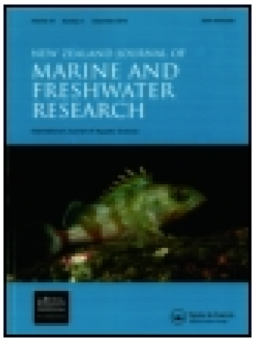

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RESEARCH ARTICLE

Multiple lines of evidence determine robust nutrient load limits required to safeguard a threatened lake/lagoon system

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ABSTRACT

Three independent scientific lines of evidence were sought to determine the nutrient load limits to safeguard the macrophyte community of an intermittently closed and open lake/lagoon (ICOLL): (1) a literature review identified nitrogen load thresholds related to the collapse of macrophytes in similar systems in Australia, Europe and elsewhere, (2) an ICOLL expert carried out an assessment based on current local data and on data from 57 Australian coastal lakes and lagoons, and (3) a deterministic coupled hydrodynamic-ecological model was developed and applied to simulate the ecological outcomes of several nutrient loading scenarios. The three lines of evidence converged on well-defined nitrogen load estimates required to avoid the collapse of the macrophyte community. Uncertainties were slightly greater in relation to required phosphorus load limits, but the evidence still helped set a precautionary phosphorus load limit that accounted for these uncertainties. Thus, despite the challenges in setting load limits for complex ecosystems, multiple lines of evidence helped derive robust nutrient load limits for managing the ICOLL to safeguard values associated with a healthy macrophyte community.

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Eutrophication; loading; *Ruppia*; dairy farming; policy; modelling; expert panel; limit setting; opening regime; nitrogen; phosphorus; sediment

Introduction

Over 40% of New Zealand's regularly monitored lakes are deemed to be affected by eutrophication (Verburg et al. 2010) and many intermittently closed and open lake/lagoon (ICOLL) ecosystems have undergone ecological regime shifts to turbid states, with compromised fisheries and loss of submerged macrophyte communities. Central government has developed a National Policy Statement for Freshwater Management (NPS-FM) as well as national water quality guidelines (Ministry for the Environment 2014) to give direction to regional environmental management authorities (Regional Councils). It includes

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definitions of water quality conditions of lakes that are unacceptable and must be remedied through restoration. The NPS-FM not only directs Regional Councils to address the condition of degraded lakes, but also empowers communities to have input into the restoration goals and the ecological, recreational, cultural, and economic values which must be enhanced and protected (Ministry for the Environment 2014). Freshwater scientists are increasingly being called upon to provide information on lake functioning and to predict outcomes in relation to the key values that can be expected under various management and restoration scenarios.

For freshwater scientists, who are often highly specialised in certain disciplines, the challenges of understanding and accurately predicting whole-lake responses, under different anthropogenic pressures and in response to various restoration methodologies, can be daunting (Peters 1991). Applying ecological theory, which is generally underpinned by highly controlled experimental studies, to predict the behaviour of large, complex and seasonally variable ecosystems can be challenging because a number of issues can potentially confound the application of this knowledge (Table 1).

Given the challenges in applying science to lake management and restoration outlined in Table 1, and given that each scientific approach has specific limitations in its ability to predict lake functioning (Peters 1991), it is sensible to employ multiple approaches to predicting lake responses to environmental change. Integration of

Table 1. Some inherent ecosystem challenges in applying scientific knowledge to lake management and restoration.

Challenge	Example
Multiple interacting stressors	Increases in nutrients, leading to lake eutrophication, are often associated with increased loads of other contaminants including sediments, faecal pollution, agricultural chemicals, heavy metals, etc. The presence of invasive species and altered hydrological regimes may exacerbate or mitigate some of these effects. Often a management or restoration approach will address only one particular contaminant (e.g. applying alum treatment for phosphorus removal, fish removal)
Non-linear dynamics	Ecosystem responses to eutrophication may show tipping points, involve stressor thresholds or show a hysteresis, often associated with alternative stable states (Scheffer 2004; Schallenberg & Sorrell 2009)
Ecological feedback and resilience	The occurrence of certain species (e.g. grazers), processes (e.g. denitrification), morphological characteristics (e.g. shoreline development) and/or physico-chemical conditions (e.g. alkalinity, humic acid staining) in lakes may impart variable amounts of ecological resistance and/or resilience to eutrophication (Atkinson and Vaughn 2015)
Non-steady state	Due to legacies, time lags or stochasticity, some lakes may rarely be in a state of equilibrium. In addition, catchment development, colonisation by invasive species, management, restoration actions and climate change impacts may push a lake out of a state of equilibrium. Non-steady-state responses are particularly difficult to model and predict
Legacies	Historical changes may continue to affect lake eutrophication long after the pressure has ceased (e.g. internal nutrient load due to historical sewage inputs)
Time lags	Lakes exhibit variable time lags to anthropogenic pressures. For example, groundwater aquifers may substantially delay the flux of nutrients leached from soils into receiving environments such as lakes (Morgenstern et al. 2005). Long hydraulic residence times of some lakes may also cause time lags between external nutrient loads and lake responses
Stochasticity	Some lakes are highly susceptible to environmental stochasticity and variability. For example, ICOLL openings, which can be driven by rainfall events, create stochasticity in water levels, salinity and food web interactions. Species introductions and impacts tend to be highly stochastic
Data availability	The ability to understand and predict ecological trajectories of lakes relies on historical time series data of sufficient temporal and spatial resolution, and over sufficient duration. Relevant data include water quality, species introductions, keystone species densities, catchment development and climate. These data are often lacking

these approaches may either help confirm a predicted outcome or, where contradictory outcomes are predicted, they can highlight the existence of knowledge gaps. Using multiple lines of evidence increases scientific robustness and reveals the degree of scientific certainty and confidence that is embodied in the predictions, which is useful when communicating the scientific information to managers, policy-makers and the public.

We describe how multiple lines of independent scientific evidence were employed to identify nutrient load limits to safeguard the aquatic macrophyte community of an ICOLL under threat from the rapid intensification of agriculture in its catchment. The investigations were commissioned by the Southland Regional Council (Environment Southland), in collaboration with Māori representatives and the Department of Conservation, to ascertain the threat status of the Waituna Lagoon ecosystem, Southland. The ultimate goal was to inform the management of land use and agricultural intensification in the catchment so as to safeguard key ecosystem services and meet statutory obligations regarding water quality and other values of the ICOLL.

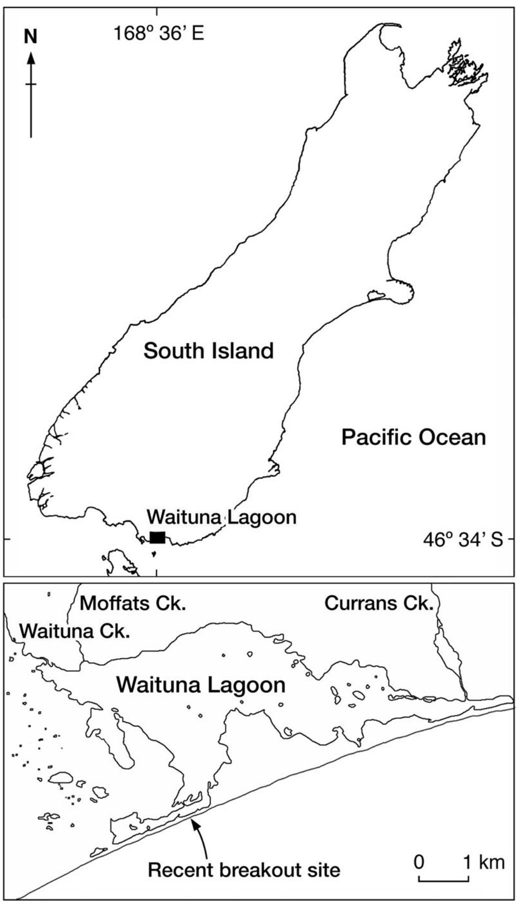

Figure 1. Location of Waituna Lagoon, Southland.

Background to the management problem

Waituna Lagoon is an ICOLL with a gravel barrier bar (Figure 1) which is periodically mechanically opened to maintain water levels below a specified elevation (Schallenberg et al. 2010). The lagoon is part of the Waituna Wetland Scientific Reserve administered by the New Zealand Department of Conservation, and is part of the 20,000 ha Awarua Wetlands complex, an internationally significant coastal wetland listed under the Ramsar Convention treaty for the conservation and sustainable use of wetlands (Robertson et al. 2009). The ICOLL supports a wide range of ecosystem services and values and has for centuries been an important food gathering site for Māori.

Unlike other ICOLLs on the eastern coasts of New Zealand's South and North Islands, Waituna Lagoon sustains significant aquatic macrophyte communities (Sutherland & Taumoepeau 2015) and has relatively low phytoplankton biomass. It is a waterbody that is valued for its fishery (eels/tuna, flounder/pātiki and brown trout), waterfowl hunting opportunities and its significant biodiversity values. More than 80 bird species and 18 fish species have been observed within the various habitats of the ICOLL and its surrounding wetland (Environment Southland 2013).

The ICOLL (mean depth = 0.7–1.6 m; surface area = 7.2–16.3 km^2) is efficiently flushed when the gravel barrier bar is opened to the sea. Tidal forcing drives marine intrusions well into the ICOLL, causing a rapid change from freshwater to nearly oceanic salinities within a few tidal cycles (Schallenberg et al. 2010). The freshwater tributaries drain a low-lying catchment (210 km^2) in which soils grade from well-drained brown soils in the northern headwaters of the catchment, to the typically poorly drained gley and organic soils that characterise the southern half of the catchment, merging into the wetland-fringed lake margin (Rissmann et. al. 2012). The peaty soils and fringing wetlands impart a humic staining to the lake water, which is considered meso/eutrophic with an annual mean chlorophyll *a* concentration of 5.2 μg/L (range: 0.5–37 μg/L; Environment Southland 2013) and annual mean concentrations of total nitrogen (TN) and total phosphorus (TP) of 770 μg N/L and 40 μg P/L, respectively (Schallenberg et al. 2010).

A report on the health of Waituna Lagoon suggested that the macrophyte community, which is dominated by *Ruppia* spp., could be at risk from eutrophication (Schallenberg & Tyrrell 2006), and subsequent monitoring of *Ruppia* and other macrophytes showed that macrophyte distributions within the ICOLL had fluctuated markedly in recent years (Robertson & Funnell 2012; Sutherland & Taumoepeau 2015). The susceptibility of the macrophyte community to multiple stressors (e.g. altered hydrological regime, increased nutrient loading, reduced water clarity, salinity) has been highlighted as a major concern for the health of the ICOLL (Schallenberg & Tyrrell 2006; Robertson & Funnell 2012).

Concerns over the health of the ICOLL were heightened by a rapid expansion of dairy farming in the Southland region that began in the 1990s. By 2011, 44% of the catchment was intensively farmed for dairy production (Figure 2) and over 70% of the catchment was in agricultural use (Environment Southland 2013). The value of farmland increased substantially during this period and wetlands within the ICOLL catchment have declined in extent as a consequence of farm expansions. The land use change also led to increases in drainage networks to rapidly shunt water from farmland into Waituna Lagoon.

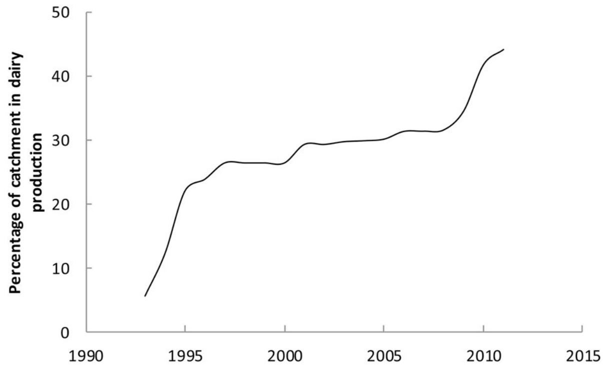

Figure 2. Percentage of the Waituna Lagoon catchment in dairy production, from 1993 to 2011. Data from Environment Southland.

Other evidence also pointed to increasing threats to the ICOLL as a result of agricultural intensification: (1) phosphorus loads in some of the tributaries were increasing, (2) during ICOLL closures, TP concentrations were rising, suggesting that internal P loads were increasingly important, (3) evidence of a reducing and highly fluctuating biomass of *Ruppia* sp. in the ICOLL, (4) an increase in the cover of macroalgae in the ICOLL, and (5) increased nutrient concentrations in the ICOLL. Together, these lines of evidence caused concern that a rapid regime shift and the collapse of aquatic macrophytes and loss of associated values could be imminent (Environment Southland 2013).

These concerns together with the special status of Waituna Lagoon, and the statutory obligations to protect, maintain and enhance the ecological conditions and water quality of the ICOLL, prompted the Southland Regional Council (Environment Southland) to form a lagoon technical group. This technical advisory group (TAG), consisted of aquatic scientists including environmental consultants, university scientists, Māori scientists (representing the interests of local tribes), and scientists from the Southland Regional Council and the Department of Conservation. The TAG was charged with (1) determining the water quality and quantity limits for the lagoon and catchment necessary to safeguard the ecological condition and water quality of Waituna Lagoon and (2) evaluating the urgency of achieving the limits.

Methods

Scientifically framing the management questions

Ecosystem health is a normative concept, requiring definition and translation before it can be addressed scientifically (Lackey 2002). Thus, the Waituna TAG set a number of primary and secondary targets for key ecological indicators, which, if met, were deemed to safeguard the health of the ICOLL. In setting these, the protection of the macrophyte community in the ICOLL was identified as the key high-level ecological health indicator due to the multiple beneficial ecological functions that the existence of macrophytes confers on shallow lakes and lagoons (Søndergaard et al. 2010). The benefits include: (1) the suppression of sediment resuspension, (2) the provision of habitat for fish and invertebrates, (3) the resilience to eutrophication by competition with phytoplankton and macroalgae for nutrients, and (4) the oxygenation of bottom sediments which inhibits the release to the water column of P bound to metal oxyhydroxides. Thus, the maintenance of a minimum of 30% cover of macrophytes at permanently wetted sites in the ICOLL was linked to the sustainable provision of the ecosystem services and social, cultural and ecological values that the ICOLL is recognised for.

By defining the maintenance of macrophyte cover in the ICOLL as the keystone of ecological health and water quality, the TAG defined a number of measurable indicators or attributes that could be monitored and analysed to gauge the vulnerability of the macrophytes to collapse, causing a catastrophic regime shift in the system. Based on an analysis of the existing data on the Waituna Lagoon system and of published research on vulnerabilities of similar systems to catastrophic regime shifts, the TAG decided on a set of primary indicators related to vulnerability of Waituna Lagoon to a regime shift (Table 2). A set of secondary indicators was also defined as measures which could inform the interpretation of the primary indicator data. Secondary indicators included attributes such as water column TN and TP concentrations, water levels, salinity levels in the ICOLL during the germination and early growth phases of *Ruppia* sp., light attenuation in the water column and extent of sediment anoxia (Environment Southland 2013).

In acknowledgment of the importance of multiple stressors to macrophyte health and cover, the TAG recommended nutrient load limits, sediment load limits and aspects of the opening regime of Waituna Lagoon. However, multiple lines of evidence were not available to support recommendations concerning sediment loads and the opening regime. Therefore, we report here only evidence supporting recommendations concerning nutrient loads to Waituna Lagoon, and the loads discussed are calculated at the point of entry to the ICOLL.

Multiple lines of evidence: setting the nutrient load limits to safeguard **Ruppia** *biomass*

To estimate the nutrient load thresholds for *Ruppia* collapse and a catastrophic regime shift (*sensu* Scheffer 2004) in Waituna Lagoon, the TAG decided to use three independent approaches. These included: (1) a literature review of published information on nitrogen

Table 2. Primary indicators to safeguard the macrophyte community of Waituna Lagoon. From Environment Southland (2013).

Primary indicators	References
Mean aquatic plant cover in March/April >30–60% at permanently inundated sites	Jeppesen et al. (1994); Blindow et al. (2002); Kosten et al. (2009); Tatrai et al. (2009)
Mean aquatic plant biomass index between 1000 and 1500 at permanently inundated sites	Index developed specifically for Waituna Lagoon and target range is preliminary. Lower and upper limits will be needed
Mean macroalgal cover <10% at permanently wetted sites	Joint Nature Conservation Committee (2005); Sutherland et al. (2013)
Mean chlorophyll *a* in water column during closed periods <5 µg/L (mesotrophic-eutrophic boundary), on occasions when samples are not affected by wind-induced re-suspension	Burns et al. (2000)
Cyanobacteria counts <500 cells/mL and cyanobacteria biovolume <0.5 mm^3/L (for bloom forming cyanobacteria such as *Nodularia* and *Anabaena*) (does not include picocyanobacteria)	Ministry for the Environment and Ministry of Health (2009)

loads leading to the collapse of macrophytes (mainly seagrasses) in coastal environments similar to Waituna Lagoon, (2) an independent expert assessment of the sensitivity of Waituna Lagoon to a regime shift, and (3) the application of a dynamic, coupled hydrodynamic-ecological model to Waituna Lagoon using measured data to calibrate and validate the model.

Results

Literature review and analysis (Schallenberg & Schallenberg 2012)

A literature survey was carried out using article databases and other methods to collect published studies and 'grey literature' reports on ICOLLs, estuaries and coastal embayments. The studies collected either quantified empirical relationships between abiotic drivers and biological responses, contained relevant raw data or developed deterministic eutrophication models for ICOLLs and estuarine embayments. The literature review concluded that the majority of studies on the impairment of relevant estuarine macrophyte communities had been carried out in Australian ICOLLs and estuaries and that the macrophyte communities (composed mainly of seagrasses, including *Ruppia* species) were predominantly vulnerable to high rates of areal nitrogen loading. From the relevant studies, data were extracted related to nitrogen loading thresholds that resulted in a high risk of macrophyte collapse. The thresholds ranged between 20 and 100 kg N per ha of estuarine surface area per year. When compared to the then-current estimate of nitrogen loading to Waituna Lagoon, it was apparent that the N loading rate to the ICOLL was approximately 50% above the highest reported loading rates which seagrasses could endure, which was 100 kg N ha^{-1} y^{-1} (Figure 3).

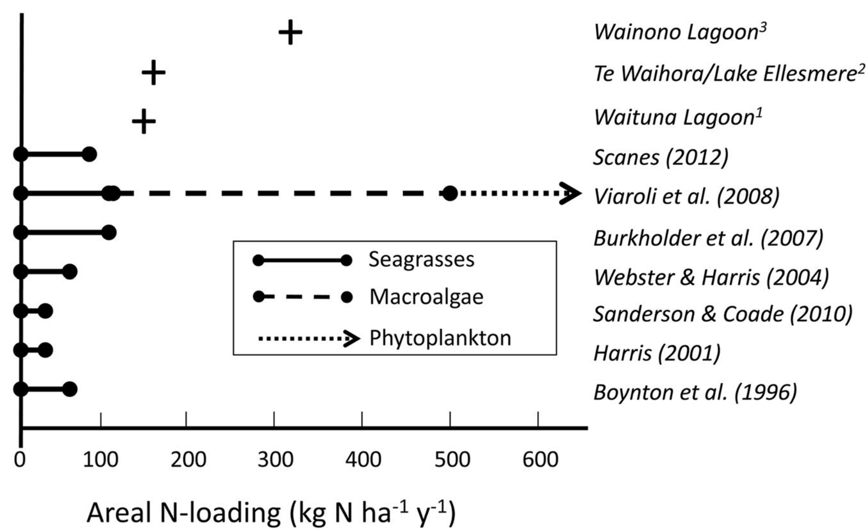

Figure 3. Ranges of areal nitrogen loading rates (per ha of estuary) supporting healthy seagrass communities, dominance by macroalgae, and dominance by phytoplankton. Also indicated are estimates of the nitrogen loading rates of Waituna Lagoon (Schallenberg et al. 2010), Te Waihora/Lake Ellesmere (Canterbury; Schallenberg et al. 2010) and Wainono Lagoon (Canterbury; Schallenberg 2013).

Estimates of N loading rates for two other ICOLLs located north of Waituna Lagoon and on the east coast of the South Island indicated that these were also over the literature-derived maximum threshold to safeguard seagrass communities (Figure 3). These ICOLLs are Te Waihora/Lake Ellesmere and Wainono Lagoon, which have undergone regime shifts, are dominated by phytoplankton and are highly eutrophic systems.

The TAG was not able to identify P loading thresholds related to seagrass collapse because very few studies have reported effects of P loading on seagrass communities within ICOLLs, estuaries and coastal embayments (Schallenberg & Schallenberg 2012).

Expert assessment (Scanes 2012)

Although it has been used in Europe (Wallin & Solheim 2005), the USA (Horner et al. 1986) and New Zealand (Drake et al. 2011; Hamilton & Parparov 2010), expert limnological assessment is an often overlooked approach for determining the ecological condition of lakes and their vulnerability to eutrophication. An expert on estuaries was contracted by Environment Southland to undertake an assessment of the vulnerability of Waituna Lagoon to then-present nutrient loads and to recommend nutrient load targets to safeguard the macrophyte community of the ICOLL (Scanes 2012). The expert compared information provided on the nutrient loads, water quality and ecological condition of Waituna Lagoon with modelled catchment nutrient load estimates and ecological information for 57 coastal lakes and lagoons along the New South Wales coast of Australia, which were classed by the expert as exhibiting either low, moderate or high levels of degradation. In addition, the tidal prism of Waituna Lagoon as well as its greater latitude (>8 degrees further south than the New South Wales coastal lakes and lagoons) were taken into account in the assessment.

Scanes (2012) calculated a nutrient load to Waituna Lagoon consistent with a moderate level of degradation of the ecosystem –that is, a load that allows for 'some eutrophic conditions but still supporting healthy seagrass and fish communities'. The assessment determined that a 52% reduction in areal nitrogen load (to 90 kg ha^{-1} y^{-1}) and a 23% reduction in the areal phosphorus load (to 0.57 kg ha^{-1} y^{-1}) would be required to safeguard the ecological values. Scanes (2012) recommended that these loads be set as interim measures until more detailed ecological information on Waituna Lagoon could be collected and analysed because the ecological resistance and resilience of Waituna Lagoon could be different in some unaccounted way to the resistance and resilience of the Australia ICOLLs.

Lake model (Hamilton et al. 2012)

A number of data sets were collected and fed into a coupled hydrodynamic-ecological deterministic model to simulate *Ruppia* dynamics in Waituna Lagoon in relation to catchment nutrient loads. The one-dimensional DYRESM-CAEDYM modelling platform was used and key biological state variables were identified as *Ruppia* (*Ruppia megacarpa* and *Ruppia polycarpa*), phytoplankton (three phytoplankton groups) and macroalgae biomass (one group). This model structure required algorithms for a number of specific interactions, including the shading of *Ruppia* sp. by macroalgae, the effects of salinity on primary producer growth rates and a dynamic feedback between *Ruppia* and the wind-induced resuspension of sediment, organic matter, and phytoplankton. The model was calibrated with data available for the period from 2001 to 2007 and was validated with data from the period from 2007 to 2011. *Ruppia* cover and distribution data for Waituna Lagoon were available only after 2007 and no macroalgae biomass estimates were available for model calibration/validation (i.e. model output was compared with qualitative assessments).

Validation statistics indicated that the coupled model was relatively accurate at simulating water temperature, salinity and nitrate concentrations, but gave lower simulation accuracy for chlorophyll *a*, total suspended sediment and phosphorus concentrations (Figure 4). Insufficient data were available to statistically test the predictive power of the model for *Ruppia* and macroalgal biomass, although the model output approximately reflected the temporal dynamics of the available data and qualitative observations of biomasses (Figure 4).

Although a number of different management scenarios were tested with the model (including different opening regimes and climate change scenarios), here we focus only on the catchment nutrient loading scenarios. The model indicated that nutrient load reductions of 50% for N and 25% for P would ensure that the biomass of *Ruppia* was stable over the duration of the simulations and that the biomasses of phytoplankton and macroalgae remained low (Figure 4). This result was obtained only for a simulation which included regular, annual, 3-month ICOLL openings during winter.

Discussion

Intersection of multiple lines of evidence and responses to the nutrient load recommendations

Three independent lines of evidence were sought to establish robust nutrient load limits to safeguard the *Ruppia* community, and thereby the ecological health, of Waituna Lagoon. The N load limits estimated by the three studies (a literature review, an expert assessment and a deterministic model) were similar and substantially lower than the range of estimated actual N and P loads to Waituna Lagoon (Figure 5). With regard to P loading, the Waituna model suggested a marginally better outcome for *Ruppia* with a 25% reduction in P load (concomitant with a 50% reduction in N load). This 25% reduction was calculated in relation to an estimated load of 14.4 t P y^{-1} (Hamilton et al. 2012). The expert assessment (Scanes 2012) recommended that, in addition to a 50% reduction in the N load, a 23% reduction in TP load was sufficient to ensure that Waituna Lagoon would remain in a moderately disturbed condition. This 23% reduction (to 7.4 t P y^{-1}) was calculated in relation to an estimated load of 10 t y^{-1} (Scanes 2012), which equates to a 50% reduction from the TP load estimated by Hamilton et al. (2012). In light of this information, the TAG recommended that N loading should be reduced to 125 t y^{-1} and P loading should be reduced to 7.7 t y^{-1} (Figure 5). These recommendations equate to approximately 50% reductions from the load to Waituna Lagoon calculated by Hamilton et al. (2012). The TAG recommended a more aggressive 50% reduction of the P load than was indicated by the model because the TAG was concerned that a more aggressive reduction of N than P loading could result in N-limitation of phytoplankton

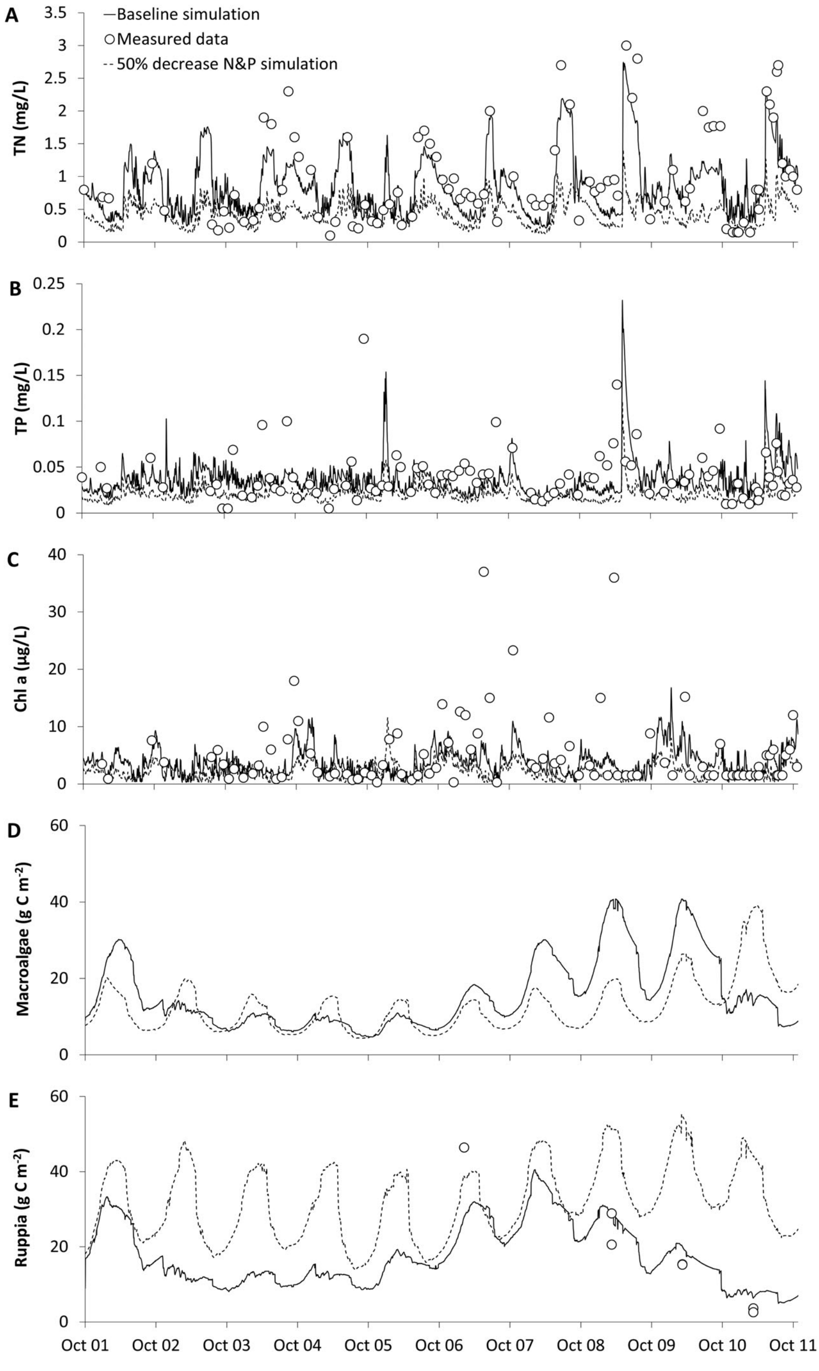

Figure 4. Measured data (open circles) and simulated data for the baseline (dark line) and for a 50% reduction of TN and TP (broken line). (a) TN. (b) TP. (c) Chlorophyll *a*. (d) Biomass of macroalgae. (e) Biomass of *Ruppia.* From Hamilton et al. (2012).

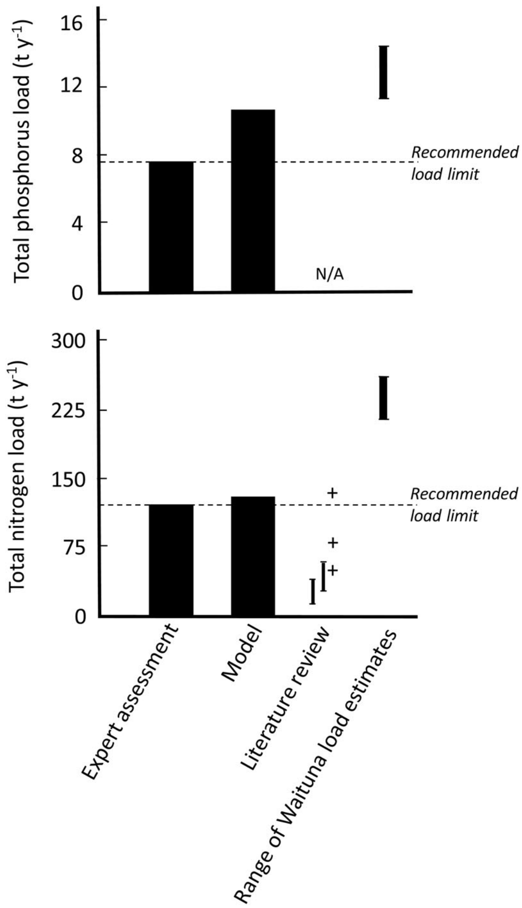

Figure 5. Estimated catchment nutrient load limits to safeguard the *Ruppia* community of Waituna Lagoon. Expert assessment is from Scanes (2012). Model is from Hamilton et al. (2012). Literature review data are from Schallenberg and Schallenberg (2012). The range of estimated actual loads and the recommended load limits are from Environment Southland (2013).

growth – a situation that could favour the development of nuisance blooms of potentially toxic, N-fixing cyanobacteria such as *Nodularia spumigena* and *Anabaena* sp., which are common in eutrophic ICOLLs in New Zealand (Pridmore & Etheredge 1987; Waters 2016; M. Schallenberg, pers. obs.). In addition, bioassay experiments showed that at certain times during the growing season, additions of N or P or both stimulated phytoplankton and macroalgal growth in Waituna Lagoon (Environment Southland 2013). Thus, an equally aggressive proportional reduction in N and P loading was recommended.

The literature review found a range of thresholds of N loading related to seagrass collapse. Variation in thresholds is not unexpected due to difference in biophysical aspects of the various systems, their variation in latitudes and differences in seagrass species examined in the studies. The upper range of thresholds reported in the literature (100 kg N ha^{-1} y^{-1}) corresponded roughly to the thresholds recommended by expert assessment (90 kg N ha^{-1} y^{-1}) and the Waituna model (96.2 kg N ha^{-1} y^{-1}), thus confirming that the relevant

N loading threshold for Waituna Lagoon is likely to be in the upper range of thresholds reported in the literature. Thus, the analysis of published thresholds for seagrass collapse gave the TAG confidence in setting an N load limit of 90 kg N ha^{-1} y^{-1} or 125 t N y^{-1} for Waituna Lagoon.

Estimates of actual nutrient loads to Waituna Lagoon showed some variation, depending on the methods used (Figure 5) and this meant that expressing the recommended load reductions either as a percentage of the current load or as an absolute amount of load reduction was difficult. The difficulties and inconsistencies in estimating nutrient loads (e.g. Johnes 2007) probably also affected the TAG's literature review, where different studies used different methods to estimate N loads, and the expert assessment, in which the nutrient loads to Australian ICOLLs were modelled. Furthermore, inter-annual considerations such as climate variations (e.g. El Niño/La Niña oscillations) and time lags for groundwater transport can also confound accurately estimating nutrient loads from catchments to water bodies.

Despite these challenges, the three independent lines of evidence converged, facilitating a scientific consensus on the nutrient load limits required to safeguard the Waituna Lagoon (and other similar systems). To date, however, specific policy reflecting the recommended nutrient load limits has been lacking. The work of the TAG has raised awareness in the farming community of the potential ecological outcomes for the ICOLL under current farming pressures and of the importance of reducing nutrient losses from fertiliser applications, animal effluent disposal, and land drainage practices. The key statutory stakeholders have formed a Partners Group and published a Waituna Strategy (Environment Southland 2015) to advocate for a coordinated response to catchment management, but this is a non-statutory document and does not have any specific funding or policy change associated with it. A new partnership between New Zealand's largest dairy company (Fonterra Ltd.) and the Department of Conservation is reviving a version of the Waituna Lagoon TAG to interact with the Partners Group and to help action the Waituna Strategy. Due in part to an increased awareness of the vulnerability of the Waituna Lagoon ecosystem to nutrient and sediment loads, Environment Southland has recently declined some consent applications to convert more farms in the catchment to dairying. However, a proposed policy in Environment Southland's draft Regional Plan, which referenced the limiting of nutrient loads in the Waituna Catchment, was challenged by some interest groups and was subsequently removed from the Regional Plan. The challenge was not focused on the recommended load limits, but mainly took issue with the Waituna catchment having additional land use rules placed on it, when other sensitive catchments in Southland did not have a similar policy proposed to protect their associated aquatic ecosystems.

Ecological resistance and resilience

The TAG studied Waituna Lagoon's vulnerability to increased nutrient loading using the conceptual framework of alternative stable states and ecological thresholds developed by Scheffer (2004) and others. Concepts of ecological resistance (inertia to change) and resilience (ability to return to a previous state after a perturbation) are important properties for understanding ICOLL responses to management and restoration. Data and observations of other New Zealand (Schallenberg & Sorrell 2009;

Schallenberg et al. 2010) and overseas coastal lakes and lagoons (Viaroli et al. 2008; Duarte et al. 2015) indicate that ICOLLs experiencing increasing nutrient loading initially show ecological resistance to nutrient loads. Exceeding ecological resistance thresholds results in rapid changes from a state where macrophytes were a key ecological component to one where they are largely absent and macroalgae and/or phytoplankton dominate primary production.

The TAG's literature review (Schallenberg & Schallenberg 2012) found that the nutrient load thresholds for safeguarding macrophytes in such systems varied between 20 and 100 kg N ha^{-1} y^{-1} – a fivefold variation (Figure 3), suggesting that variability in ecological resistance and resilience exists among these systems. For example, the difference in condition between Waituna Lagoon and Te Waihora/Lake Ellesmere, which has been virtually devoid of macrophytes since 1968, is notable when one considers that the areal nitrogen loading rates to these two systems are similar (Figure 3). Some of this uncertainty may be intrinsic and related to the different plant and animal communities of the two ICOLLs, some may be due to lag effects (e.g. Waituna Lagoon likely has not approached a state of quasi-equilibrium in response to recent increases in catchment nutrient loading), and some may reflect other factors such as differences in the extent of tidal flushing rates during barrier bar openings or in water temperatures affecting biological productivity and biogeochemical cycling rates (Table 1).

At the time of the TAG's work, little was known about nutrient attenuation in the soils of the Waituna catchment. Subsequent study has shown that the peaty soils of the lower catchment are effective at removing nitrate (probably via denitrification), but not very effective at retaining phosphorus (e.g. McDowell & Monaghan 2015; Simmonds et al. 2015). This contrasts with typical mineral soils, through which nitrate readily leaches (Di & Cameron 2002) but in which phosphate is largely retained within the mineral and organic soil matrix (McDowell et al. 2001; Gray et al. 2015). Thus, the peaty soils of the lower Waituna catchment may confer some resistance to nitrogen leached from farms, but offer minimal attenuation of phosphorus. We caution, however, that the temporal dynamics and pathways of nitrogen delivery to the lagoon are not fully understood. For example, tile drains are known to short-circuit the transit of nitrate through saturated peat zones where anaerobic processes would otherwise facilitate denitrification, and similarly, denitrification may be greatly reduced during high-flow events (Tiemeyer & Kahle 2014).

Little is known about in-lake processing and cycling of N and P once these nutrients have entered the Waituna Lagoon. For example, there have been no direct measurements of denitrification or internal P release from sediments. A recent study has found that these processes are important in Te Waihora/Lake Ellesmere and have the potential to mediate the eutrophication process (Schallenberg & Crawshaw, in review). In addition, waterfowl can increase nutrient input and cycling and have the potential to reduce macrophyte biomass, particularly if the macrophyte distribution and biomass is restricted by other environmental factors (Søndergaard et al. 1996).

Physico-chemical attributes of Waituna Lagoon may also confer a degree of ecological resistance and resilience to eutrophication. For example, the higher latitude and colder climate of Waituna Lagoon may slow nutrient cycling and may enhance seasonality in many environmental drivers, compared with ICOLLs at lower latitudes. In an attempt to address potential effects of latitude, Scanes (2012) analysed the New South Wales coastal lakes' and lagoons' dataset for an effect of latitude on chlorophyll *a*, but found none. However, the range of latitudes of ICOLLs in his dataset was well north (between 28°S and 38°S) of Waituna Lagoon, which is situated at 46.56°S. In addition, the presence in Waituna Lagoon of high levels of humic acids and chromophoric dissolved organic matter leached from the surrounding wetlands and peaty soils (conferring a distinct brown colour to the water) has the potential to reduce phosphorus availability to phytoplankton (Jansson 1998). While this may confer some resilience, the humic matter also reduces light penetration and has been identified as a factor that potentially exacerbates the effects of eutrophication on *Ruppia* in the ICOLL (Schallenberg & Tyrrell 2006).

Conclusions

While there are a number of challenges in setting nutrient load limits for ICOLLs such as Waituna Lagoon, the three lines of independent scientific evidence converged on quite specific nitrogen and phosphorus loading limits for the ICOLL. Thus, despite these challenges (Table 3), the convergence of multiple lines of evidence gave robustness to the proposed nutrient load limits recommended by the TAG, as evidenced by the consensus of the TAG members on the recommended limits.

Table 3. Summary of challenges in applying scientific knowledge to the management of Waituna Lagoon (from Environment Southland 2013).

Challenge	Relevance to Waituna Lagoon
Multiple interacting stressors	Rapid expansion and intensification of dairy farming in the catchment increases nitrogen and phosphorus loads to the lagoon. These interact with variable opening and closing regimes, changes in light climate, and internal nutrient loading and recycling, to influence the balance of productivity amongst phytoplankton, macrophytes and macroalgae
Non-linear dynamics	The TAG identified Waituna Lagoon as a system that has the potential to undergo rapid regime shifts resulting in the loss of *Ruppia* and its associated values
Ecological feedback and resilience	Macrophyte biomass has been identified as the keystone of ecological health and water quality. Water clarity is in turn critical to plant cover in the lagoon. Healthy levels of *Ruppia* and a supporting light climate are integral to the ecological resistance of the lagoon, imparting resilience to eutrophication, and likely structuring complex food web linkages that in turn contribute ecological resistance and resilience
Non-steady state	While a vegetated state has persisted, conditions are in fact dynamic, with light, nutrients, salinity, sediment redox and water levels (desiccation) interacting to induce substantial temporal fluctuations in dominant macrophyte species, biomass and distributions. Because the ICOLL is not manually closed, occasional long periods of opening to the sea (e.g. >1 y) cause stress to the macrophyte community and encourage macroalgae to bloom. This pattern tends to reverse when there is a short winter or early spring opening
Legacies	With the continued removal of wetland in the catchment, the accumulation of fine sediments and increasing sediment anoxia in the ICOLL reflect a land use legacy that could affect *Ruppia* distributions directly (via habitat suitability) and indirectly (via internal nutrient loading)
Time lags	Groundwater lags and responses to increases in land use intensification were identified as a key issue of concern at an early stage in the project (Rissmann et al. 2012). The regular artificial opening of Waituna Lagoon decreases its hydraulic residence time, enhancing the flushing of accumulated fine sediments and nutrients out of the ICOLL
Stochasticity	Stochastic rainfall events can cause the water level to rise to the trigger point and the subsequent opening of the ICOLL at any time of year. Furthermore, ICOLL closure, and thus the period of opening to the sea, is dependent on interactions between tides, lagoon water levels and storm surges. Consequently, major events transferring nutrients and sediments into and out of the ICOLL can be unpredictable
Data availability	The TAG was required to set nutrient load limits with a paucity of data of some key ecosystem components such as macroalgae distributions and density, macrophyte biomass and distributions, and episodic (stormflow) loads of nutrients to the ICOLL

However, the challenges, which apply to the management of most ecosystems, highlight the need to incorporate the precautionary principle and the concept of adaptive management (Westgate et al. 2013) into policies that aim to safeguard ecosystem health where there are pressures to develop the catchment. While the precautionary principle and adaptive management approaches may appear to be too conservative to some, these approaches can serve to optimise long-term environmental outcomes by accounting for uncertainty where knowledge gaps exist. For example, a type of precautionary approach was used by the TAG to achieve a consensus on the phosphorus load limits to Waituna Lagoon, where some uncertainties existed and additional expert knowledge had a bearing on the interpretation of the slightly discordant lines of evidence. Ecosystems like Waituna Lagoon, which have been identified as being susceptible to rapid regime shifts, with strong ecological feedback and non-linear behaviour in relation to pressures (sensu Scheffer 2004), highlight the need for guarded management approaches. Once such systems undergo regime shifts to undesirable states, their restoration to prior healthy conditions may require severe nutrient reduction targets and, in some cases, a full recovery to a pre-degradation state may not be possible (Duarte et al. 2009, 2015).

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