Spears, Bryan M.; Hamilton, David P.; Pan, Yang; Zhaosheng, Chu; May, Linda. 2022. **Lake management: is prevention better than cure?** Inland Waters, 12 (1). 173-186.

Lake management: is prevention better than cure?

Bryan M. Spears[a], David P. Hamilton[b], Yang Pan[c], Chu Zhaosheng[c] and Linda May[a]

[a]UK Centre for Ecology & Hydrology, Penicuik, Midlothian, UK, EH26 0QB

[b]Australian Rivers Institute, Nathan campus, Griffith University, 170 Kessels Road, QLD 4111, Australia

[c] Institute of Lake Environment, National Engineering Laboratory for Lake Pollution Control and Ecological Restoration Chinese Research Academy of Environmental Sciences (CRAES), Da Yang Fang, Chaoyang District Beijing 100012

CONTACT: B.M. Spears spear@ceh.ac.uk

Abstract

Globally, anthropogenic actions of land use change and intensification, and deliberate or unintentional species invasions have adversely affected lakes, resulting in widespread loss of benefits to society. In recognition of these impacts, restoration efforts have increased in recent years. Restoration is a challenging and expensive process, however, and success rates are variable and often unpredictable. Here, we demonstrate that early actions to prevent degradation of lakes currently in good ecological condition are preferable to attempting to restore lakes that have been allowed to degrade, to allow for continuity of ecosystem services. We compare case studies for three lakes that use preventative approaches to mitigate the effects of anthropogenic pressures. These initiatives aim to protect or enhance long-term societal benefits through building resilient ecosystems and maintaining ecological integrity. They differ from restoration projects, where lakes are often in an advanced state of degradation that is resilient to modest restoration efforts. We identify the need to mainstream preventative lake management including building a robust evidence base to support initiatives aimed at reversing the early stages of changes in ecological state.

Keywords restoration, Loch Leven, Lake Rotorua, Lake Erhai, policy, ecological state, nutrients

Quote 'Prevention is better than cure'; Desiderius Roterodamus, 1466-1536.

Introduction

For centuries, society has relied on lakes for water supply, food production and delivery of many other ecosystem services. These services, however, may be jeopardised by anthropogenic activities that alter the physical, ecological and geochemical conditions of these systems. Lakes are threatened by future warming (O'Reilly et al. 2015), more extreme weather events (IPCC 2014, Havens et al. 2016), and increasing nutrient losses from agricultural land (Lee et al. 2016). In combination, these pressures are predicted to result in unprecedented losses of biodiversity and breakdown of the ecological processes that underpin delivery of ecosystem services (Rodriguez, et al. 2008). Worryingly, the evidence base required to support preventative management is often limited, even though the need to safeguard high value ecosystems has been recognised for some time (Julius et al. 2008, Beddington 2009).

The task of restoring damaged lakes is daunting, with restoration costs for the USA alone estimated at approximately $2.2 billion per year for eutrophication (Dodds et al. 2009). Globally, the estimated costs of responding to the impacts of extreme weather events have increased from $528 billion in the 1980s to $1213 billion in the 1990s (Michel-Kerjan 2012). On a global scale, dealing with cyanobacterial blooms, which are symptomatic of degraded lakes, has resulted in billions of dollars of new investment in water treatment plants and recurrent operational costs (Hamilton et al. 2014). Invasive species have also triggered massive losses of ecosystem services. For example, when the spiny water flea (*Bythotrephes longimanus*) invaded Lake Mendota, USA, the mitigation action of reducing nutrient inputs to offset the reduction in water clarity from the invasion was estimated to cost hundreds of millions of dollars (Walsh et al. 2016). The cost of successful restoration increases with levels of degradation, with some systems considered ‘beyond repair’ (Carpenter et al. 1999, Søndergaard et al. 2007, Sharpley et al. 2013, Dodds et al. 2009, Douglas et al. 2016), i.e., costs would be prohibitive. A key goal of preventative management is to reduce the need for such costly restoration activities by implementing measures that prevent undesirable ecological responses occurring in the first place.

Lake ecosystems can become unstable in response to changes in external pressures, increasing the likelihood of regime shifts resulting in sudden losses in ecosystem function and service delivery (Scheffer 2009, Scheffer et al. 2015). In the European Union (EU), a total lake area of about 61,466 km^2 is deemed to have low levels of degradation in terms of meeting water quality objectives set under the EU Water Framework Directive. Of this area, 37,153 km^2 are considered to be in acceptable condition (European Parliament 2000; sum of lake area in ‘good’ and ‘moderate’ classes representing 70% of total lake area assessed; data accessed 2013 European Environment Agency Web Portal; Fig. 1). These data suggest most lakes assessed within the EU exhibit low levels of degradation but that shallow lakes may be highly sensitive to change, supported also by ecological resilience theory that indicates ecosystems are most unstable under intermediate stressor conditions (Carpenter et al. 1999, Scheffer et al. 2009).

We highlight the need to restore not only lakes that are exhibiting unacceptable levels of degradation, but to also implement measures for those exhibiting moderate levels of deterioration in responses to imposed stressor(s). The planning and implementation of costly interventions to achieve ‘no ecological change’ is a difficult concept to promote in terms of lake management, where stakeholders may expect dramatic ecological responses to be associated with restorative management.

Here, we demonstrate the general approaches that have been used in the planning and implementation of preventative lake management. Drawing on experiences from established catchment management groups, we compare plans that have been designed to mitigate the impacts of anthropogenically induced environmental change through to 2050, which threatens the capacity of three iconic lakes to deliver key ecosystem services (Loch Leven, UK; Lake Rotorua, New Zealand; Lake Erhai, China). We synthesise these experiences, outlining the expected impacts of a 'do nothing' approach, and critically compare estimates of confidence in the effectiveness of planned preventative measures, as assessed by expert interpretation of the evidence available for each case study. Lessons learned are presented for each case, with general recommendations provided to support improvement and implementation of the preventative management approach.

Loch Leven, Scotland, UK

Loch Leven – site description and benefits to society

Loch Leven (Figure 2) has a world famous trout fishery, is internationally recognised as a conservation area for waterfowl and macrophytes (Sites of Special Scientific Interest; Ramsar; Special Areas of Conservation, Natura network 2000) and is a source of water supply to downstream industry (May & Spears 2012). Its catchment is farmed intensively for livestock, poultry, and crop production (Castle et al. 1999, LLCMP 1999), with a human population of about 10,720 (pers. com., Perth and Kinross Council, Feb. 2018).

Historically, the lake has received nutrient pollution from industry (i.e., from c. 1840 to the 1990s; D'Arcy et al. 2006), wastewater treatment works and farm runoff (May et al. 2012, Spears and May 2015). In the past, these stressors resulted in an increase in in-lake total phosphorus (TP) and chlorophyll *a* concentrations, a decrease in Secchi disk transparency and deterioration in the extent and diversity of the aquatic macrophyte and bird communities (Dudley et al. 2012, May and Carvalho 2010, Carss et al. 2012). In the 1980s and 1990s, measures were implemented to reduce nutrient inputs. The focus was mainly on point sources, achieving a 60% reduction in the TP input to the lake. Although the lake ecosystem improved sufficiently to meet the restoration targets set by the catchment management group for water clarity, macrophyte maximum growing depth, and TP and chlorophyll *a* concentrations, it took decades to achieve the targets because of internal cycling of P (Spears et al. 2012). Also, warming related to climate change (Carvalho et al. 2012, O'Reilly et al. 2015) delayed the recovery process. However, the lake is now a nationally important destination for eco-tourism and recreation, attracting more than 200,000 visitors per year (ScotInform 2015). The lake is now an important focus of income generation for many local businesses, and the current management plan for the site has been designed to balance biodiversity protection with controlled visitor access to support these socio-economic benefits (SNH 2016). The downstream catchment will undergo ecological enhancements, with investment of about £312,000, beginning in 2019 and aimed at delivering additional socio-economic benefits.

Loch Leven – drivers of change

By 2050, there is a 10% probability that the east of Scotland will have experienced a 1-2 ^{o}C rise in annual and summer average daily temperatures based on a medium greenhouse gas emissions scenario (UKCP09 SRES A1B[1]; Nakićenović et al. 2000). Under this scenario, summer and winter precipitation levels are predicted to decrease by 20-30% and increase by 0-10%, respectively. More frequent and intense rainfall events are also predicted. This change has already commenced. O'Reilly et al. (2015) reported a summer warming rate of about 0.7 ^{o}C per decade in Loch Leven surface waters since 1985; a rate faster than the corresponding rise in air temperature and making Loch Leven one of the fastest warming lakes on record in the world. In addition, May et al. (2017) report that diffuse P pollution is increasing relative to

[1] https://www.metoffice.gov.uk/research/collaboration/ukcp?emission=low

point source pollution, probably as a result of more frequent and intense rainfall events across the catchment in recent years.

The Strategic Development Plan for Kinrossshire, an area that includes Loch Leven, indicates that about 70 houses per year will need to be built within the catchment to meet projected population growth rates by 2050, which equates to 2240 additional houses. Using methods recommended by local authorities and demonstrated by Brownlie et al. (2014), we estimate that the TP discharge to the environment from these houses, if built with on-site wastewater treatment systems providing only secondary treatment, would be about 3.7 t yr^{-1}. Without mitigation for the effects of increased population, which could include connection to mains sewage, the annual TP load estimated to be 11.2 t yr^{-1} (2.02 mg m^{-2} d^{-1}) in 2015/2016 could increase by about 30% (Spears et al. 2019).

Loch Leven – evidence of impending ecological deterioration

We describe below the strength of evidence on process understanding that underpins current management at Loch Leven and this has been used to construct the process flows (or 'logic chains') summarised in Figure 2 (as for all subsequent case studies). Changes in the nutrient loading to Loch Leven over time (May et al. 2012) have resulted in measurable ecological responses across all trophic levels in the lake (May and Spears 2012). Initially, in the early 1900s, the catchment TP load to the lake was estimated at 5 t y^{-1}, which corresponds approximately to the natural background (reference) level. By 1985, the TP load had increased to about 20 t y^{-1}; however, by the mid-1990s, it had been reduced to about 12 t y^{-1}. TP concentrations in the lake declined thereafter and the water quality restoration targets set by the Loch Leven Catchment Management Plan (LLCMP 1999) of <40 µg L^{-1} for TP, <15 µg L^{-1} for chlorophyll *a*, and >2.5 m for Secchi disk transparency depth, had been met by 2010 (Carvalho et al. 2012). The period of recovery is well documented and provides a relatively broad TP stressor gradient over which ecological responses to eutrophication and recovery can be quantified. As TP concentrations in the lake increased, chlorophyll *a* concentration also increased and Secchi depth decreased; these relationships have been well established for the lake and have been used to underpin the catchment management plan and nutrient targets (LLCMP 1999).

Macrophyte colonisation depth (MCD) varied inversely with catchment TP load (MCD = 15.2 x TP load$^{-0.73}$; R^2 = 0.64) and positively with annual mean Secchi depth (MCD = 2.4 x Secchi depth – 1.05; R^2 = 0.77; May and Carvalho 2010). In addition, Dudley et al. (2012) observed that macrophyte diversity tended to increase with decreasing TP load to the lake, although no statistical relationship was presented. Similarly, an apparent increase in fish body size was recorded following improvements in water quality (Winfield et al. 2012). Increases in the diversity of zooplankton, leading to increases in *Daphnia*, and of macroinvertebrates, also occurred when the water quality improved (Gunn et al. 2012). Carvalho et al. (2012) associated a significant increase in spring *Daphnia* densities in recent years with increases in water temperature that coincided with lower chlorophyll *a* concentrations and higher water clarity in spring and early summer. At the same time, high rainfall appears to have resulted in low chlorophyll *a* concentrations in some years, probably as a result of increased flushing rates (Carvalho et al. 2012).

Using the phytoplankton community model PROTECH, Elliott et al. (2008) showed that increased P load was the main factor that had caused observed increases in chlorophyll *a* concentrations, and that the key stressor that had determined the observed response in *Anabaena sp.*, the dominant cyanobacteria in Loch Leven in summer, was nitrogen (N) loading. Reductions in N loading correlated with an increase in the relative abundance of *Anabaena* sp., probably due to its ability to fix atmospheric N. Elliott and Defew (2012) concluded that there was no evidence to suggest that the relative abundance of cyanobacteria would increase in Loch

Leven under the most sever warming scenarios. In contrast, changes in chlorophyll *a* concentration were more likely to occur under extreme rainfall-runoff conditions, with high flows resulting in greater losses of phytoplankton from the outflow and low flows resulting in reduced nutrient inputs from the catchment (Elliott and Defew 2012). It should be noted that this modelling approach did not account for any future changes in internal P loading which may increase under low rainfall conditions (Spears et al. 2019).

No significant relationships have been reported between ecological responses within the loch and the number of recreational visitors. On average, 69% of visitors reported that 'clear water' was an important influencing factor in their visitation of the loch (ScotInform 2015). On average, visitors spend about £10 each per visit, contributing about £2 million of income per year to local businesses (>£150,000 per km^2 lake surface area from tourism, alone). However, anecdotal evidence suggests that the occurrence of cyanobacterial blooms in the 1980s and 1990s affected the reputation of the loch as a destination for visitors and anglers. As a result, the adverse economic effects of the blooms as a fishery continued many years beyond the period of recovery in water quality.

Loch Leven – proposed mitigation measures to prevent future deterioration

Measures are being developed to mitigate P loading to Loch Leven from the catchment (Table 1). Policy measures are being implemented to control the inputs of P to the loch from new housing developments. For example, the proposed Local Development Plan for Perth and Kinross (http://www.pkc.gov.uk/ProposedLDP) outlines a limit on housing development to 90% of the projected figures. It also indicates that new developments will be located, as far as possible, in areas that are currently served by wastewater treatment works (WWTWs) or are situated outside of the surface water catchment of the loch. Assuming that the WWTWs have tertiary treatment and are operating within their design capacity, these measures should be effective at minimising any additional P load to Loch Leven due to population growth. In addition, where housing developments are planned but cannot connect to WWTWs, mitigation measures must be implemented that are capable of removing 125% of the estimated increase in P load that is likely to be generated by the development (Brownlie et al. 2014). Such measures might include, for example, upgrading other on-site sewage treatment systems within the catchment or installing constructed wetlands.

Riparian buffer strips and soil retention barriers are being considered to redress the apparent increase in particulate P load to Loch Leven since 1985 (May et al. 2017). Previous field trials have demonstrated that these measures can be effective in the Loch Leven catchment under certain flow conditions (Greig 2004). However, if shown to be effective, this type of diffuse pollution control could be designed to, at least, offset any increase in P load to the loch that is likely to result from house building and associated works, although no specific targets have been set.

Lake Rotorua, Bay of Plenty, New Zealand

Lake Rotorua – site description and benefits to society

Lake Rotorua (Fig. 2) is a tāonga (a 'treasure' translated from Māori to English) to the Māori tribe of the region, Te Arawa (Stafford 1994). This spiritual and cultural connection is recognised by the Te Arawa Lakes Settlement Act 2006. Historically, Lake Rotorua was also a rich source of food for the Te Arawa tribe, providing freshwater crayfish/kōura (*Paranephrops planifrons*) and whitebait/kōaro (*Galaxias brevipinnis*) (Kusabs and Quinn 2009). The introduction of rainbow trout (*Oncorhynchus mykiss*) and brown trout (*Salmo trutta*) has resulted in a world class recreational trout fishery, largely at the expense of the heavily predated kōaro. The Rotorua region also supports a highly active geothermal field, and geothermally heated waters enter many of the lakes, including Rotorua. The value of ecosystem services provided by Lake Rotorua has been estimated to exceed NZ $120 million p.a. (NZ $1.5 million per km^2 lake surface area; Mueller et al. 2016).

The catchment of Lake Rotorua has been progressively cleared of native vegetation and replaced with pastoral agriculture over the past 150 years. Increasing urban development resulted in centralisation of wastewater treatment and disposal to the lake, commencing in the late 18th century. The initial deterioration of Lake Rotorua was mainly associated with loss of habitat and amenity value caused by the proliferation of an invasive macrophyte (oxygen weed: *Lagarosiphon major*) in the 1960s. In 1991, a major upgrade of wastewater treatment led to an advanced system that included tertiary treatment and disposal to a plantation forest within the catchment. At the time, the upgrade was thought to be a solution to lake water quality problems that had progressively intensified since the 1970s (Rutherford et al. 1996). However, subsequent studies have shown that diffuse pollution from expansion and intensification of agricultural land has largely negated any benefits from this upgrade (Palliser et al. 2019). Noteworthy is a projected long-term increase in the N load resulting from a legacy of nitrate leaching from agricultural land resulting in progressive N enrichment of large aquifers that supply most inflows (Morgenstern et al. 2015). Severe cyanobacterial harmful algal blooms occurred in Lake Rotorua in the mid-2000s. These blooms, and a more general deterioration of water quality, triggered management measures (Hamilton and Dada 2016). These measures were implemented to prevent further deterioration of Lake Rotorua Lakes and its downstream tributary lake, including alum dosing of tributaries to Lake Rotorua (the first in 2006 followed by a second in 2009) and a NZ $10 million diversion wall to direct the outflow of Lake Rotorua away from receiving waters of Lake Rotoiti and towards the outflow of that lake (Hamilton and Dada 2016).

Lake Rotorua – drivers of change

Numerical modelling results predict potential future ecological deterioration of Lake Rotorua (Lehmann and Hamilton 2018). Specifically, the trophic state, as indicated by the phytoplankton biomass of Lake Rotorua, is impacted by: (1) nutrient release from bottom sediments, a process that has increased with higher trophic status (Burger et al. 2008), (2) climate change associated with predicted warming (an increase of about 2.5 – 2.7 ^{o}C by 2090; Özkundakci et al. 2012) and greater storm frequency and rainfall (Me et al. 2017), and (3) increased nutrient delivery from legacy stores in the catchment including agricultural land, aquifers and forest blocks where wastewater has been disposed of since 1991 (Abell and Hamilton 2015; Morgenstern et al. 2015; Peryer-Fursdon et al. 2015). Of these, Me et al. (2017) propose that climate change will pose the greatest threat in relation to meeting goals for trophic state that are embedded into policies of the regional management authority, Bay of Plenty Regional Council.

Lake Rotorua – evidence of impending ecological deterioration

Phytoplankton responses to environmental change have been well documented in Lake Rotorua. A number of bioassay studies have shown limitation of phytoplankton growth by N (White and Payne 1978, White et al. 1985) and/or N and P co-limitation (Burger et al. 2007) in the lake (see Smith et al. 2016 for a review). Lake Rotorua is particularly sensitive to warming, because it is polymictic and eutrophic. Warmer air temperature is therefore likely to increase the duration of stratification events and bottom-water anoxia. Based on DYRESM-CAEDYM simulations, Özkundakci et al. (2012) predicted increases in the frequency of harmful cyanobacterial blooms and the duration of anoxia of bottom waters under a future warmer climate. Me et al. (2019) showed how changes in stratification associated with a 2090 climate could increase chlorophyll *a* concentration by approximately 50% compared with a ‘baseline’ (2005-2010) climate. Model simulations show water quality of Lake Rotorua is more sensitive to in-lake changes driven by stratification, bottom-water anoxia and bottom-sediment nutrient releases, than changes in water and nutrient delivery from the catchment (Burger et al. 2008).

Incursions of invasive macrophytes to Lake Rotorua have affected the amenity value of the lake. The proliferation of the invasive macrophyte, *Egeria densa*, in Lake Rotorua began in the 1980s (Wells and Clayton 1991). However, the invasive species *Elodea canadensis*, *Lagarosiphon major* and *Ceratophyllum demersum* are also present in the lake. A comprehensive discussion of potential dispersal pathways in this region is provided by de Winton et al. (2009), who suggested that dumping of contaminated aquaria and pond supplies was the most likely primary route of infestation.

Lake Rotorua – proposed mitigation measures to prevent future deterioration

In the short-term (i.e., one decade) the water quality of Lake Rotorua will almost certainly be closely tied to the continuation and scale of alum dosing of the inflow (Smith et al. 2016). There is a strong desire, however, to progressively phase out this activity as land use controls are implemented and their effects become evident, and many Māori tribal groups have voiced opposition to alum dosing (pers. com., A. Bruere, Lake Operations Manager, Bay of Plenty Regional Council).

Two policy measures are important to prevent further degradation in the water quality of Lake Rotorua, and these are linked to a range of mitigation measures (Table 1). The first, known as Rule 11, is part of the Bay of Plenty Regional Council's Water and Land Plan and allocates a maximum nutrient loss from agricultural land using a 2001-2004 benchmark in the catchment. Rule 11 was implemented because each of the five lakes that it includes was showing evidence of increasing trophic status. For Lake Rotorua, the follow-up policy is the proposed Plan Change 10. This policy specifically seeks to allocate a limit for N loads and to tightly manage P loads, using implementation of rules if necessary, to achieve the required lake trophic status target. For TN, the policy seeks to attain a reduction in the catchment load by approximately 250 t yr^{-1} to 435 t yr^{-1} (36%). Early iterations of Plan Change 10 focused almost entirely on catchment N controls and not P controls, even though subsequent work suggests that limitation by N and P can control phytoplankton biomass in the lake (Smith et al. 2016). The implementation of Plan Change 10 was strongly challenged, especially by the farming community, after public notification by the regional council in 2017 of its intention to embed it into the overarching Water and Land Plan. Arguably, alum dosing may have offset the urgency of Plan Change 10 implementation by 'artificially' reducing the trophic status of the lake while catchment nutrient loads remained high. Only with accumulation of time series data on water quality (Smith et al. 2016), and detailed modelling studies (Lehmann and Hamilton 2018), has it been possible to isolate the effect of alum dosing and confirm that this geoengineering technique has been the primary driver of recent improvements in the water quality of Lake Rotorua.

While Plan Change 10 is forward-looking in terms of managing nutrient loads, it does not consider climate change. Modelling studies indicate that additional reductions in catchment nutrient loads will be required to meet lake trophic state targets due to increased duration of stratification events, and, associated internal loading of P, resulting from climate change (Özkundakci et al. 2012, Me et al. 2019). To date, no specific measures have been implemented to offset the effects of climate change, although there is general recognition of the need for further mitigation of nutrient loads beyond those currently proposed.

A number of invasive species affect the ecological state of the Rotorua lakes. Herbicide is sprayed, intermittently, through many of the Rotorua Lakes to control invasive macrophyte species, mostly for public amenity purposes. Lake Rotorua is also at risk of invasion by new species, including macrophytes (de Winton et al. 2009) and fish (Rowe 2007). For example, catfish were discovered for the first time in Lake Rotorua in 2018 by the Bay of Plenty Regional Council. National-scale monitoring programmes are being considered to track and mitigate the spread of invasive species (e.g. Howell and Terry 2016).

Lake Erhai, Yunnan Province, China

Lake Erhai – site description and benefits to society

Lake Erhai (Fig. 2) is the main drinking water source of Dali City and provides important services to about 800,000 people in its catchment. These services include climate regulation, irrigation, and water supply for industrial and domestic use, as well as recreation, tourism and navigation. Lake Erhai also supports a cage fish farming industry (Du 1992; Dong et al. 2004). Industrial activity in the lake basin includes the manufacture of pulp, chemical fibre and leather, all of which produce organic pollutants. In addition, there are cement, textile and paper industries within the catchment (Shaoming 1997, Li et al. 2007).

Lake Erhai is situated in an important conservation area in the Cangshan Mountains and the Erhai Lake National Nature Reserve (Wang et al. 2015). It is rich in biodiversity and is one of only three major Yunnan lakes that have a high number of endemic species; the other two being Lakes Fuxian and Dian (Dianchi) (Wang et al. 2013). Wang et al. (2013) found that, of 23 fish species and subspecies known from Lake Erhai, eight are endemic but only two of these have been recorded since 2000. The remaining six species appear to have become extinct. In contrast, between the 1960s and 2012, the number of exotic fish species increased to 22, impacting natural biodiversity (Tang et al. 2013). Some native macrophyte species have also disappeared in recent years (Wang et al. 2013).

Lake Erhai – drivers of change

Lake Erhai is in the early stages of eutrophication, but is believed to be under serious threat of becoming highly eutrophic (Yu et al. 2014). Wang et al. (2015) reported that the water quality of Lake Erhai is becoming increasingly degraded, with worrying signs of rapid degradation in recent years. More specifically, the authors reported that in-lake annual average TP concentrations ranged from 14-20 µg L^{-1} between 1992 and 1998, and 12-35 µg L^{-1} between 1999 and 2010. The corresponding values for TN were 0.2-0.36 mg L^{-1} between 1992 and 1998, and 0.33-0.55 mg L^{-1} between 1999 and 2010. In addition, the areal coverage of submerged vegetation within the lake has shown a steady decline from 40% in the 1970s to 1990s, to 10% by 2003 and 5% by 2014 (Wang et al. 2015). Dearing et al. (2008) provide an historical context for the problems that have been developing within the catchment. Recently, the biggest threat to the lake has been from high magnitude but low frequency flooding of low altitude dry-farmed terraces and irrigated valley plains, which delivered high nutrient loads to the lake. Pollutants discharged to the lake in 2016 were about 50% greater than in 2004 (China Daily 2017). In addition, changes in agricultural intensity and land-use patterns have impacted the hydrology of the Lake Erhai Basin, resulting in greater soil erosion, water yields and agricultural pollution, which are important factors in the eutrophication of the lake (Chunmei and Limin 2011). Although it is unclear whether the release of P from bed sediments in the lake is also driving the eutrophication process, it has been suggested that nutrient-laden sediments in some areas have great potential for releasing nutrients into the water column under some conditions (Zhu et al. 2016). Whatever the main causes, water quality deterioration associated with rapid socio-economic development within the Lake Erhai basin is attracting increasing attention from the public and the Chinese government (Guo et al. 2001).

Lake Erhai– evidence of impending ecological deterioration

Increased nutrient loading has resulted in detectable ecological changes in Lake Erhai. Concentrations of chlorophyll *a* and microcystin-producing *Microcystis* species correlate positively with TP concentration and negatively with Secchi disk transparency, nitrate concentration and the TN to TP ratio, but not with water temperature (Yu et al. 2014). An increase of about 13% in annual average chlorophyll *a* concentration was reported between 2006 and 2009 (Han et al. 2014), and this has been anecdotally attributed to wastewater discharges from Dali City. External nutrient inputs have also been identified as one of the causes of degradation of the native macrophyte community (Han et al. 2014). It is unclear whether this change has occurred as a result of lower water transparency or through the impacts of non-native species. The relative abundances of *Bosmina* and *Daphnia* spp. have increased and decreased, respectively, in relation to increasing temperature and chlorophyll *a* concentration (Li et al. 2016) and warming is expected to lead to smaller-bodied zooplankton, such as *Bosmina*, reducing the grazing pressure on phytoplankton in the future (Jeppesen et al. 2005). Fish distributions in the lake are related to the composition and coverage of the aquatic plant community, water temperature, pH and season (Tang et al. 2013).

Liu et al. (2015) suggest that accelerating urbanisation and increasing energy consumption are likely to lead to an increase in industrial pollution in the area. The direct impacts of this pollution on the ecology of Lake Erhai are not well understood.

Lake Erhai – proposed mitigation measures to prevent future deterioration

Underpinning the shift towards preventative management in the Lake Erhai basin is a move from the traditional industries described above, towards low-polluting industries (e.g., tobacco production) and ecotourism (Table 1). To support socioeconomic change, predictive models have been constructed for the lake basin that reflect social, economic and environmental costs, allowing benefits and their interactions to be assessed under different change scenarios to inform decision making (Chen at al. 2011, Dong and Yang 2009). The proposed move towards ecotourism has the potential to increase the number of guesthouses, restaurants and hotels within the catchment, which is likely to increase the nutrient load to the lake. Although the exact consequences of ecotourism on the ecology of the lake are unclear, new management measures are already being implemented. These measures have resulted in the closure of about 1,800 restaurants, hotels and guesthouses until improved sewage treatment facilities have been installed (ECNS 2017), while some will remain closed, because of close proximity to the lake. To safeguard water quality, Wang et al. (2015) propose preventative measures in addition to the control of sewage discharges to Lake Erhai. These measures include integrated catchment management initiatives to reduce nutrient loads to the lake, the improvement of wetland habitat around the lake to support biodiversity and ecotourism, the implementation of an ecologically-based fishery policy, and a macrophyte transplantation scheme. In addition, temporary and permanently sited algal bloom harvesting systems remove excess algal material from the lake and convert it into fertilisers.

Hu et al. (2015) assessed the effectiveness of vegetated (*Cynodon dactylon* and *Zoysia japonica* mixed grass) buffer strips in controlling diffuse nutrient pollution of rivers and streams within the Lake Erhai basin. They demonstrated that mixed community swards could achieve TN and TP removal rates of up to 60%. Tang et al. (2013) outlined possible actions to improve habitat quality and protect natural fish populations. These actions included the restoration and protection of their spawning grounds, the control of non-native fish species by stocking with their natural predators and indigenous species, and improved fishing regulation. The cumulative effects of the measures described above are unclear. For example, an increase in tourism may result in more sewage-related inputs of nutrients to the lake, offsetting any reductions achieved through land-use change. The number of tourists visiting the area has already increased from 2 million in 2014 to 3.2 million in 2016 (ECNS 2017).

Synthesis and recommendations

Preventative management in the face of high uncertainty

The need for preventative management to address lake degradation is clear, but the evidence base with which to support the approach can be limited. Significant weaknesses were identified in the logic chains available to support the preventative management plans for all three of our case studies (Fig. 2; Table 1). At Loch Leven, low levels of confidence were reported in relation to the impacts of nutrient load, cyanobacterial dominance and macrophyte colonisation on the health of the fish community. Although the national level conservation status of Loch Leven is well quantified, the more site-specific relationships between water quality, macrophytes, fish, birds, and recreational reputation and income from tourism are not well established. In both Lake Rotorua and Lake Erhai, indications are that climate change needs to be taken into account when planning preventative management. However, the relationships between temperature change and ecological responses (other than general increase in trophic status) are not currently well understood. As for Loch Leven, the effects of loss of biodiversity on conservation status are well quantified in Lake Erhai, but the relationships between water quality, biodiversity and ecosystem services and benefits, e.g., tourist income or water purification capacity, are not. What is clear is that all lakes are likely to be impacted by multiple and potentially interacting stressors in the future and there is a need to consider more adaptive management approaches to address the stressors (Spears et al. 2014). To support this approach, we draw attention to impressive advances in conceptualising (Piggott et al. 2015), detection (Birk et al., 2020) and predicting (Feld et al., 2016; Spears et al., 2021) the ecological responses associated with the management of interacting stressors.

Julius et al. (2008) conducted an analysis of resilience to climate change for various ecosystem types in the USA. The authors reported on the levels of agreement between indicators of expert opinion and the quality of the evidence that is available to support the implementation of effective climate change mitigation measures, producing a confidence rating. In general, the level of confidence in mitigation options for freshwater ecosystems was low for both indicators, as found in our case studies. However, relatively novel approaches to lake management have been proposed by Julius et al. (2008) to address this problem. These approaches include creating refugia for migrant species (e.g. Chester and Robson 2013), relocating sensitive native species to high quality ecosystems (e.g. Winfield et al. 2004), creating replicate ecosystems within a specific area to provide protection against biodiversity loss (e.g., to control the spread of invasive species; Peters and Lodge 2013), and reducing other anthropogenic stressors to offset the effects of climate change (Hamilton et al. 2016a, Pearl et al. 2016). The wider applicability and effectiveness of these and other novel interventions should be considered further.

Nutrient load reductions are the most likely interventions to avert the more obvious manifestations of eutrophication, such as cyanobacterial blooms (Carpenter and Lathrop 2008, Brookes and Carey 2011, Moss et al. 2011). Our case studies reinforce the importance of nutrient load reductions as this measure has been most commonly considered for mitigation of multiple stressors, including climate change. The attraction of this approach is likely to have been influenced by the strong, published evidence that links decreases in nutrient load to improvements in water quality indicators. The expected time to implementation of these measures ranged from 1 to more than 20 years in our cases studies and, based on expert opinion, the levels of confidence in their effectiveness to mitigate future degradation in ecosystem service provision was generally moderate to high. However, Osgood (2017) suggests that levels of confidence in the effectiveness of these so called 'best-management-practices', when applied more generally (at least in relation to those targeting nutrient interception within the catchment), may offer false hope. That view is challenged by case study reports demonstrating effective nutrient management based on site-specific process understanding through the implementation of catchment and in-lake measures, and combinations thereof (Phillips et al. 2015, Huser et al. 2016) and modelling that predicts the cost-effectiveness of such approaches to mitigate climate change impacts (Crossman et al. 2013).

Preventative management requires a new perspective and a new framework to complement existing restoration approaches, including adaptive management (e.g., Carpenter et al. 1999; Spears et al. 2015). The four Priorities for Action for Disaster Risk Reduction of the United Nations Sendai Framework are generally applicable here (UNISDR 2015). These are (1) to understand disaster risk in terms of vulnerability, exposure, capacity to resist change, and potential asset losses; (2) to strengthen the governance of disaster risk management at local to global scales to support the development and implementation of prevention and mitigation policies; (3) to continually build ecological resilience-to-change through investment in disaster prevention measures, including those discussed above, and (4) to construct response or recovery plans so that asset losses are minimised in the event of a disaster and that all water managers are ready and equipped to respond appropriately. We encourage the development of such plans based on sound scientific evidence in support of a robust cost-benefit analysis, as demonstrated recently for Lake Rotorua (Mueller et al. 2016), including novel landscape planning approaches (Mueller et al. 2019).

The science-policy time lag

Prevention of further degradation is a key requirement of current water quality policies and directives (reviewed by Mackay et al. 2013). These include the European Union Water Framework Directive (EC 2000), the Chinese "Water 10 Plan" (State Council 2015; http://chinawaterrisk.org/notices/new-water-ten-plan-to-safeguard-chinas-waters/), and the USA Clean Water Act (Clean Water Act 1972). The New Zealand National Policy Statement for Freshwater Management 2014 (Ministry for the Environment 2014), for example, includes a strong focus on preventative management in relation to relatively unimpacted waterbodies (Hamilton et al. 2016b). So, if the need is implicitly stated by policy, why is preventative management not more commonly applied? The simple answer is that there is neither the money nor the confidence in its effectiveness for widespread implementation. This lack of confidence is due, in part, to the scale of the current lake management challenge (Fig. 1), and, the time lags involved in implementing large scale policies (Mueller et al. 2015), which have, understandably, tipped the balance towards restoration as the focus over prevention in recent decades.

Carvalho et al. (2019) reviewed the experiences of European Union Water Framework Directive practitioners concerning the apparent slow progress in meeting ecological quality targets (restoration and prevention combined). A lack of investment in restorative measures was cited as a significant limiting factor, with the most significant causes of failure to achieve good water quality being an inability to reduce nutrient loading sufficiently combined with a lack of evidence on the causes of degradation. The practical demonstration of links between lake ecological status and ecosystem service provision, and of our ability to manipulate them, was highlighted as a critical evidence gap, as it was in our own case studies.

Returning to our original question of *whether prevention is better than cure*, we argue that management of a lake should consider a balance between preventative and restorative measures. Where preventative measures are not implemented effectively, restoration will continue to be a more expensive alternative. As restoration success grows, so the demand to protect past investments will grow. In addition, we expect long-term preventative management plans to become more mainstream, as our understanding of climate change effects improves. For example, where climate change is predicted to amplify the water quality response to nutrient enrichment, policies may need to be revised to reflect more stringent nutrient reduction targets as a preventative measure. As we have demonstrated in our case studies, a significant evidence gap exists with respect to the effectiveness of multiple local scale interventions to prevent future degradation. There is a pressing need for the community to fill this evidence gap, as has been attempted for restoration actions in previous decades. The need for preventative management is recognised, for example, by the World Bank Group, who call for preventative management as the most effective means of tackling global scale water quality issues whilst acknowledging that wide scale implementation will be prohibitively expensive (Damania et al., 2019). So lies the challenge.

Acknowledgements

Research on Lake Rotorua is supported by Environment Bay of Plenty Regional Council and the New Zealand Ministry of Business, Innovation and Employment (UOWX1503; Enhancing the health and resilience of New Zealand lakes). The work on Loch Leven was supported by the Scottish Government RESAS Project and by the Natural Environment Research Council (NERC) award number NE/R016429/1 as part of the UK-SCAPE programme, which is delivering UK National Capability and as part of the RePhoKUs project funded by BBSRC, ESRC, NERC, and the Scottish Government under the UK Global Food Security research programme (Grant Nos. BB/R005842/1). The work on Lake Erhai was supported by the NERC funded SUNRISE programme (NE/R000131/1), which is a National Capability Long-Term Science – Official Development Assistance award.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Bryan M. Spears http://orcid.org/ 0000-0002-0876-0405

David P. Hamilton http://orcid.org/0000-0002-9341-8777

Linda May http://orcid.org/0000-0003-3385-9973

References

Abell JM, Hamilton DP. 2015. Biogeochemical processes and phytoplankton nutrient limitation in the inflow transition zone of a large eutrophic lake during a summer rain event. Ecohydrology. 8:243–262.

Beddington J. 2009. Food, energy, water and the climate: a perfect storm of global events? World Development. London, UK: Government Office for Science.

Brookes JD, Carey CC. 2011. Resilience to blooms. Science. 334:46–47.

Brownlie W, Spears BM, McDonald C, Roaf S, May L. 2014. Assessment of a novel development policy for the control of phosphorus losses from private sewage systems to the Loch Leven catchment, Scotland, UK. Environ Sci Policy. 38:207-216.

Birk S, Chapman D, Carvalho L, Spears BM, Andersen HE, Argillier C, Auer S, Baattrup-Pedersen A, Banin L, Beklioğlu M, et al. 2020. Impacts of multiple stressors on freshwater biota across spatial scales and ecosystems. Nat Ecol Evol. doi:10.1038/s41559-020-1216-4

Burger DF, Hamilton DP, Hall JA, Ryan EF. 2007. Phytoplankton nutrient limitation in a polymictic eutrophic lake: community versus species-specific responses. Fund Appl Limnol. 169:57–68.

Burger DF, Hamilton DP, Pilditch CA. 2008. Modelling the relative importance of internal and external nutrient loads on water column nutrient concentrations and phytoplankton biomass in a shallow polymictic lake. Ecol Model. 211:411–423.

Carss D, Spears BM, Quinn L Cooper R. 2012. Long-term variations in waterfowl populations in Loch Leven: identifying discontinuities between local and national trends. Hydrobiologia. 681:85-104.

Carpenter SR, Ludwig D, Brock WA. 1999. Management of eutrophication for lakes subject to potentially irreversible change. Ecol Appl. 9:751–771.

Carpenter SR, Lathrop RC. 2008. Probabilistic estimate of a threshold for eutrophication. Ecosyst. 11:601–613.

Carvalho L, Miller C, Spears BM, Gunn IDM, Bennion H, Kirika A, May L. 2012. Water quality of Loch Leven: responses to enrichment, restoration and climate change. Hydrobiologia. 681:35-47.

Carvalho L, Mackay E, Cardoso AC, Baatrtrup-Pedersen A, Birk S, Blackstock KL, Borics G, Borja A, Feld CK, Ferreira MT, et al. 2019. Protecting and restoring Europe's waters: an analysis of the future development needs of the Water Framework Directive. Sci Total Environ. 658:1228-1238.

Castle K, Frost CA, Flint DF. 1999. The Loch Leven Project – Buffer strips in practice on a catchment scale. Asp Appl Biol. 54:71-78.

Chen K, Li Y, Yang Y, Yang K. 2011. The simulation of land use type change in Erhai Basin based on agent based modeling. In: 2011 19th International Conference on Geoinformatics, Geoinformatics 2011, Shanghai, 2011.

Chester ET, Robson BJ. 2013. Anthropogenic refuges for freshwater biodiversity: their ecological characteristics and management. Biol Conserv. 166:64-75.

China Daily (2017) Businesses around tourist lake shut for inspections. http://europe.chinadaily.com.cn/china/2017-04/01/content_28764836.htm (accessed 1/4/17).

Chunmei L, Limin D. 2011. Research on the soil and water conservation division management mode in Erhai Lake Basin. In: 2011 4th International Conference on Intelligent Computation Technology and Automation, ICICTA 2011, Shenzhen, Guangdong, 2011. Vol 2; p. 158-161.

Clean Water Act. 1972. 2002. Federal Water Pollution Control Act 33 U.S.C. 1251 et seq. Available from: http://epw.senate.gov/water.pdf.

Crossman J, Futter MN, Oni SK, Whitehead PG, Jin L, Butterfield D, Baulch HM, Dillon PJ. 2013. Impacts of climate change on hydrology and water quality: future proofing management strategies in the Lake Simcoe watershed, Canada. J Great Lakes Res 39:19-32.

Damania R, Desbureaux S, Rodella AS, Russ J, Zaveri E. 2019. Quality Unknown: The Invisible Water Crisis. Washington, DC: World Bank. doi:10.1596/978-1-4648-1459-4.

D'Arcy BJ, May L, Long J, Fozzard IR, Greig S. Brachet A. 2006. The restoration of Loch Leven, Scotland, UK. Wat Sci Tech. 53:183- 191.

de Winton, MD, Champion PD, Clayton JS, Wells RDS. 2009. Spread and status of seven submerged pest plants in New Zealand lakes. New Zeal J Mar Fresh Res 43:547-561.

Dearing JA, Jones RT, Shen J, Yang X, Boyle JF, Foster GC, Crook DS, Elvin MJD. 2008. Using multiple archives to understand past and present climate-human-environment interactions: the lake Erhai catchment, Yunnan Province, China. J Paleolimnol. 40:3-31.

Dodds WK, Bouska WW, Eitzmann JL, Pilger TJ, Pitts KL, Riley AJ, Schloesser JT, Thornbrgh DJ. 2009. Eutrophication of U.S. freshwaters: analysis of potential economic damages. Environ Sci Tech. 43:12-19.

Dong YX, Li JJ, Zuo YF, Tang, J., Wei, Z. 2004. Current situation and treatment counter measures of water environment in Erhai Lake. Yunnan Environ Sci. 23:102-103.

Dong LM, Yang H. 2009. Model formulation for analyzing social structure, economic development and environmental protection in the Erhai Lake basin region. Proceedings for the 5th Euro-Asia Conference on Environment and Corporate Social Responsibility: Management Science and Engineering, Pt 1; p. 67-70.

Douglas G, Hamilton DP, Robb MS, Pan G, Spears BM, Lurling M. 2016. Guiding principles for the development and application of solid phase phosphorus-adsorbents for freshwater ecosystems. Aquat Ecol. 50:385-405.

Du B. 1992. Study on eutrophication of Erhai Lake. J Lake Sci. 4:86-92.

Dudley B, Gunn IDM, Carvalho L, Proctor I, O'Hare MT, Murphy KJ, Milligan A. 2012. Changes in aquatic macrophyte communities in Loch Leven: evidence of recovery from eutrophication? Hydrobiologia. 681:49-57.

European Parliament 2000. Directive of the European Parliament and of the Council 2000/60/EC establishing a framework for community action in the field of Water Policy. PE-CONS 3639/1/00; p. 72.

ECNS. 2017. Government to 'rescue' Erhai Lake. http://www.ecns.cn/2017/04-12/253088.shtml (accessed 12/7/19).

Elliott JA, Defew L. 2012. Modelling the response of phytoplankton in a shallow lake (Loch Leven, UK) to changes in lake retention time and water temperature. Hydrobiologia. 681:105-116.

Elliott JA, May L. 2008. The sensitivity of phytoplankton in Loch Leven (UK) to changes in nutrient load and water temperature. Freshwater Biol. 53:32-41.

Feld CK, Segurado P, Gutiérrez-Cánovas C. 2016. Analysing the impact of multiple stressors in aquatic biomonitoring data: A 'cookbook' with applications in R. Sci Tot Environ. 573:1320-1339.

Frost CA. 1996. Loch Leven and diffuse pollution. In: Petchey AM, D'Arcy BJ, Frost CA, editors. Diffuse pollution and agriculture. Aberdeen (Scotland): Scottish Agricultural College; p. 174-182.

Greig S. 2004. Trends in diffuse pollution: data report to assist with the design and implementation of effective diffuse pollution monitoring programmes. Diffuse Pollution Initiative Special Report. Scottish Environment Protection Agency; 25 pp.

Gunn IDM, O'Hare MT, Maitland PS, May L. 2012. Long-term trends in Loch Leven invertebrate communities. Hydrobiologia. 681:59-72.

Guo HC, Liu L, Huang GH, Fuller GA, Zou R, Yin YY. 2001. A system dynamics approach for regional environmental planning and management: A study for the Lake Erhai Basin. J Environ Manage. 61:93-111.

Hamilton DP, Dada, A. 2016. Lake management: A restoration perspective. In: Jellyman PG, Davie TLA, Pearson CP, Harding JS, editors. Advances in New Zealand Freshwater Sciences. Christchurch (New Zealand): New Zealand Freshwater Sciences Society and New Zealand Hydrological Society; p. 531-552.

Hamilton DP, McBride CG, Jones HFE. 2014. Assessing the effects of alum dosing of two Inflows to Lake Rotorua against external nutrient load reductions: Model simulations for 2001-2012. The University of Waikato (New Zealand). Environmental Research Institute Report 49; 56 pp.

Hamilton DP, Wood SA, Dietrich DR, Puddick J. 2014. Costs of harmful blooms of freshwater cyanobacteria. In: Sharma NK, Rai AK, Stal LJ, editors. Cyanobacteria. An Economic Perspective. Chichester (UK). John Wiley & Sons, Ltd; p. 245-256.

Hamilton DP, Salmaso N, Paerl HW. 2016a. Mitigating harmful cyanobacterial blooms: strategies for control of nitrogen and phosphorus loads. Aquatic Ecol. 50:351-366.

Hamilton DP, Collier KJ, Howard-Williams C. 2016b. Lake Restoration in New Zealand. Ecol Manag Restor. 17:191–199.

Han XX, Feng L, Chen XL, Yesou H. 2014. MERIS observations of chlorophyll-a dynamics in Erhai Lake between 2003 and 2009. Int J Remote Sens. 35:8309-8322.

Havens K, Pearl H, Phillips E, Zhu M, Beaver J, Srifa A. 2016. Extreme weather events and climate variability provide a lens to how shallow lakes may respond to climate change. Water. 8:229.

Howell CJ, Terry JA. 2016. The creation of a New Zealand weed atlas. Science for Conservation 328. Wellington (NZ). Department of Conservation; 21 pp.

Hu W, Wang Y, Chu Z. 2015. Reduction effect of non-point pollution in Erhai Lake Basin through sward buffer strips. Chinese J Environ Eng. 9:4138-4144.

Huser BJ, Egemose S, Harper H, Hupfer M, Jensen H, Pilgrim KM, Reitzel K, Rydin E, Futter M. 2016. Longevity and effectiveness of aluminium addition to reduce sediment phosphorus release and restore lake water quality. Water Res 97:122-132.

IPCC. 2014. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker TF, editor. Cambridge (UK). Cambridge University Press.

Jeppesen E, Søndergaard M, Jensen JP, Havens K, Anneville O, Carvalho L, Coveney MF, Deneke R, Dokulil MT, Foy B, et al. 2005. Lake responses to reduced nutrient loading – an analysis of contemporary long-term data from 35 case studies. Freshwater Biol. 50:1747-1771.

Julius SH, West JM, Blate GM, Baron JS, Joyce LA, Kareiva P, Keller BD, Palmer MA, Peterson CH, Scott JM. 2008. Executive Summary. In: Julius SH, West JM, editors. Preliminary review of adaptation options for climate-sensitive ecosystems and resources. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research. Washington DC (USA); pp. 1-1 to 1-6.

Kusabs IA, Quinn JM. 2009. Use of a traditional Maori harvesting method, the tau koura, for monitoring ko-ura (freshwater crayfish, *Paranephrops planifrons*) in Lake Rotoiti, North Island, New Zealand. New Zeal J Mar Fresh. 43:713-722.

Lee RY, Seitzinger S, Mayorga E. 2016. Land-based nutrient loading to LMEs: a global watershed perspective on magnitudes and sources. Environ Dev. 17:220-229.

Lehmann MK, Hamilton DP. 2018. Modelling water quality to support lake restoration. In: Hamilton D, Collier K, Quinn J, Howard-Williams C, editors. Cham (Switzerland). Lake Restoration Handbook. Springer; p. 67-105.

Li W, Cao T, Zhang X, Duan H, Fu H, Song X, Ni L. 2015. Interspecific and seasonal variations of phosphorus content in submersed macrophytes in Erhai Lake. Res Environ Sci. 28:877-882.

Li Y, Xie P, Zhao D, Zhu T, Guo L, Zhang J. 2016. Eutrophication strengthens the response of zooplankton to temperature changes in a high-altitude lake. Ecol Evol. 6:6690-6701.

Li W, Zhong J, Yuan G, Fu H, Fan H, Ni L, Xie P, Cao T. 2017. Stoichiometric characteristics of four submersed macrophytes in three plateau lakes with contrasting trophic statuses. Ecol Eng. 99:265-270.

Liu WH, Zhang CG, Gao PF, Liu H, Song YQ, Huang BS, Yang JF. 2015. Construction of Water Environment Carrying Capacity Evaluation Model in Erhai River Basin. Adv Soc Sci, Educ Hum Research. 38:247-250.

LLCMP. 1999. Loch Leven Catchment Management Plan. Report of the Loch Leven Area Management Advisory Group; 93 pp.

Mackay E, Maberly SC, Pan G, Reitzel K, Bruere A, Corker N, Douglas G, Egemose S, Hamilton D, Hatton-Ellis T, et al. 2014 Geo-engineering in lakes: welcome attraction or fatal distraction? Inland Wat. 4:349-356.

May L, Carvalho L. 2010 Maximum growing depth of macrophytes in Loch Leven, Scotland, United Kingdom, in relation to historical changes in estimated phosphorus loading. Hydrobiologia. 646:123-131.

May L, Defew L, Bennion H, Spears B. 2012. Historical changes (1905-2005) in the external phosphorus loads to Loch Leven, Scotland, UK. Hydrobiologia. 681:11-12.

May L, Moore A, Woods H, Bowes M, Watt J, Taylor P, Pickard A. 2017. Loch Leven nutrient load and source apportionment study. Scottish Natural Heritage Commissioned Report No. 962; 65 pp.

May L, Spears BM. 2012. A history of scientific research at Loch Leven, Kinross, Scotland. Hydrobiologia. 681:3-9.

May L, Spears B. 2012. Loch Leven: 40 years of scientific research. Understanding the links between pollution, climate change and ecological response. Dev Hydrobiol 218: 130 pp.

Me W, Hamilton DP, McBride CG, Abell JM, Hicks BJ. 2019. Modelling hydrology and water quality in a mixed land use catchment and eutrophic lake: Effects of nutrient load reductions and climate change. Environ Model Softw. 109:114-133.

Michel-Kernan E. 2012. How resilient is your country. Nature 491:497.

Ministry for the Environment. 2014. National Policy Statement for Freshwater Management. Wellington (NZ). Ministry for the Environment.

Mueller H, Hamilton DP, Doole GJ. 2015. Response lags and environmental dynamics of restoration efforts for Lake Rotorua, New Zealand. Environ Res Lett. 10:074003

Mueller H, Hamilton DP, Doole GJ. 2016. Evaluating services and damage costs of degradation of a major lake ecosystem. Ecosys Serv 22:370-380.

Mueller H, Hamilton D, Doole G, Abell J, McBride C. 2019. Economic and ecosystem costs and benefits of alternative land use and management scenarios in the Lake Rotorua, New Zealand, catchment. Global Environmental Change 54:102-112.

Morgenstern U, Daughney CJ, Leonard G, Gordon D, Donath FM, Reeves R. 2015. Using groundwater age and hydrochemistry to understand sources and dynamics of nutrient contamination through the catchment into Lake Rotorua, New Zealand. Hydrol Earth Sys Sci. 19:803- 822.

Moss B, Kosten S, Meerhof M, Battarbee R, Jeppesen E, Mazzeo N, Havens K, Lacerot G, Liu Z, de Meester L, Paerl H, Scheffer M. 2011. Allied attack: climate change and eutrophication. Inland Wat. 1:101-105.

Nakicenovic N, Alcamo J, Davis G, de Vries B, Fenhann J, Gaffin S, Gregory K, Grübler A, Yong Jung T, Kram T, et al. 2000. IPCC Special Report on Emission Scenarios. Cambridge (UK). University Press.

O'Reilly CM, Sharma S, Gray DK, Hampton SE, Read JS, Rowley RJ, Schneider P, Lenters JD, McIntyre PB, Kraemer BM, et al. 2015. Rapid and highly variable warming of lake surface waters around the globe, Geophys Res Lett. 42:10773-10781.

Osgood RA. 2017. Inadequacy of best management practices for restoring eutrophic lakes in the United States: Guidance for policy and practice. Inland Wat. 7:401-407.

Özkundakci D, McBride CG, Hamilton DP. 2012. Parameterisation of sediment geochemistry for simulating water quality responses to long-term catchment and climate changes in Polymictic, eutrophic Lake Rotorua, New Zealand. WIT Trans Ecol Environ. 164:171-182.

Paerl HW, Gardner WS, Havens KE, Joyner AR, McCarthy MJ, Newell SE, Qin B, Scott JT. 2016. Mitigating cyanobacterial harmful algal blooms in aquatic ecosystems impacted by climate change and anthropogenic nutrients. Harmful Algae. 54:213-222.

Palliser, CC, Rutherford JC, MacCormick A. 2019. Eutrophication in Lake Rotorua. 1. Using OVERSEER to estimate historic nitrogen loads. New Zeal J Mar Fresh Res. 62:112-129.

Peryer-Fursdon J, Abell JM, Clarke D, Özkundakci D, Hamilton DP, Pearson L. 2015. Spatial variability in sediment phosphorus characteristics along a hydrological gradient upstream of Lake Rotorua, New Zealand. Environ Earth Sci. 73:1573–1585.

Peters JA, Lodge DM. 2013. Habitat, predation, and coexistence between invasive and native crayfish: prioritizing lakes for invasion prevention. Hydrobiologia. 15:2849-2502.

Phillips G, Kelly A, Pitt J-A, Spears BM. 2019. Barton Broad, UK: over 40 years of phosphorus dynamics in a shallow lake subject to catchment load reduction and sediment removal.

In: Steinman AD, Spears BM, editors. Internal phosphorus loading: Causes, case studies, and management. Plantation, Florida (USA). J. Ross Publishing.

Piggott JJ, Townsend CR, Matthaei CD. 2015. Reconceptualizing synergism and antagonism among multiple stressors. Ecol Evol. 5:1538-1547.

Rowe DK. 2007. Exotic fish introductions and the decline of water clarity in small North Island, New Zealand lakes: a multi-species problem. Hydrobiologia. 583:345-358.

Rutherford JC, Dunmov SM, Ross AH. 1996. Predictions of phosphorus in Lake Rotorua following load reductions. New Zeal J Mar Fresh. 30:383-386.

ScotInform 2015. Loch Leven Heritage Trail. Visitor Survey 2014/15. Edinburgh (UK). ScotInform Ltd; 57 pp.

Shaoming W. 1997. Multi-objective water quality planning for the Lake Erhai watershed. Masters, Faculty of Engineering, University of Regina, Saskatchewan, Canada.

Sharpley A, Jarvie HP, Buda A, May L, Spears BM, Kleinman P. 2013. Phosphorus Legacy: Overcoming the Effects of Past Management Practices to Mitigate Future Water Quality Impairment. J Environ Qual. 42:1308-1326.

Scheffer M. 2009. Critical transitions in nature and society. New Jersey (USA). Princeton University Press; 384 pp.

Scheffer M, Carpenter S, Dakos V, van Nes EH (2015). Generic indicators of ecological resilience: Inferring the chance of a critical transition. Annu Rev Ecol Evol Syst 46:145–167.

Scottish Natural Heritage. 2016. The management plan for Loch Leven National Nature Reserve, 2016-2026. Draft for Consultation. Scottish Natural Heritage, The Pier, Loch Leven, Kinross, UK.

Smith VH, Wood SA, McBride CG, Atalah J, Hamilton DP, Abell J. 2016. Phosphorus and nitrogen loading restraints are essential for successful eutrophication control of Lake Rotorua, New Zealand. Inland Wat. 6:273-283.

Søndergaard M, Jeppesen E, Lauridsen TL, Skov C, Van Nes EH, Roijackers R, Lammens E, Potielje R. 2007. Lake restoration: successes, failures and long-term effects. J Appl Ecol. 44: 1095-1105.

Spears BM, Carvalho L, Perkins R, Kirika A, Paterson DM. 2012. Long-term variation and regulation of internal phosphorus loading in Loch Leven. Hydrobiologia. 681:23-33.

Spears BM, Chapman D, Carvalho L, Rankinen K, Stefanidis K, Ives S, Vuorio K, Birk S, 2021. Assessing multiple stressor effects to inform climate change management responses in three European catchments. Inland Water. This issue.

Spears BM, Ives SC, Angeler DG, Allen CR, Birk S, Carvalho L, Cavers S, Daunt F, Morton RD, Pocock MJO, et al. 2015. Effective management of ecological resilience – are we there yet? J Appl Ecol. 52:1311-1313.

Spears BM, Ives S, May L. 2019. Loch Leven, UK: Long-term (1985 to 2016) phosphorus dynamics in a shallow lake and its implications for water quality management. In: Steinman AD, Spears BM, editors. Internal phosphorus loading: Causes, case studies, and management. Plantation, Florida (USA). J. Ross Publishing.

Stafford DM. 1994. Landmarks of Te Arawa. Volume 1: Rotorua. Auckland (NZ). Reed Books; 197 pp.

Tang JF, Ye SW, Li W, Liu JS, Zhang TL, Guo ZQ, Zhu FY, Li ZL. 2013. Status and historical changes in the fish community in Erhai Lake. Chin J Oceanol Limnol. 31:712-723.

Marine and Research United Nations Office for Disaster Risk Reduction [UNISDR]. 2015. Sendai framework for risk reduction, 2015-2030UNISDR/GE/2015 - ICLUX EN5000 1st edition. 9-11 Rue de Varembé, Geneva Switzerland.

Walsh JR, Carpenter SR, Vander Zanden MJ. 2016. Invasive species triggers a massive loss of ecosystem services through a trophic cascade. PNAS. 113:4081-4085.

Wang S, Wang J, Li M, Du F, Yang Y, Lassoie JP, Hassan MZ. 2013. Six decades of changes in vascular hydrophyte and fish species in three plateau lakes in Yunnan, China. Biodiv Conserv. 22:3197-3221.

Wang SR, Zhang L, Ni LY, Zhao HC, Jiao LX, Yang SW, Guo LG, Shen JZ. 2015. Ecological degeneration of the Erhai Lake and prevention measures. Env Earth Sci. 74:3839-3847.

Wells RDS, Clayton JS. 1991. Submerged vegetation and spread of *Egeria densa* Planchon in Lake Rotorua, central North Island, New Zealand. New Zeal J Mar Fresh. 25:63-70.

White E, Law K, Payne G, Pickmere S. 1985. Nutrient demand and availability among planktonic communities - an attempt to assess nutrient limitation to plant growth in 12 central volcanic plateau lakes. New Zeal J Mar Fresh 19:49–62.

White E, Payne GW. 1978. Chlorophyll production, in response to nutrient additions, by the algae in Lake Rotorua water. New Zeal J Mar Fresh. 12:131–138.

Winfield IJ, Adams C, Armstrong JD, Gardiner R, Kirika A, Montgomery J, Spears BM, Stewart DC, Thorpe JE, Wilson W. 2012. Changes in the fish community of Loch Leven: untangling anthropogenic pressures. Hydrobiologia. 681:73-84.

Winfield IJ, Fletcher JM, James JB. 2004. Conservation ecology of the vendace (*Coregonous albula*) in Bassenthwaite Lake and Derwent Water, UK. Annales Zoologici Fennici. 41:155-164.

Yu GL, Jiang YG, Song GF, Tan WH, Zhu ML, Li RH. 2014. Variation of *Microcystis* and microcystins coupling nitrogen and phosphorus nutrients in Lake Erhai, a drinking-water source in Southwest Plateau, China. Env Sci Poll Res. 21:9887-9898.

Zhu TS, Cao T, Ni Y, Ni L, He L, Yi CL, Yuan CB, Xie P. 2016. Improvement of water quality by sediment capping and re-vegetation with *Vallisneria natans* L.: A short-term investigation using an in situ enclosure experiment in Lake Erhai, China. Ecol Eng. 86:113-119.

Figure 1. Proportional surface area of 19,054 lakes reported on by 24 European countries with responsibility for meeting ecological water quality targets under the European Water Framework Directive. The reported status classes are shown; these are based on common assessment and reporting procedures. In 2003, 31,887 km^2 of lakes within the remit of the EU Water Framework Directive were found to need restorative measures to enable them to meet required ecological quality standards. Another 37,153 km^2 were deemed to have acceptable levels of degradation, making them highly sensitive to further pressures, and 11,842 km^2 were classified as relatively unimpacted. Raw data and guidance on status class boundaries and their determination are available from: www.eea.europa.eu/data-and-maps/data/wise_wfd (data collated following access 27/02/2013). AT - Austria; BE – Belgium; BG - Bulgaria; CY – Cyprus; CZ – Czech Republic; DE - Germany; DK – Denmark; EE - Estonia; EL – Greece; ES – Spain; FI – Finland; FR – France; HU – Hungary; IE – Ireland; IT – Italy; LT – Lithuania; LV – Latvia; NL – Netherlands; PL – Poland; PT – Portugal; RO – Romania; SE – Sweden; SI – Switzerland; UK – United Kingdom.

Figure 2. Flow diagrams indicating a 'future world' for each lake case study in 2050 if no mitigation measures are implemented. Relationships between drivers of change, environmental stressors, ecological responses and ecosystem service responses are shown. The format of each arrow indicates the level of confidence reported in the relationships, as determined by experts in each case study after reviewing the relevant literature. Solid lines indicate 'high confidence' relationships that have been quantified statistically and modelled; medium dashed arrows indicate 'moderate confidence' relationships, based on correlation analysis or the interpretation of observational data; short dashed lines indicate 'low confidence' relationships based on inference or relationships from other study sites. Lake typology data are shown for Loch Leven (May et al. 2012), Lake Rotorua (Burger et al. 2008) and Lake Erhai (Dearing et al. 2008, Li et al. 2016).

Table 1. Summary of responses from experts on planned or active measures for each lake designed to mitigate future anthropogenic environmental change assessed to pose a threat to service delivery, as outlined in Figure 2. The implementation status of each measure is listed along with the scale of implementation, the time scales to completion of implementation and the strength of the scientific evidence base on effectiveness of the measure to result in 'no-change' or an improvement in service delivery.

Mitigation measure	Planned or active	Scale of implement-ation	Years to implement-ation	Strength of evidence of effectiveness
Loch Leven				
Install buffer strips	Active	Local	5	Moderate
Reduce fertiliser application rates	Active	Regional/ National	5	Moderate
Install soil retention barriers	Planned	Local	5	High
Reduce phosphorus load from rural developments	Active	Local/ Regional	10	Low
Lake Rotorua				
Continuous alum dosing of inlet(s) to reduce P load	Active	Local	Continuous	High
Reduce catchment load of total nitrogen by 250 t yr^{-1}	Active	Regional	12	High
Comply with National Objectives Framework – National Policy Statement for Freshwater Management	Planned	National	12	Moderate
Upgrade wastewater treatment plant	Planned	Local	5	Moderate

Lake Erhai				
Install buffer strips	Planned	Regional	2	Moderate
Implement sustainable fisheries policy	Planned	Regional	10	Moderate
Reduce nutrient and industrial pollution	Planned	Regional	1	High
Develop sustainable economy, e.g., ecotourism	Active	Regional	20	Moderate

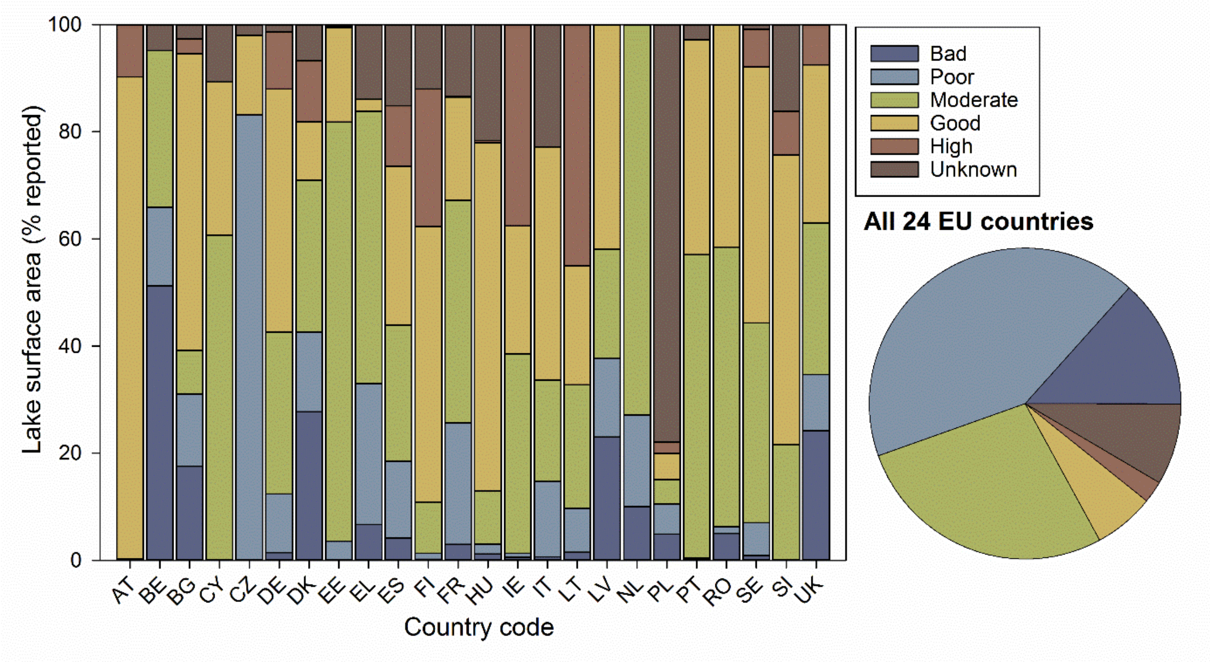
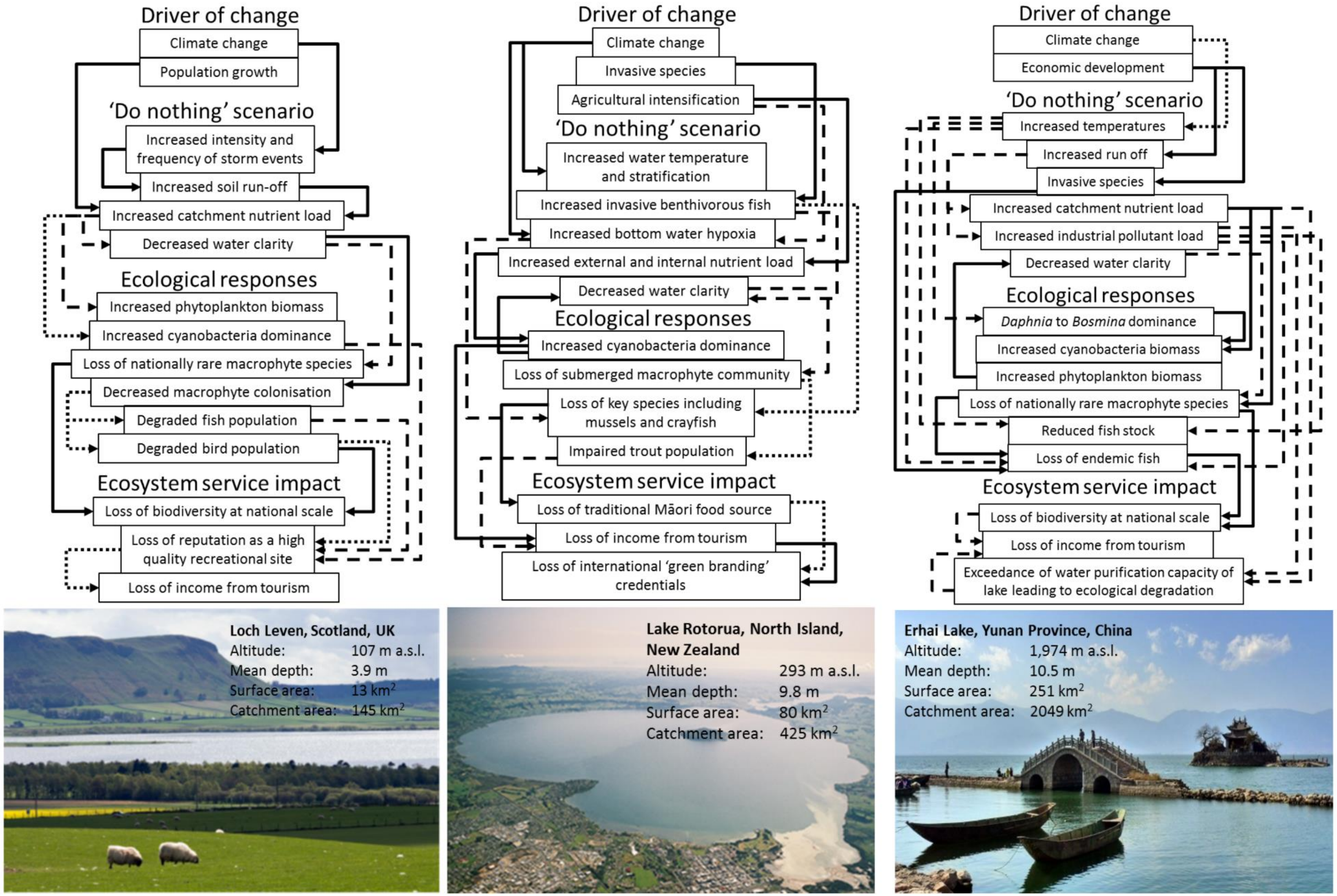


Fig. 1.


Driver of change
Climate change
Population growth
'Do nothing' scenario
Increased intensity and frequency of storm events
Increased soil run-off
Increased catchment nutrient load
Decreased water clarity
Ecological responses
Increased phytoplankton biomass
Increased cyanobacteria dominance
Loss of nationally rare macrophyte species
Decreased macrophyte colonisation
Degraded fish population
Degraded bird population
Ecosystem service impact
Loss of biodiversity at national scale
Loss of reputation as a high quality recreational site
Loss of income from tourism
Driver of change
Climate change
Invasive species
Agricultural intensification
'Do nothing' scenario
Increased water temperature and stratification
Increased invasive benthivorous fish
Increased bottom water hypoxia
Increased external and internal nutrient load
Decreased water clarity
Ecological responses
Increased cyanobacteria dominance
Loss of submerged macrophyte community
Loss of key species including mussels and crayfish
Impaired trout population
Ecosystem service impact
Loss of traditional Māori food source
Loss of income from tourism
Loss of international 'green branding' credentials
Driver of change
Climate change
Economic development
'Do nothing' scenario
Increased temperatures
Increased run off
Invasive species
Increased catchment nutrient load
Increased industrial pollutant load
Decreased water clarity
Ecological responses
Daphnia to Bosmina dominance
Increased cyanobacteria biomass
Increased phytoplankton biomass
Loss of nationally rare macrophyte species
Reduced fish stock
Loss of endemic fish
Ecosystem service impact
Loss of biodiversity at national scale
Loss of income from tourism
Exceedance of water purification capacity of lake leading to ecological degradation
Loch Leven, Scotland, UK
Altitude: 107 m a.s.l.
Mean depth: 3.9 m
Surface area: 13 km2
Catchment area: 145 km2
Lake Rotorua, North Island, New Zealand
Altitude: 293 m a.s.l.
Mean depth: 9.8 m
Surface area: 80 km2
Catchment area: 425 km2
Erhai Lake, Yunan Province, China
Altitude: 1,974 m a.s.l.
Mean depth: 10.5 m
Surface area: 251 km2
Catchment area: 2049 km2