TITLE

A robust and transparent framework for weaving together diverse values in freshwater management: a case study of the Lake Wānaka catchment, Aotearoa/New Zealand

AUTHORS

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HIGHLIGHTS

- Inadequate success casts doubt about the effectiveness of top-down driven management approaches
- Multi-Criteria Decision Analysis (MCDA) may help weave together top-down and bottom-up values
- We trialed the approach in Wānaka, Aotearoa, to co-develop a management plan with the community
- It successfully integrated ecological, socioeconomic, indigenous and western cultural values
- The MCDA-framework promotes transformative change towards collaborative freshwater management

ABSTRACT

Fresh waters are among the most seriously threatened ecosystems on the planet and managing them for good ecological and human health and wellbeing is one of the challenges of the UN Decade on Ecosystem Restoration. The inadequate successes of decades-long attempts to restore aquatic biodiversity casts doubt on the effectiveness of common top-down driven approaches which focus solely on ecological and socio-economic objectives. Approaches based on public engagement that take into account cultural values and knowledge of local communities are a way forward to enhance environmental management while improving people's wellbeing. Little guidance on the integration of diverse values is provided in respective directives. We demonstrate a values-based framework based on Multi-Criteria Decision Analysis (MCDA) to integrate diverse values in the development of a catchment management plan for the Lake Wānaka catchment in Aotearoa/New Zealand, which is one of the few countries that mandates that action plans for fresh waters be developed based on a community water vision. The MCDA-framework successfully wove together diverse cultural, ecological, and socio-economic values in a co-developed freshwater management plan with buy-in from the community. In particular, clearly translating values into objectives and structuring them allowed the identification of potential management actions that target current system deficits and the ranking of potential management actions based on the objective assessment of their performance against all objectives. In terms of management actions, stakeholder-specific preferences did not lead to rank reversals, highlighting the community's unity in the local water vision which is an optimal basis upon which to agree on a collective action plan. Based on this case study, we recommend values-based approaches such as MCDA as a way forward to develop inclusive freshwater co-management not only in New Zealand, where community input to management is mandated, but elsewhere as well.

KEY WORDS

biocultural management, ecosystem-based management, catchment management, Māori, structured decision making, local knowledge

GLOSSARY OF MĀORI TERMS

Aotearoa – the Māori name for New Zealand

Māori – the indigenous peoples of Aotearoa/New Zealand

te mana o te wai **–** a Māori concept that refers to the fundamental importance of water and recognises that protecting the health of freshwater protects the health and well-being of the wider environment, including people

mahinga kai – resources that are customarily used/harvested

mātauranga Māori – Māori knowledge

pā – a settlement/village

nohoaka – seasonal occupation site

Pākehā – a non-*Māori* New Zealander

iwi – the largest tribal unit in Māoridom

hui – a meeting

tuna – freshwater eels indigenous to New Zealand (*Anguilla dieffenbachii* and *Anguilla australis*), important mahinga kai species

kōaro – an endemic New Zealand fish species (*Galaxias brevipinnis*)

kōkopu – a group of endemic New Zealand fish species in the family *Galaxiidae*

kākahi – large freshwater mussel species including *Echyridella menziezii*

raupō **–** wetland plant (bullrush; *Typha orientalis*)

runaka **–** small or local tribal unit

waka **–** canoe

1. INTRODUCTION

Freshwater systems are essential to peoples' economic, cultural, and social wellbeing. They are also among the most threatened and modified environments on Earth, showing alarming losses of biodiversity as well as of benefits that humans receive from these ecosystems (Vörösmarty et al., 2010; WWF, 2020). Consequently, the goals of restoring and safeguarding aquatic biodiversity, habitats and/or their ecosystem services (ES) have become the focus of many national and international policies (e.g., the European Union EU Water Framework Directive (2000/60/EC), the Convention on Biological Diversity's post-2020 global biodiversity framework (CBD/WG2020/2/3) or the United Nations' Sustainable Development Goals (A/RES/70/1)). These policies all advocate for some form of public engagement, including informing to empowering people, while the more recent ones specifically call for a full and effective participation of indigenous peoples and local communities and the accounting for their cultural and spiritual values (e.g., EU Biodiversity Strategy for 2030 (COM(2020) 380 final) or New Zealand's and Australia's water quality management strategies (New Zealand Ministry for the Environment, 2020; Australian Government, 2018), respectively)). However, the complexity of weaving together diverse values in a biocultural fashion (Wali, Alvira, Tallman, Ravikumar, & Macedo, 2017) seems to be stifling such that top-down governance, focusing on ecological and socio-economic objectives alone, is still the norm (du Toit & Pollard, 2008; Jager et al., 2016; Kochskaemper, Challis, Newig, & Jager, 2016; Long, Charles, & Stephenson, 2015; Rimmert, Baudoin, Cotta, Kochskamper, & Newig, 2020; Rollason, Bracken, Hardy, & Large, 2018). Neglecting public participation and the consideration of cultural values risks losing buy-in from the communities and may, therefore, lead to management plans which are less likely to be effective (Huitema et al., 2009; Kochskaemper et al., 2016).

Aotearoa/New Zealand is among the few countries whose freshwater quality and management policy, i.e. the National Policy Statement for Freshwater Management (NPS-FM; New Zealand Ministry for the Environment, 2020), gives effect to the ***Māori*** cultural concepts of ***mauri*** and ***te mana o te wai.*** The Treaty of Waitangi (1840) instantiates a relationship between the Crown and ***Māori*** which declares ***Māori*** as partners in the governance of New Zealand and recognition of this bi-cultural partnership has strengthened in recent years. Thus, the New Zealand Government strives to give effect to the Treaty of Waitangi, mandating the recognition of ***mātauranga Māori***, the ***mauri*** of water and ***te mana o te wai*** in environmental legislation and in its implementation (e.g., New Zealand Ministry for the Environment 2020). Consequently, management plans must be developed based on a shared community vision for water bodies. The National Objectives Framework (NOF) gives specific guidelines on mandatory freshwater objectives and attributes as well as on minimum standards (national bottom lines) for them (New Zealand Ministry for the Environment, 2020). The community can agree to add more objectives and/or define stricter local bottom lines for attributes for specific water bodies. A critical challenge in this process is to successfully account for potentially conflicting objectives in a framework that supports decision-making. This challenge rests largely with Regional Councils/Territorial Authorities, i.e. the regulatory bodies in Aotearoa/New Zealand responsible for freshwater management and for developing freshwater management plans that are consistent with the NPS-FM and for implementing them by the end of 2025.

The contemporary concept to guide decision-making that embraces community participation is Ecosystem-Based Management (EBM). EBM considers ecological integrity, biodiversity, and resilience, while accounting for benefits to human wellbeing and contributions to societal objectives (Borgstrom, Bodin, Sandstrom, & Crona, 2015; Cormier et al., 2017; Long et al., 2015). Thus within EBM, biocultural interactions are acknowledged rather than treating society and the environment as separate entities (Piet et al., 2020). Originally outlined for marine adaptive management, EBM has recently been put forward as a way to bridge theory and practice in freshwater management (Langhans, Jahnig, Lago, Schmidt-Kloiber, & Hein, 2019; O'Higgins, Lago, & DeWitt, 2020).

Developing management plans based on EBM involves an overarching regulatory framework and local, bottom-up driven solutions with trade-offs and compromises (Kiker, Bridges, Varghese, Seager, & Linkov, 2005). Consequently, in the absence of transparent processes EBM easily becomes complicated, inscrutable, and prone to misapplication. Hence, there is an urgent need for a support framework, based on participation that is (i) transparent, (ii) allows for the whole range of values (including ecological, socio-economic, and cultural ones) to be quantified and accounted for, (iii) can robustly test outcomes of different management scenarios, and (iv) can ultimately prioritise management actions with collective buy-in while considering uncertainty. Multi-Criteria Decision Analysis (MCDA) provides the means to operationalize the EBM concept (Eisenführ, Weber, & Langer, 2010). Originating in decision theory and risk analysis, MCDA has become popular in nature resource management (Gregory et al., 2012; Gregory & Keeney, 2002). Recently MCDA has also gained momentum in the freshwater realm as a tool to structure and facilitate water quality assessments (Kuemmerlen, Reichert, Siber, & Schuwirth, 2019; Langhans, Lienert, Schuwirth, & Reichert, 2013; Langhans, Schuwirth, & Reichert, 2014; Martin, Piscopo, Chintala, Gleason, & Berry, 2019), river restoration (Langhans & Lienert, 2016; Paillex et al., 2017) and catchment management (Martin, Powell, Webb, Nichols, & Poff, 2017; Reichert, Langhans, Lienert, & Schuwirth, 2015).

Here, we demonstrate that MCDA provides an effective framework to develop freshwater co(llaborative)-management plans with a specific focus on weaving together peoples' diverse cultural values with commonly used scientifically defined ecological and socio-economic objectives. We use the term collaborative co-management to mean 'a situation in which two or more social actors negotiate, define and guarantee amongst themselves a fair sharing of the management functions, entitlements, and responsibilities for a given territory, area, or set of natural resources', as defined by Carlsson & Berkes (2005). Here, we describe the application of the MCDA-framework through the case study of the Lake Wānaka catchment in Aotearoa/New Zealand.

2. MATERIAL AND METHODS

2.1 Case study site and community

The Lake Wānaka catchment is located in the south-west of the South Island of Aotearoa/New Zealand. Its main tributaries, the Mātukituki and the Makarora Rivers flow into the oligotrophic Lake Wānaka (Fig. 1). Due to its clear waters and surrounding mountainous landscape, Lake

Wānaka is a significant tourist destination and attracts a rapidly growing resident population. It provides drinking water for the region, is popular for trout and salmon fishing, and is a magnet for water-related recreational activities. While the lake still exhibits good water quality, it has recently experienced problems related to an increase in algal biomass, a shift in algal community structure, and the development of nuisance, planktonic mucilage called lake snow (Novis, Schallenberg, Saulnier-Talbot, Kilroy, & Reid, 2017). The lake also has a long history of nuisance growth of the invasive submerged aquatic macrophyte *Lagarosiphon major* (Kelly & Hawes, 2005). Due to these changes in the lake, together with the recent rapid development of tourism (e.g., 455,033 tourists visited the Wānaka area in 2018/2019; Wanaka Tourism, 2019), the resident population (e.g., growth from 3,740 to 15,910 people since 1996; Infometrics, 2021), and farming in the catchment, the community is concerned about the future health of the lake and the deterioration of related cultural and socio-economic benefits (Perkins, Muller, Boyens, & Langhans, 2019). Consequently, in the last five years the local community initiated the development of a community-led management plan to safeguard the lake and its catchment.

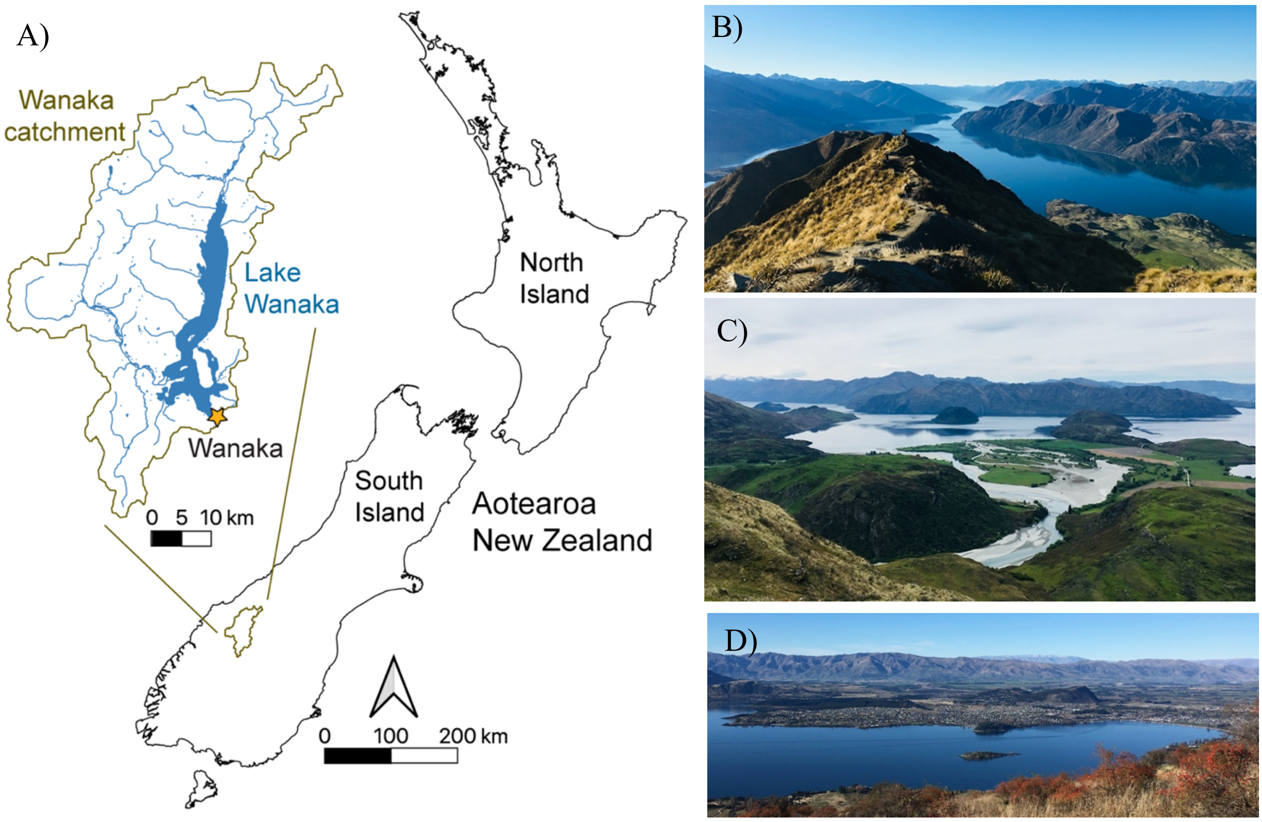


Figure 1. Description of the case study area: the Lake Wānaka catchment. A) Location of Lake Wānaka and its catchment; B) Lake Wānaka viewed from Roys Peak; C) Lake Wānaka and

Mātukituki River estuary viewed from Rocky Peak; and D) Wānaka town area from halfway up Roys Peak. Photo credits: S.D. Langhans.

2.2 MCDA method of choice: Multi-Attribute Value Theory

We used multi-attribute value theory (MAVT), one of the many methods within MCDA (Eisenführ et al., 2010), because it is useful for environmental decision making (Paillex et al., 2017; Reichert et al., 2015): MAVT (i) is based on the axioms of rational choice for justifying decisions, (ii) focuses on objectives to be achieved instead of direct adoption of apparently typical or favorable management actions, (iii) does not lead to rank reversals when new action alternatives are included, (iv) allows consideration of uncertainties (e.g., in the assessment of the objectives, the prediction of the outcomes of potential actions as well as of the stakeholders' weightings for different objectives), and (v) it can combine multiple ecological, socio-economic, and cultural objectives.

2.3 Operationalizing the MCDA-framework

Information gathered throughout the MCDA-process was implemented in a R-script based on the R-package "utility" (Reichert, Schuwirth, & Langhans, 2013), which was used for all analyses.

3. RESULTS

We followed the MCDA-framework outlined in Schuwirth, Reichert & Lienert (2012) and used the illustration from Langhans, Jähnig & Schallenberg (2019) to communicate the different elements of the framework to the community and stakeholders. In the following, we explain each element as applied in our case study (Fig. 2).

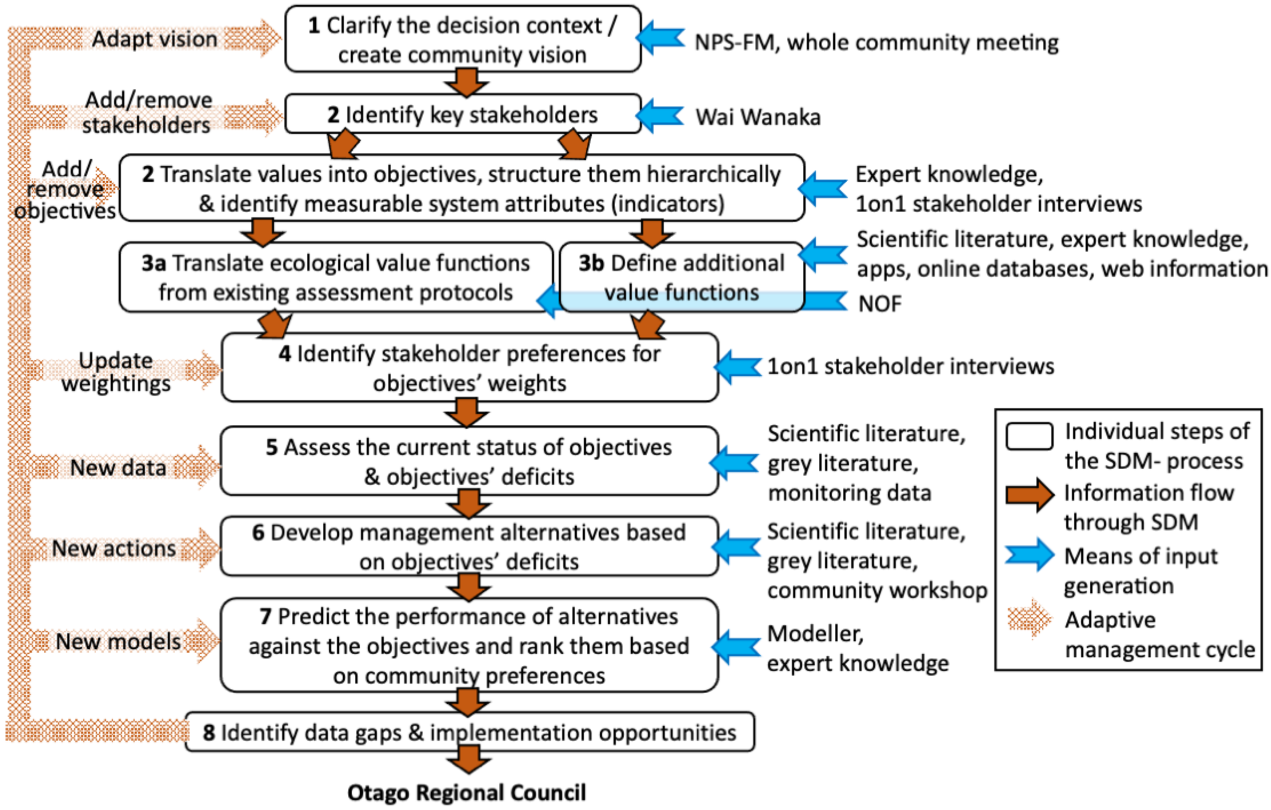


Figure 2. Flow diagram showing the different steps involved in the Multi-Criteria Decision Analysis framework. Blue arrows indicate the means of input generation from the community to support the development of a management plan for the Lake Wānaka catchment. NPS-FM: National Policy Statement for Freshwater Management; NOF: New Zealand's National Objectives Framework (NOF), both from the New Zealand Ministry for the Environment (2014, 2019).

3.1 Decision context and community water vision

Based on the NPS-FM guidelines, the task to develop a *catchment management plan for the Lake Wānaka catchment with buy-in from the community* was undertaken. During a public water forum in April 2018, 85 residents workshopped their vision for the future of the lake and waterways in the Wānaka region (Shaping our Future, 2018). The outcome was the expression of a community water vision that comprised:

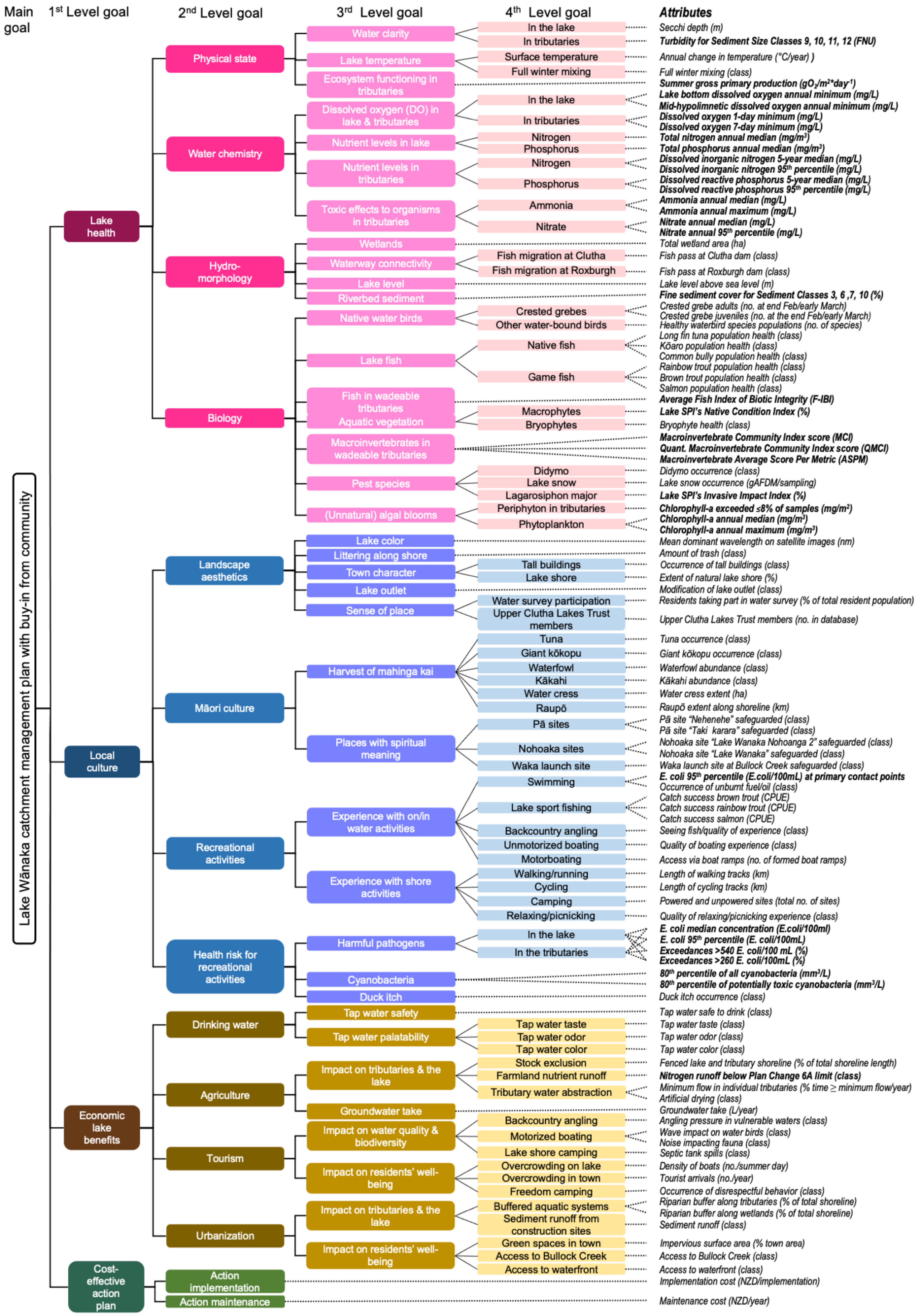
- a pristine environment that provides high quality drinking water
- the district is 100% pure
- Wānaka is the first water-neutral town in New Zealand where water use is reduced by 50%
- the district's water quality is the best in the world
- waterbodies with the healthiest underwater ecosystems in New Zealand
- no avoidable impacts of climate change

In addition, the attendees of the forum identified the values they held for the local waterbodies. The values were collated and collectively discussed before grouping them thematically.

3.2 Objectives and attributes

We translated the community values expressed in the collective water vision into measurable objectives. For example, a dominant value was that the lake and other waterways in the catchment are safe for swimming. We translated this value into two different objectives including *E.coli concentrations safe for swimming* and *no toxic cyanobacteria blooms*. We also translated the compulsory values in the NPS-FM: (1) *ecosystem health, (2) water safety for human primary contact, (3) threatened species,* and (4) ***mahinga kai*** into measurable objectives. ***Māori*** (i.e., cultural indigenous) objectives related to Lake Wānaka and its tributaries were identified by Aukaha (2019) and Hewitt (2013, 2017, 2018), and were informed through the Cultural Health Index (Tipa & Teirney, 2003, 2006).

We drafted an objectives hierarchy in which objectives were arranged from fundamental objectives to more specific objectives at four levels (Fig. 3). We discussed an initial draft of the objectives hierarchy with selected key stakeholders during one-on-one interviews (see below), and together developed it further until we reached a comprehensive and coherent version. The final hierarchy comprised four first-level objectives, 14 second-level objectives, 37 third-level objectives, and 66 fourth-level objectives (Fig. 3). We assigned at least one attribute to each lowest-level objective – these attributes were either one of the compulsory ecological attributes defined in the NOF or a new direct or proxy attribute (Table 1; Fig. 3).



Main goal
1st Level goal
2nd Level goal
3rd Level goal
4th Level goal
Attributes
Lake Wānaka catchment management plan with buy-in from community
Lake health
Physical state
Water clarity
In the lake
Secchi depth (m)
In tributaries
Turbidity for Sediment Size Classes 9, 10, 11, 12 (FNU)
Lake temperature
Surface temperature
Annual change in temperature (°C/year))
Full winter mixing
Full winter mixing (class)
Ecosystem functioning in tributaries
Summer gross primary production (gO2/m2*day-1)
Water chemistry
Dissolved oxygen (DO) in lake & tributaries
In the lake
Lake bottom dissolved oxygen annual minimum (mg/L)
Mid-hypolimnetic dissolved oxygen annual minimum (mg/L)
In tributaries
Dissolved oxygen 1-day minimum (mg/L)
Dissolved oxygen 7-day minimum (mg/L)
Nutrient levels in lake
Nitrogen
Total nitrogen annual median (mg/m3)
Phosphorus
Total phosphorus annual median (mg/m3)
Nutrient levels in tributaries
Nitrogen
Dissolved inorganic nitrogen 5-year median (mg/L)
Dissolved inorganic nitrogen 95th percentile (mg/L)
Phosphorus
Dissolved reactive phosphorus 5-year median (mg/L)
Dissolved reactive phosphorus 95th percentile (mg/L)
Toxic effects to organisms in tributaries
Ammonia
Ammonia annual median (mg/L)
Ammonia annual maximum (mg/L)
Nitrate
Nitrate annual median (mg/L)
Nitrate annual 95th percentile (mg/L)
Hydro-morphology
Wetlands
Total wetland area (ha)
Waterway connectivity
Fish migration at Clutha
Fish pass at Clutha dam (class)
Fish migration at Roxburgh
Fish pass at Roxburgh dam (class)
Lake level
Lake level above sea level (m)
Riverbed sediment
Fine sediment cover for Sediment Classes 3, 6 ,7, 10 (%)
Biology
Native water birds
Crested grebes
Crested grebe adults (no. at end Feb/early March)
Crested grebe juveniles (no. at the end Feb/early March)
Other water-bound birds
Healthy waterbird species populations (no. of species)
Lake fish
Native fish
Long fin tuna population health (class)
Kōaro population health (class)
Common bully population health (class)
Game fish
Rainbow trout population health (class)
Brown trout population health (class)
Salmon population health (class)
Fish in wadeable tributaries
Average Fish Index of Biotic Integrity (F-IBI)
Aquatic vegetation
Macrophytes
Lake SPI's Native Condition Index (%)
Bryophytes
Bryophyte health (class)
Macroinvertebrates in wadeable tributaries
Macroinvertebrate Community Index score (MCI)
Quant. Macroinvertebrate Community Index score (QMCI)
Macroinvertebrate Average Score Per Metric (ASPM)
Pest species
Didymo
Didymo occurrence (class)
Lake snow
Lake snow occurrence (gAFDM/sampling)
Lagarosiphon major
Lake SPI's Invasive Impact Index (%)
(Unnatural) algal blooms
Periphyton in tributaries
Chlorophyll-a exceeded ≤8% of samples (mg/m2)
Phytoplankton
Chlorophyll-a annual median (mg/m3)
Chlorophyll-a annual maximum (mg/m3)
Local culture
Landscape aesthetics
Lake color
Mean dominant wavelength on satellite images (nm)
Littering along shore
Amount of trash (class)
Town character
Tall buildings
Occurrence of tall buildings (class)
Lake shore
Extent of natural lake shore (%)
Lake outlet
Modification of lake outlet (class)
Sense of place
Water survey participation
Residents taking part in water survey (% of total resident population)
Upper Clutha Lakes Trust members
Upper Clutha Lakes Trust members (no. in database)
Māori culture
Harvest of mahinga kai
Tuna
Tuna occurrence (class)
Giant kōkopu
Giant kōkopu occurrence (class)
Waterfowl
Waterfowl abundance (class)
Kākahi
Kākahi abundance (class)
Water cress
Water cress extent (ha)
Raupō
Raupō extent along shoreline (km)
Places with spiritual meaning
Pā sites
Pā site "Nehenehe" safeguarded (class)
Pā site "Taki karara" safeguarded (class)
Nohoaka sites
Nohoaka site "Lake Wanaka Nohoanga 2" safeguarded (class)
Nohoaka site "Lake Wanaka" safeguarded (class)
Waka launch site
Waka launch site at Bullock Creek safeguarded (class)
Recreational activities
Experience with on/in water activities
Swimming
E. coli 95th percentile (E.coli/100mL) at primary contact points
Occurrence of unburnt fuel/oil (class)
Lake sport fishing
Catch success brown trout (CPUE)
Catch success rainbow trout (CPUE)
Catch success salmon (CPUE)
Backcountry angling
Seeing fish/quality of experience (class)
Unmotorized boating
Quality of boating experience (class)
Motorboating
Access via boat ramps (no. of formed boat ramps)
Experience with shore activities
Walking/running
Length of walking tracks (km)
Cycling
Length of cycling tracks (km)
Camping
Powered and unpowered sites (total no. of sites)
Relaxing/picnicking
Quality of relaxing/picnicking experience (class)
Health risk for recreational activities
Harmful pathogens
In the lake
In the tributaries
E. coli median concentration (E.coli/100ml)
E. coli 95th percentile (E. coli/100mL)
Exceedances >540 E. coli/100 mL (%)
Exceedances >260 E. coli/100mL (%)
Cyanobacteria
80th percentile of all cyanobacteria (mm3/L)
80th percentile of potentially toxic cyanobacteria (mm3/L)
Duck itch
Duck itch occurrence (class)
Economic lake benefits
Drinking water
Tap water safety
Tap water safe to drink (class)
Tap water palatability
Tap water taste
Tap water taste (class)
Tap water odor
Tap water odor (class)
Tap water color
Tap water color (class)
Agriculture
Impact on tributaries & the lake
Stock exclusion
Fenced lake and tributary shoreline (% of total shoreline length)
Farmland nutrient runoff
Nitrogen runoff below Plan Change 6A limit (class)
Tributary water abstraction
Minimum flow in individual tributaries (% time ≥ minimum flow/year)
Artificial drying (class)
Groundwater take
Groundwater take (L/year)
Tourism
Impact on water quality & biodiversity
Backcountry angling
Angling pressure in vulnerable waters (class)
Motorized boating
Wave impact on water birds (class)
Noise impacting fauna (class)
Lake shore camping
Septic tank spills (class)
Impact on residents' well-being
Overcrowding on lake
Density of boats (no./summer day)
Overcrowding in town
Tourist arrivals (no./year)
Freedom camping
Occurrence of disrespectful behavior (class)
Urbanization
Impact on tributaries & the lake
Buffered aquatic systems
Riparian buffer along tributaries (% of total shoreline)
Riparian buffer along wetlands (% of total shoreline)
Sediment runoff from construction sites
Sediment runoff (class)
Impact on residents' well-being
Green spaces in town
Impervious surface area (% town area)
Access to Bullock Creek
Access to Bullock Creek (class)
Access to waterfront
Access to waterfront (class)
Cost-effective action plan
Action implementation
Implementation cost (NZD/implementation)
Action maintenance
Maintenance cost (NZD/year)

Figure 3. Objectives hierarchy for the main objective of co-developing a management plan for the Lake Wānaka catchment. Attributes in bold are mandatory attributes from the New Zealand National Objectives Framework (NOF) (New Zealand Ministry for the Environment, 2014, 2019).

3.3 Value functions

For each attribute, a value function was either identified or elicited from experts, i.e. people with some deep knowledge of the biocultural system (Fig. 4; Supporting Information (SI) Fig. 1). A value function describes the degree of fulfilment of each objective as a function of the associated attribute, in effect normalising attributes' levels measured in different units into a standardised value score between 0 and 1 (Langhans et al., 2013). This allows for the direct, quantitative comparison of fulfilments among objectives. In addition, objective scores can then be aggregated up the hierarchy to calculate scores of higher-level objectives as well as an overall score for the fulfilment of the main objective (i.e., *a management plan for the Wānaka catchment with buy-in from the community*). Value functions can either be translated from existing ecological assessments or elicited from experts (Langhans et al., 2014). We translated the value functions for the compulsory ecological attributes from the NOF (Langhans, Jähnig, et al., 2019; NZ Ministry for the Environment, 2019) and constructed the remaining ecological value functions based on information from various sources such as websites (e.g., for the value function of *lake level*), the technical literature (e.g., *secchi depth*, *lake water colour* or *gross primary production*), or from experts (e.g., *health of native fish populations*). Value functions for the social and economic objectives were defined based on information from the literature (e.g., *safeguarding* ***pā*** *and* ***nohoaka*** *sites* or *cost of implementing a fish pass*), from experts (e.g., *overcrowding on lake* or *game fish catch rate*), or from selected community opinions (e.g., *length of walking and cycling tracks* or *overcrowding in town*). Attributes and references for the sources of input information, which we used to define attributes' ranges from worst to best status, are listed in Table 1.

Table 1. Attributes selected for the most specific, lowest-level objectives, their measurement units, and attribute ranges (from potentially worst to potentially best status for Lake Wānaka and its upper catchment, respectively). Information was taken from the literature or elicited from experts, as indicated in the footnotes. Attributes in bold are mandatory for any freshwater system assessment according to the New Zealand National Objectives Framework (NOF) (New Zealand Ministry for the Environment, 2014, 2019). n.d. = no data; n.e.d. = not enough data to calculate a score.

Attribute	Measurement unit	Attribute range (worst-best)	Current attribute level
Secchi depth	m	6.7-23.7[1]	14.4[2*]
Turbidity in tributaries	FNU	SSC9: 2-0; SSC10: 1.9-0; SSC11: 2-0; SSC12: 3.5-0[3,4]	n.e.d.
Annual change in temperature	°C/year	2-0	0.065[1]
Full winter mixing	quality class	no-yes	yes
Summer gross primary production	gO_2/m^2*day^{-1}	0/10-0.5[5]	n.d.
Lake bottom dissolved oxygen annual minimum	mg/L	0-12[4]	n.d.
Mid-hypolimnetic dissolved oxygen annual minimum	mg/L	0-12[4]	n.d.
Dissolved oxygen 1-day minimum in tributaries	mg/L	0-12[5]	7.6[6]
Dissolved oxygen 7-day minimum in tributaries	mg/L	0-12[5]	7.6[6]
Total nitrogen annual median	mg/L	52-0.050[4]	0.050[2*]

[1] Monitoring data provided by the Otago Regional Council
[2] (Bayer, Schallenberg, & Burns, 2016); based on monthly measurements taken since 1994 by the Otago Regional Council
[3] Tributaries of Lake Wānaka belong to the suspended sediment classes (SSC) 9, 10, 11, and 12 according to the mfe-river-environment-classification-new-zealand-2010-SHP-2 (accessed 25 September 2019 at https://data.mfe.govt.nz/layer/51845-river-environment-classification-new-zealand-2010/)
[4] (NZ Ministry for the Environment, 2019)
[5] (Langhans & Lienert, 2016)
[6] Proxy value due to not enough data to calculate as described in (NZ Ministry for the Environment, 2019): Minimum measured in eight different tributaries through the austral spring of 2011 through the autumn of 2012 (Weaver, Schallenberg, & Burns, 2017)

Total phosphorus annual median	mg/L	0.300-0.004[4]	0.004[2**]
DIN 5-year median in tributaries	mg/L	1.4-0.1[4]	n.e.d
DIN 95th percentile in tributaries	mg/L	3-0.07[4]	0.076[2*]
DRP 5-year median in tributaries	mg/L	0.02-0.004[4]	0.004[2*]
DRP 95th percentile in tributaries	mg/L	0.07-0.006[4]	0.006[2*]
Ammonia annual median in tributaries	mg/L	30-0.005[4]	0.005[2*]
Ammonia annual maximum in tributaries	mg/L	50-0.01[4]	0.041[2*]
Nitrate annual median in tributaries	mg/L	13.5-0.2[4]	0.478[2*]
Nitrate annual 95th percentile in tributaries	mg/L	20.0-0.2[4]	n.d.
Total wetland area	ha	0-4366.91[7]	325.45[8]
Fishpass at Clutha dam	quality class	no-yes	no
Fishpass at Roxburgh dam	quality class	no-yes	no
Lake level above sea level	m	281.3[9]- 276.5[10]	276.6[***]
Fine sediment cover in tributaries	%	0-100 (DSC 3, 6, 7, 10)[4,11]	n.d.
Crested grebe adults	no. at end Feb/early March	0-92[12]	63±4[12]
Crested grebe juveniles	no. at end Feb/early March	0-62[12]	35±20[12]

[7] Predicted prehuman wetland extent = 3466.91 ha; calculated from file “Prediction of wetlands before humans arrived” provided by the NZ Ministry for the Environment (https://data.mfe.govt.nz/data/)

[8] current wetland extent (2013) calculated from the GIS-file “Current wetland extent” provided by the NZ Ministry for the Environment (https://data.mfe.govt.nz/data/) = 325.45 ha

[9] Continuous data available at: https://www.orc.govt.nz/managing-our-environment/water/water-monitoring-and-alerts/upper-clutha/lake-; 281.3 m above sea level = historical flood November 1999

[10] (New Zealand Government, 1973)

[11] Tributaries of Lake Wānaka belong to the Deposited Sediment Classes 3, 6, 7, 10, and 12 (mfe-river-environment-classification-new-zealand-2010-SHP-2; accessed 25 September 2019 at https://data.mfe.govt.nz/layer/51845-river-environment-classification-new-zealand-2010/)

[12] Expert information: J. Darby (personal communication, April 2019). Monthly counts of adults and chicks from 2014 to 2017. Attribute range: maximum number previously counted

Healthy waterbird species populations occurring in	no. of non-threatened species	0-23[13]	13[14]
Long fin ***tuna*** population health	quality class	bad/no-excellent	moderate
Kōaro population health	quality class	bad/no-excellent	high[15]
Common bully population health	quality class	bad/no-excellent	high[16]
Rainbow trout population health	quality class	bad/no-excellent	excellent[17]
Brown trout population health	quality class	bad/no-excellent	moderate[17]
Salmon population health	quality class	bad/no-excellent	good[17]
Average Fish Index of Biotic Integrity in wadeable tributaries (WT)	FIBI	0-60[4,18]	n.d.
Lake SPI's Native Condition Index	%	0-100[4,19]	87[20]
Bryophyte health	quality class	bad/no-excellent	good
Macroinvertebrate Community Index score in WT	MCI	20-200[4,21]	n.d.
Quantitative Macroinvertebrate Community Index score in WT	QMCI	1-10[4,19]	n.d.
Macroinvertebrate Average Score Per Metric in WT	ASPM	0-1[4,22]	n.d.
Didymo occurrence	quality class	extensive-absent	little/few
Lake snow occurrence	gAFDM/sampling	0.002-0.179[2]	0.046±0.038[2]
Lake SPI's Invasive Impact Index	%	100-0[4,18]	25[20]

[13] Total freshwater-related species regularly occurring in Wānaka = 25 (Robertson & Blair, 1980)
[14] 10 species are listed from declining to nationally critical (http://nzbirdsonline.org.nz/name search?title=grebe&field_other_names_value=grebe&field_search_scientific_name_value=grebe)
[15] Expert information: J. Augspurger (personal communication)
[16] Expert information: T. Ingram (personal communication)
[17] Expert information: J. Herzinger (personal communication)
[18] (Joy & Death, 2004)
[19] (Clayton & Edwards, 2006)
[20] From LAWA Land Air Water Aotearoa: https://www.lawa.org.nz/explore-data/otago-region/lakes/lake-/ (June 2019)
[21] (Stark & Maxted, 2007)
[22] (Collier, 2008)

Chlorophyll-a exceeded in ≤ 8% of samples in tributaries[23]	mg/m^2	1400-50[4]	n.d.
Chlorophyll-a annual median	mg/m^3	150.0-0.5[4]	0.90[2*]
Chlorophyll-a annual maximum	mg/m^3	225-1[4]	1.80[2*]
Mean dominant wavelength on satellite images	nm	480.1-577.7[24]	495.5[25]
Amount of trash	quality class	extensive-absent	little
Occurrence of tall buildings	quality class	extensive-absent	absent
Extent of natural lake shore	% of total shoreline	0-100[26]	63[27]
Modification of lake outlet	quality class	yes-no	no
Residents taking part in water survey	% of total resident population	0-100	3.6[28]
Upper Clutha Lakes Trust members	no. in database	0-900[29]	760[30]
Tuna occurrence	quality class	absent-plenty	few
Kōkopu occurrence	quality class	absent-plenty	absent
Waterfowl abundance	quality class	absent-plenty	plenty
Kakahi abundance	quality class	absent-plenty	absent
Water cress extent	ha	0-9.6[31]	0
Raupō extent along shoreline	km	0-1.06[32]	0

[23] Catchment = default class (NZ Ministry for the Environment, 2014)
[24] Expert information: M. Lehmann (personal communication)
[25] (Lehmann, Nguyen, Allan, & van der Woerd, 2018)
[26] Settlements account for approx. 2.5% of the lake shore (calculated from maps based on the lcdb-v41-land-cover-database-version-41-mainland-new-zealand dataset and classifications see footnote 21)
[27] Estimation from the map based on the lcdb-v41-land-cover-database-version-41-mainland-new-zealand dataset (LINZ, 2019)
[28] (Muller, 2019)
[29] Elicited from long-term Wānaka residents (mean of n=4)
[30] Expert information: M. Williams (personal communication, June 2019)
[31] Estimated as 0.5 % of lake surface (192 km^2)
[32] Calculated as 0.5% of total lake shoreline perimeter of 213.2 km (calculated from NZ Ministry for the Environment GIS file lds-nz-lake-polygons-topo-150k-SHP)

Pā site "Nehenehe" safeguarded	quality class	no-yes	no
Pā site "Taki karara" safeguarded	quality class	no-yes	no
Nohoaka site "Lake Wānaka Nohoanga 2" safeguarded	quality class	no-yes	no
Nohoaka site "Lake Wānaka" safeguarded	quality class	no-yes	no
Waka launch site at Bullock Creek safeguarded	quality class	no-yes	no
***E. coli* 95th percentile primary contact points**	***E. coli*/100 mL**	5000-0[4]	n.d.
Occurrence of unburnt fuel/oil	quality class	always-never	regularly
Catch success brown trout	CPUE (no./fishing trip)	0-8	3[17]
Catch success rainbow trout	CPUE (no./fishing trip)	0-8	3[17]
Catch success salmon	CPUE (no./fishing trip)	0-2	0[17]
Seeing fish/quality of experience[33]	quality class	never-always	frequently[33]
Quality of boating experience	quality class	bad-excellent	high
Access via boat ramps	no. of formed boat ramps	0-6	6[34]
Length of walking tracks	km	0-400[29]	227.1[35]
Length of cycling tracks	km	0-400[29]	162.912[36]
Powered and unpowered sites	total no. of sites	0-1500[29]	846[37]
Quality of relaxing/picnicking experience	quality class	bad-excellent	excellent
***E. coli* median concentration**	***E. coli*/100 mL**	2300-0[4]	1.6[2****]
***E. coli* 95th percentile**	***E. coli*/100 mL**	5000-0[4]	67[2****]

[33] Depending on location; only rainbow and brown trout, salmon hide in the lake during summer (expert information: P. Wright, personal communication, April 2019)
[34] J. Donaldson (personal communication, June 2019)
[35] Calculated from the Wānaka Track Guide app for Apple products
[36] Length of cycling track estimation from https://www.bike.org.nz/trail-maps#Interactive
[37] Extracted from CamperMate (4 September 2019)

Exceedances >540 *E. coli*/100ml	**%**	100-0[4]	0[2]
Exceedances >260 *E. coli*/100ml	**%**	100-0[4]	0[2]
***E. coli* median concentration in tributaries**	***E. coli*/100 mL**	2300-0[4]	19
***E. coli* 95th percentile in tributaries**	***E. coli/*100 mL**	5000-0[4]	445
Exceedances over 540 *E. coli*/100ml in tributaries	**%**	100-0[4]	4.5[38]
Exceedances over 260 *E. coli*/100ml in tributaries	**%**	100-0[4]	8.1
80th percentile of all cyanobacteria	**mm^3/L**	10-0[4]	n.d.
80th percentile of potentially toxic cyanobacteria	**mm^3/L**	5-0[4]	0
Duck itch (schistosome dermatits) occurrence	quality class	yes-no	yes
Tap water safe to drink	quality class	no-yes	yes
Tap water taste	quality class	bad-excellent	excellent
Tap water odor	quality class	bad-none	none
Tap water color	quality class	heavily discolored-transparent	transparent
Fenced lake and tributary shoreline	% of total shoreline length	0-100	n.d.
Nitrogen runoff below Plan Change 6A limit	quality class	no-yes	yes
Minimum flow in tributaries	% time with ≥ minimum flow	0-100	n.d.
Artificial drying	quality class	always-never	rare
Groundwater take	L/year	to be defined	n.d.
Angling pressure in vulnerable waters	quality class	yes-no	yes
Wave impact on water birds	quality class	always-never	n.d.
Noise impacting fauna	quality class	always-never	n.d.

[38] For the Matukituki River; no information for other tributaries available

Septic tank spills	quality class	always-never	rare
Density of boats	no./summer day	800-0[34]	400[34]
Tourist arrivals	no./year	0/600,000-500,000	435,397[39]
Occurrence of disrespectful camping behavior (defaecating, littering)	quality class	never-always	sometimes
Riparian buffer along tributaries	% of total shoreline	0-100[40]	n.d.
Riparian buffer along wetlands	% of total shoreline	0-100	n.d.
Sediment runoff	quality class	yes-no	yes
Impervious surface area	% town area	70-5[41]	n.d.
Access to Bullock Creek	quality class	no-yes	yes
Access to waterfront	quality class	no-yes	yes
Implementation cost	NZD/implementation	depending on action	n.e.d
Maintenance cost	NZD/year	depending on action	n.e.d.

* in 2018

** at lake outlet in 2018

*** September 2019

**** in 2017

[39] Set target for 2017/2018 = 336,529 tourists/year (Wanaka Tourism, 2018)

[40] Good ecosystem health: ≥ 80% of hydrologically active areas in close proximity to the stream have mid-dense forest cover; moderate health: 60-80% cover (Sheldon et al., 2012)

[41] 10 percent in low-density subdivisions to over 50 percent in multi-family communities (https://en.wikipedia.org/wiki/Impervious_surface)

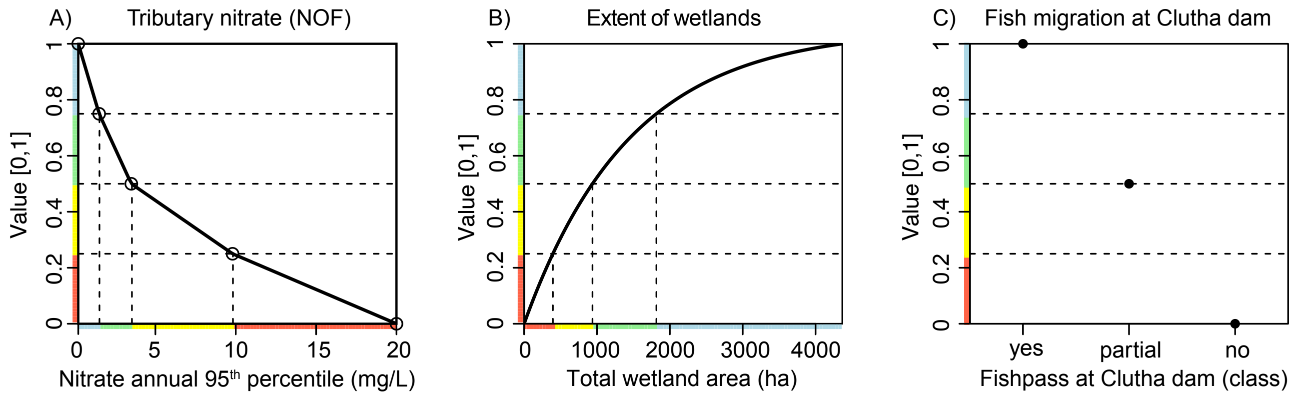


Figure 4. Examples of value functions. Value functions for A) the attribute *nitrate concentration* translated from the assessment provided in the National Objectives Framework (NOF) and B) the attribute *extent of wetlands*, established with data from the New Zealand Ministry for the Environment (Tab. 2), and C) the attribute *fish migration at the Clutha dam*. A) and B) assessed quantitatively and C) qualitatively. A complete set of value functions can be found in the SI (Figure S1).

3.4 Community preferences

An outcome of a decision-making process which has buy-in from the whole community must account for all local interests. We used a common method, the elicitation of preferences from area-specific key stakeholders (Grimble & Wellard, 1997), to do so. We defined stakeholders as local community members who have an interest specifically related to fresh water within the case study area. We invited representatives of stakeholder groups to participate in one-on-one interviews. We covered key interests including sheep and beef farming (3 representatives; preference weights were averaged), tourism, freshwater ecology, bird conservation, economy, development/construction, backcountry fishing, the Department of Conservation, the Queenstown Lakes District Council, marine fisheries management, biosecurity, the Friends of Bullock Creek, and Extinction Rebellion (one representative each). ***Māori*** values were represented by a long-term resident with strong ties to the relevant ***Māori*** tribe (Kai Tahu), who is an expert in the history of ***Māori*** values in the case study area.

Each interview lasted between 60 and 120 minutes and followed a structured format. First, the interviewee was asked to explain her/his background and expertise related to freshwater. Then, each objective was explained to the interviewee and its relevance was discussed. After going through all the objectives, the interviewee was asked to suggest additional objectives or identify any missing or superfluous values (only for the third and fourth levels of the hierarchy). In the second part of the interview, we used the reverse swing method to elicit subjective stakeholder weightings (Schuwirth et al., 2012) for the first- and second-level objectives (Tab. 2).

Table 2. Weights elicited from key stakeholders in the Wānaka region for first-level and second-level objectives. Stakeholder backgrounds: ***iwi*** = ***iwi*** representative, fa = farmer, ec = economist, to = tourism, fg = fishing guide (catchment, not lake), do = Department of Conservation, qldc = Queenstown Lakes District Council, bs = biosecurity, fm = fisheries management, fbc = Friends of Bullock Creek, be = bird expert, fe = freshwater ecologist, ex = extinction rebellion.

Level of objective		Stakeholder weights												
	Objective	iwi	fa	ec	to	fg	doc	qldc	bs	fm	fbc	be	fe	ex
1st	Lake health	0.38	0.27	0.32	0.31	0.36	0.28	0.5	0.53	0.39	0.28	0.37	0.47	0.42
2nd	Physical state	0.25	0.32	0.20	0.29	0.25	0.25	0.25	0.08	0.31	0.25	0.25	0.25	0.00
	Chemical state	0.25	0.22	0.24	0.29	0.25	0.25	0.25	0.38	0.22	0.25	0.25	0.25	0.00
	Hydromorphology	0.25	0.17	0.24	0.21	0.25	0.25	0.25	0.17	0.10	0.25	0.25	0.25	0.00
	Biology	0.25	0.28	0.33	0.21	0.25	0.25	0.25	0.38	0.37	0.25	0.25	0.25	1.00
1st	Local culture	0.38	0.24	0.28	0.24	0.32	0.22	0.4	0.26	0.3	0.26	0.33	0.13	0.33
2nd	Aesthetics	0.27	0.30	0.19	0.32	0.26	0.21	0.28	0.31	0.16	0.27	0.28	0.18	0.07
	Māori culture	0.27	0.15	0.29	0.04	0.23	0.25	0.25	0.12	0.3	0.24	0.24	0.29	0.30
	Recreation	0.18	0.26	0.27	0.32	0.23	0.32	0.19	0.23	0.23	0.24	0.21	0.21	0.33
	No health risk	0.27	0.30	0.25	0.33	0.29	0.21	0.28	0.35	0.3	0.25	0.28	0.32	0.30
1st	Lake benefits	0.25	0.30	0.16	0.21	0.28	0.22	0.10	0.00	0.11	0.23	0.11	0.33	0.08
2nd	Drinking water	0.38	0.28	0.21	0.48	0.45	0.41	0.69	0.45	0.35	0.54	0.77	0.43	0.53
	Agriculture	0.38	0.29	0.24	0.05	0.15	0.09	0.15	0.20	0.18	0.46	0.00	0.30	0.47
	Tourism	0.21	0.27	0.41	0.45	0.40	0.41	0.15	0.35	0.29	0.00	0.23	0.10	0.00
	Urbanization	0.04	0.16	0.14	0.03	0.00	0.09	0.00	0.00	0.18	0.00	0.00	0.14	0.00
1st	Management action	0.00	0.20	0.24	0.24	0.04	0.28	0.00	0.21	0.2	0.23	0.19	0.07	0.17
2nd	Action implementation	0.50	0.45	0.70	0.50	0.56	0.50	0.50	0.50	0.77	0.50	0.80	0.20	0.36
	Action maintenance	0.50	0.55	0.30	0.50	0.44	0.50	0.50	0.50	0.23	0.50	0.20	0.80	0.64

3.5 Current status and deficit assessment

To identify the levels of the attributes indicative of the current conditions of the catchment's water bodies, we used various information sources such as peer-reviewed scientific articles, books, reports, monitoring data (provided by the Otago Regional Council, H. Borges), GIS map data (downloaded from the Ministry for the Environment Data Service website; https://data.mfe.govt.nz/data/) as well as expert knowledge in cases for which no other information was available (Tab. 1). We then assessed objectives based on the identified current attribute levels and the respective value functions. Fourth, third, and second level objectives were averaged and those on the first level were aggregated with an additive-minimum function (Langhans et al., 2014). This led to an overall score of 0.36 for the current status of the Lake Wānaka catchment (yellow quality status; Fig. 5A) considering all community, legislative, cultural, ecological, and socio-economic objectives. The assessment revealed the most severe deficits (defined as red or yellow quality status for third-level objectives, on a scale from red-yellow-green-blue) for the objectives *wetland area, fish migration, lake level,* ***mahinga kai****, spiritual places, duck itch* (i.e. Schistosome dermatitis, which is reflected in itching of the skin after swimming due to penetration of the skin by a cercarial parasite of the New Zealand scaup and the freshwater snail *Lymnaea*)*, angling impact on backcountry streams,* and *sediment runoff from construction sites.*

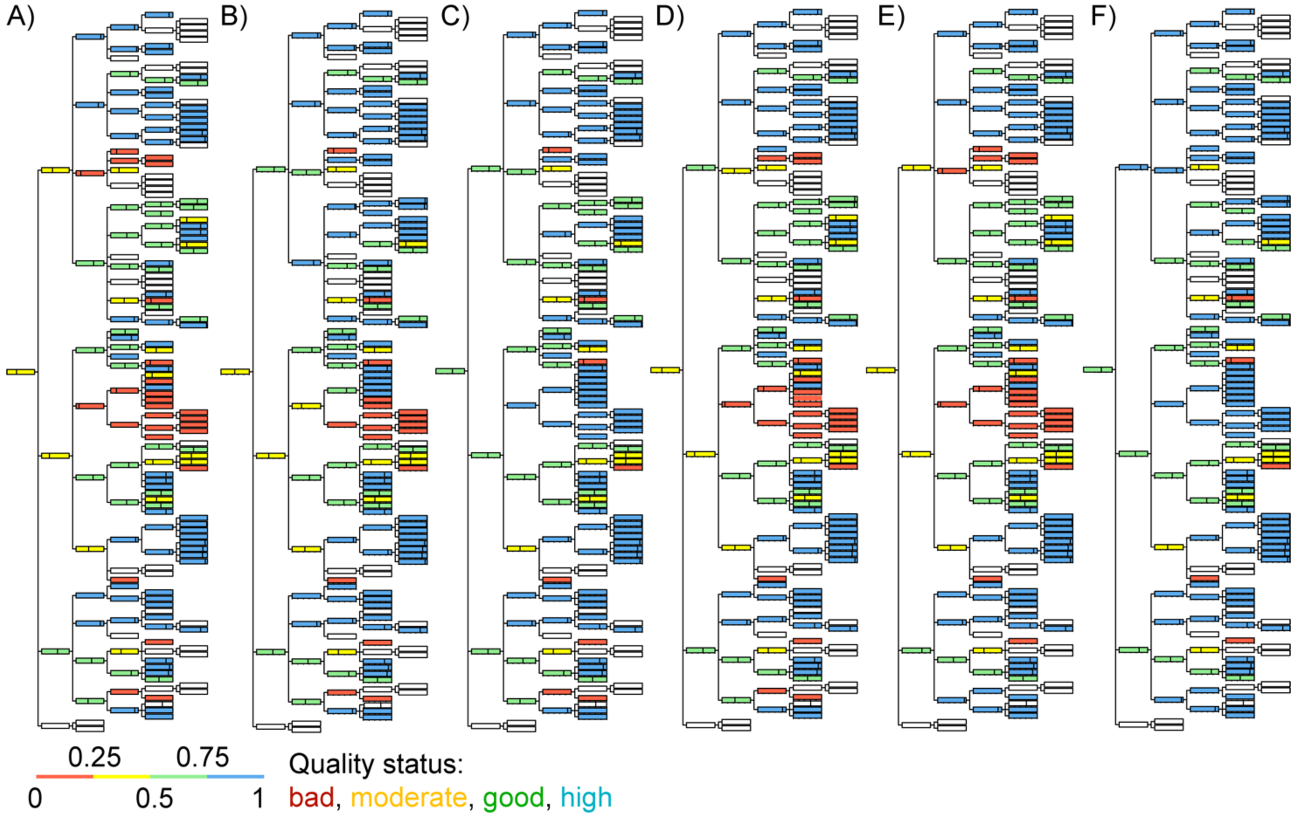


Figure 5. Fulfillment of objectives estimated for the current status and for all action alternatives. Objectives hierarchy calculated with A) the current status of attributes or the "business-as-usual" or "do-nothing" alternative (value for overall objective = 0.36), and with predicted consequences for actions, B) restore native fauna (overall value = 0.49), C) restore ***Māori*** objectives (overall value = 0.59), D) restore wetlands (overall value = 0.39), E) manage sediment runoff from construction sites (overall value = 0.38), and F) a combination of B, C, D, and E

(overall value = 0.62). White boxes indicate no available data for the respective attributes. Aggregations: Additive-minimum at the uppermost level, otherwise additive.

3.6 Management action alternatives

Considering the identified deficits as well as potential future impacts to the relevant waterbodies under the "business-as-usual" or "do-nothing" scenario and also considering climate change, we created a list of potentially relevant management action alternatives. The list was discussed and amended during a second public community meeting. From the list, we selected the four most relevant actions: restoring native fauna (A1), restoring ***Māori*** values (A2), wetland restoration (A3), and managing sediment runoff from construction sites (A4). We also included the combination of all four actions (A5).

We did not include actions that specifically address *lake level, duck itch,* and *angling impact on backcountry streams,* despite deficits in these having been identified. Reasons for that are that regulation of the lake's level is prohibited (New Zealand Government, 1973); there is no specific remedy known to control duck itch (Davis, 1998); and it was recognised that more data were required to develop an effective strategy to protect backcountry streams from angling pressure in the case study catchment.

3.7 Performance of actions and ranking

We used scenario planning (Dong, Schoups, & van de Giesen, 2013), i.e., we based the predictions of the performance of the five action alternatives on the assumption that the targeted objectives would be fully restored. For example, the action *restoring native fauna* was assumed to completely fulfil the relevant objectives: *functioning fish migration, healthy grebe populations, healthy populations of other water birds, healthy native fish populations,* and *abundant and healthy mahinga kai (tuna, kokopu* and *kakahi)* (Fig. 5B). Based on these assumptions, the combined actions (A5) performed best (overall value = 0.62) followed by the restoration of ***Māori*** values (A2 = 0.59), native fauna (A1 = 0.49) and wetlands (A3 = 0.39), and the management of sediment runoff at construction sites (A4 = 0.38) (Figs. 5B-F).

It should be noted that, due to the lack of information, assessments of costs were not included. When analysing action performance, including very rough cost estimates (i.e. based on qualitative value functions for implementation and maintenance costs with attribute levels: *no, low* (A4), *moderate* (A3), *high* (A1 and A2), and *exorbitant* (A5)), managing sediment runoff performed best (A4 = 0.41) closely followed by restoring wetlands (A3 = 0.39), ***Māori*** values (A2 = 0.38), and native biodiversity (0.36), while the combined actions performed significantly worse due the much higher costs associated with this alternative (A5 = 0.25). When including stakeholder-specific weights for the first- and second-level objectives in the assessment of action alternatives (without considering costs), the ranking of actions remained the same for all stakeholder groups (best to worst: A5-A2-A1-A3-A4) (Fig. 6).

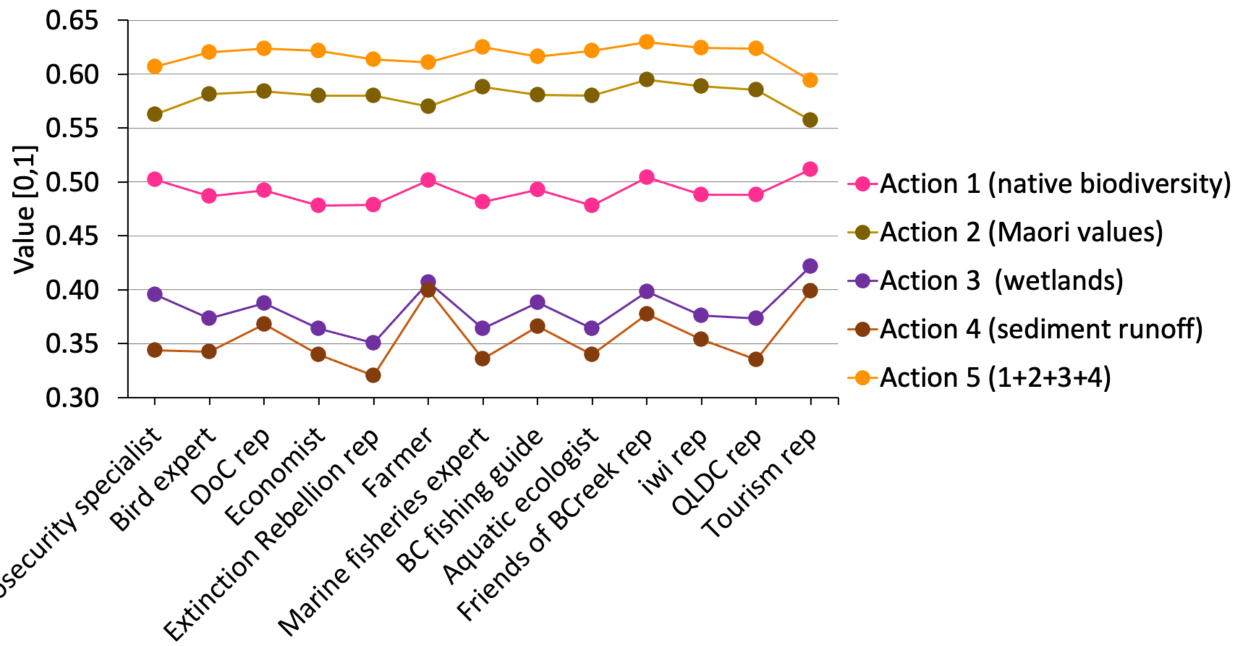


Figure 6. Ranking of potential management actions for stakeholder groups considering stakeholder-specific weightings for first- and second-level objectives.

3.8 Data/knowledge gaps and implementation opportunities

For 25 attributes there was insufficient data and no expert knowledge available to assess the respective objectives (Fig. 5A, white boxes). These attributes were *turbidity in tributaries, primary production in tributaries, lake-bottom and mid-hypolimnetic dissolved oxygen, dissolved inorganic nitrogen (5 year median) and nitrate (annual 95 percentile) in tributaries, fine sediment cover of riverbeds, fish and macroinvertebrates in wadeable tributaries (Macroinvertebrate community index score, quantitative macroinvertebrate community index score, macroinvertebrate average score per metric), periphyton in tributaries, E.coli at swimming sites (annual 95 percentile), cyanobacteria (all and only toxic), groundwater take, fenced off tributary and lake shorelines, minimum flow in tributaries, wave impact on water birds and noise impact on fauna (both from motorboating), riparian buffer along shorelines of tributaries and wetlands, area of green spaces in town,* and *cost of action implementation and action maintenance.*

The Otago Regional Council (ORC) is the regulatory authority responsible for managing water quality and use in the area. Consequently, carrying out water quality monitoring, developing catchment management plans, and filling knowledge gaps relevant to water management are statutory tasks of the ORC. However, several grass-root initiatives are implementing management actions in the catchment to improve water management. For example, WAI Wānaka together with Te Kākano Aotearoa Trust, landowners, the Queenstown Lakes District Council, ORC and other stakeholders have begun planting 24,000 native plants to restore riparian margins (WAI Wanaka, 2021b). In addition, WAI Wānaka supports catchment landowners in establishing multiple catchment groups operating in the district. These catchment groups facilitate and support various management actions such as testing water, planting riparian margins, calculating carbon emissions, supporting the development of business environment plans, organizing regenerative farming workshops, and managing wetlands and biodiversity (WAI Wanaka, 2021a). Better support of such community-initiated actions by the ORC could improve synergies and reduce the costs of filling the knowledge gaps that the MCDA process identified.

4. DISCUSSION AND CONCLUSIONS

Despite decades of efforts, the restoration of freshwater ecosystems is slow and piecemeal (European Environment Agency, 2018; Ministry for the Environment and Stats NZ, 2020; WWF, 2020). This leaves one questioning whether the typically top-down management approaches taken so far, which are consultative rather than collaborative (De Stefano, 2010; Hughey, Jacobson, & Smith, 2017; Siegmund-Schultze, Rodorff, Koppel, & Sobral, 2015), are effective at managing biocultural systems. Recently, some water management policies have begun mandating more of a mixed, top-down-bottom-up co-management model, harnessing different ways of knowing (Australian Government, 2018; New Zealand Ministry for the Environment, 2020). However, while theoretical and ethical issues regarding the integration of diverse values has been widely discussed in the freshwater management literature (e.g., Ayre, Wallis, & Daniell, 2018; Chan, Gould, & Pascual, 2018; Pahl-Wostl et al., 2008), there is still a lack of practical examples. Some studies have highlighted the use of indigenous knowledge (Moggridge, Betterridge, & Thompson, 2019; Tipa, 2009; Tipa & Nelson, 2012), while others have compared and integrated western science-based system knowledge with local cultural knowledge (Abu, Reed, & Jardine, 2020; Harmsworth, Young, Walker, Clapcott, & James, 2011; Mantyka-Pringle et al., 2017). We believe that our case study is the first to comprehensively integrate a broad range of cultural, environmental, and socio-economic values, knowledge systems, aims, and strategies.

The MCDA-process proved to be successful to move away from traditional uni- or bilateral methods by operationalizing the weaving together of diverse value systems such as those informed by science, ***Matauranga Māori***, and ***Pākehā*** cultures for freshwater co-management. Hence, our results show that the MCDA-framework provides the means to realise the legal mandate of co-managing environmental resources as set out in the Treaty of Waitangi, the New Zealand

Conservation Act (New Zealand Government, 1975, 1991), and the NPS-FM (New Zealand Ministry for the Environment, 2020). Consequently, we recommend MCDA to facilitate the co-development of management plans for New Zealand catchments as well as for any other freshwater decision-making situation mandating the integration of diverse values.

The community found the MCDA-framework to be practical and supportive in developing the co-management plan. Most significantly, it helped express their water values and to present them as objectives in a clearly structured and transparent way (Fig. 3). Identifying fundamental values comprehensively at the outset of the process ultimately facilitated the development of a management plan that was sensitive to social and cultural values. Using a comprehensive objectives hierarchy reflecting the diverse values, the current status of the system was identified, and management actions were identified, assessed, and ranked. In contrast to scientists preparing potential management actions to be judged *a posteriori*, or in contrast to decision makers approving management actions without a strong evidence base, we evaluated alternative actions against all the diverse objectives using value functions and stakeholder-specific value preferences (Reichert et al., 2015). In this way, the resulting co-management plan was inclusive, based on evidence, and considered diverse community preferences.

Among the stakeholders in our case study, the resulting ranking of alternative actions did not vary (Fig. 6). This can be explained by the result that stakeholders held similar preferences for the objectives, with ecological lake health and the safeguarding of local culture both being more important than economic values or the cost-effectiveness of a management plan (Tab. 2). In addition, aggregated weights of the four cultural sub-objectives did not significantly differ among the stakeholders, highlighting that they valued specific ***Māori*** and ***Pākehā*** objectives similarly. These results are consistent with Miller et al. (2015) who found widespread support among stakeholders to manage rivers in Canterbury (New Zealand) for ***mahinga kai***, which was moderately valued in relation to environmental, recreational, and employment (i.e. economic) values. Our results indicate that the community shared a similar water vision for the catchment, which is beneficial for reaching agreement on which management action(s) to implement.

Our results highlighted the importance of having high quality environmental data in management planning. Thus, there is an urgent need to implement a comprehensive freshwater ecosystem health monitoring programme in the catchment of Lake Wānaka. The hierarchical structuring of objectives by the MCDA highlighted some considerable knowledge gaps. For example, long-term, spatially explicit water quality data for Lake Wānaka was lacking, while only scattered information on water quality in its tributaries was available (Fig. 5). Addressing these data gaps will improve understanding of lake functioning, which is a prerequisite for the development of ecological models to be used to project the consequences of various management actions and their uncertainties (Schuwirth et al., 2019). A strength of the MCDA approach is that it can be easily re-iterated incorporating new information regarding mechanistic understanding, new empirical data, new stakeholders, and new stakeholder preferences at any time (Fig. 2). Ultimately, the more knowledge that exists about a system, the better its response can be predicted and robust decisions about its management can be made (Schuwirth et al., 2019).

A major challenge in our case study was to enlist the participation of Māori representatives who could speak on behalf of local rūnaka and broader iwi values. The participation of people who can represent ***iwi*** interests and share collective ***iwi*** knowledge with the process is essential. In the Otago region, conversations with local ***Māori*** about collaboration in freshwater management processes are ongoing, having only recently been initiated in Wānaka during several ***hui*** as part of the Wānaka MCDA-process. The decision about who officially may represent the five southern ***rūnaka*** in water engagement processes in the region was still being undertaken while we carried out this study (personal communication *Aukaha*). Van Cauwenbergh et al. (2018) also highlighted the discrepancy between time needed and time available for such participatory projects (e.g. due to funding or time constraints) to reach a basis of trust with indigenous groups that allows sharing knowledge and to accommodate different ways of working together (McMurdo Hamilton et al., 2020). To improve capacity of communities for meaningful engagement and to maintain relationships and efficacy in co-management efforts which often require much dialogue, financial compensation of indigenous representatives is essential (Gorris, 2019; Wheeler et al., 2020b; Wheeler & Root-Bernstein, 2020). Similar support should be made available to other groups, who are consistently disadvantaged in the participation of decision-making processes (Albrecht, 1995; Lundberg, 2018).

MCDA unfolds its full capacity when all relevant decision makers participate in the process, based on an agreement that the outcomes of the process will be faithfully implemented. We were not able to gain buy-in from the ORC, i.e. from the water authority, in the region. Therefore, it is unclear how the resulting community-led management plan will be incorporated into the regional land and water plans. The ORC recently initiated a separate stakeholder consultation process to gather community values. As a result, engagement fatigue, which we had already encountered in the case study area, may undermine future attempts at community engagement, especially where prior community input has not been recognized or implemented (du Toit & Pollard, 2008). We avoided further disillusion by fully disclosing to our stakeholders the details of the engagement process, what kind of involvement was expected from them, and how the outcomes of the MCDA-process would be used (Barreteau, Bots, & Daniell, 2010). Again, our results highlight the importance of not treating community and stakeholder engagement as an afterthought, but instead treating communities in accordance with best practice recommendations (Gregory et al., 2012; Gregory & Keeney, 2017).

A transformative change will be required (Wheeler et al., 2020a) to move from simply recognizing and eliciting diverse community values to fully and transparently integrating them into decision making (Zafra-Calvo et al., 2020). The MCDA-framework, which we successfully trialed in Wānaka, is a mixed top-down-bottom-up approach, which incorporated the best available scientific evidence while accounting for the diverse values of the community. This approach is ideally suited for the type of community-authority co-management that is being increasingly mandated in New Zealand, and elsewhere.

CONSENT

Written informed consent for publication of the participants' preferences was obtained from the participants. The interviews were conducted according to the requirements of ethics and integrity in Article 34 of the H2020 Programme Multi-Beneficiary Model Grant Agreement, i.e. ethic's approval to interview stakeholders was granted by the Human Ethics Committee of the University of Otago.

ACKNOWLEDGEMENTS

We greatly appreciate the collaboration with WAI Wānaka (former Upper Clutha Lakes Trust) and the time and willingness to share information of all the involved stakeholders contributing to this study. The authors would like to thank everyone who attended the community workshops and who contributed their time, values, and expertise. We also thank Marion Caduff who helped with the collation of literature. This work was supported by the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No 748625 and through the Spanish Government's María de Maeztu excellence accreditation 2018-2022 (Ref. MDM-2017-0714).

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SUPPORTING INFORMATION

TITLE

A robust and transparent framework for weaving together diverse values in freshwater management: a case study of the Lake Wānaka catchment, Aotearoa/New Zealand

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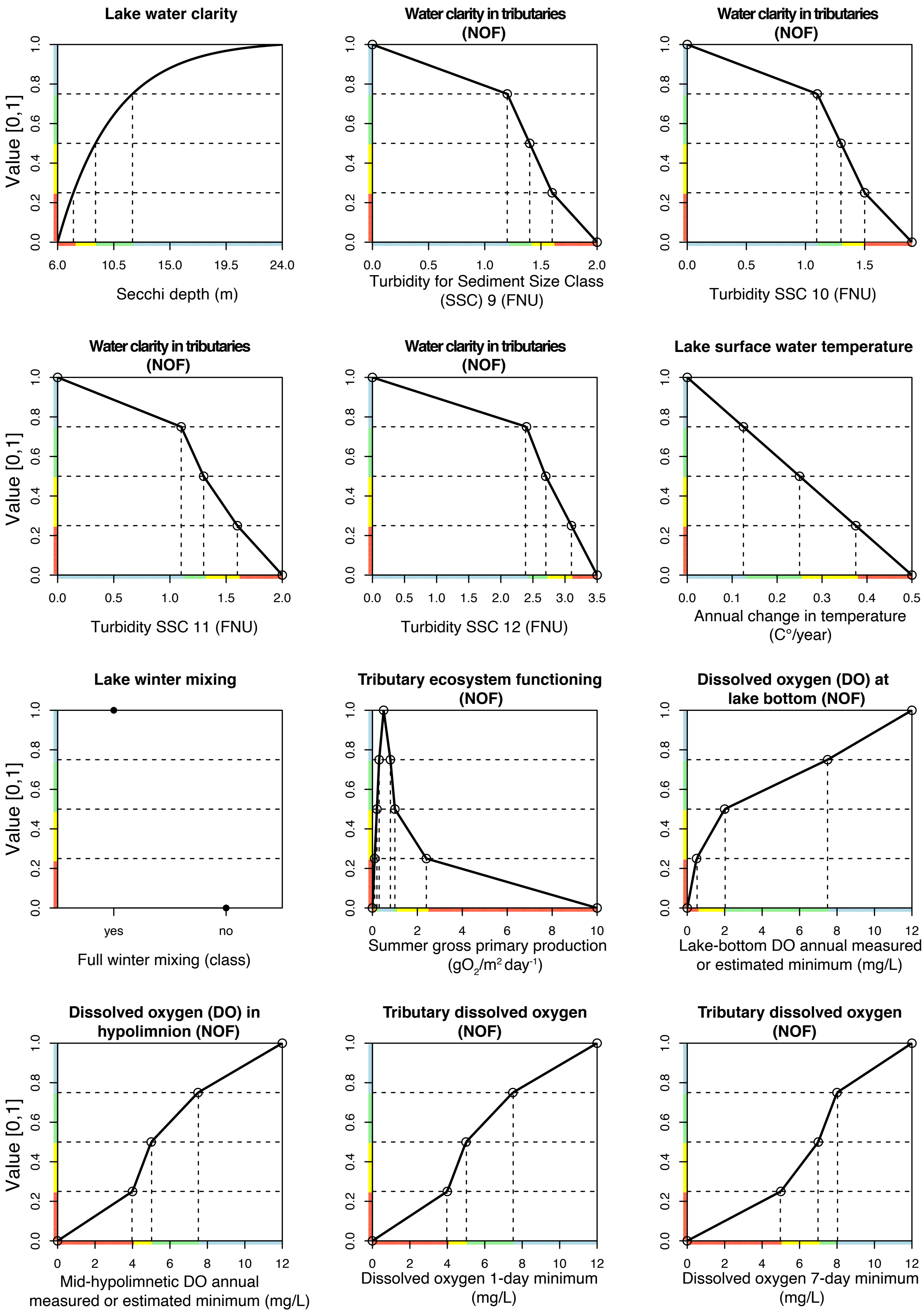
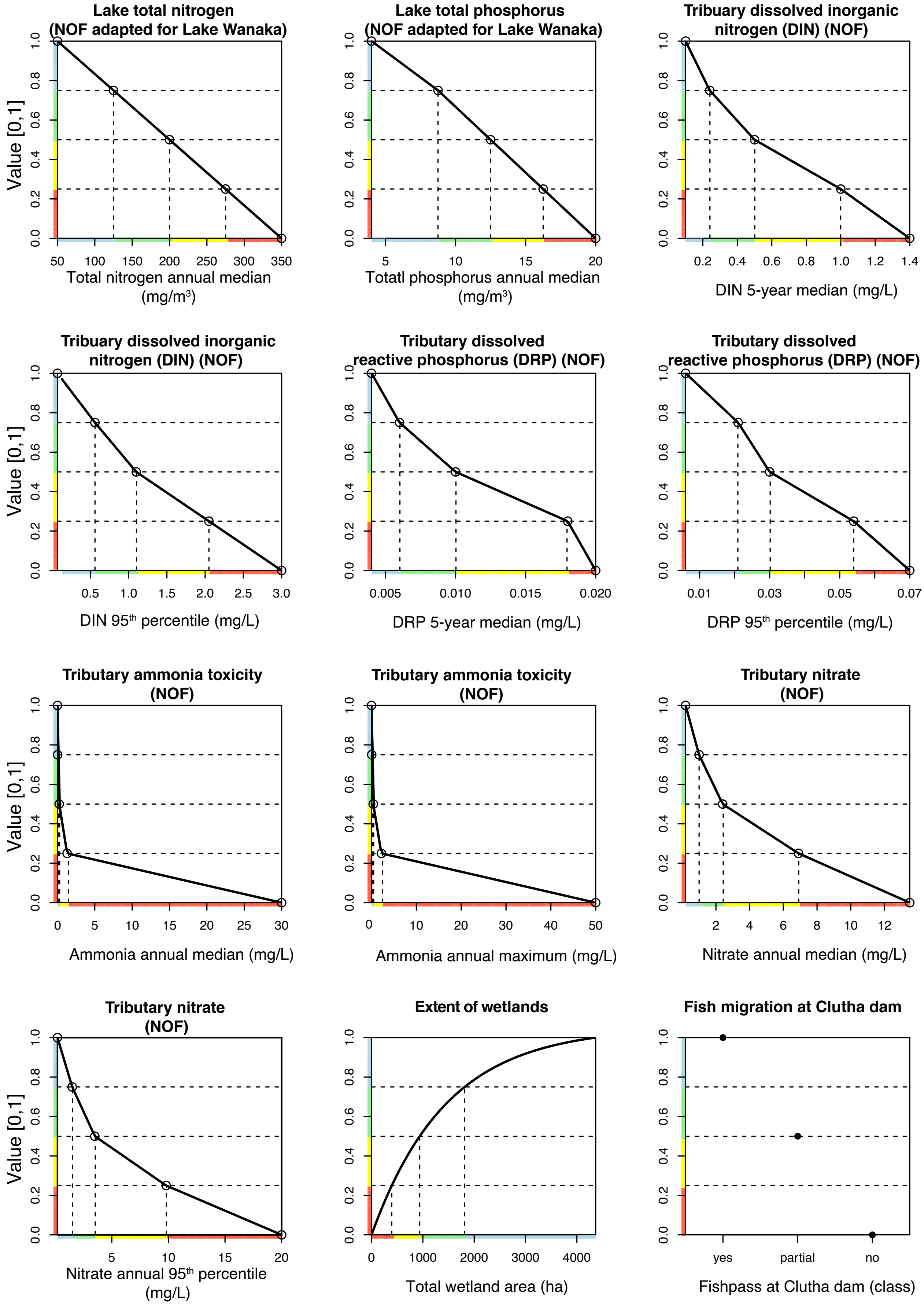
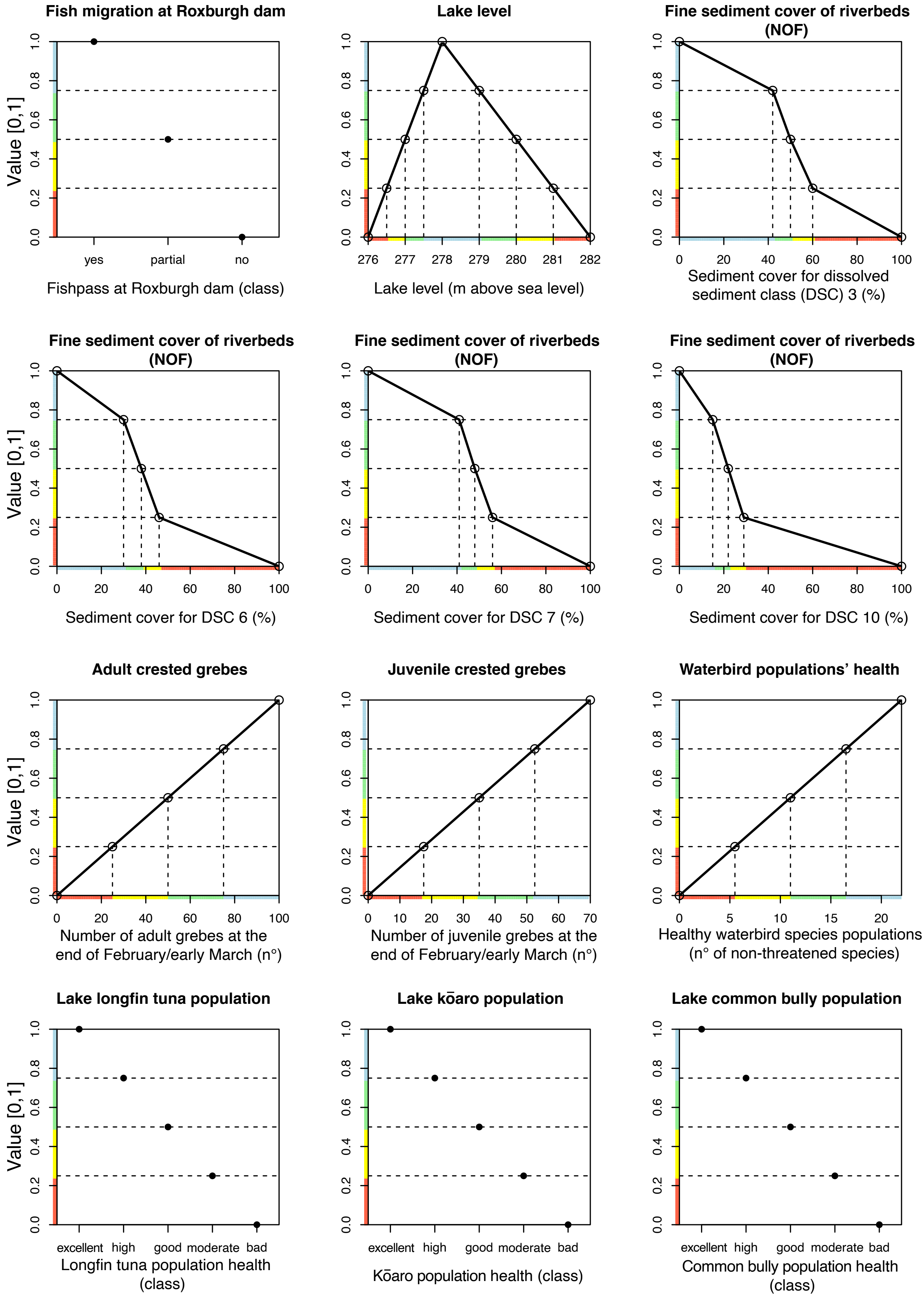
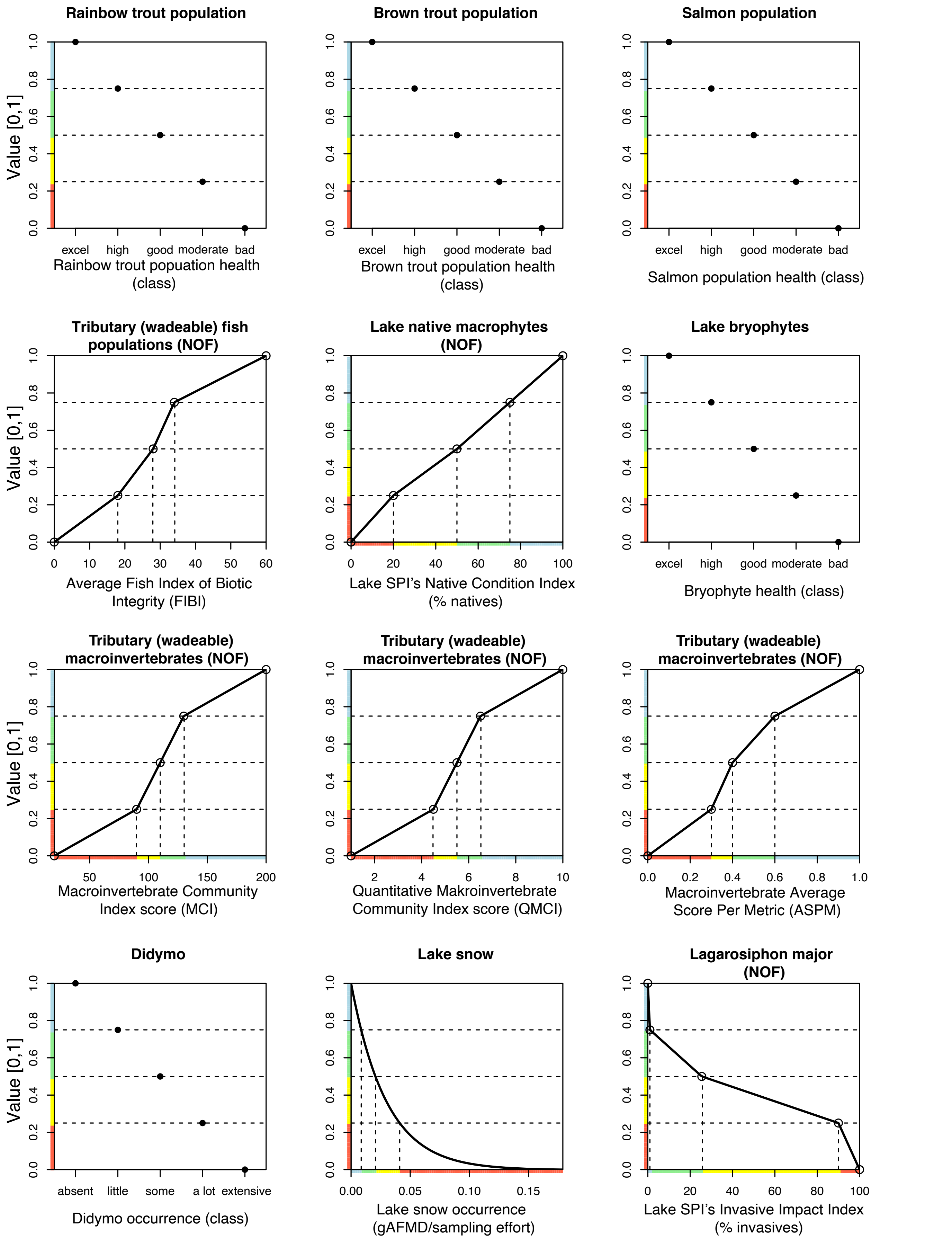
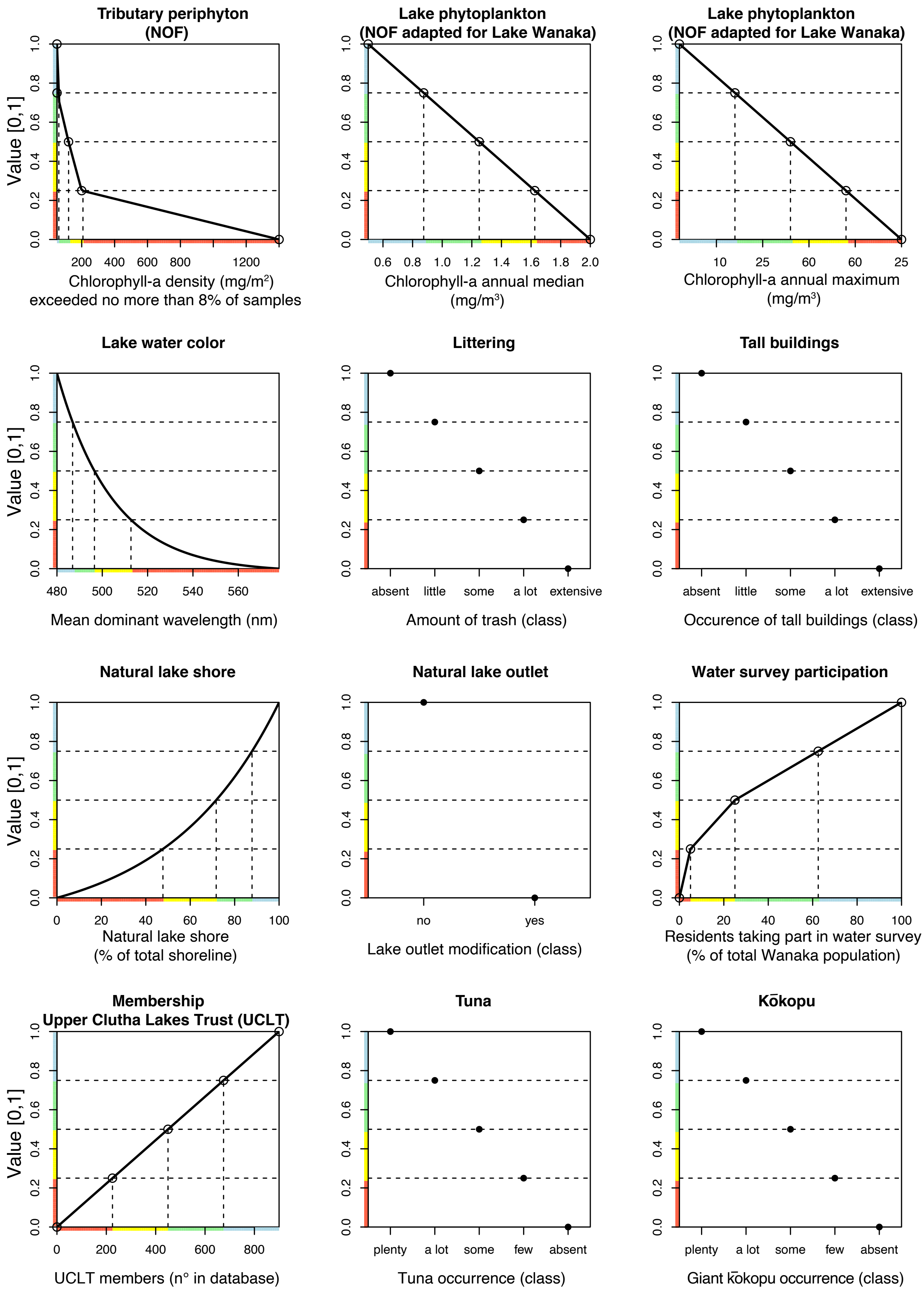
Figure S1. Value functions for all attributes.

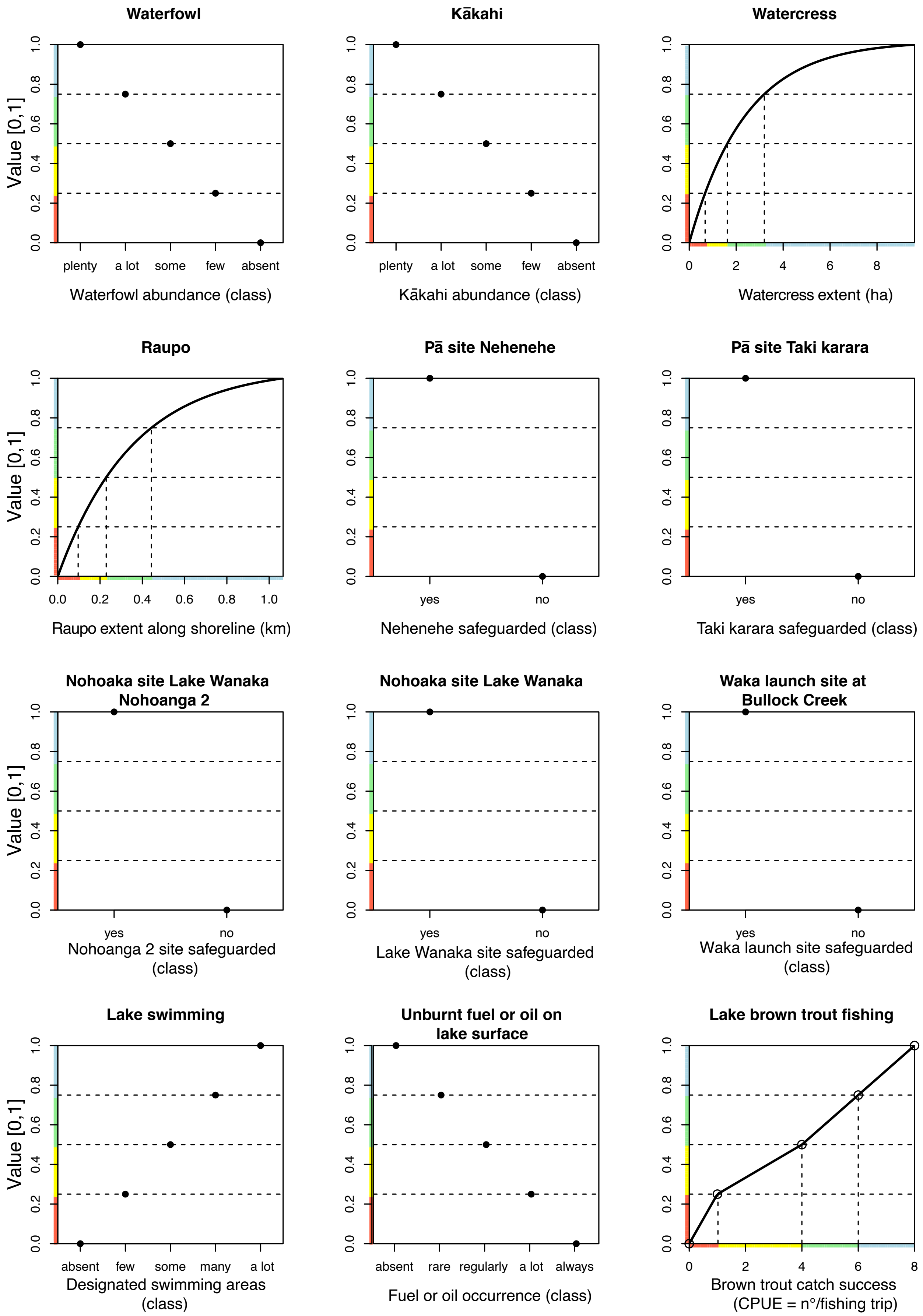

Lake water clarity
Value [0,1]
Secchi depth (m)
Water clarity in tributaries (NOF)
Turbidity for Sediment Size Class (SSC) 9 (FNU)
Water clarity in tributaries (NOF)
Turbidity SSC 10 (FNU)
Water clarity in tributaries (NOF)
Value [0,1]
Turbidity SSC 11 (FNU)
Water clarity in tributaries (NOF)
Turbidity SSC 12 (FNU)
Lake surface water temperature
Annual change in temperature (C°/year)
Lake winter mixing
Value [0,1]
yes
no
Full winter mixing (class)
Tributary ecosystem functioning (NOF)
Summer gross primary production (gO_2/m^2 day^{-1})
Dissolved oxygen (DO) at lake bottom (NOF)
Lake-bottom DO annual measured or estimated minimum (mg/L)
Dissolved oxygen (DO) in hypolimnion (NOF)
Value [0,1]
Mid-hypolimnetic DO annual measured or estimated minimum (mg/L)
Tributary dissolved oxygen (NOF)
Dissolved oxygen 1-day minimum (mg/L)
Tributary dissolved oxygen (NOF)
Dissolved oxygen 7-day minimum (mg/L)

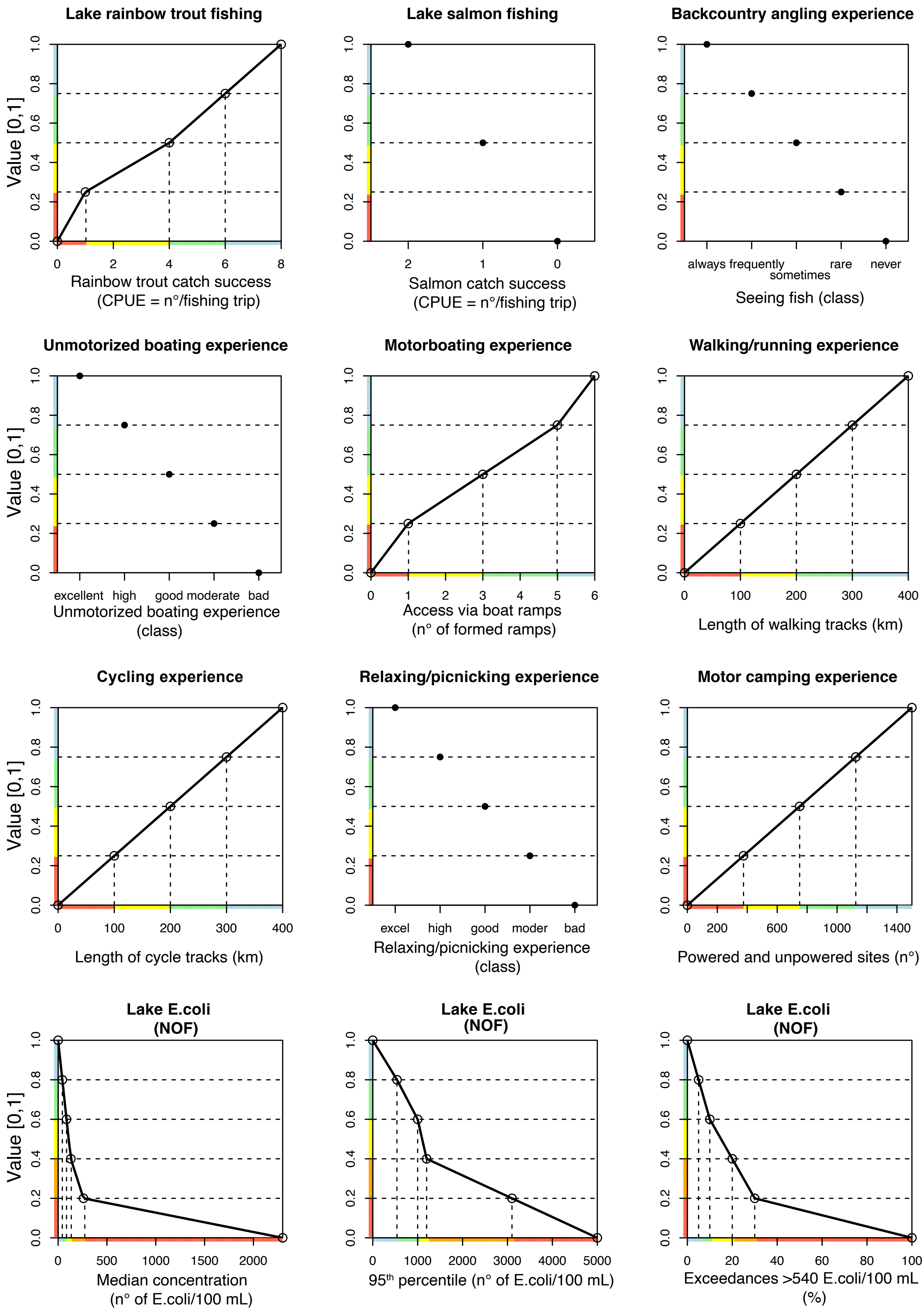

Lake total nitrogen (NOF adapted for Lake Wanaka)
Value [0,1]
Total nitrogen annual median (mg/m³)
Lake total phosphorus (NOF adapted for Lake Wanaka)
Totatl phosphorus annual median (mg/m³)
Tribuary dissolved inorganic nitrogen (DIN) (NOF)
DIN 5-year median (mg/L)
Tribuary dissolved inorganic nitrogen (DIN) (NOF)
Value [0,1]
DIN 95th percentile (mg/L)
Tributary dissolved reactive phosphorus (DRP) (NOF)
DRP 5-year median (mg/L)
Tributary dissolved reactive phosphorus (DRP) (NOF)
DRP 95th percentile (mg/L)
Tributary ammonia toxicity (NOF)
Value [0,1]
Ammonia annual median (mg/L)
Tributary ammonia toxicity (NOF)
Ammonia annual maximum (mg/L)
Tributary nitrate (NOF)
Nitrate annual median (mg/L)
Tributary nitrate (NOF)
Value [0,1]
Nitrate annual 95th percentile (mg/L)
Extent of wetlands
Total wetland area (ha)
Fish migration at Clutha dam
yes
partial
no
Fishpass at Clutha dam (class)

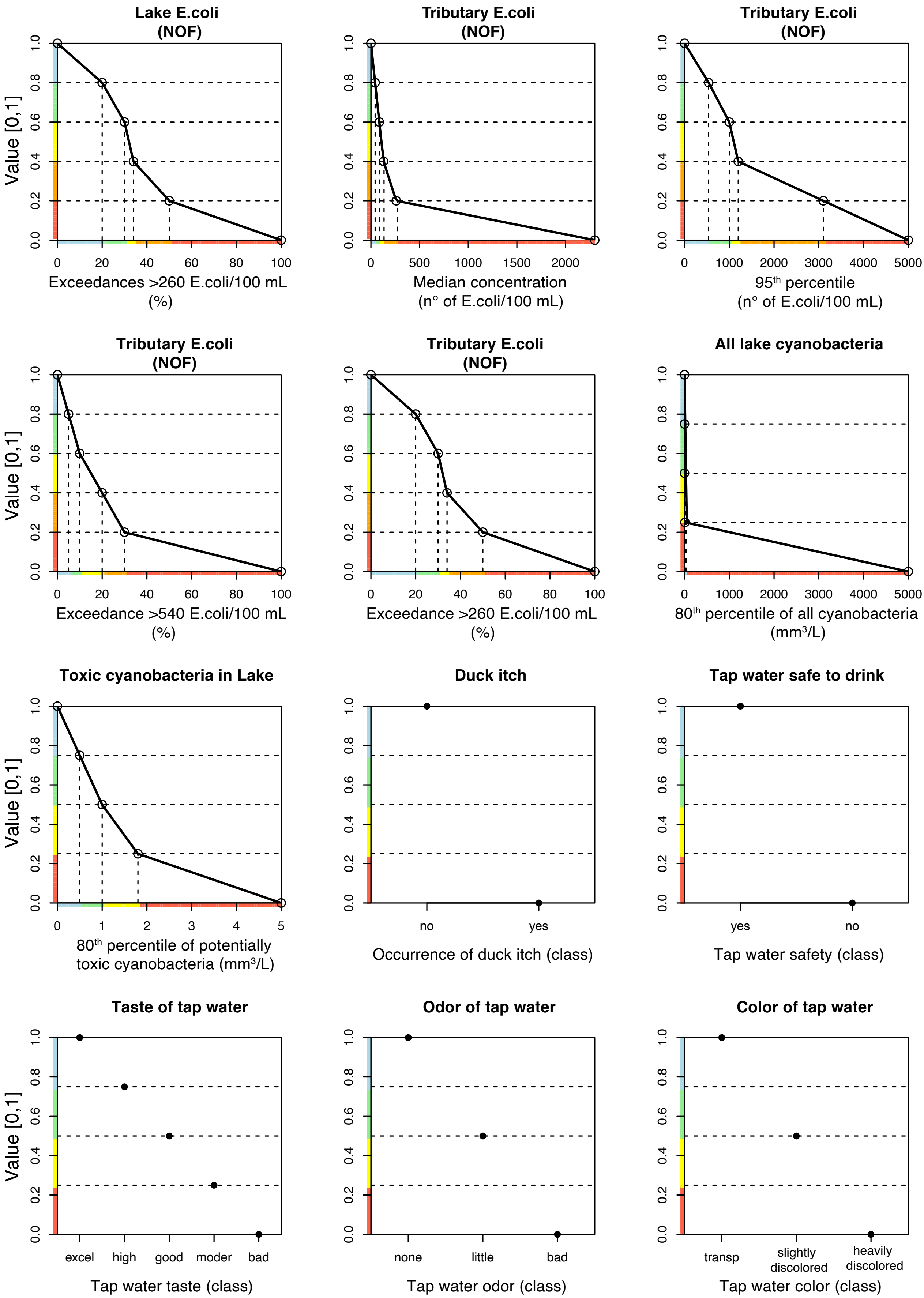

Fish migration at Roxburgh dam
Value [0,1]
yes
partial
no
Fishpass at Roxburgh dam (class)
Lake level
Lake level (m above sea level)
Fine sediment cover of riverbeds (NOF)
Sediment cover for dissolved sediment class (DSC) 3 (%)
Fine sediment cover of riverbeds (NOF)
Sediment cover for DSC 6 (%)
Fine sediment cover of riverbeds (NOF)
Sediment cover for DSC 7 (%)
Fine sediment cover of riverbeds (NOF)
Sediment cover for DSC 10 (%)
Adult crested grebes
Number of adult grebes at the end of February/early March (n°)
Juvenile crested grebes
Number of juvenile grebes at the end of February/early March (n°)
Waterbird populations' health
Healthy waterbird species populations (n° of non-threatened species)
Lake longfin tuna population
excellent high good moderate bad
Longfin tuna population health (class)
Lake kōaro population
Kōaro population health (class)
Lake common bully population
Common bully population health (class)


Rainbow trout population
Value [0,1]
excel high good moderate bad
Rainbow trout popuation health (class)
Brown trout population
Brown trout population health (class)
Salmon population
Salmon population health (class)
Tributary (wadeable) fish populations (NOF)
Average Fish Index of Biotic Integrity (FIBI)
Lake native macrophytes (NOF)
Lake SPI's Native Condition Index (% natives)
Lake bryophytes
Bryophyte health (class)
Tributary (wadeable) macroinvertebrates (NOF)
Macroinvertebrate Community Index score (MCI)
Quantitative Makroinvertebrate Community Index score (QMCI)
Macroinvertebrate Average Score Per Metric (ASPM)
Didymo
absent little some a lot extensive
Didymo occurrence (class)
Lake snow
Lake snow occurrence (gAFMD/sampling effort)
Lagarosiphon major (NOF)
Lake SPI's Invasive Impact Index (% invasives)

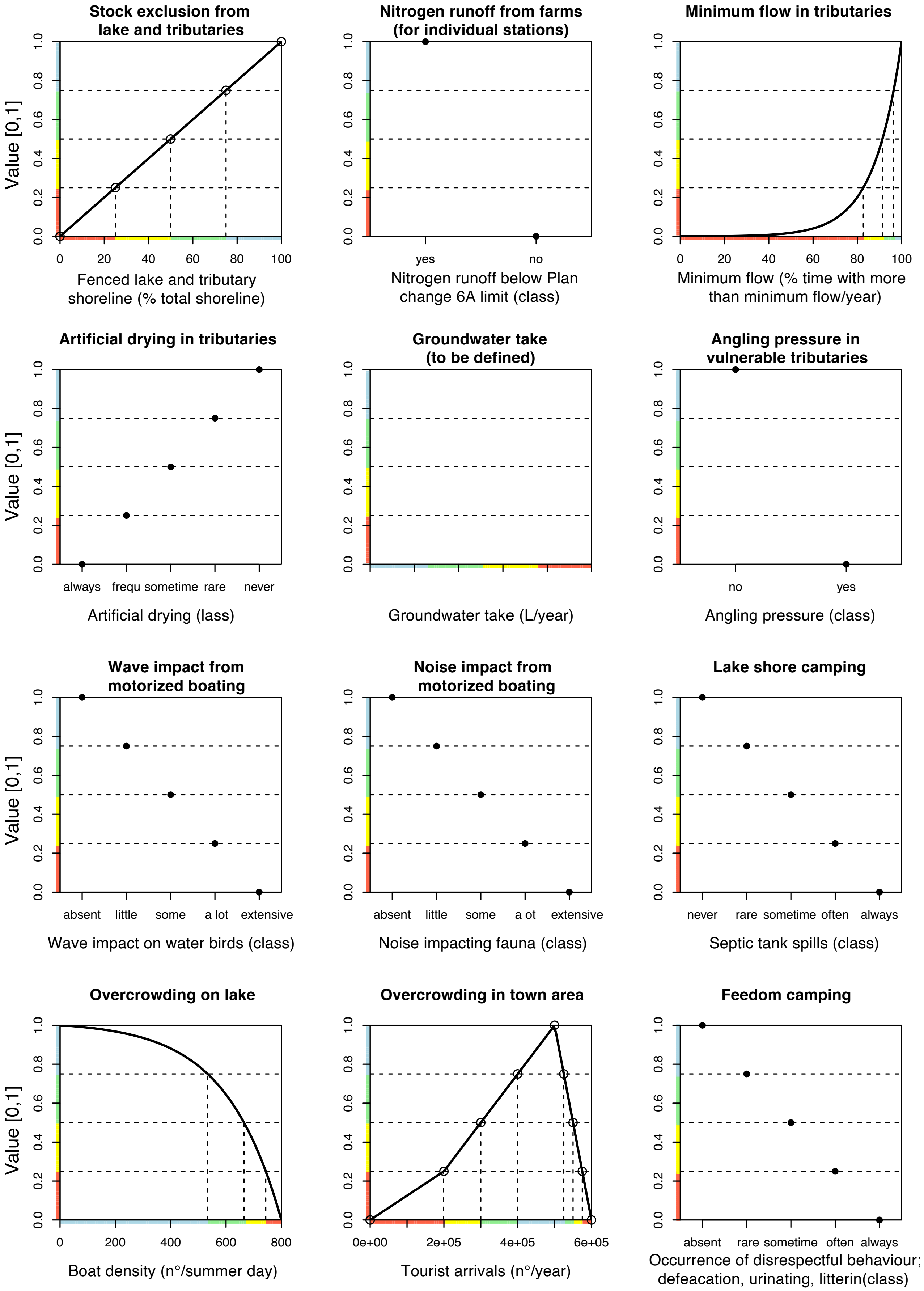

Tributary periphyton (NOF)
Value [0,1]
Chlorophyll-a density (mg/m²) exceeded no more than 8% of samples
200 400 600 800 1200
Lake phytoplankton (NOF adapted for Lake Wanaka)
Chlorophyll-a annual median (mg/m³)
0.6 0.8 1.0 1.2 1.4 1.6 1.8 2.0
Lake phytoplankton (NOF adapted for Lake Wanaka)
Chlorophyll-a annual maximum (mg/m³)
10 25 60 60 25
Lake water color
Mean dominant wavelength (nm)
480 500 520 540 560
Littering
Amount of trash (class)
absent little some a lot extensive
Tall buildings
Occurence of tall buildings (class)
absent little some a lot extensive
Natural lake shore
Natural lake shore (% of total shoreline)
0 20 40 60 80 100
Natural lake outlet
Lake outlet modification (class)
no yes
Water survey participation
Residents taking part in water survey (% of total Wanaka population)
0 20 40 60 80 100
Membership Upper Clutha Lakes Trust (UCLT)
UCLT members (n° in database)
0 200 400 600 800
Tuna
Tuna occurrence (class)
plenty a lot some few absent
Kōkopu
Giant kōkopu occurrence (class)
plenty a lot some few absent
0.0 0.2 0.4 0.6 0.8 1.0

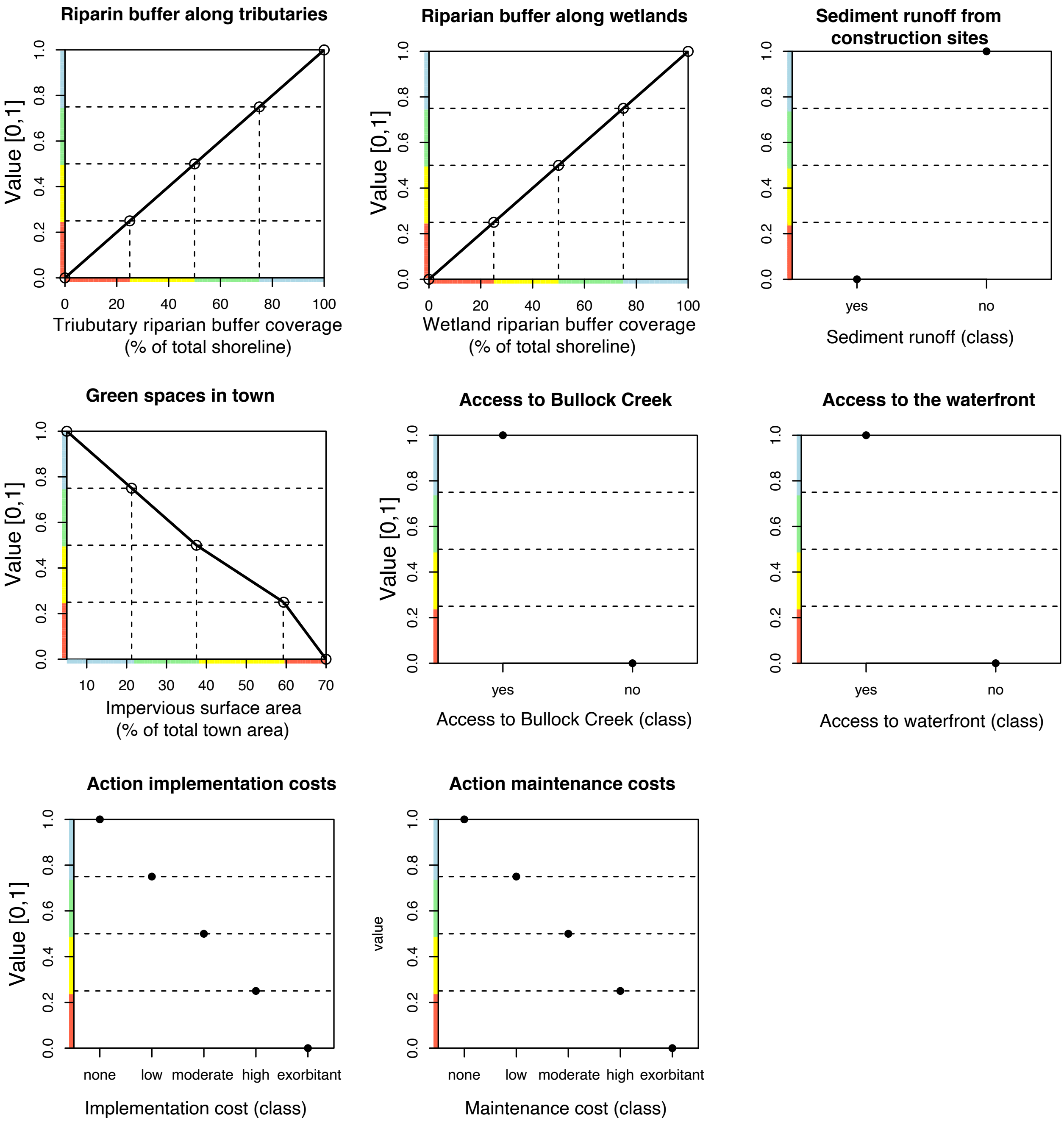

Waterfowl
Value [0,1]
plenty
a lot
some
few
absent
Waterfowl abundance (class)
Kākahi
plenty
a lot
some
few
absent
Kākahi abundance (class)
Watercress
Watercress extent (ha)
Raupo
Value [0,1]
Raupo extent along shoreline (km)
Pā site Nehenehe
yes
no
Nehenehe safeguarded (class)
Pā site Taki karara
yes
no
Taki karara safeguarded (class)
Nohoaka site Lake Wanaka Nohoanga 2
Value [0,1]
yes
no
Nohoanga 2 site safeguarded (class)
Nohoaka site Lake Wanaka
yes
no
Lake Wanaka site safeguarded (class)
Waka launch site at Bullock Creek
yes
no
Waka launch site safeguarded (class)
Lake swimming
Value [0,1]
absent
few
some
many
a lot
Designated swimming areas (class)
Unburnt fuel or oil on lake surface
absent
rare
regularly
a lot
always
Fuel or oil occurrence (class)
Lake brown trout fishing
Brown trout catch success (CPUE = n°/fishing trip)


Lake rainbow trout fishing
Value [0,1]
Rainbow trout catch success
(CPUE = n°/fishing trip)
Lake salmon fishing
Salmon catch success
(CPUE = n°/fishing trip)
Backcountry angling experience
always frequently sometimes rare never
Seeing fish (class)
Unmotorized boating experience
excellent high good moderate bad
Unmotorized boating experience
(class)
Motorboating experience
Access via boat ramps
(n° of formed ramps)
Walking/running experience
Length of walking tracks (km)
Cycling experience
Length of cycle tracks (km)
Relaxing/picnicking experience
excel high good moder bad
Relaxing/picnicking experience
(class)
Motor camping experience
Powered and unpowered sites (n°)
Lake E.coli
(NOF)
Median concentration
(n° of E.coli/100 mL)
95th percentile (n° of E.coli/100 mL)
Exceedances >540 E.coli/100 mL
(%)



Lake E.coli (NOF)
Exceedances >260 E.coli/100 mL (%)
Tributary E.coli (NOF)
Median concentration (n° of E.coli/100 mL)
Tributary E.coli (NOF)
95th percentile (n° of E.coli/100 mL)
Tributary E.coli (NOF)
Exceedance >540 E.coli/100 mL (%)
Tributary E.coli (NOF)
Exceedance >260 E.coli/100 mL (%)
All lake cyanobacteria
80th percentile of all cyanobacteria (mm³/L)
Toxic cyanobacteria in Lake
80th percentile of potentially toxic cyanobacteria (mm³/L)
Duck itch
no
yes
Occurrence of duck itch (class)
Tap water safe to drink
yes
no
Tap water safety (class)
Taste of tap water
excel
high
good
moder
bad
Tap water taste (class)
Odor of tap water
none
little
bad
Tap water odor (class)
Color of tap water
transp
slightly discolored
heavily discolored
Tap water color (class)
Value [0,1]


Stock exclusion from lake and tributaries
Value [0,1]
Fenced lake and tributary shoreline (% total shoreline)
Nitrogen runoff from farms (for individual stations)
yes
no
Nitrogen runoff below Plan change 6A limit (class)
Minimum flow in tributaries
Minimum flow (% time with more than minimum flow/year)
Artificial drying in tributaries
always
frequ
sometime
rare
never
Artificial drying (lass)
Groundwater take (to be defined)
Groundwater take (L/year)
Angling pressure in vulnerable tributaries
no
yes
Angling pressure (class)
Wave impact from motorized boating
absent
little
some
a lot
extensive
Wave impact on water birds (class)
Noise impact from motorized boating
absent
little
some
a ot
extensive
Noise impacting fauna (class)
Lake shore camping
never
rare
sometime
often
always
Septic tank spills (class)
Overcrowding on lake
Boat density (n°/summer day)
Overcrowding in town area
0e+00
2e+05
4e+05
6e+05
Tourist arrivals (n°/year)
Feedom camping
absent
rare
sometime
often
always
Occurrence of disrespectful behaviour; defeacation, urinating, litterin(class)


Riparin buffer along tributaries
Value [0,1]
Triubutary riparian buffer coverage
(% of total shoreline)
Riparian buffer along wetlands
Value [0,1]
Wetland riparian buffer coverage
(% of total shoreline)
Sediment runoff from
construction sites
yes
no
Sediment runoff (class)
Green spaces in town
Value [0,1]
Impervious surface area
(% of total town area)
Access to Bullock Creek
Value [0,1]
yes
no
Access to Bullock Creek (class)
Access to the waterfront
yes
no
Access to waterfront (class)
Action implementation costs
Value [0,1]
none
low
moderate
high
exorbitant
Implementation cost (class)
Action maintenance costs
value
none
low
moderate
high
exorbitant
Maintenance cost (class)