Lake levels and water abstraction limits for Lake Wanaka and Lake Whakatipu

Prepared for Otago Regional Council

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By: Ian Hawes, Aquatic Research Solutions Ltd.

Summary

The contract

Aquatic Research Solutions Ltd has been asked to provide information to assist Otago Regional Council in developing plans to guide abstraction of water from lakes Wanaka and Whakatipu, to minimise risk of impact on ecosystem integrity.

The purpose of this report is to provide guidance on the current dynamics of water level in lakes Wanaka and Whakatipu, the ecological significance of water level and guidance on the potential impacts of future abstraction on these values. Specifically, this report will focus on:

1. summary level statistics for lakes Wanaka and Whakatipu, with trend analysis, together with a commentary on the implications of change for in-lake biological communities,
2. developing a simple calculator that allows the potential effects of differing rates of abstraction applied to historic scenarios to allow a risk assessment of various abstraction scenarios and to provide recommendations on what may be acceptable,
3. the implications of lake level manipulation via in-lake consumptive abstraction on flows in the Kawarau and Clutha/Mata-Au rivers.

Water level regimes

The water level regimes of lakes Wanaka and Whakatipu are dominated by event-driven water level changes, overlain on a weak seasonal pattern with a winter minimum. We use median as a measure of central tendency, and inter-quartile range (the range over which the central 50% of observations occurs) and 5-95 percentile range (within which 90% of observations occur) as metrics describing variation about the median. Level variation is approximately 1.5 x higher in Lake Wanaka than in Lake Whakatipu. Neither lake showed a statistically significant monotonic trend in lake level over time. Both lakes showed variability in median level and interquartile range between years, again this was greatest in Lake Wanaka .

Annual median water levels, averaged over the 1963-2023 water years were 277.22 ± 0.19 m in Lake Wanaka and 309.88 ± 0.12 m in Lake Whakatipu. Corresponding annual interquartile and 5-95 percentile ranges were 0.68 ± 0.18 m and 1.66 ± 0.36 (Lake Wanaka) and 0.40 ± 0.12 and 0.99 ± 0.25 (Lake Whakatipu). The mean annual

Ecological significance of water level range and setting criteria

The potential impacts of a change to water level regime that need to be considered when assessing how much allocation to abstraction can be made without compromising freshwater values potentially include:

- water quality and clarity,
- shoreline erosion
- marginal wetlands,
- connectivity to tributaries,
- exceptional littoral zone communities, including deepwater bryophytes
- river flow downstream.

After consideration of these needs, and the existing water level fluctuation regimes in the two lakes, criteria were developed to guide allocation setting. These were:

1. Outflow discharge should not be lowered more than 10% from the current regime to protect downstream flow-dependencies.

2. Periodicity should not be affected – new regimes should neither increase nor decrease frequency of flood peaks to safeguard varial zone and wetland communities.
3. Average monthly interquartile range and 5-95%ile range should not change by more than 5%, to safeguard varial zone, hydrologically linked wetland communities and tributary connectivity.
4. Extensive shifts in median, quartile and 95%ile level should be avoided, to maintain the lake within its current bounds and minimise shoreline change and sustain connectivity. A 20 mm long term change is suggested as likely to cause minimal adverse impact given natural variability.
5. Lower 5%ile of lake level should not decrease by more than 20 mm to protect groundwater levels for wetlands, sustain connectivity, avoid erosion and damage to submerged littoral zone communities.

Of these, only criterion 1 is based on an established standard, and all others are specific to this investigation. Because these criteria are untested, a conservative approach in limit setting was taken and we advocate significant discussion with stakeholders, in particular with Tangata Whenua. It is pertinent to note that projections of future hydrology under a range of climate change scenarios are for increased flow in the catchments of both lakes, adding conservatism to these criteria. Monitoring to confirm that desired values are being sustained is recommended.

Simple models of water level change

Day-to-day changes to water level are determined by the balances of inflows and outflows. In addition to the obvious overland inflows, water enters the lakes via groundwater and direct precipitation. Water leaves both lake via their main outflows the Clutha/Mata-Au River and Kawarau River, but also via evaporation from the water surface and groundwater. A simple description of the daily water balance of a lake, as change in volume, can be given as:

$$\text{Flow}_{(\text{inflow-outflow})} + \text{Groundwater}_{(\text{inflow-outflow})} + \text{Atmosphere}_{(\text{precip-evap})} + \text{Human}_{(\text{discharge-abstract})}$$

Change in lake level can be estimated from change in volume where the surface area of the lake is known, ideally using a relationship that estimates lake area from lake level as sloping shores affect this relationship.

Neither lake Wanaka nor Whakatipu have comprehensive data to allow a complete water balance model to be produced. Instead, a model was developed that exploits the long record of level in both lakes and allows the impacts of water abstraction on lake level to be estimated without a comprehensive hydrological approach. Several approximations are required, and the approach is limited to addressing the question “what effect would an additional abstraction have had on historic daily lake level, if nothing else were to have changed?”.

Briefly, the historic level record was used to estimate; D - the daily average outflow (well predicted by lake level), ΔV - the daily change in volume of water in each lake (which required an estimate of lake area) and I, the daily sum of all other inflows and outflows (as $I = D + \Delta V$). Additional abstraction was added to outflow, allowing the effect on ΔV and hence lake level to be estimated. We used the approach to test a range of abstraction scenarios to determine which would accommodate all criteria.

Scenario testing

The model hindcasting lake level included an estimate of discharge with additional abstraction. In consultation with Otago Regional Council staff, two primary constant abstraction scenarios were selected for modelling, 2 and 4 $m^3\ s^{-1}$. An additional scenario was run for Lake Wanaka with a 3 m^3 s^{-1} abstraction rate. A conditional model that reduced abstraction rate from 4 to 2 m^3 s^{-1} when lake level fell below median was also examined.

All scenarios met the criterion of no more than a 10% reduction in lake discharge at any time.

All scenarios met the criterion of no effect on water level periodicity or flood peak frequency.

All scenarios met the criterion of no more than a 5% effect on interquartile range.

All scenarios met the need for a reduction in lake level of less than 20 mm for Lake Whakatipu, but continuous 4 m^3 s^{-1} abstraction from Lake Wanaka breached this requirement. The lower continuous or the conditional abstraction scenarios were both compliant for Lake Wanaka.

Conclusion

Removal of water from a natural lake or its upstream catchment will always lower its water level and reduce outflow volume. The impact of this on lake ecosystem function depends on the scale of the effect, its timing, and the natural variability to which the lake ecosystem has acclimated. In this report we show that the impact of abstraction scenarios is likely reduce water level on a cm scale, and have little impact on level variability. Given that natural within-year water level variability in the lakes is on m scale, and natural inter-annual variability in water level is on dm scales, we suggest that lakes could accommodate the reduction in the overall level of the lakes with little measurable impact on lake ecosystems, connected wetlands or shoreline processes. However, should the increased abstraction be agreed to, targeted monitoring to ensure that this is indeed the case would be advisable.

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Introduction

The development of plans to guide the management of land and freshwater, within the spirit of Te Mana o te Wai requires consideration of the needs of freshwater ecosystems, and the extent to which use of such systems to support life and enterprise can be accomplished without compromising those needs. Multiple threats current challenge freshwater ecosystem values, and across Aotearoa New Zealand Almost half of the monitored lakes above 1 ha in size are in poor or very poor state (Ministry for the Environment & Stats NZ 2023). For those lakes, rehabilitation is required. For lakes where ecosystem values are currently very high, the challenge is to develop policy with respect to exploitation that have minimal risk of impacting Te Mana o te Wai.

Aquatic Research Solutions Ltd has been asked to provide information to assist Otago Regional Council in developing plans to guide usage of two critically important lakes, Lakes Wanaka and Whakatipu, to minimise any risk of impact on ecosystem integrity from water abstraction. Based on the national metrics of Trophic Level Index (TLI) and Lake SPI, these two lakes currently have very high water quality, and high ecological integrity, though the expansion of *Lagarosiphon major* and *Elodea canadensis* in Lake Wanaka appears to be a potential threat to the latter index. *L. major* has yet to be detected in Lake Whakatipu. Both lakes are microtrophic (low nutrient) lakes (TLI = 0-2), with correspondingly clear water that support extensive littoral zones rich in native biodiversity, including iconic deepwater bryophytes (de Winton & Beever, 2004) that tend to be indicators of persistent high water clarity and low disturbance. Discharge from neither lake is currently regulated by a dam, though water is extracted from both to service local populations.

The purposes of this report are to provide guidance on the current dynamics of water level in lakes Wanaka and Whakatipu, with specific reference to the ecological significance of water level and to provide guidance on the potential impacts of future abstraction on these values. Specifically, this report will focus on:

4. summary level statistics for lakes Wanaka and Whakatipu, with trend analysis, together with a commentary on the implications for in-lake biological communities,
5. developing a simple calculator that allows the potential effects of differing rates of abstraction applied to historic scenarios to allow a risk assessment of various abstraction scenarios and to provide recommendations on what may be acceptable,
6. the implications of lake level manipulation via in-lake consumptive abstraction on flows in the Kawarau and Clutha/Mata-Au rivers.

Level variability in uncontrolled lakes

Many processes, acting on a range of time scales, impact the water levels of lakes. Short term variations are driven by, waves, wind set-up and seiching that redistribute water within the lake basin. Longer term variability comes with seasonal and storm-driven changes in the balance between inflows and outflows. Water level in lakes in areas with highly seasonal rainfall, or where winter precipitation is largely as snow, tend to show strong seasonal variability in level due to the seasonal change in inflow volume. For example, in Lake Constance, a pre-alpine Swiss lake, water level is minimal at the end of winter, but increases rapidly through summer as snow melts. The annual water level range of ~1.5-2 m primarily reflects this seasonal change (Figure 1a). In regions where rainfall is less seasonal, rainfall events themselves can come to dominate water level variability. Such event-driven dynamics is more typical of New Zealand alpine lakes (Figure 1 b).

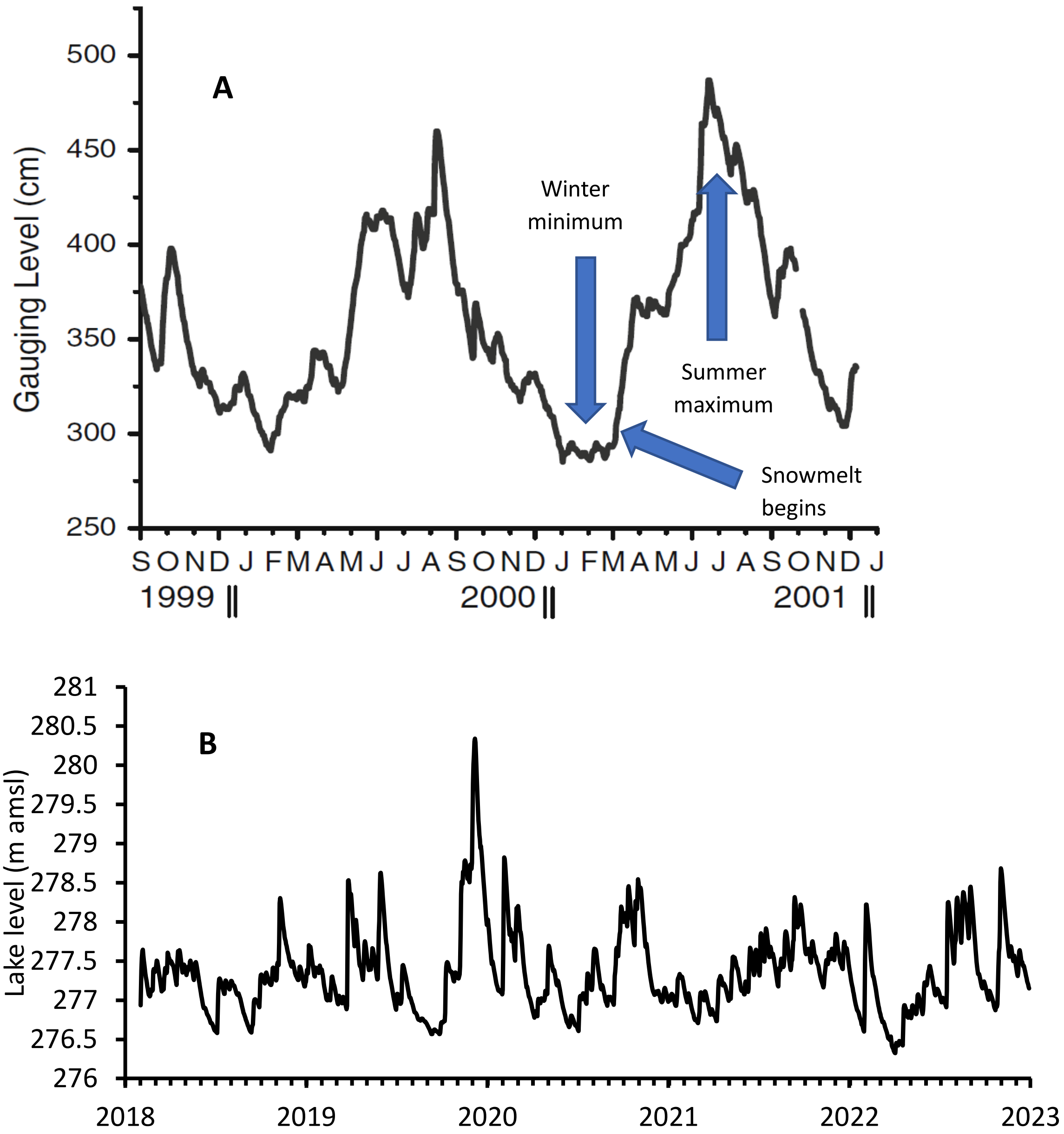
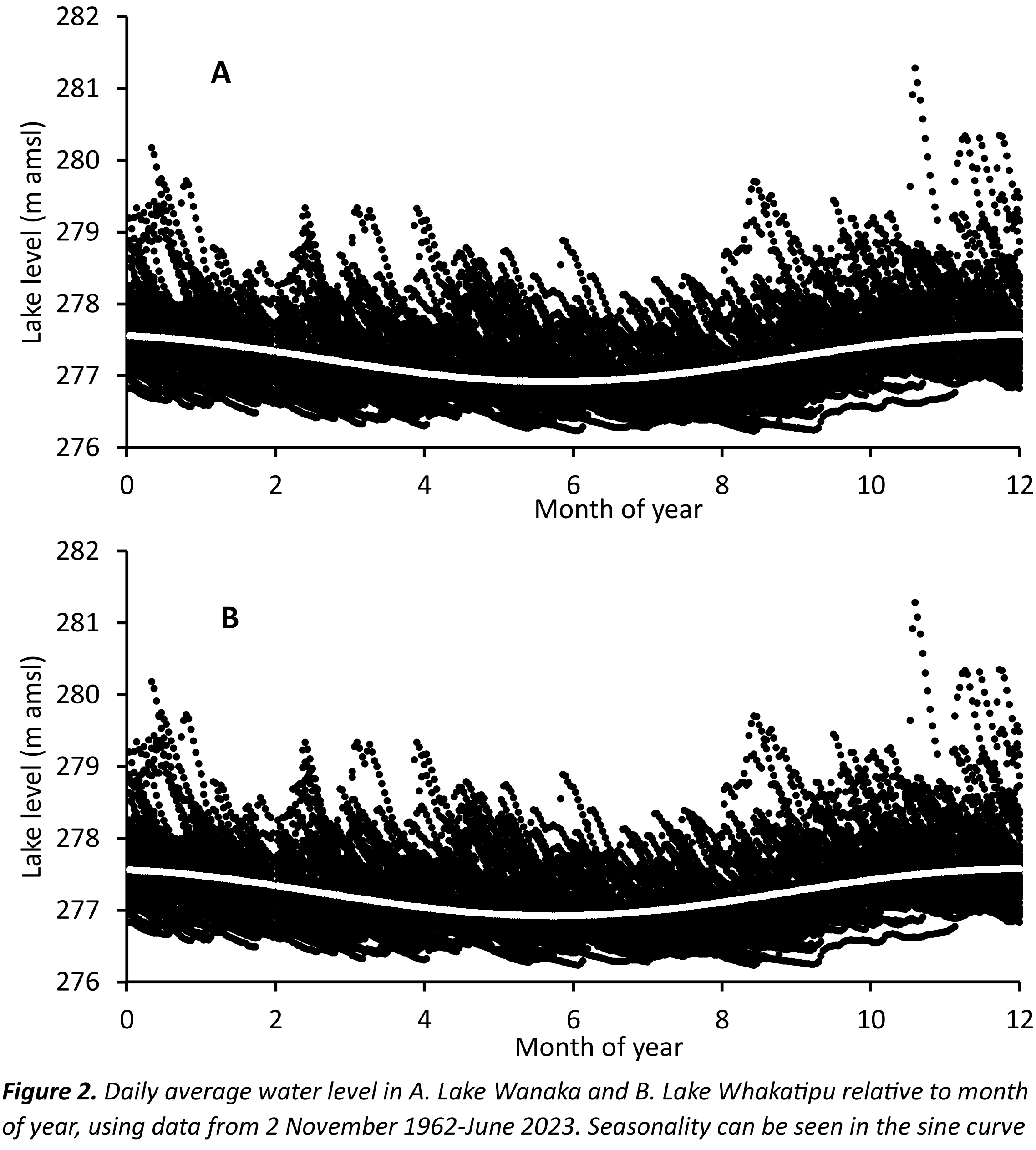


***Figure 1**. Changes in the water level of A. Lake Constance, Switzerland, where a distinct summer-winter cycle is evident (after Baumgärtner et al., 2008) and B. Lake Wanaka, New Zealand where no strong seasonal signal can be seen (Data from ORC).*

An agreed approach for describing water level in lakes is currently absent, not least because of the differences in drivers of water level variance regime between lakes. Where water level is highly seasonal, a measure of the central tendency of water level (median, mode or mean) is not a useful concept, as this is simply a level through which the lake passes, not one about which it oscillates on a regular basis through the year. In such lakes the reference level is often the long term mean low water level.

A measure of central tendency, about which level fluctuates, has more meaning for lakes with low seasonal variability and more event-driven variation, such as Lake Wanaka (Figure 1b). The term *varial zone* is then frequently used to describe the part of such a lake that is alternately flooded and dry, though there is currently no standard that defines the upper and lower limits of the varial zone. Lakes Wanaka and Whakatipu do show seasonal water level, with a winter minimum (Figure 2), but short-term variability dominates over long term (Figure 2), and from here discussion will be confined to this specific type of lake.



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Ecological significance of water level variability.

Wate level can have particularly strong impacts on the littoral zone, defined as the part of a lake within which rooted vegetation can be found. This zone can be disproportionately important in supporting biodiverse communities in clear, oligotrophic New Zealand lakes (James et al., 2000; Weatherhead et al., 2001; James & Graynoth, 2002; Kelly & Hawes, 2005). In such lakes the benthic vegetation can be profuse, and provides a concentrated food resource, coupled to a structurally complex refuge habitat that supports not only plants but also invertebrates and native an exotic fish. This part of the lake is that most affected by water level change. In New Zealand it is often divided into a series of overlapping depth-dependent vegetation zones (Figure 3). The depths occupied by these vegetation types are defined by aerial and wave exposure, and minimum light requirements (Hawes et al., 2003).

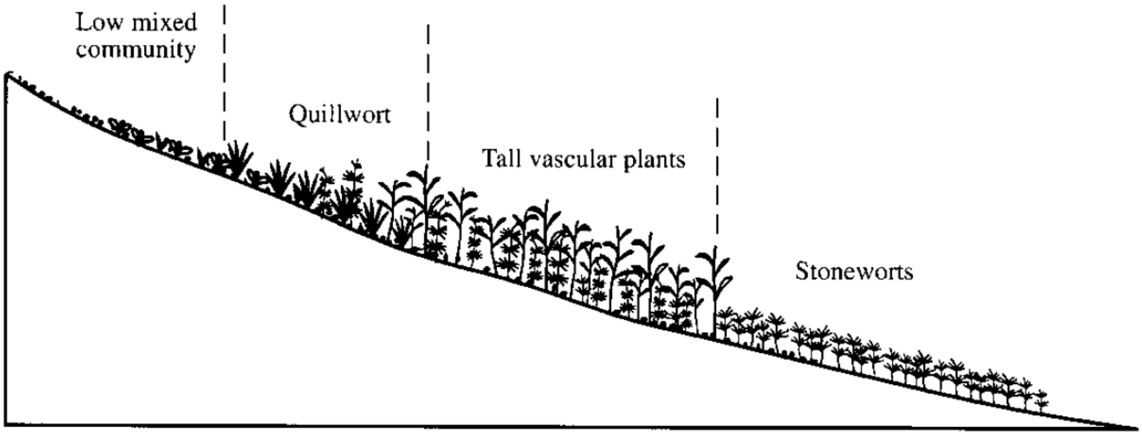

Figure 3. *A stylised vegetation profile of a clearwater Aotearoa New Zealand lake (after Hawes et al 2003). In lakes Wanaka and Whakatipu, a diverse bryophyte community extends below the stoneworts (de Winton and Beever, 2004).*

Within, and extending just below, the varial zone is the *native turf community*, which is tolerant to episodic air exposure, is comprises a diverse group of low growing, rhizomatous native taxa tolerant of a degree of wave exposure and often flowering when emerged. Species growing in this specialist environment need to tolerate alternating submersion and emersion, along with exposure to wave action. At its upper end, the turf grades into terrestrial species that are tolerant of occasional inundation. The richness of this community tends to increase with the vertical range of water level, but declines when air exposure exceeds 30 days (Riis & Hawes, 2002).

Overlapping and below the turf is the native aquatic fern *Isoetes alpinus* (quillwort), which is more erect than the native turf and less tolerant of wave action and emersion. Its upper limit is set by wave exposure and it's lower limit by its need for high irradiance and increasing competition from tall-growing angiosperms (Hawes et al., 2003).

Quillwort thus grades into the *tall vascular* zone at its lower margin, a vegetation that contains a number of native milfoils (*Myriophyllum* spp), pondweeds (*Potamogeton* spp) and other tall-growing species (e.g. *Utricularia*). This zone often also includes non-native taxa, including

Lagarosiphon major and *Elodea canadensis*, both of which are present in Lake Wanaka and Lake Whakatipu (the latter has recently received *Lagarosiphon* and eradication is being attempted). These tall-growing taxa are vulnerable to strong wave action, which sets their upper depth limits, while the lower depth extension appears to be set by irradiance (Hawes et al., 2003).

Stoneworts (macroscopic characean algae) are another native-dominated, species diverse community that extends below the tall vascular plants to a depth set by their ability to harvest sufficient light to persist (Schwarz et al., 1996). Below the stoneworts, bryophytes (mosses and liverworts) have still lower light requirements and when undisturbed by browsing fish and invertebrates, can extend to greater depths. Lakes Whakatipu and Wanaka both have well developed, species diverse bryophyte communities, which are recognised as exceptional biodiversity elements and indicators of high lake water quality (de Winton & Beever, 2004).

All of these vegetation zones (except bryophytes) were looked for and confirmed present in the most recent vegetation survey of lakes Wanaka and Whakatipu (NIWA, 2021). While the zones are defined by their vegetation, they also support distinct animal populations (Kelly & McDowall, 2004). The shallow, wave swept area often has an invertebrate fauna similar to that of cobble-bedded rivers, including mayflies, caddis and, in some cases, stoneflies. Such larvae can be expected to tolerate short-term emersion by retreating down-slope or into the interstitial water in the coarse substrate, as they do in rivers during low-flow events. Invertebrate communities in deeper water are increasingly lake-oriented, with snails, chironomids and purse caddis dominating tall vegetation. The richest and most abundant invertebrate fauna tends to be associated with the stoneworts (James et al. 2000).

Consistent with the abundance of invertebrate taxa that constitute a major part of their food supply, many native fish depend on littoral zones for significant parts of their life cycles (Kelly & McDowall, 2004; Kelly & Hawes, 2005), as do some introduced salmonids (James & Graynoth 2002). The assumption that the vegetation zones are thus useful indicators of multiple ecological values is supported by the invertebrate and fish faunas.

In addition to direct impacts on in-lake communities, water level variation can also affect habitats that are hydraulically linked to lake level. Specific issues here are effects on water table level for lake edge wetlands, which with some lag tracks that of the lake itself, and access to tributaries that are important for spawning fish. Compared to littoral zone ecology, the significance of these effects in uncontrolled water bodies, as opposed to hydro-lakes, has been little studied in Aotearoa New Zealand.

In summary, water level can have direct effects on the ecologically important littoral communities. At the shallow end, this is via the extent and frequency of wet-dry cycles and through changes in water depth that effectively increase the vertical extent of wave action. Extensive changes in lake level can affect the light environment, both by affecting the depth of water and, where shoreline erosion is increased at low lake levels, increased water turbidity.

Additional impacts on lake-linked ecosystems are possible by changing the connectivity with lake tributaries and marginal wetlands. Sustaining the ecologically important littoral and lake margin communities thus requires that any activities that can impact on water level are managed to minimise this effect. To this end, the remainder of this report considers the current water level regimes in lakes Wanaka and Whakatipu, how these could be affected by water abstraction from the lakes, and how a water management plan could be designed to minimise the impacts of use of water on the values of these currently high-quality ecosystems.

Sensitivity to water level and designing criteria for limiting abstraction.

To align with Aotearoa New Zealand's fundamental concept of "te Mana o te Wai", further degradation of aquatic ecosystems should be minimised, and efforts should be made to preserve, restore and enhance waterways in ways that will sustain future generations. Significant policy elements of the National Policy Statement for Freshwater Management (NPS-FM) that have direct bearing on lakes Wanaka and Whakatipu include, *inter alia,* the involvement of Tangata Whenua, enhancement of freshwater values, avoidance of any further loss of value or extent of wetland and rivers, protection of significant values of outstanding water. At the same time, the life supporting attributes of freshwater for people need to be recognised.

At a minimum, the impacts of abstraction of water that need to be considered when assessing how much allocation to abstraction can be made involve avoiding compromising their ecological values, including their exceptional water quality and clarity, the connectivity to marginal wetlands and tributaries where they interact with lake fish and invertebrate populations, the impact on the highly indigenous littoral zone communities within the lakes and implications for downstream river flow.

Current water level regimes in lakes Wanaka and Whakatipu

In examining water level dynamics, we used mean daily values from 2 November 1962-June 2023. This is the full extent of the dataset for Lake Whakatipu and, while the record from Lake Wanaka is longer, using the same dates allows meaningful comparisons to be made. When annual water levels are described, these refer to the southern hemisphere water year, such that 2022 includes date from 1 July 2021 to 30 June 2022.

As discussed above, the water level regimes of lakes Wanaka and Whakatipu are dominated by event-driven water level changes, overlain on a weak seasonality. Exceedance curves for the two lakes are of similar shape, both showing that most of the time lake levels fall within a relatively narrow range, with infrequent excursions to low and high lake levels (Figure 4). In both lakes the "tail" of extreme values is greater at the high end of the range than the low.

The level data for both lakes failed a statistical test for normality, and hence a non-parametric approach to defining these distributions is preferred. We use median as a measure of central tendency, inter-quartile range (the range over which the central 50% of observations occurs) and 5-95 percentile range (inside of which 90% of observations occur) as metrics describing variation about the median. These metrics show considerable year-to-year variability, with the variability greater at the highest levels (i.e. 75 and 95%iles) than lower levels (Table 1). Water level range is greatest for Lake Wanaka, and year-on-year variation for all lake level measures and ranges, indicated by the standard deviations in Table 1, are approximately 1.5 x higher in Lake Wanaka than in Lake Whakatipu.

The mean annual low level for the two lakes, also shown in Table 1, is close to the 5%ile level in Lake Whakatipu (0.07 m lower), but 0.45 m lower than the 5%ile in Lake Wanaka, reflecting the greater overall range of level, particularly of the longer "tails" to the level distributions in the latter.

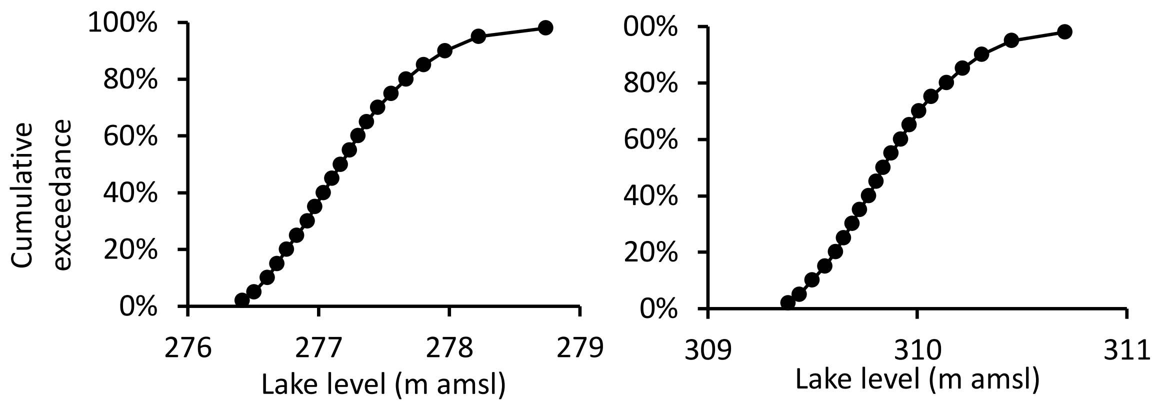

Figure 4. *Water level cumulative exceedance curves for lakes Wanaka (left) and Whakatipu (right). Data used was from water years 1963 to 2023. Note differences in horizontal axis scales.*

Water levels in the two lakes were analysed for trends using a Mann-Kendall analysis. The Mann-Kendall test determines whether there is a tendency for later levels to be higher or lower than earlier levels by analysing the direction of the difference between each later-measured data and all earlier-measured data. We used this non-parametric test as it does not require that data are normally distributed, identifies monotonic trends that need not be linear and provides an estimate of the probability that trends seen in data are likely to be significant, as a p value. A likely trend is identified by a p value of 0.05, and a possible trend by a p value of 0.20. Over time there has been year on year variability in median lake level and level range for both lakes, (Figures 5, 6) but no trends. In both cases the analysis found that the p value was more than 0.65.

Table 1. *Water level central tendency (median) and ranges in lakes Wanaka and Whakatipu. Each value is the mean ± standard deviation of annual values between water years 1962 to 2023.*

Metric	**Lake Wanaka**	**Lake Whakatipu**
Median (m)	277.22 ± 0.19	309.88 ± 0.12
25 %ile (m)	276.91 ± 0.16	309.70 ± 0.09
75 %ile (m)	277.59 ± 0.23	310.10 ± 0.16
Inter-quartile range (m)	0.68 ± 0.18	0.40 ± 0.12
5 %ile (m)	276.59 ± 0.18	309.52 ± 0.10
95 %ile (m)	278.25 ± 0.36	310.52 ± 0.27
90% range (m)	1.66 ± 0.36	0.99 ± 0.25
Annual low level (m)	276.14 ± 0.14	309.45± 0.09

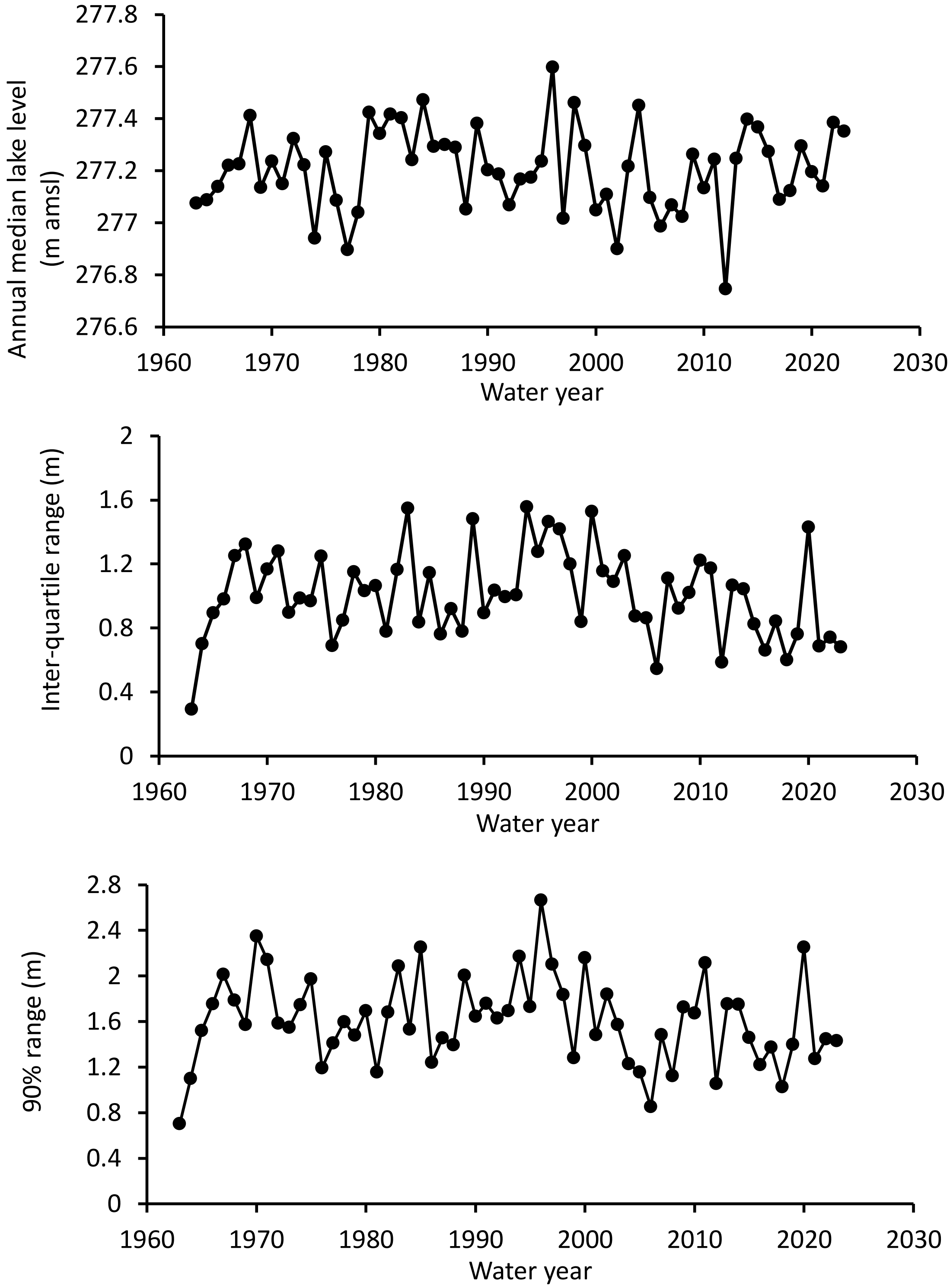

Figure 5. *Annual median lake level (top) interquartile range (centre) and 90%ile range (below) over time at Lake Wanaka. Data used was from water years 1963 to 2023.*

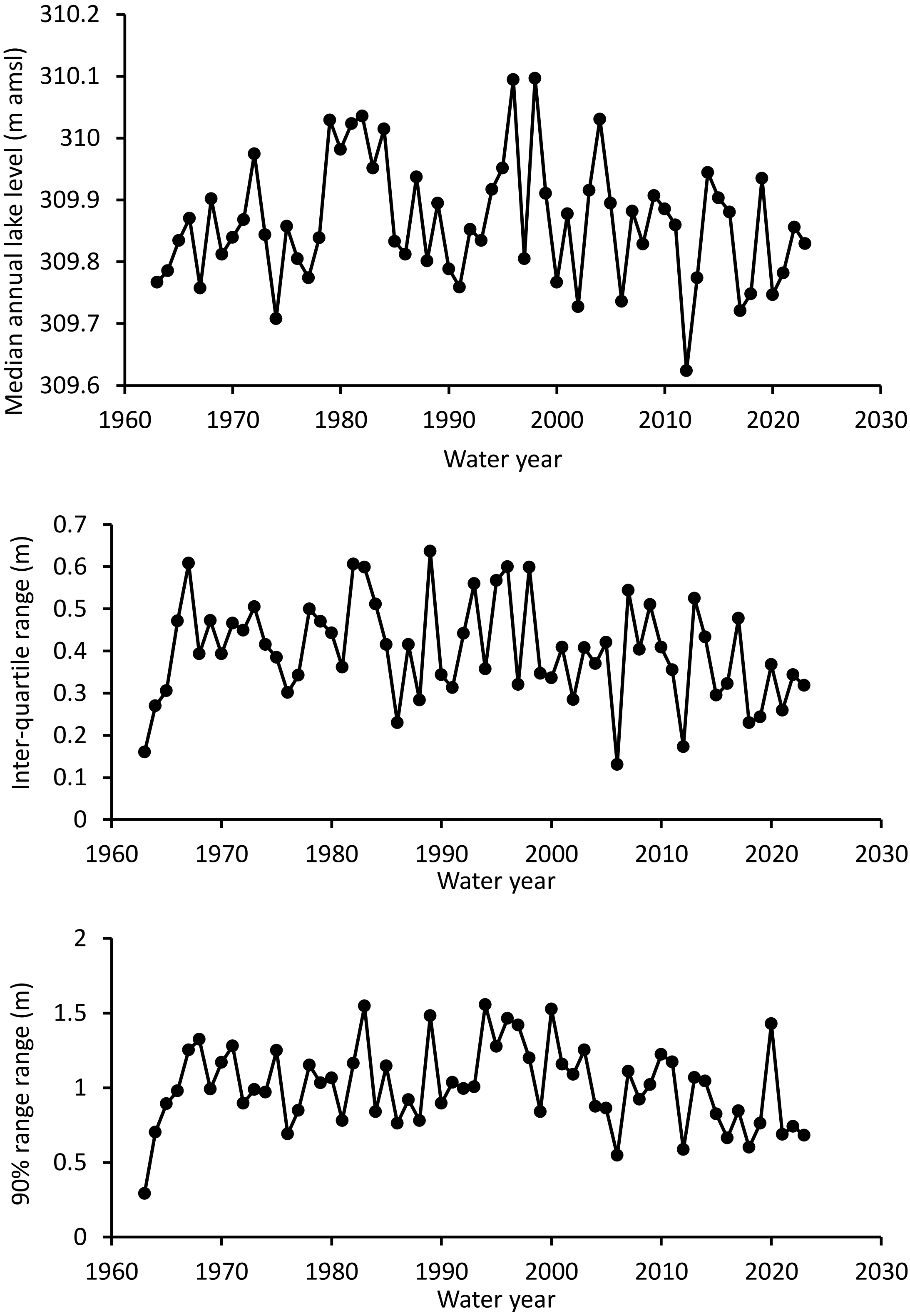

Figure 6. *Annual median lake level (top) interquartile range (centre) and 90%ile range (below) over time at Lake Whakatipu.* ***Data used was from water years 1963 to 2023.***

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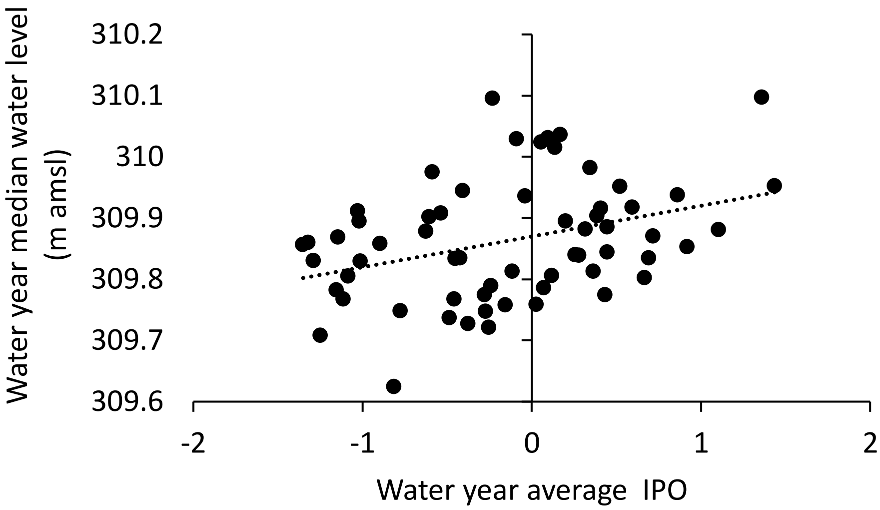

Figure 7. *Relationship between median water level of Lake Whakatipu and condition of the Interdecadal Pacific Oscillation (IPO). The dotted line is a linear regression, significant at p=0.016, with an* r^2 *of 0.13.*

As water levels in lakes Wanaka and Whakatipu are impacted by rainfall events, we examined whether there was a relationship between level and two broad scale climate indicators, the El Nino Southern Oscillation (ENSO) index, from https://psl.noaa.gov/enso/data.html and the Interdecadal Pacific Oscillation (IPO) index, from https://psl.noaa.gov/data/timeseries/IPOTPI/. No relationships were found for Lake Wanaka, but a significant positive relationship between IPO and water level was observed at Lake Whakatipu ($p = 0.016$, $r^2 = 0.13$). A weak relationship between ENSO and median water level was seen for Lake Whakatipu ($p=0.107$), but this may have been due to an existing corelation between ENSO and IPO. A multiple regression model using both ENSO an IPO to predict water level showed no significant improvement to the IPO-only model.

The analysis above, which uses annual statistics, defines a baseline against which to view long term dynamics of water levels in lakes Wanaka and Whakatipu. The baseline is one of interannual variation of median level, with both lakes showing a considerable annual range of water level overlain on a weak summer-high winter-low seasonality. Water level parameters show no long-term trends, but an influence of the Interdecadal Pacific Oscillation, albeit explaining a small proportion of overall variability, was evident for Lake Whakatipu.

This dynamic baseline has defined long term physical and biological characteristics of each lake. Lake shore profiles have been set by the interactions between level, erosion, and deposition over time. Likewise, the morphology of inflow deltas, the hydrology of marginal wetlands and the zonation of in-lake and riparian communities. If water level regime continues to follow this baseline pattern those parts of the lakes' ecology that are impacted by water level should be protected. It should form the basis against which consideration of managing water takes needs to take place.

Setting Abstraction Limits

Current Abstraction

Otago Regional Council provided a summary of consented abstractions for both lakes and their catchments. Excluding hydrogeneration schemes, where the water removal can be considered non-consumptive as it will be returned to the system, we estimate that the current total consented abstraction rate for Lake Wanaka and catchment is 1.22 $m^3 s^{-1}$ and for Lake Whakatipu and catchment 1.23 $m^3 s^{-1}$. In addition, takes that qualify as permitted activities are in operation and are not listed or metered.

Given that no details are available of actual volumes abstracted from consented takes (which typically are approximately 50% of consented takes – ORC personal communication), or for permitted takes, these values are at best indicators of the possible magnitude of existing takes.

Water Quality and clarity

Consumptive abstraction of small amounts of water from highly oligotrophic lakes such as Wanaka and Whakatipu have little direct impact on water quality, in terms of nutrients or phytoplankton productivity (eutrophication). The issue is, however, whether abstractions are simply consumptive, or if increased use of water for industrial, domestic or irrigation purposes risks delivering increasing loads of contaminants to the lake. For example, use of lake water to develop amenities or to intensify agriculture will potentially contaminate surface and groundwater with nutrients that will ultimately reach the lake margins, will impact on habitat quality. Likewise, domestic wastewater that enters groundwater via septic systems rather than being eliminated from the catchment may also eventually impact lake water quality. The purpose for which water is abstracted is beyond the scope of this report, but caution is needed whenever consenting large water takes for potentially contaminating activities within these lake catchments.

An exception to the issue of water quality can be made when large excursions occur that can expose deeper parts of the lake shoreline to erosion (prolonged low level) or cause erosion to upper shorelines that normally are not wave impacted. To minimise risk, we suggest designing abstraction rules to ensure that extreme low levels, perhaps the lower 5%ile lake levels, are not lowered by more than 20 mm and interquartile and 90% ranges are not changed by more than 5%.

Littoral vegetation zones.

Lowering of lake level will result in wave action penetrating deeper within the lake. By avoiding lowering the lower 5%ile lake level by more than 20 mm will also provide a high level of protection to submerged vegetation.

Critical to sustaining the biodiverse varial zone turf community is to sustain current level variation regimes. Small changes to median lake level would be less significant that changes to level range. Riis and Hawes (2002) found that the average monthly interquartile range, calculated over five years, was the best predictor of richness in this community. Consistent with this, Lake Wanaka, which has a greater interquartile range than Lake Whakatipu, also has the richest turf community. The most recent LakeSPI analysis (NIWA 2020) yielded 8 and 7 species from five sites in each lake, while Riis and Hawes (2002) counted 10 and 8 species respectively, though they looked at more sites. The relationship between species number and interquartile range established by Riis and Hawes using data from multiple lakes showed some variability, such that predicting species from interquartile range had an error of at least 10%, and we suggest that an initial criterion be set that allowable water take should ensure that, to sustain varial zone function, the average monthly interquartile range should not change by more than 5%. This value is substantially less than the historic inter-annual variability in lake level range (Table 1), under which the current vegetation developed, and should be conservative. To our knowledge there are no precedents for setting such a standard and it should be viewed as experimental.

Connectivity, wetlands and tributaries

Across Aotearoa New Zealand, less than 10% of native wetlands remain, and those left are specifically targeted for protection by the NPS-FM. The steep shorelines of the lakes Wanaka and Whakatipu mean that there are relatively few connected wetlands, but they do exist in the coastal plains, particularly near major gravel-bedded river inflows (Figures 8 and 9). The NPS-FW requires that the loss of extent of natural wetland is avoided. Maintaining hydrology is critical to sustaining the character, size and biodiversity of a lakeside wetland (Mitsch & Gosselink, 2000; Sorrell et al., 2004). Lake margin wetlands are typically flooded during high water levels (and during flood flows when also river fed), and levels fall as the water table gradual declines. For wetlands, it is the hydroperiod – the patten of rise and fall of the water table – that defines the species that can be present, and this needs to be protected to support the existing biodiversity. Year on year variation in wetland hydrology is to be expected, and by analogy with the varial zone, which is also dependent on hydroperiod, in the absence of existing criteria, maintenance of the range of levels within 5% of current could be a useful criterion for sustaining wetland character. While it is possible to retain the range by dropping all levels by a certain amount, absolute upper and lower levels need to be sustained to protect wetland size. Recognition also needs to be made that water levels vary substantially from year to year in both lakes, and the extant regime has adapted to this. The requirement to prevent wetland area reduction to limit reductions in the lower 5%ile of lake level to 20 mm has already been suggested, and may be suitable to protect wetland area, but would require monitoring to confirm its suitability.

Access between tributaries and lakes is particularly important for migratory fish. Both Wanaka and Whakatipu support populations of trout (rainbow, brown, brook) and salmon (chinook), which may benefit from access to potential spawning streams in early winter. Avoiding prolonged low levels in the migratory period will favour spawning. Native fish within the lakes and their catchments are less dependent on movement between lake and tributaries. Longfin eels will migrate into and out of streams, while most galaxiids will mostly be in running waters, as will upland bullies, while common bullies and some koaro occupy the lake littoral zone. In general, maintaining lake levels and periodicity close to existing ranges can be expected to sustain required tributary access for existing fish populations.

Outflow discharge

Otago Regional Council have adopted the “presumptive standard” of Richer et al. (2010) regarding environmental flows. After reviewing international literature, these authors recommend that a high level of ecological protection (i.e “the natural structure and function of the river system will be maintained with minimal changes”) would accompany a criterion that required that daily flow alterations were no more than 10%. They considered that changes that resulted in 11-20% alterations in flow risked moderate to major changes to river function. We set a goal of not reducing flow in the outlet rivers by more than 10% through abstraction. Both rivers receive tributaries soon after leaving the lakes, continuing to do so on their journey to the sea, thus diluting the impact of removal at source. This is therefore a conservative standard.

Climate change

Setting limits on water abstraction during a period of climate change must consider any likely effects on water yield from the catchment, particularly if a decline is anticipated. However, projections to date suggest that the headwaters of lakes Wanaka and Whakatipu will likely experience an increased rainfall under reasonable climate change scenarios. Collins (2020), using optimistic (RCP 2-6) and pessimistic (RCP8.5) climate change scenarios, estimated mean annual low flow and mean annual flow would increase by ~20% or more across the Otago region. Abstraction limits are unlikely to be compromised by reduced inflow volumes due to changing climate.

Criteria

Combining the above considerations, we suggest that a starting point to setting level criteria to sustain ecological function could be:

1. Outflow discharges should not be lowered more than 10% from the current regime;
2. Periodicity should not be affected – new regimes should not increase or decrease frequency of flood peaks;
3. Average monthly interquartile range should not change by more than 5%;
4. Extensive shifts in annual median, quartile and 5%ile and 95%ile level should be avoided, to maintain the lake within its current bounds and minimise shoreline change. A 20 mm long term change may be acceptable;
5. Lower annual 5%ile of lake level should not decrease by more than 20 mm to minimise threats to connected wetlands.

At present the setting of these criteria is based on limited existing knowledge. We are aware of no precedents in New Zealand for setting water level regimes in non-regulated water bodies. For this reason, they are set to values we consider be conservative, but need to be discussed with all stakeholders and particularly Tangata Whenua who are intimately connected to these lakes.

It would be sensible to support any decision made based on these suggestions by ongoing monitoring of the target values to ensure that the desired state is being maintained.

Figure 8. *Lake Wanaka, to show the main wetland areas connected to the lake. Recognised wetlands are shown in pale blue (arrowed red). From LUCAS database (//data.mfe.govt.nz/layer/52375-lucas-nz-land-use-map-1990-2008-2012-2016-v011/).*

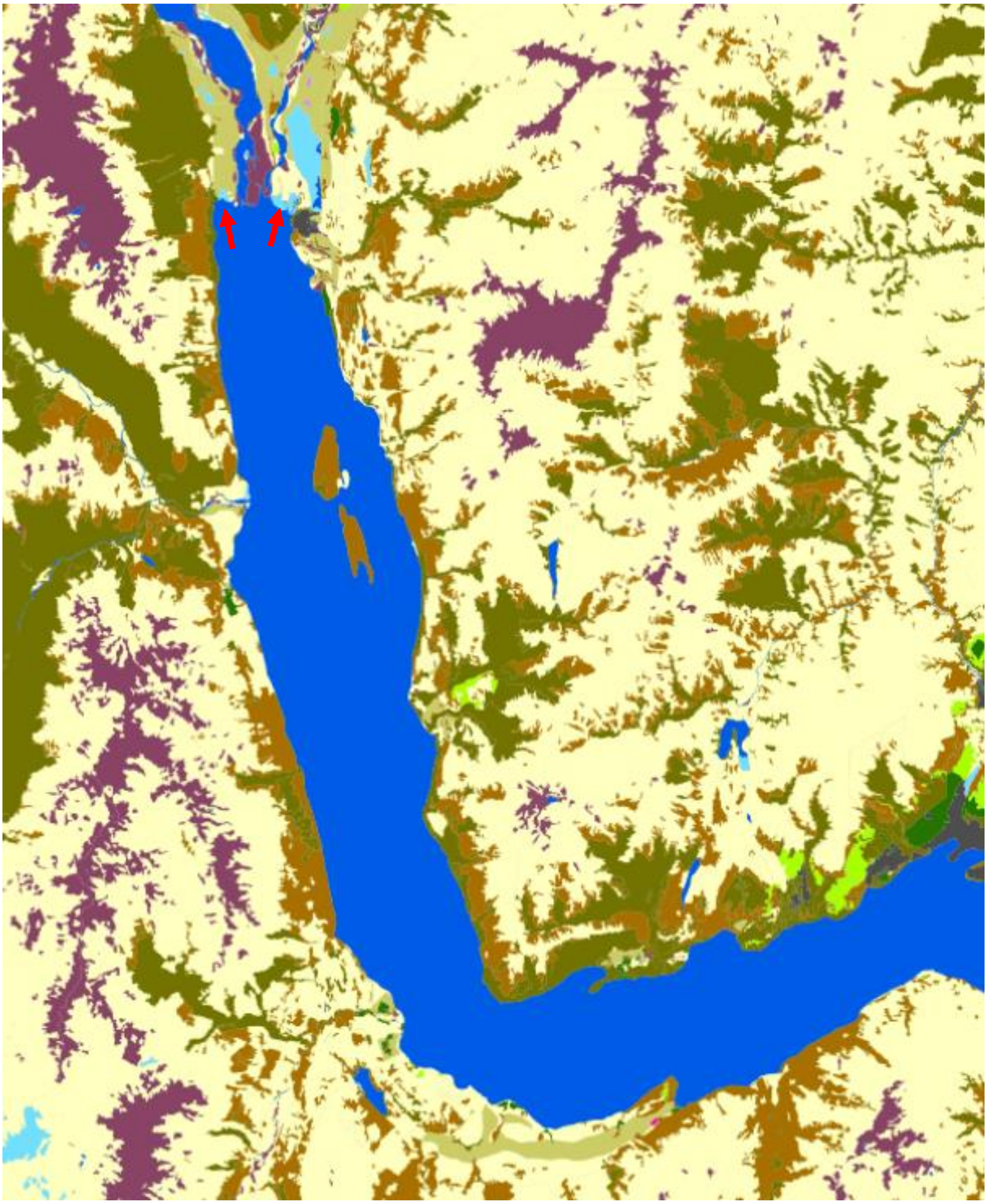

Figure 9. *Northern arm of Lake Whakatipu to show the main wetland areas close to the Rees River. Recognised wetlands are shown in pale blue (arrowed red). From LUCAS database (//data.mfe.govt.nz/layer/52375-lucas-nz-land-use-map-1990-2008-2012-2016-v011/).*

Simple models of water level change

Day-to-day changes to lake water level are determined by the balances of inflows and outflows. In addition to the obvious overland inflows, water enters the lakes via groundwater and direct precipitation. Water leaves both lakes via their main outflows, the Clutha/Mata-Au River and Kawarau River, but also via evaporation from the water surface and groundwater. A simple arithmetic description of the daily water balance of a lake as change in volume (Δ volume) can be given as:

Equation 1:

$$\text{Flow}_{(\text{inflow-outflow})} + \text{Groundwater}_{(\text{inflow-outflow})} + \text{Atmosphere}_{(\text{precip-evap})} + \text{Human}_{(\text{discharge-abstract})}$$

Change in lake level can be estimated from change in volume where the surface area of the lake is known, ideally using a relationship that estimates lake area from lake level as sloping shores affect this relationship.

A comprehensive model of lake level thus has substantial data requirements. While both lakes Wanaka and Whakatipu have long term records of some of these variables, notably lake level, neither have comprehensive data to allow a complete water balance model to be produced. Gauging periods are also often short (Table 2) and gauging sites of tributaries in places are well upstream of where they discharge into the lake.

***Table 2.** Available data used to develop water level estimates for lakes Wanaka and Whakatipu.*

Water body	Measurement	Start	Finish
Lake Wanaka	Lake Level and outflow, Roys Bay	01 February 1933	Ongoing
	Flow, Clutha/Mata-Au River below Cardrona confluence	25 November 2021	Ongoing
	Flow, Hawera River	1 December 2020	Ongoing
	Flow, Cardrona	6 May 2008	Ongoing
	Flow, Matukituki	22 August 1979	Ongoing
	Flow, Wilkin River	24 August 2016	Ongoing
	Flow, Young North Branch	10 August 2016	Ongoing
			Ongoing
Lake Whakatipu	Lake Level and outflow, Willow Place	28 November 1962	Ongoing
	Flow, Kawarau below Shotover confluence	1 December 2020	Ongoing
	Flow, Shotover River	29 June 1967	Ongoing
	Flow, Dart River	12 June 1996	Ongoing
	Flow, Rees River	21 December 2021	Ongoing

While modelling of catchment processes can provide estimates of ungauged tributaries and groundwater flows (e.g. Peng et al., 2019), these are beyond the resources of the current contract. Even if carried out, they often have significant proportions of observed variability not explained. Instead, we explore a series of approximations that allow the scales of impacts of water abstraction from the lakes to be estimated to develop scenarios that may be likely to meet the requirements discussed above. To do this we exploit the long records of lake level, the relationships between lake level and discharge, and the fact that the only question we are asking is "what effect would an additional abstraction have on daily lake level if nothing else were to change".

Step 1 – Estimating overland outflow.

In general, we expect a robust relationship between Lake Level and outflow. This is because it is the shape of the lake outflow and the head of water that determines the flow.

The Clutha/Mata-Au River is gauged at the exit from Lake Wanaka and the Kawarau River on leaving Lake Whakatipu. In both cases highly significant polynomial relationships between discharge and water level could be obtained (Figure 10).

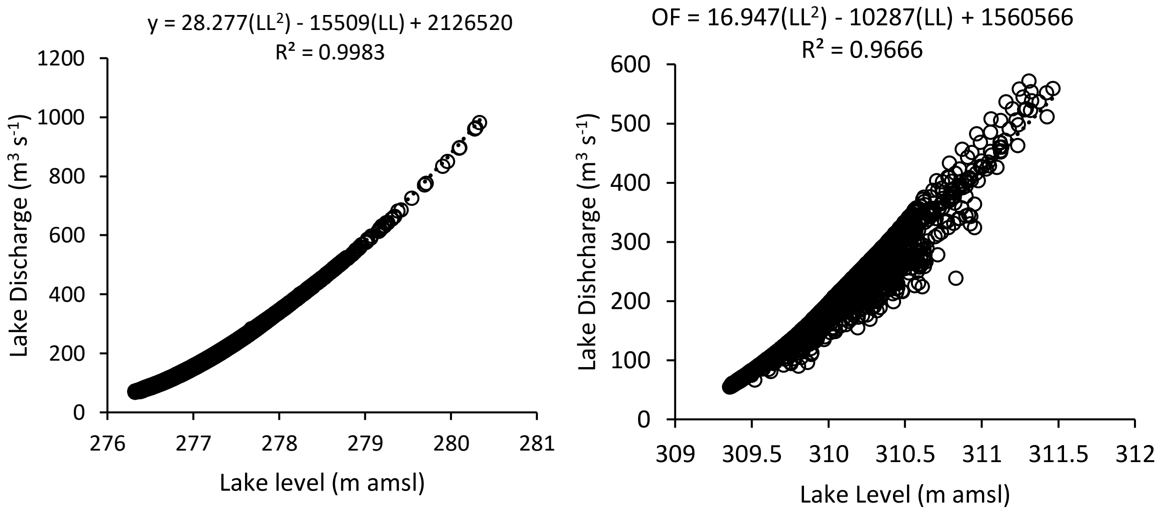

Figure 10. *Relationship between Wanaka Lake level and estimated flow in the Clutha/Mata-Au River on leaving the lake (left) and Whakatipu Lake level and estimated flow in the Kawarau River (right). Dots are mean daily level and mean daily discharge (excluded if >5% missing values) dotted lines are second order polynomials fitted by regression (curve equations and r^2 at top).*

Step 2 – Estimating daily volume change.

Daily volume change was estimate from recorded daily change in lake level. We used the area of the two lakes obtained from GIS layers in the Land Information New Zealand (https://data.linz.govt.nz/) 1:50K topographic database (Table 3). We did not adjust for changes in surface area with changing lake level, as this information was not available. However, we estimated that, for a 10:1 shoreline slope, the error in estimation of volume that would accompany a 0.1 m change in lake level for both lakes was <0.1%. Given the accuracies of other parameters we considered this to be acceptable error for the purposes of our task.

Table 3. *Lake morphological parameters obtained from the LINZ topographic database (https://data.linz.govt.nz/* : lds-nz-lake-polygons-topo-150k-SHP).

Lake	Area (m^2)	Perimeter (m)
Wanaka	198,548,398	213,225
Whakatipu	294,762,938	213,364

Step 3 – Estimating water balance

The goal of our modelling was simply to use the records of lake level as the basis of a simple arithmetic model to hindcast what would have happened to lake level under a range of increased abstraction scenarios.

The existing data provides us with average daily lake level, from which we could estimate average daily outflow based on Figure 8. We used daily averages as they reduce impacts of waves, seiches and wind set-up. The daily change in lake level provides us with an estimate of daily volume change (via table 3 parameters) and hence the daily net water balance, which may be positive (rising level) or negative (falling level) and is defined as total influx minus total efflux.

In the absence of complete information on influx and efflux, we can use the estimates of water volume increase and water exiting the lake to estimate the "net inflow" required to achieve the observed net water balance as:

$$[\text{net inflow}]_{Dn} = [\text{net water balance}]_{Dn} + [\text{outflow}]_{Dn} \qquad \text{Eq 2}$$

where Dn is day(n).

Using Equation 1 as reference, net inflow is equivalent to the daily sum of:

$$\text{Flow}_{(\text{inflow})} + \text{Groundwater}_{(\text{inflow-outflow})} + \text{Atmosphere}_{(\text{precip-evap})} + \text{Human}_{(\text{discharge-abstract})} \qquad \text{Eq 3}$$

While we are unable to resolve net inflow into component parts, that is not necessary for our purpose and this estimate becomes a tabulated daily "net inflow" for all subsequent manipulations that assess how lake level would have responded to added abstraction. We need to assume that "net inflow" is not affected by changes to level that accompany abstraction scenarios, which will not be quite the case, particularly for groundwater flows. However, it provides a method for estimating the consequences of increased abstraction from an otherwise limited dataset. We outline below some steps taken to provide a degree of validation to this approach.

Relating "net inflow" to measured inflows.

Overland inflows are measured in some sub-catchments of both lakes, and we would expect that these would be a would be a substantial contributor to estimated net inflow. To test this, we undertook linear regression analysis of the relationship between total gauged inflow and estimated net inflow for both lakes, for the period 1 Jan 2022 to 31 March 2023 when the best measured inflow data were available. In both cases highly significant relationships emerged ($p<<0.001$), that indicated that the measured inflows explained substantial amounts of the variance (Wanaka 66%, Whakatipu 56%) in net inflow (Figure 11, Table 4). In addition, we carried out a similar analysis for the longer record of flow in the Matukituki River, a tributary of Lake Wanaka that has been gauged since 1979.

Catchments included in the gauged tributaries are indicated in Table 2, though no case is the gauging station at the lake entrance. Coefficients of regression lines suggest that half of net inflow to Lake Whakatipu would come from the gauged rivers (Rees and Dart), and it has been shown that these contribute approximately 31% total catchment area (Pickering & Irwin, 1982).

The 40 year run of data for the Matukituki River showed a strong relationship with the estimated total inflow to Lake Wanaka over that time, and the coefficient suggested that this river contributed approximately 20% of flow. This is consistent with the proportion of the lake catchment (approximately 2500 km^2) contributed by the Matukituki River (approx. 500 m^2).

These observations provide support for the use of estimated net inflow for lake water budget calculations.

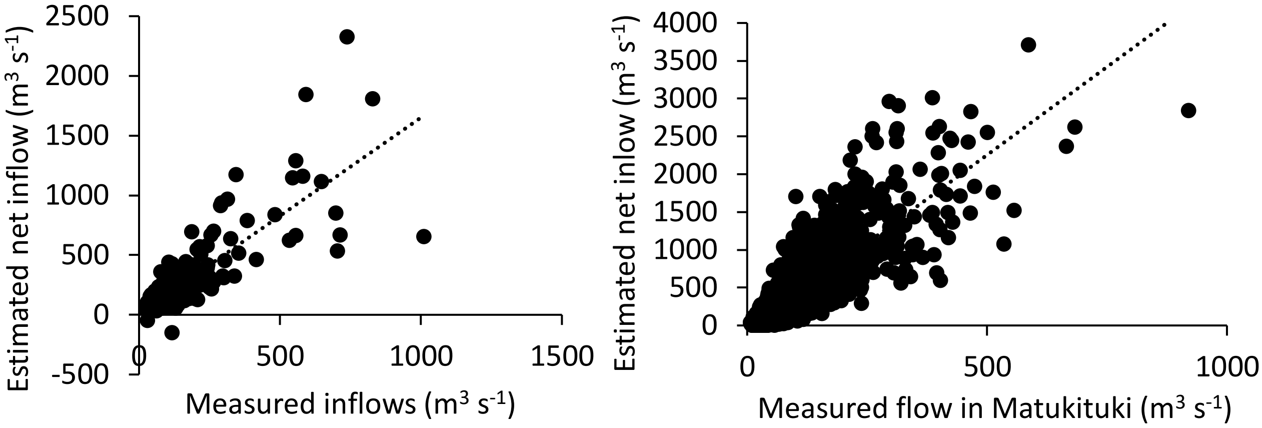

Figure 11 *Relationship between measured inflow volume (daily average) to Lake Wanaka and net inflow volume estimated form lake level change and outflow volume. At left, the short run of data for which multiple inflows were available, at left the longer dataset from Matukituki River only. Dotted lines are linear regressions (Table 4).*

Table 4. *Regression parameters describing the relationships (linear regression) between inflow volume from gauged tributaries and estimated net inflow volume based on lake level data.*

Parameter	Lake Wanaka	Lake Wanaka Matukituki only	Lake Whakatipu
R^2	0.656	0.726	0.561
Slope	1.654 ± 0.058	4.657 ± 0.033	2.009 ± 0.091
Slope p-value	<<0.001	<<0.001	<<0.001
Intercept	-5.7 ± 3.42	-74.7 ± 237	4.13 ± 8.39
Observations	421	7166	386

Estimating lake level with increased abstraction

Estimations of lake levels that would have been expected with additional abstraction are hindcasts, based primarily on historical water daily average level data, from which we use Eq 2 to estimate net inflow (Eq 3). Average lake level is used to derive outflow volume (Figure 10). Over daily time steps we then estimate Day(n+1) level using the estimates of Day(n) outflow, to which we add abstraction, and Day(n) net inflow which was determined from the observed time series. The prediction then runs freely producing a synthetic lake level projection.

As expected, when allowed to run from an observed starting lake level with no additional abstraction, this simple model reproduces a realistic level regime for Lake Wanaka (Figure 12). Errors in modelled level differ from observed level by at most a few cm, though are biased through rise and fall cycles, with overestimates of level occurring at high lake levels and underestimates at low levels. Manipulations involving adding abstraction of water on Day(n) allow the impact of abstraction to be observed (e.g. Figure 14). Similar results were achieved for Lake Whakatipu.

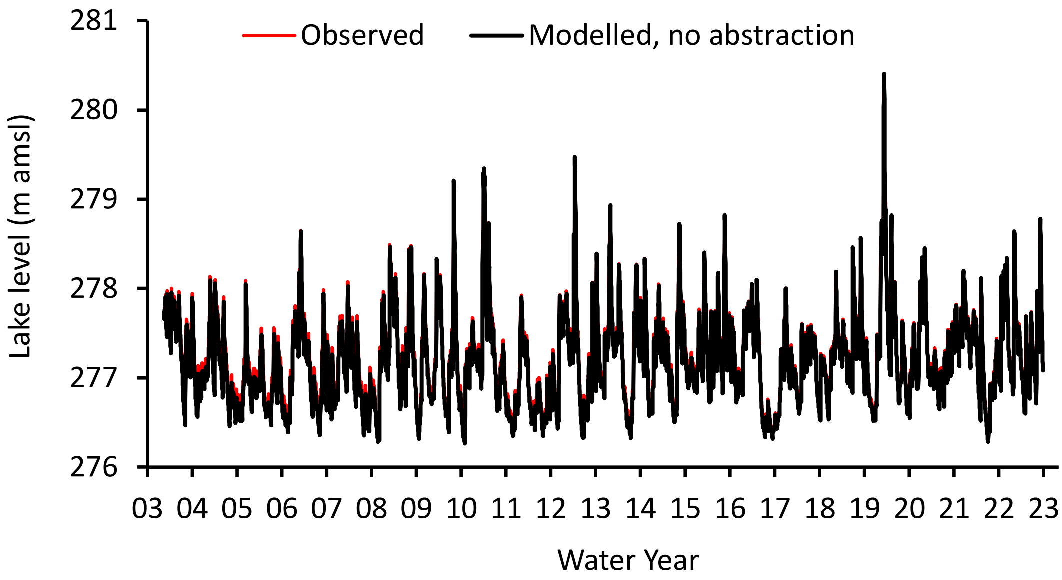

Figure 12. *Observed and modelled level of Lake Wanaka from November 2003 to June 2023 with no additional abstraction.*

Scenario testing

Abstraction scenarios were then run to estimate how the lake level and discharge would have varied over the ~20 year model period had those extra abstractions been active. The scenarios were: no further abstraction (baseline), a constant rates of 2 $m^3 s^{-1}$ 4 $m^3 s^{-1}$ and, for Lake Wanaka only, at 3 $m^3 s^{-1}$. In addition, a scenario for both lakes where the abstraction was 4 $m^3 s^{-1}$ when the lake was above historic median level and 2 $m^3 s^{-1}$ when below. The models were used to predict lake discharge and level, evaluated against the no additional abstraction scenario. This allowed evaluation of model predictions against the criteria developed above for protecting ecosystem values. For discharge, we calculated: the average and maximum % decreases in discharge relative to no additional abstraction, and the precent of time that the reduction in discharge exceeded 5% (Table 5). For levels we derived the resulting monthly median level and inter-quartile ranges, the annual median, 5, 25, 75 and 95 percentile levels and the annual interquartile and 5-95% ranges (Table 6).

Table 5. *Estimates of the effects additional abstraction scenarios on the average and maximum reduction in discharge of the outflows from lakes Wanaka and Whakatipu relative to no additional abstraction. The right hand column in each block shows the percent of days that the discharge reduction exceeds 5%. nd – not done.*

Abstraction	**Wanaka**			**Whakatipu**		
$m^3 s^{-1}$	**Average reduction**	**Maximum reduction**	**>5% reduction**	**Average reduction**	**Maximum reduction**	**>5% reduction**
0	0%	0%	0%	0	0%	0%
2	1.2%	2.8%	0%	1.5%	3.9%	0%
3	1.7%	4.14	0%	nd	nd	nd
4	2.3%	5.5%	0.5%	2.9%	7.8%	6.5%
2 & 4*	1.4%	2.8%	0%	2.0%	4.1%	0%

**this scenario allocates 4 $m^3 s^{-1}$ when the lake level is above long term median and 2 $m^3 s^{-1}$ when below.*

Inevitably, abstraction reduced lake discharge, and this increased with the volume taken (Table 5). Maximum average daily reduction predicted was 5.5% of discharge for Lake Wanaka and 7.8% for Lake Whakatipu. For both lakes proportional reduction rarely exceeded 5%.

The greatest percent reduction in discharge due to constant abstraction inevitably occurred when lake level, and hence discharge, was low (e.g. Figure 13). In Lake Whakatipu the proportional increase in discharge reduction increased rapidly as level fell below ~309.8 m amsl, close to median lake level (309.87 m amsl). A similar pattern was evident in Lake Wanaka, with the rate of increase in proportional reduction in discharge occurring close to the median level of 277.16 m amsl. By reducing abstraction rate from 4 to 2 $m^3 s^{-1}$ when water level fell below median values, the flow reduction at low lake levels was reduced (Figure 13), with overall reduction only slightly higher than at a constant rate of 2 $m^3 s^{-1}$ (Table 5).

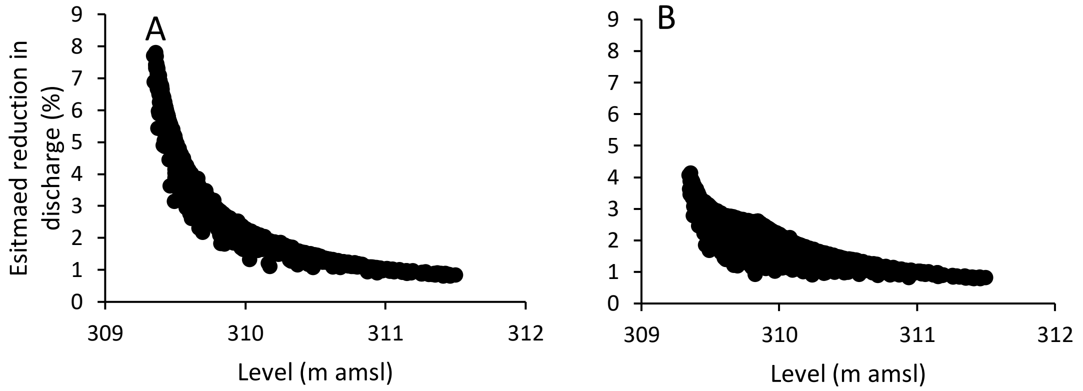

Figure 13. *Model predictions of the relative size of reduction in discharge of the Kawarau River when (A) an additional 4 $m^3 s^{-1}$ was constantly abstracted from Lake Whakatipu and (B) the abstraction rate was reduced from 4 to 2 $m^3 s^{-1}$ when Lake Whakatipu fell below median level.*

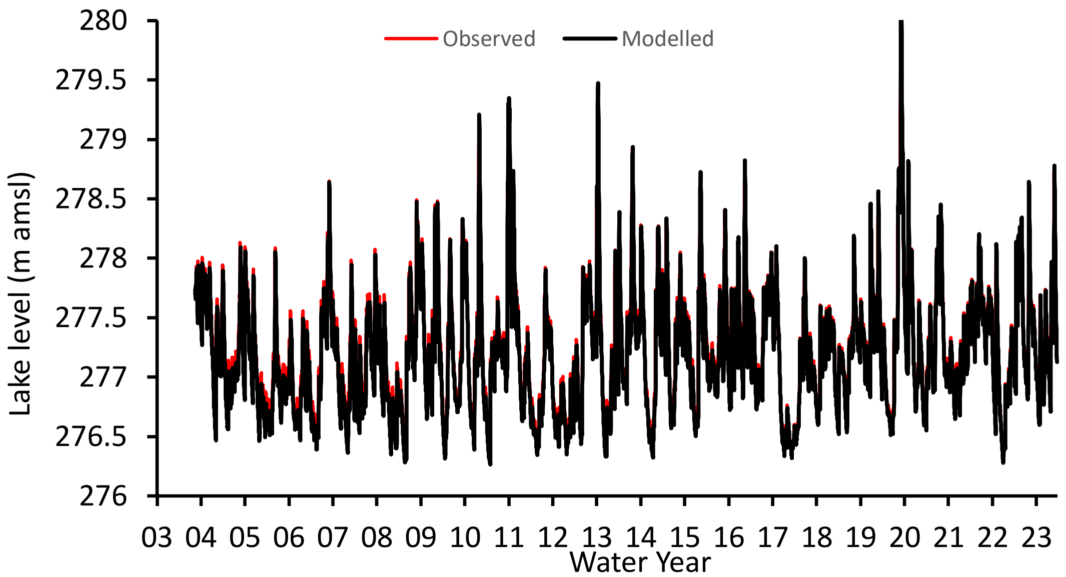

Figure 14. *Modelled vs observed water level in Lake Wanaka over a twenty-year period. In this scenario, abstraction has been set high (10 $m^3 s^{-1}$) to make separation of the lines more evident. While abstraction lowered lake level, it had no impact on level periodicity.*

Models predicted that constant abstraction would reduce the lake median levels but have little impact on the periodicity of water level rise and fall (Figure 14). As expected, the magnitude of the of impact on lake level increased with the volume removed (Tables 6, 7). In Lake Wanaka, abstraction at 2 $m^3 s^{-1}$ was predicted to reduce annual median water level by approximately 12 mm, and at 4 $m^3 s^{-1}$ by 25 mm, while in Lake Whakatipu the equivalent reductions were 9 and 19 mm (Table 7). Reductions in annual water level ranges were much less. The variable abstraction rate had an effect on lake levels that was intermediate between the two constant rates and had a slight damping effect on level variation.

Table 6. *The effects of simulated water abstraction regimes on key metrics describing the water regime in lakes Whakatipu and Wanaka calculated from 2003 to 2023. The tables list average monthly median and monthly interquartile range (MIQR) for each lake, and the 5, 25, 75, and 95% levels, median inter-quartile range (IQR) and 90% range over that period. Abstraction regime is shown at top, where 4 & 2 $m^3 s^{-1}$ indicates a change in allocation of abstraction rates above and below long term median lake level.*

Lake Wanaka

Abstraction	**0 $m^3 s^{-1}$**	**2 $m^3 s^{-1}$**	**3 $m^3 s^{-1}$**	**4 $m^3 s^{-1}$**	**4 & 2 $m^3 s^{-1}$**
Monthly					
Median	277.16 ± 0.43	277.15 ± 0.43	277.14 ± 0.43	277.13 ± 0.43	277.13 ± 0.43
MIQR	0.339 ± 0.245	0.339 ± 0.245	0.339 ± 0.242	0.340 ± 0.245	0.325 ± 0.234
Overall					
5%ile	276.49	276.48	276.47	276.46	276.48
25%ile	276.80	276.79	276.78	276.78	276.79
Median	277.12	277.11	277.11	277.10	277.11
75%ile	277.47	277.46	277.45	277.45	277.46
95%ile	278.06	278.05	278.04	278.04	278.04
IQR	0.667	0.669	0.670	0.671	0.670
90% Range	1.568	1.570	1.572	1.574	1.567

Lake Whakatipu

Abstraction	**0 $m^3 s^{-1}$**	**2 $m^3 s^{-1}$**	**4 $m^3 s^{-1}$**	**4 & 2 $m^3 s^{-1}$**
Monthly				
Median	309.87 ± 0.26	309.86 ± 0.27	309.86 ± 0.27	309.86 ± 0.26
MIQR	0.182 ± 0.145	0.175 ± 0.138	0.189 ± 0.146	0.188 ± 0.146
Overall				
5%ile	309.51	309.50	309.49	309.50
25%ile	309.67	309.66	309.65	309.66
Median	309.85	309.84	309.83	309.83
75%ile	310.05	310.04	310.03	310.03
95%ile	310.39	310.38	310.37	310.37
IQR	0.380	0.381	0.382	0.376
90% Range	0.880	0.881	0.882	0.874

Table 7. *Changes in annual mean water level metrics (mean values over the 2003-2023 period) in Lakes Wanaka and Whakatipu as a result of the abstraction regimes in Table 6. In each case the tabulated value is the difference between no abstraction and the listed rate of abstraction is shown, with negative denoting a reduction due to abstraction. Values are in mm (levels) or % (ranges).*

	Change Lake Wanaka				**Change Lake Whakatipu**		
Metric	**2 $m^3 s^{-1}$**	**3 $m^3 s^{-1}$**	**4 $m^3 s^{-1}$**	**4 & 2 $m^3 s^{-1}$**	**2 $m^3 s^{-1}$**	**4 $m^3 s^{-1}$**	**4 & 2 $m^3 s^{-1}$**
5%ile	-15 mm	-22 mm	-29 mm	-17 mm	-10 mm	-19 mm	-10 mm
25%ile	-13 mm	-20 mm	-27 mm	-17 mm	-9 mm	-19 mm	-11 mm
Median	-12 mm	-18 mm	-25 mm	-14 mm	-9 mm	-19 mm	-14 mm
75%ile	-11 mm	-17 mm	-23 mm	-14 mm	-9 mm	-18 mm	-16 mm
95%ile	-12 mm	-18 mm	-23 mm	-18 mm	-9 mm	-18 mm	-16 mm
IQR	0.3%	0.4%	0.6%	0.5%	0.1%	0.3%	-1.2%
90% Range	0.2%	0.3%	0.4%	-0.1%	0.1%	0.2%	-0.6%

Evaluation against criteria

Above we developed criteria against which to view the impact of abstraction on features of lake level that might be most relevant to sustaining ecological values. Here the results of the models are examined against those criteria.

1. Outflow discharges should not be lowered more than 10% from the current regime;

The purpose of this criterion was to meet the needs of the rivers departing the lakes. Models suggested that the abstraction scenarios would result in maximum reductions in discharge into the Kawarau River and Clutha/Mata-Au rivers would be reduced by maxima of 5.5 and 7.8%, with average reductions of less than 3%.

2. Periodicity should not be affected – new regimes should not increase or decrease frequency of flood peaks;

The models showed that the reduction in level would be of the order of a few cm, and these would have no substantial impact on the pattern of water level rise and fall in the two lakes.

3. Average monthly interquartile range should not change by more than 5%;

Monthly interquartile range has been shown to play a role in sustaining lake edge community diversity. The proportional reduction in this metric were all less than 1.2% and, combined with the small vertical displacement and maintained temporal dynamics of this zone are unlikely to have adverse impact.

4. Extensive shifts in annual median, quartile and 5%ile and 95%ile level should be avoided, to maintain the lake within its current bounds and minimise shoreline change. A 20 mm long term change may be acceptable;
   and
5. Lower annual 5%ile of lake level should not decrease by more than 20 mm.

The aims of these criteria are to sustain current shoreline dynamics, minimise deepening of wave action and sustaining connectivity to wetlands and tributaries. For Lake Whakatipu, all scenarios meet the goal of not reducing the any of the water level metrics by 20 mm or more, but only just. For Lake Wanaka, continuous abstraction at 4 $m^3 s^{-1}$ does not meet this requirement, though all other scenarios do.

Setting a minimum level

It may be appropriate to set a minimum lake level below which as much abstraction as is possible should cease. The intent would be to provide protection to lake values in cases where prolonged low inflows were causing unusually low lake levels. Extreme low lake levels would also be resulting in low outflow from the lakes, potentially impacting on downstream habitats.
At the request of the Otago Regional Council, the effect of selecting the long term mean annual low level as the trigger for stopping abstraction was evaluated under the range of scenarios tested. Specifically, the percent of days when abstraction would be halted was calculated.

Table 8. *Estimates of the percent of time that abstraction would be halted, if the trigger were the long term annual average low water level, under the various allocation scenarios modelled for lakes Wanaka and Whakatipu. Table uses data from the abstraction models run from 2003 to 2023. "nd" indicates not done.*

Lake	**0 $m^3 s^{-1}$**	**2 $m^3 s^{-1}$**	**3 $m^3 s^{-1}$**	**4 $m^3 s^{-1}$**	**2 & 4 $m^3 s^{-1}$**
Wanaka	4.46%	5.06%	5.29%	5.57%	5.08%
Whakatipu	3.86%	4.45%	nd	4.98%	4.46%

Final Considerations

This report describes the effect of water abstraction, at a series of rates, on water levels of and water discharge from, lakes Wanaka and Whakatipu based on a simple arithmetic model. The hindcast estimates are based on assumptions, some of which are readily falsifiable. In particular, the assumptions that the lake area and unmeasured fluxes of water (particularly groundwater) do not change with lake level are unlikely to be true, and add error to the estimates. However, with the difference between the baseline and the post-abstraction water levels typically being on cm scales, we argue that the errors induced should be small and that the model is sufficient to assist in setting abstraction guidelines. We emphasise, however, the need to engage openly with all stakeholders, particularly Tangata Whenua, in the spirit of te Mana o te Wai, to discuss these suggestions.

In our analysis we prioritise protection of connectivity, particularly with lakeside wetlands, and the shallow water communities that are most impacted by changing lake levels. All these connections are highly dynamic, and the resistance and resilience of the communities in these habitats to rapidly changing conditions is high. We argue that maintaining water level variability about long term central tendencies is critical to supporting existing diverse and dynamic communities, through robust habitat protection. The scenarios developed make very little difference to lake level variation, but do result in an overall drop in lake level of 10-25 mm. Given the natural within- and between-year variation in lake level considerably exceeds this, the small change is likely to be accommodated with minor effects on shoreline physical processes and have little impact on the size of vegetation zones and especially wetlands. In addition, existing projections of the impacts of climate change on rainfall in this region are for an overall increase, offsetting the impact of abstraction.

Overall, we suggest that the small level changes that are anticipated, set against the ongoing rapid and extensive level variations (that will be largely preserved), and the existing seasonal and year-on-year variation, means that detailed studies of wetland and tributary connectivity will provide little additional insights for assessing the impacts of level change. However, as increased abstraction rates are introduced, it will be important to ensure that adequate monitoring is in place to ensure that potentially vulnerable systems are not adversely affected.

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