper surface water layer of Lake Hayes. I calculated the amount of lake surface water that would be displaced by the cumulative input of Arrow River water from September to June. The volume of the surface water layer (to 12 m depth) is 31.03 million cubic metres, and the cumulative inflow from the Arrow River is 4.05 million cubic metres by the end of June. Thus, the Arrow River would displace around 13% of the lake's surface water over the stratified period.

Displacement of total phosphorus:

The average total phosphorus concentration in the surface water of Lake Hayes from September to June is 59 mg/m^3, while that in the Arrow River (at Morven Ferry) is 9 mg/m^3 (Table 2). The difference in concentration is 50 mg/m^3. When multiplied by the volume of the lake's surface layer and by the cumulative inflow from the Arrow River, respectively, the phosphorus in the lake displaced by the augmented flow would equal approximately 11% of the phosphorus content of the surface layer of the lake. This would bring the average phosphorus concentration in the surface water down from 59 mg/m^3 to around 52.5 mg/m^3, by the end of the augmentation period in June. The lake's trophic state would remain high as the boundary between mesotrophic (moderately productive) and eutrophic (productive) is 20 mg P/m^3. By these estimates of the average augmented lake phosphorus concentration, the lake would remain in the supertrophic category (48 – 96 mg P/m^3) (see Appendix 2.1). However, persistent flushing of this sort over a number of years could contribute to an improvement of the lake's trophic state.

Displacement of chlorophyll a (algal biomass):

The average chlorophyll *a* content of the surface water of Lake Hayes from September to June is estimated to be around 30 mg/m^3 (Bayer & Schallenberg 2009). We have no chlorophyll *a* data for the Arrow River, but this is expected to be quite low during moderate to low flow periods (probably not more than 2 mg/m^3 of chlorophyll *a* during the augmentation period). Again, multiplying by the volume of the lake's surface layer and by the cumulative inflow from the Arrow River, respectively, the chlorophyll *a* in the lake displaced by the augmented flow would equal approximately 12% of the chlorophyll *a* content of the surface layer of the lake. This would bring the average chlorophyll *a* concentration in the surface water down from 30 mg/m^3 to around 26.7 mg/m^3, by the end of the augmentation period in June. The lake's trophic state would remain high as the boundary between mesotrophic (moderately productive) and eutrophic (productive) is 5 mg $Chla/m^3$. By these estimates of the average augmented lake chlorophyll *a* concentration, the lake would remain in the supertrophic category (12 – 31 mg $Chla/m^3$) (see Appendix 1). However, persistent flushing of this sort over a number of years could contribute to an improvement of the lake's trophic state.

Caveats

There are a number of caveats that should be considered before employing augmentation flow from the Arrow River to help flush and, thereby, restore Lake Hayes. For example, the increased flow discharge and velocity of Mill Creek could increase stream bed erosion and reduce nutrient attenuation by stream periphyton due to the more rapid descent of water downstream to the lake. This would have the effect of increasing sediment and nutrient loads to the lake. In addition, some of the costly augmented flow could be lost to aquifer recharge in the catchment, in effect reducing the desired flushing effect. A groundwater hydrologist could advise on the likelihood of this occurring. Furthermore, as mentioned above, the augmentation flow, although low in nutrient concentrations relative to the lake, would likely add dissolved inorganic N and P to the lake during the summer months, when these nutrients are in short supply. This could stimulate phytoplankton production.

Summary

In Table 3, I summarise the information presented in this report and I show some issues to consider regarding the findings of the report. The above caveats should also be carefully considered before augmentation flow is employed for lake flushing.

Table 3. Summary of findings assessing the potential for Arrow River augmentation to speed the recovery of Lake Hayes.

Augmentation questions	Answer	Things to consider
1. Would it flush a substantial amount of phosphorus from the lake?	• Up to 11% per annum	• If internal load increases again, this could be useful if it could displace bottom water.
2. Would it naturally plunge into the bottom waters or would it flow into the surface waters of the lake?	• Naturally, the inflow is likely to be less dense than the cold bottom water, meaning it will flow over top of the bottom water, displacing and flushing surface water only.	• This conclusion assumes that the combined Mill Creek/Arrow River inflow would not be colder/denser than the current Mill Creek inflow. Temperature data are lacking to test this assumption.
3. If it were injected into the bottom waters, could it supply enough oxygen to prevent the bottom water from losing all of its oxygen during the stratified period?	• No, the oxygen augmentation effect is small compared to the oxygen demand of the bottom waters of the lake.	• In the calculations, I didn't include the oxygen that could also be supplied by the Mill Creek inflow. • Assuming that the Mill Creek discharge is around the same as the Arrow River augmented flow, and assuming that Mill Creek flows could also be harnessed and injected into the bottom waters of the lake, then the oxygen supply rate that I calculated would be doubled. • Injecting both these inflows into the bottom waters would still be insufficient to prevent deoxygenation of the bottom waters because the oxygen demand is around 10 times greater than the combined supply rate would be.
4. Could the augmented flow displace substantial amounts of phosphorus and chlorophyll *a* from the lake?	• The augmented flow would reduce the average surface water phosphorus concentration in the period from September to June by 11% and the chlorophyll *a* concentration by 12%. Neither of these reductions would reduce the trophic status of the lake from its current supertrophic condition.	• Persistent flushing of around 11% of the phosphorus and 12% of the phytoplankton from the lake per year could contribute to a speeding of the lake's recovery if maintained for a number of years.

Acknowledgements

I thank Rob Hay (Friends of Lake Hayes) for providing information on the available flows from the Arrow River irrigation scheme and for other background information about the proposed augmented inflow. I thank Dean Olsen from the Otago Regional Council for providing data on Mill Creek and

Arrow River temperatures and water quality. The New Zealand Ministry of Business, Innovation and Employment have funded this work via a subcontract with NIWA.

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Appendix 2.1

Attribute ranges for different lake trophic levels. From Burns, N, Bryers, G, & Bowman, E (2000).Protocols for monitoring trophic levels of New Zealand lakes and reservoirs.Available from www.mfe.govt.nz.

Lake type	Trophic level	Chla ($mg\ m^{-3}$)	Secchi depth (m)	TP ($mg\ m^{-3}$)	TN ($mg\ m^{-3}$)
Ultra–microtrophic	0.0–1.0	0.13–0.33	31-23.5	0.84–1.8	16–34
Microtrophic	1.0–2.0	0.33–0.82	23.5-14.8	1.8–4.1	34–73
Oligotrophic	2.0–3.0	0.82–2.0	14.8-7.8	4.1–9.0	73–157
Mesotrophic	3.0–4.0	2.0–5.0	7.8-3.6	9.0–20	157–337
Eutrophic	4.0–5.0	5.0–12	3.6-0.7	20–43	337–725
Supertrophic	5.0–6.0	12–31	0.7-0.3	43–96	725–1558
Hypertrophic	6.0–7.0	>31	<0.3	>96	>1558

Appendix 3: A rough Lake Hayes alum dosing estimate

This Appendix is based on a report that was prepared by John Quinn, Max Gibbs and Chris Hickey (NIWA) in 2012.

The most common chemical method for capping phosphorus in lake bed sediment is to distribute alum (aluminium sulphate) solution into the lake, which flocculates and settles to the lake bed where it binds free phosphorus in the sediments, even under anoxic conditions. During the process of flocculation, alum also collects algae and suspended solids, clarifying lake water. Under conditions of pH > 6.5, alum can bind sufficient phosphorus to create conditions where restricted P availability limits algal growth. Alum applications have been successfully used in Lakes Okaro (Paul et al. 2008) and Rotorua (Hamilton et al. 2015) in the Bay of Plenty to reduce phosphorus concentrations in lake water.

Because of alum's flocculating capability, it is best used when the bottom waters are anoxic and phosphorus released from the sediments has accumulated to its maximum level (toward the end of the stratified period in Lake Hayes). As a sediment capping agent, the effect of a single appropriately-dosed treatment can last for 5 years and sometimes up to 20 years (Welch & Cooke 1999). Studies on toxicity of aluminium derived from alum to sediment-dwelling fauna and to fish indicate that as long as the lake pH buffering (i.e. alkalinity) is sufficient to preclude acidification, then toxic effects are minimal (Tempero 2015).

The least expensive way to deliver alum to lakes is to add it to inflowing tributaries. This will be most effective if the tributaries are colder than the lake water and carry the alum directly to the bottom waters where dissolved reactive phosphorus concentrations are highest and where phosphorus cycling is strongest. This is the approach used to deliver alum to Lake Rotorua (Hamilton et al. 2015).

Below is a rough calculation of the estimated cost of an alum treatment for Lake Hayes. The amount of P to be sequestered in this calculation is based on the maximum dissolved reactive phosphorus concentration at end of stratification in recent years (c. 300 ppb; M. Schallenberg, unpublished data) multiplied by the hypolimnetic (pertaining to the deep water layer) volume (28,937,495 m^3). This calculates a total hypolimnetic dissolved reactive phosphorus amount to be 8,681 kg, equating to 4.15 g $P/m^2$of hypolimnetic lake-bed area. When the top of the hypolimnion (deep water layer) is at 10m depth, around 78% of the lake bed is within the hypolimnion.

At a pH of 7 the aluminium-phosphorus binding is < 50%. If we conservatively assume 20% binding efficiency, then we will need an Al:P ratio of 5. Alum comes as 666.42 g/mol (octadecahydrate) containing 2mol of Al, which is 54g/mol, so the amount of alum needed is 535,343 kg. Alum comes in an aqueous solution of 47% alum, so the volume needed for the treatment of Lake Hayes would be 856,412 L- equivalent to ca. 40 standard (22,000L) water tanks full or ca. 20 tanker-trailer loads.

At a cost of alum solution at $1000/tonne, the cost of the alum for a Lake Hayes treatment under the above assumptions would be $535,343, which would provide an alum dose to the hypolimnetic sediments of 200 g alum per m^2 of hypolimnetic lake bed.

Dosing would occur during the stratified period (mid-October to May) by addition to the Mill Creek inflow stream which would ideally carry the alum into the bottom waters. Lake currents would provide further mixing of the alum floc around the lake. Studies carried out by NIWA in 2011/12 confirmed the existence of sufficient hypolimnetic currents to distribute the alum throughout the hypolimnion.

The lake is well buffered, so buffering the alum additions to avoid pH drops below 5 (which would cause concern regarding aluminium toxicity) would not be necessary.

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Appendix 4: Catchment management to restore and protect Lake Hayes

Importance of the Mill Creek catchment

Prior to major catchment drainage operations in 1961, there had been no reports of discoloured waters flowing into Lake Hayes and the bottom waters were aerobic during summer with little internal P release. After the wetland drainage and channelization works in the early 1960's, growing pressures from further catchment alterations and land use conversions continued and lake health further declined into the 70's and 80's. This prompted investigations into catchment nutrient loading and ways to mitigate the nutrient increases observed. The vast majority of nutrients enter the lake through the Mill Creek catchment (ORC 1995), with around 80% of the P load bound to soil particles which were historically mobilised through channel cutting and removal of the catchment wetlands which acted as sediment sinks. The high historical catchment P load had settled in the lake to become the internal P load which greatly contributed to the decline and maintenance of poor lake health seen over recent decades. Previous publications have outlined the importance of reducing nutrient concentrations in Mill Creek and noted this as a requirement for the successful restoration of Lake Hayes (Robertson 1988; ORC 1995).

Bayer & Schallenberg (2009) found nutrient levels in Mill Creek had decreased from the 1980's to 2009 however, more recent data (2005-present) available on the LAWA website, indicates the improving water quality trends in Mill Creek have since stabilised and may be, in some cases reversing. Fore example, summer nitrate and ammonia concentrations in Mill Creek appear to have been increasing since 2005 along with *E. coli* counts (Fig. 1). Compared with other upland rivers in New Zealand, levels of *E. coli*, turbidity, TN and nitrate are worse than the average upland river (LAWA 2017). The sensitivity and importance of this lake, together with the current and projected population growth rate and associated land use changes in the area, should recommend better than average water quality in the Mill Creek catchment.

Previous suggestions for catchment management

Robertson (1988) looked at the Lake Hayes catchment in detail, describing historical land use change and outlining potential mitigation measures that would lead to reduced inputs of P into the lake. Most of these recommendations involved controlling catchment landuse practices such as reducing fertiliser runoff, controlling channelling operations and managing future development in the catchment to ensure a reduced external P load to the lake. In addition, Robertson (1988) suggested many of what we now call on-farm best management practices (BMPs) such as reducing fertiliser use and establishing stream bank buffers. Improvement of land use practices in the Mill Creek catchment was recommended by the author to be highly important for the restoration of Lake Hayes.

In 1995 the Otago Regional Council (ORC) developed a Lake Hayes Management Strategy with the overall goal being to 'to improve the water quality of Lake Hayes, to achieve a standard suitable for contact recreation year round and to prevent further algal blooms' (ORC 1995). The strategy highlighted the major catchment issues affecting water quality and put in place relevant policies as well as outlined ambitious actions the ORC would take to reduce the P load in the catchment. Examples of these actions included negotiating with landowners around Mill Creek to establish riparian zones, advocating and assisting with the protection and re-establishment of wetlands and encouraging sustainable land use in the catchment, among many others. Some successes have since been documented, an example being the decommissioning of septic tanks in the catchment as encouraged in the strategy, however it is unknown how many actions have been carried out and how many policies have been implemented. Section 1.9 of the management strategy stated that reviews of the strategy will be undertaken at 5 year intervals, including an assessment of any changes in the catchment P load, however no notes on these can be found. It would be useful to document which policies and actions outlined in the strategy have been implemented and which are still required, to assess both the success of the management strategy to date and what remains to be done in the future, particularly in light of the rate of development in the catchment.

Wetland restoration/re-establishment

The two major catchment management directions actions recommended for Lake Hayes are wetland restoration/re-establishment, and on-farm BMP's (Robertson 1988; ORC 1995; Bayer 2009; Ozanne 2014). Wetland re-establishment was discussed by Robertson (1988) who noted the draining and channelization of numerous wetlands in the catchment during the 1960's led to a decrease in the sediment retention and buffering capacities of the Mill Creek catchment. The option for wetland restoration in the catchment was looked into to recover some of these lost ecosystem services and the cost was estimated at around $50,000 (Robertson 1988).

However, the Lake Hayes Management Strategy (ORC 1995) mentioned a report commissioned by the ORC looking into the viability of wetland re-establishment in the catchment which found it to be unfeasible. The main reasons given were the long calculated retention time required to settle out sediment bound P and the large areas required in order to reduce the catchment P load by a significant amount (ORC 1995). The study reportedly stated that the largest site available for wetland re-establishment was 93ha of land which was deemed non advantageous due to its position in the upper catchment. A review of the methodology of the report, particularly in identifying P loss hotspots in the catchment, and therefore how much can be removed by targeting different subcatchment areas, would be useful. Caruso (2001) filled some of these knowledge gaps by measuring P loads at multiple points in different subareas of Mill Creek to determine P hotspots, even identifying these down to the individual property level. Interestingly the author found that the O'Connell Creek catchment was a hotspot of P release (Figure 2) and it was suggested that the results of the investigation could inform more targeted mitigation actions in the catchment (Caruso 2001).

Best Management Practices (BMPs)

Best management farming practices include actions such as managing land for erosion and leaching, managing to minimise losses of sediment and nutrient to waterways, and stock exclusion from waterways. Ensuring on-farm BMPs are employed in the catchment is an obvious requirement for successful lake restoration. Using the results from Caruso (2001), a strategy for targeting BMPs, particularly in subareas or even on properties which are contributing high P loads would be highly beneficial. BMPs for lifestyle blocks, golf courses and activities that disturb ground in the catchment should also be communicated to relevant land owners and developers.

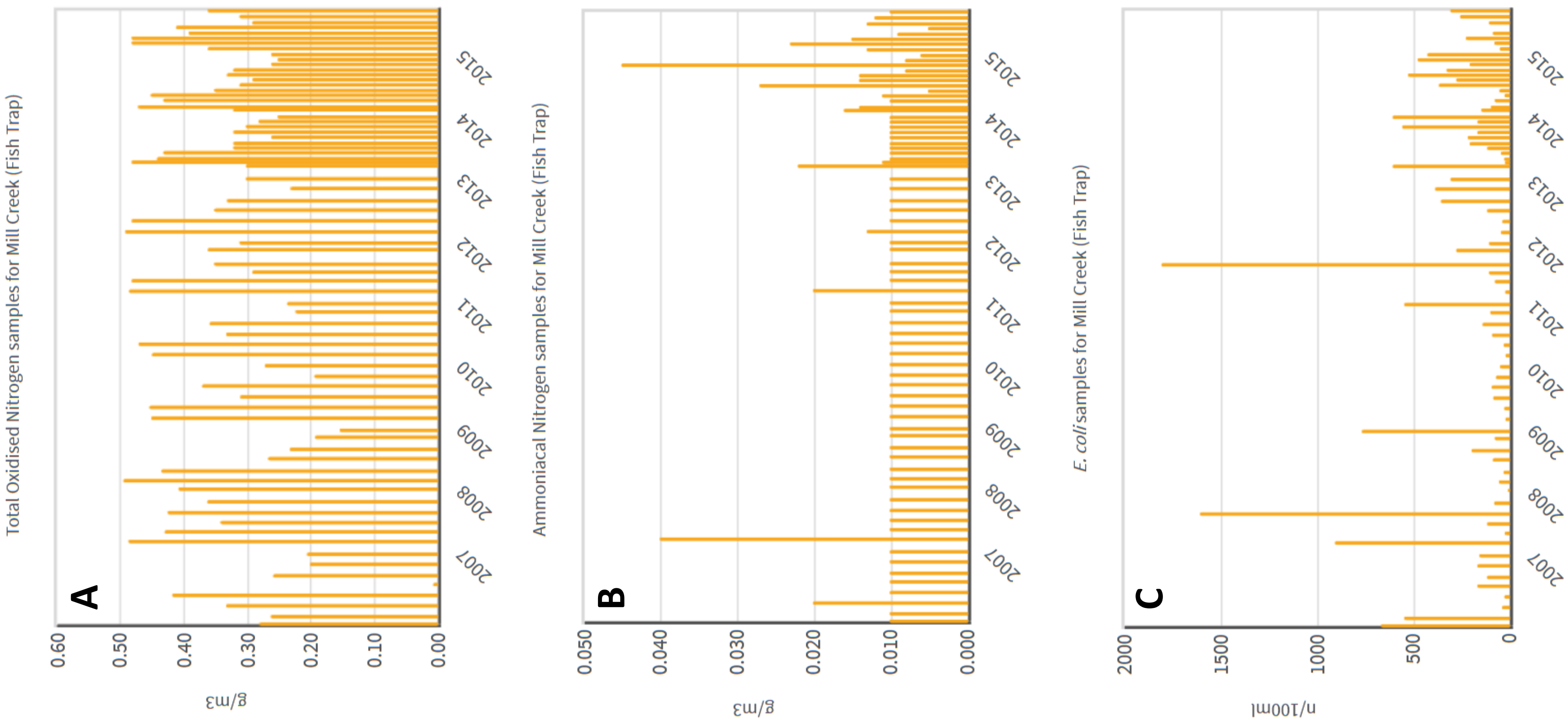

Figure 1. Nitrate (A), ammonium (B) and *E. coli* concentrations (C) in Mill Creek from 2006-present. Summer nitrate concentrations (the regular periods of lowest nitrate concentrations) appear to have been increasing over the sampling period (A). In addition, recent ammoniacal N (B) and *E. coli* concentrations (C) may also be increasing. From LAWA website (https://www.lawa.org.nz/explore-data/otago-region/river-quality/clutha-river/mill-creek-(fish-trap)/)

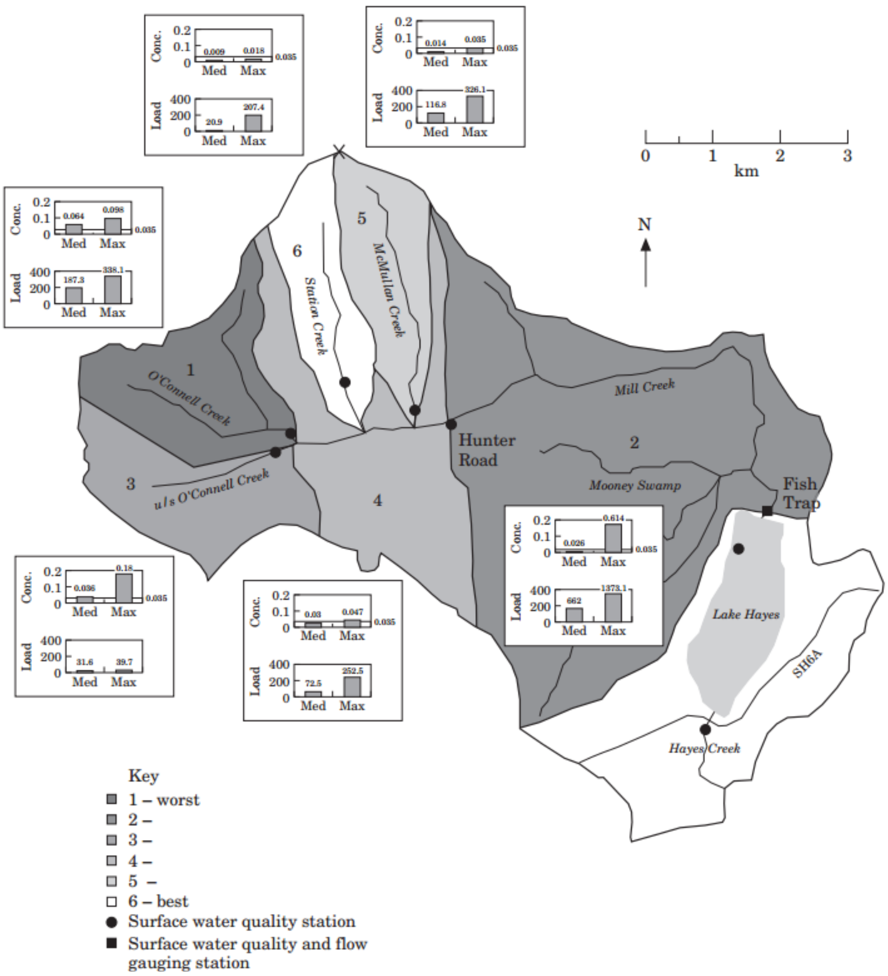

Figure 2. Results from Mill Creek catchment subarea phosphorus targeting in Caruso (2001), showing catchments ranked from highest to lowest P contribution. Taken from Caruso (2001).

A lake catchment management plan to ensure continuing reductions in nutrient and sediment losses from the catchment.

In order to ensure that landowners in the catchment minimise nutrient and sediment concentrations in streams and springs draining into Lake Hayes, a collaborative, community-driven lake and catchment management plan could be developed and implemented by undertaking the following:

i. Identify iwi, stakeholders, industries, scientists and other interested parties.
ii. Review the ORC (1995) Lake Hayes Management Strategy and its implementation.
iii. Undertake a catchment-wide N, P, sediment and *E. coli* survey based on the design of Caruso (2001) to identify current hotspots of contaminant contributions to the lake.
iv. Determine the feasibility of setting nutrient caps on the catchment.
v. Collaboratively develop a lake/catchment management plan with community participation at all stages.

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