FRESHWATER BIOLOGICAL ASSOCIATION

Windermere Integrated Science Plan (WISP)

Report to the Environment Agency

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Context

The Love Windermere partnership was formed in 2022 and originally comprised 10 partner organisations, each with a stake in Windermere, whether that be scientific, cultural and/or economical. The partnership currently comprises the Environment Agency, Lake District National Park Authority, Lake District Foundation, National Trust, South Cumbria Rivers Trust, National Farmers Union, Westmorland and Furness Council, United Utilities and Cumbria Local Enterprise Partnership.

The partnership aims to take a scientific and evidence-based approach to better understand the complex and interdependent pressures facing Windermere and prioritise effective solutions to improve the condition of the lake. The partnership operates as seven workstreams.

The Data, Science & Evidence workstream (led by the Freshwater Biological Association from 2022 to 2024) is continuing to build and maintain the evidence base for the current state of the Windermere catchment. This involves identifying the gaps in knowledge and setting monitoring and research priorities to help support and direct future collaborative work activity.

The Long-term Management Plan workstream (led by the Environment Agency) is engaging with stakeholders and the public as well as using the available science to create a long-term management plan for Windermere and the wider Leven catchment. This plan will include a suite of collaborative projects that aim to address the overarching issue of nutrient enrichment in the catchment, tackling the multiple sources. The plan will focus on strategic future activity, collaborative working and ensure long term funding.

The Mains Drainage workstream (led by United Utilities) is considering ways to improve wastewater treatment in the Leven catchment and will focus on the delivery of £41 million of investment from 2023 to 2030 to reduce spills from four assets in the area (Ambleside WwTW storm overflow, Near Sawrey WwTW storm overflow, Elterwater Pumping Station, and Hawkshead Pumping Station).

The Non-mains Drainage workstream (led by South Cumbria Rivers Trust) complements the Environment Agency's regulatory work on permitted sites and incident reports within the catchment by ensuring all non-mains drainage systems, such as private septic tanks or package treatment plants, are being operated effectively by owners under the General Binding Rules. The workstream will develop local advice and guidance, including details of new and innovative practices that enhance performance and reduce phosphorus inputs of non-mains drainage systems into watercourses.

The Land Management workstream (led by the Lake District National Park Authority) is helping to collate evidence for the current state of the Windermere catchment as it relates to land management. This will improve collective understanding of dissolved phosphorus pollution and help develop a suite of interventions for the farming community and other land managers that further reduces phosphate run-off into the catchment.

The Sustainable Future Finance workstream (led by the Lake District Foundation) is developing a sustainable economic model that drives investment and funding into Windermere and its catchment, to support the delivery of the long-term management plan for the lake.

The Love Windermere partnership is required to publish scientific or other information obtained as part of its activities. In fulfilment of this requirement, the partnership will endeavour to publish a quinquennial State of Windermere report which is designed to disseminate the findings and activities of the workstreams. This is a working document which may evolve with the findings of and changes to a particular workstream.

Executive summary

The 'State of Windermere in 2024' report (Harper, 2024) provides a comprehensive overview of the current ecological status of Windermere and how it has changed in response to anthropogenic and environmental pressures over time using information collected over the last nine decades.

A number of activities are ongoing to improve and understand lake health, from scientific monitoring and research to practical conservation and restoration to improvements to wastewater treatment. However, no single organisation has the responsibility or legislative power to fund and coordinate lake management and restoration, and there have been no lasting stakeholder partnerships. The resident and visitor populations are the biggest end users of the ecosystem services generated by Windermere and its catchment. As such, they share stakeholder responsibility and should be included in consultations about and delivery of lake monitoring and management.

The Love Windermere partnership tasked the Data, Science & Evidence (DSE) workstream with constructing an integrated science plan for Windermere and the wider Leven catchment. The DSE workstream is a collaboration of regulatory authorities, scientific non-governmental organisations, private businesses and academics operating within the Leven catchment. The main purpose of the Windermere Integrated Science Plan (WISP) is to identify the monitoring and research needs to address key uncertainties and information gaps that challenge stakeholders (including commercial operators, regulatory agencies, communities and recreational users) working in the Leven catchment based on an assessment of the issues Windermere faces.

This document presents the results of these efforts to organise and describe the scientific evidence needed to inform adaptive management to maintain and improve conditions in Windermere and the wider Leven catchment. Partners and collaborators also have their own organisational goals, projects and activities that will contribute or run parallel to this science plan, including routine and regulatory monitoring, modelling and digital development, improvements to infrastructure, citizen science, volunteer projects, advocacy and education work, and on-the-ground delivery programmes.

In most cases, the Leven catchment (excluding the River Leven downstream of Newby Bridge to Morecambe Bay, already the focus of the local Catchment Based Approach group coordinated by South Cumbria Rivers Trust) encompasses the entire geographic scope of this science plan, but where appropriate, the scope is broadened to consider factors (e.g. climate change) that can influence conditions or future management within the catchment.

Available data were synthesised to identify knowledge gaps across the theme areas of water quality, climate, people and monitoring, and establish aims with near-term and longer-term objectives that would coordinate and guide stakeholder efforts for

collective lake benefits in the future. The aims call for: 1) improved water quality through identification and reduction of nutrient inputs, enhanced biological monitoring, and improved awareness of and testing for bathing water quality, 2) increased understanding of the impacts of climate change, adaptation solutions, and forecasting capability, 3) better understanding of the impacts of tourism and recreation on the biology and water chemistry of the lake, and 4) continuation of existing monitoring and expanding the spatial coverage of monitoring efforts. Achievement of these goals is predicated on making progress towards 13 near-term (<5 year) objectives aimed at maintenance then sustainable improvement of conditions in Windermere and the wider Leven catchment. These objectives are intended to address knowledge gaps, ensure suitable environmental conditions and habitats for ecosystem functioning and resilience, increase scientific understanding, and identify solutions.

The Love Windermere partnership will use several strategies, including position statements (which serve to inform other stakeholders of lake management objectives), environmental objectives (which foster communication and coordination among multiple stakeholders), and habitat restoration (targeted projects that directly benefit the lake or surrounding catchment in some way) to deliver these objectives.

Emerging issues relevant to the objectives include nutrient inputs (requiring identification of sources and their contribution before setting targets for reduction), faecal material inputs (requiring expanded testing for established and emerging pathogens), land use (requiring a better understanding of the impacts of agriculture and forestry operations on sediment, nutrient and bacterial inputs), invasive non-native species (requiring a better understanding of distribution, abundance and impacts on native species as well as potential for eradication), and climate change (requiring a better understanding of its effects and forecasting of events).

A better scientific understanding is needed of Windermere's integrated response to water quality pressures, especially nutrient concentrations, ecological pressures and the ongoing impacts of climate change (e.g. temperature increase, rainfall patterns and water retention time) in order to guide future management and restoration. Any management and restoration of the lake must consider pressures jointly and the combined impacts they may have on the lake. Tackling these issues in isolation may not improve water quality sufficiently to protect the future overall condition of Windermere. A comprehensive approach based on evidence is needed.

Management and restoration action is needed to maintain the status quo but will need to go further to achieve improvement, including addressing emerging issues. For example, even greater reduction of nutrient concentrations is needed to address this pressure and counter the added effects of climate change. Stricter land management practices may be needed, especially where these will involve riparian zones which help buffer nutrient and faecal material inputs to the lake.

Lakes like Windermere are very "patchy" – conditions change a lot with depth, across the lake surface, around the lake shoreline, and over time. Therefore, it is important to take a large-scale and multi-season view of water quality over the long-term. Long-term data on the lake's biology and water chemistry are key to provide evidence-based solutions to nutrient and faecal material inputs, tourism and its impacts (e.g. pressure on wastewater system, pollution, disturbance to wildlife), and climate change (and associated weather patterns).

Priorities for the next five years are:

- Stakeholders should aim to produce a more accurate nutrient budget, including establishing the internal phosphorus load, how much this contributes to total load, and the rate of phosphorus release from the sediment. The benefits when nutrients from a given source are reduced by a certain amount need to be articulated to local communities and businesses to inspire others to take action in their personal lives
- A contemporary biological baseline for Windermere and the wider Leven catchment needs to be established, taking a whole food web approach. Routine biological monitoring should be implemented and consistently resourced. Systematic monitoring for algal blooms must be established to quantify changes in phytoplankton community composition and abundance of different species as well as timing, frequency, and intensity of bloom events over time.
- Stakeholders need to find out what water-users, especially outdoor swimmers, want to know. More communication and engagement activities are needed to educate residents and visitors on available data and information on bathing water quality as well as the potential risks of entering the water, and how these can be mitigated.
- Stakeholders should create a conceptual model of climate impacts on the lake and catchment, grounded in current evidence.
- Stakeholders should aim to understand public perception of the lake through a structured questionnaire and in-person events. More communication and engagement activities should occur to increase awareness on pressures and individual actions that can be taken.
- Existing monitoring should continue to maintain long-term data sets. Real-time phosphate monitors should be deployed across the catchment.

Several factors (e.g. changing stakeholder priorities, funding levels, and the emergence of new issues, new information, or new technologies) can influence the applicability of near-term research priorities. Therefore, the WISP should be considered as a living document. The research priorities will need to be reviewed and revised regularly to ensure they reflect the changing information needs and evolving priorities of stakeholders responsible for the health of Windermere.

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Abbreviations

AAFAF	Ambleside Action For A Future
AMP	Asset Management Plan
AONB	Area of Outstanding Natural Beauty
BWD	Bathing Water Directive
BWS	Big Windermere Survey
CiFR	Cumbria Innovative Flood Resilience
DSE	Data, Science & Evidence
EIDC	Environmental Information Data Centre
FBA	Freshwater Biological Association
INNS	Invasive non-native species
JNCC	Joint Nature Conservation Committee
LDNP	Lake District National Park
LDNPA	Lake District National Park Authority
NNR	National Nature Reserve
SAC	Special Area of Conservation
SAGIS	Source Apportionment Geographical Information System
SCRT	South Cumbria Rivers Trust
SPA	Special Protection Area
SSSI	Site of Special Scientific Interest
UKBAP	UK Biodiversity Action Plan
UKCEH	UK Centre for Ecology & Hydrology
UNESCO	United Nations Educational, Scientific and Cultural Organisation
UV	Ultraviolet
UWWTD	Urban Wastewater Treatment Directive
WFD	Water Framework Directive
WISP	Windermere Integrated Science Plan
WwTW	Wastewater treatment works

1. Overview

1.1. Introduction

Windermere is England's largest lake, situated in the Lake District National Park (LDNP), which is a United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site. The wider Leven catchment (Figure 1) contains Grasmere, Rydal Water, Loughrigg Tarn, Elterwater, Blelham Tarn and Esthwaite Water and several other tarns. The main inflows are the River Brathay and River Rothay (at the head of Windermere draining streams and small lakes, including Elterwater, Grasmere and Rydal Water), Trout Beck (which drains the northeast side of the catchment) and Cunsey Beck (which drains the Esthwaite Water sub-catchment). The outflow is the River Leven which discharges into Morecambe Bay via an estuary shared with the River Crake (which is the outflow from Coniston Water) (Maberly & McGowan 2022).

Windermere is small on a global scale, but one of the best studied lakes in the world with systematic records dating back to the 1930s, taken initially by the Freshwater Biological Association (FBA), then by the UK Centre for Ecology & Hydrology (UKCEH). Water chemistry and dynamics of phytoplankton, zooplankton and fish populations have been monitored. High-frequency, automatic monitoring buoys in the North Basin and South Basin of the lake provide hourly data on key parameters. More comprehensive water quality assessments are undertaken seasonally every 5 years. These data have provided insights into how the lake has responded to natural changes, human impacts and actions taken to improve it over seasons, years, and decades.

Windermere's sediment record reveals changes since the lake formed around 14,000 years ago, with human actions recognised for at least the last 5,000 years (Figure 2) through deforestation, industry, farming, fisheries and urbanisation (Maberly & McGowan, 2022). Impacts increased in recent centuries and especially after the middle of the 19th Century. The landscape in which Windermere is situated has undergone a series of substantial changes over the last two centuries, including changes in agriculture and forestry practices as well as growth in tourism and recreation after the railway arrived in 1847 leading to the expansion of the major settlements (McGowan *et al.*, 2012). Tourism now underpins the economy of the central Lake District, with an estimated 7 million visitors (based on 2019 data) to Windermere and its catchment annually (Tate, 2021), increasing inputs to the wastewater system. As a result, nutrient enrichment of Windermere has been occurring for almost 200 years (McGowan *et al.*, 2012), but accelerated in the 1960s due to the growing human population and the centralisation of wastewater treatment (Pickering, 2001) as well as other sources such as a fish farm established on Esthwaite Water in 1981 (George, 2012). The increased availability of nutrients, combined with warmer temperatures driven by climate change, resulted in higher frequency and intensity of potentially harmful algal blooms at the surface and associated oxygen depletion at depth due to decomposing algae (Pickering, 2001).

This threatened the health of people, pets, livestock and wildlife (Winfield *et al.*, 2008).

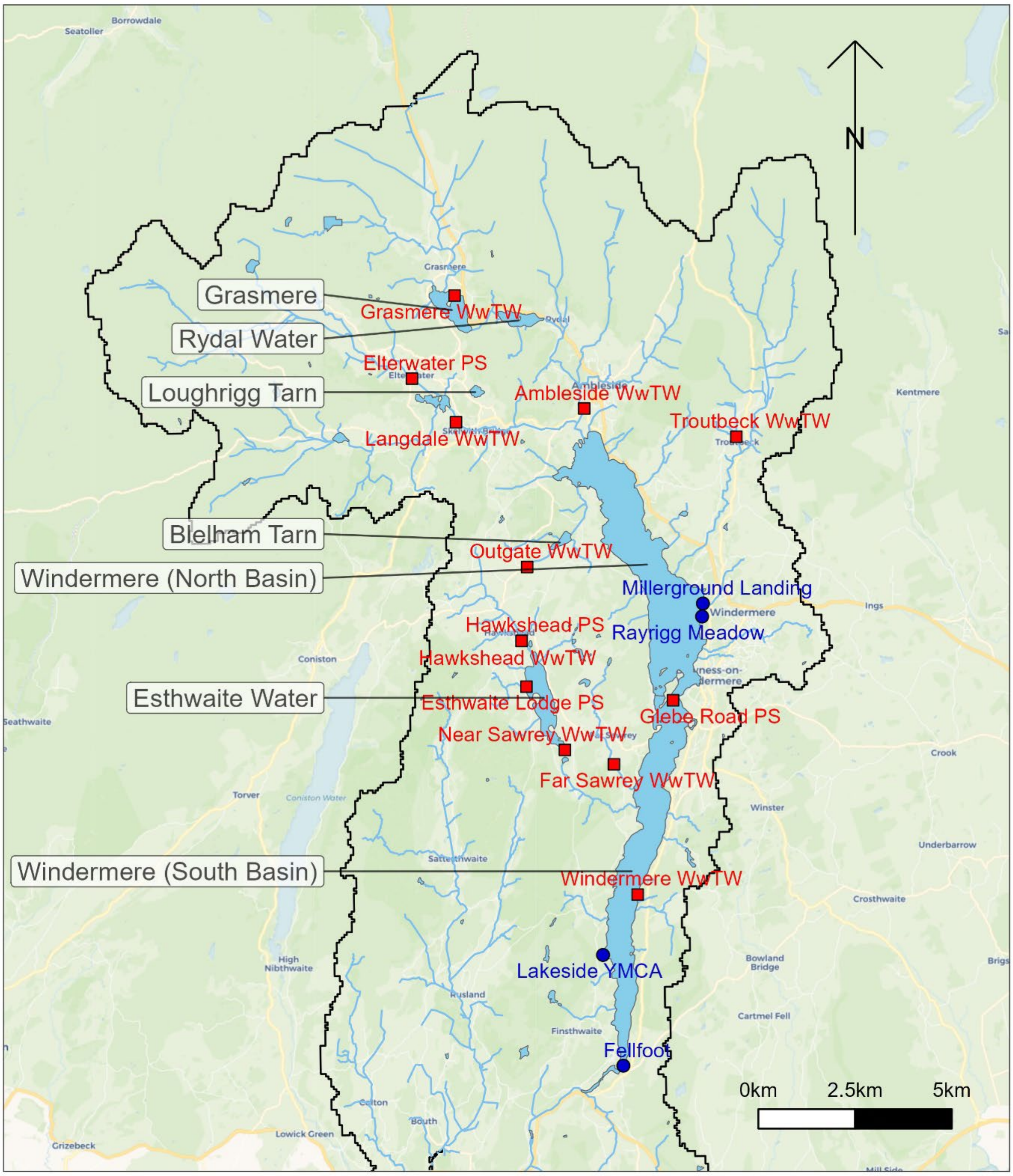

Figure 1. Map of the Leven catchment *with wastewater treatment works (WwTW) and pumping stations (PS) denoted in red, and designated bathing waters denoted in blue.*

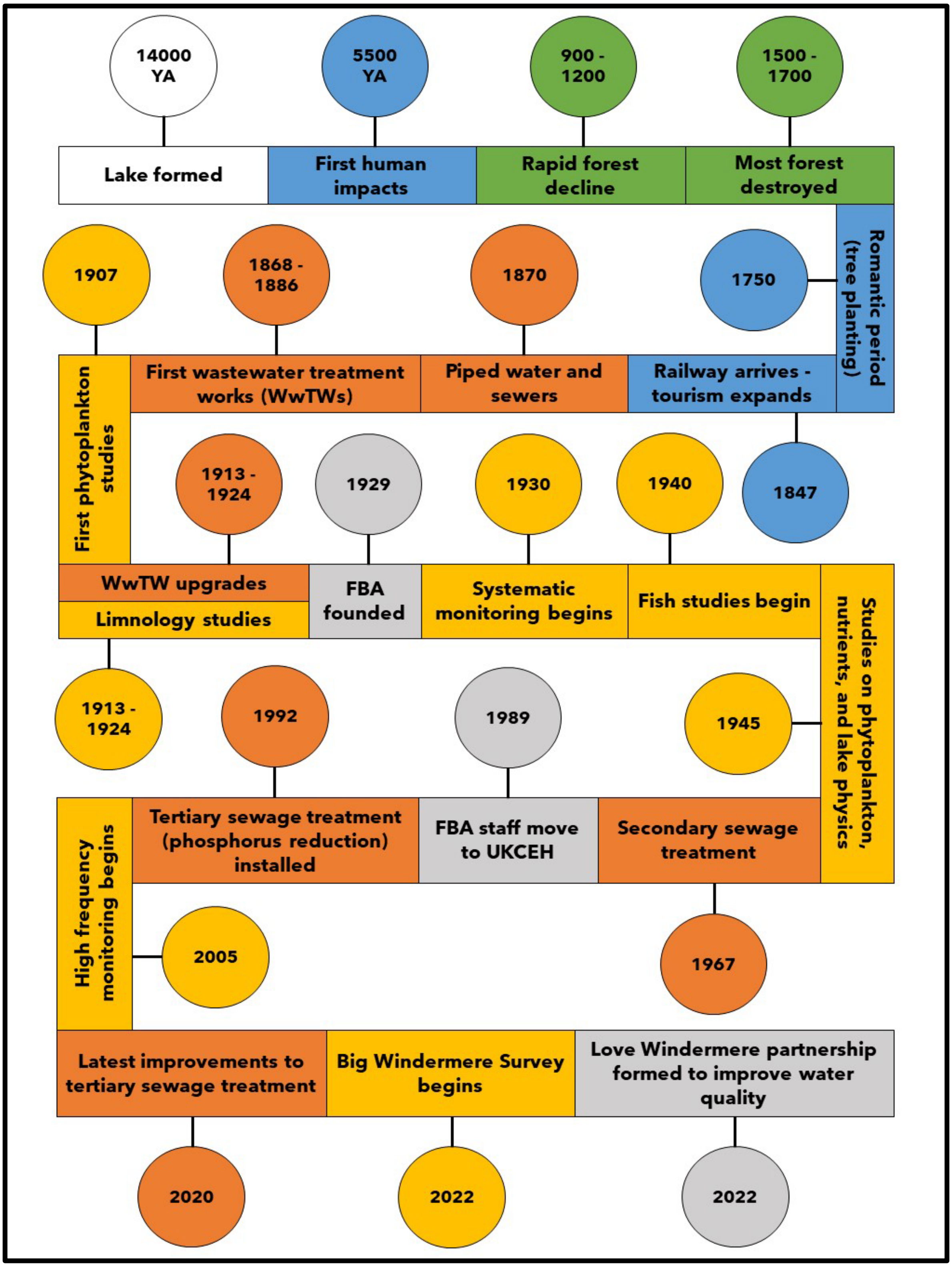

Figure 2. Timeline of events in and around Windermere *(YA = years ago), modified from Maberly & McGowan (2022). Primary sewage treatment can involve screening, grit removal, and filtration/settlement to remove solids. Secondary sewage treatment involves sewage being exposed to bacteria and protozoa to break down organic content. Tertiary sewage treatment can involve phosphorus removal, filtration, and ultraviolet (UV) radiation. Currently, phosphorus removal is implemented at Tower Wood, Ambleside, Hawkshead, Langdale, Outgate and Grasmere WwTW. UV treatment is implemented at Tower Wood, Ambleside and Near Sawrey WwTW.*

Currently, there are nine wastewater treatment works (WwTW) within the Leven catchment, with five in the north and four in the south: Grasmere WwTW, Langdale WwTW, Ambleside WwTW, Troutbeck WwTW, Outgate WwTW, Hawkshead WwTW, Near Sawrey WwTW, Far Sawrey WwTW, and Tower Wood (or Windermere) WwTW. There are also four pumping stations (PS) which direct raw sewage and wastewater into pipes connected to a WwTW or other disposal site: Elterwater PS, Hawkshead PS, Esthwaite Lodge PS, and Glebe Road PS (Figure 1). Prior to the 1880s, raw sewage was discharged into Windermere. Ambleside WwTW opened in 1886 to treat wastewater entering the North Basin, with the installation of Grasmere and Langdale WwTW in the early 1970s. Wastewater entering the South Basin was initially treated at Beemire in 1888 then moved to Tower Wood WwTW in 1924 (McGowan *et al.*, 2012). The number of WwTW increased over time, with upgrades and extensions to meet the demands of a growing resident and tourist population (Pickering, 2001). The range of organic and inorganic compounds going down drains has also increased over time, especially with the introduction of detergents containing phosphates in the 1950s (McGowan *et al.*, 2012).

A major upgrade to wastewater treatment occurred in 1992 with the implementation of phosphorus removal technology at Ambleside and Tower Wood WwTW in response to scientific monitoring and advice (Pickering, 2001), which reduced winter soluble reactive phosphorus concentrations from their peak in the early 1990s to levels broadly equivalent to those occurring during the 1960s - 1970s (Figure 3). Phytoplankton chlorophyll *a* concentrations also decreased while the minimum oxygen concentration at depth increased (Maberly & McGowan, 2022). More recent UKCEH data from 2017 - 2021 indicates that minimum oxygen concentration at depth appears to be declining again despite an initial improvement after phosphorus removal began in 1992, especially in the North Basin, but winter soluble reactive phosphorus concentrations remain lower than the peak in the early 1990s. Algal biomass has increased in the North Basin but decreased in the South Basin. This highlights the complex nature of the issues in Windermere and indicates that multiple factors are driving oxygen depletion at depth in the lake. Human activities continue to pose the biggest threats to Windermere today, and can be broadly grouped as five main pressures: nutrient inputs, faecal material inputs, land use change, Invasive Non-Native Species (INNS), and climate change.

Nutrient inputs come from multiple sources (Wurtsbaugh *et al.*, 2019) which are summarised in the 2023 Source Apportionment GIS (SAGIS) model (Environment Agency, 2023). These sources include:

- Mains drainage (e.g. WwTW and storm overflows which are regulated and operate under certain permitted conditions).
- Non-mains drainage (e.g. septic tanks operating under General Binding Rules, and permitted septic tanks and package treatment plants).
- Misconnections (i.e. when wastewater is connected to a surface water drain and vice versa).

- Agricultural run-off (e.g. the use of fertilisers in agriculture can release both phosphorus and nitrogen into the environment).
- Household products (e.g. many laundry, dish and car soaps contain forms of phosphorus).
- Atmospheric deposition.
- Potentially lake sediment.

Use of phosphate-based detergents across the UK peaked in 1987 then declined before phosphate bans were introduced for laundry (but not dishwasher) detergents in 1993. Similarly, application of fertilisers containing phosphorus and nitrogen peaked between 1980 and 1990 then declined (Moorhouse *et al.*, 2014). Elevated levels of nutrients (specifically phosphorus and nitrogen) can influence the ecology and functioning of the lake as described above and detailed in section 2 of the State of Windermere report (Harper, 2024).

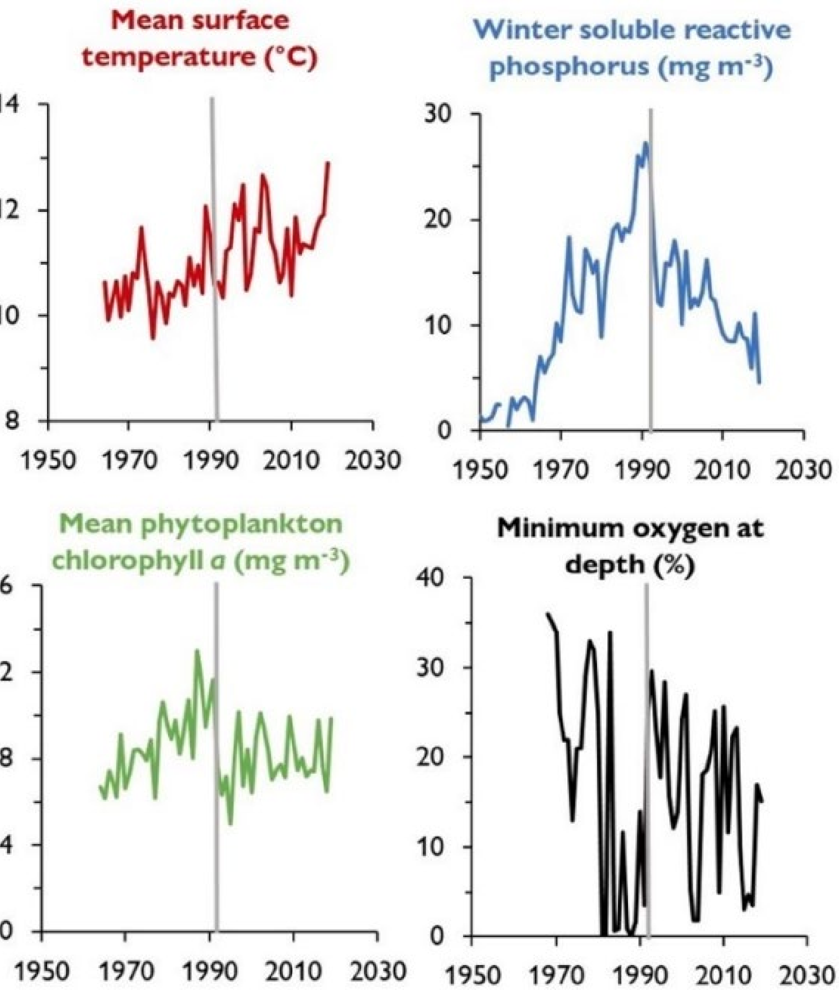

Figure 3. Changes in Windermere's South Basin over time. *The vertical grey line marks the implementation of phosphorus removal technology at Ambleside and Tower Wood WwTW. Reproduced with permission from Maberly & McGowan (2022).*

Faecal material inputs come from mains and non-mains drainage as well as misconnections, agricultural run-off, and wildlife. Elevated levels of faecal pathogens can also cause illness in animals, including humans. While microbiological water quality at designated bathing water sites on Windermere has consistently been classed as 'Excellent', a wider range of faecal pathogens that are present in Windermere as a result of animal husbandry via catchment runoff and wastewater are not assessed elsewhere in routine monitoring of water quality (Rhodes *et al.*, 2012).

Intensive historical land use, including agriculture and forestry operations, is another potential source of sediment, nutrient and bacterial inputs, detailed in section 2 of the State of Windermere report (Harper, 2024). Permanent grass and rough grazing became dominant after reductions in temporary grassland in 1881 and woodland cover in 1901. Arable farming represented 7.6% of land use in 1870 then declined to less than 3%, with further declines since 1961 (Moorhouse *et al.*, 2014). The extent that land use affects water quality depends largely on how the catchment is managed (McGowan *et al.*, 2012; Wurtsbaugh *et al.*, 2019). For example, a commercial fish farm for non-native rainbow trout (*Oncorhynchus mykiss*) was established on Esthwaite Water in 1981. The farm was estimated to produce approximately 100 tonnes of fish each year, with up to 300 kg of waste food and up to 300 kg of faeces (dry weight) introduced into the aquatic environment per tonne of rainbow trout produced (Grey *et al.*, 2004).

Invasive non-native species also affect the ecology of the lake. Roach (*Rutilus rutilus*) and ruffe (*Gymnocephalus cernua*) compete with Arctic charr (*Salvelinus alpinus*), removing zooplankton which eat algae, meaning that algae populations have fewer predators and restrictions on their growth (Maberly & Elliott, 2012). A number of invasive plant species are now present in the Leven catchment (e.g. Himalayan balsam *Impatiens glandulifera*, Japanese knotweed *Reynoutria japonica*, American skunk cabbage *Lysichiton americanus*, giant hogweed *Heracleum mantegazzianum*, and New Zealand pigmyweed *Crassula helmsii*) (Pickering, 2001), and Canada geese (*Branta canadensis*) are perceived to be a growing problem (Brides *et al.*, 2023).

Climate change affects the functioning of the lake directly through warming and weather patterns, but also indirectly by compounding the pressures mentioned above. UKCEH data show that the surface water temperature of the lake has increased by around 1.7°C over the past 70 years, which will alter the suitability of the lake for different plants and animals (Winfield *et al.*, 2008; Feuchtmayr *et al.*, 2012; Thackeray *et al.*, 2012, 2013; Ohlberger *et al.*, 2014), and favour the formation of algal blooms (Wurtsbaugh *et al.*, 2019). In addition, increased intensity of rainfall events associated with climate change accelerates the delivery of soil, nutrients and faecal bacteria from the lake's catchment (Barker *et al.*, 2005; Whitehead *et al.*, 2009). Expected and ongoing climate changes, such as extended periods of dry and wet weather affecting water quantity and quality, will make Windermere and other lakes much more sensitive to water quality decline than they were in the past (Whitehead *et al.*, 2009). These changes continually shift the historical baseline to which the lake can be restored. Consequently, management and restoration action is needed to maintain the status quo but will need to go further to achieve improvement, including addressing emerging issues (Pickering, 2001).

The high profile and recognised deterioration of the lake has led to several efforts and continued support for management and restoration activities over the last four decades (Pickering, 2001). However, despite this attention and recognition, there has been little funding for management and restoration excluding private investment by the water industry (Maberly & McGowan, 2022). Over the past 20 years, United Utilities have invested over £70 million (with £45 million between 2015 and 2020 alone) to improve the performance of their assets within the Leven catchment, including nutrient reduction from WwTW and reductions in spills from storm overflows. These improvements have been made over several Asset Management Plan (AMP) periods:

- In AMP1 (1990 – 1995), the aforementioned upgrades to Ambleside and Tower Wood WwTW were made, and an annual average permit discharge of 2 mg L^{-1} (or 2,000 mg m^{-3}) of total phosphorus for Hawkshead and Tower Wood WwTW was implemented.
- In AMP2 (1995 - 2000), there was investment to further reduce Biological Oxygen Demand and ammonia.
- In AMP3 (2000 - 2005), tighter annual average permit discharges of 1 mg L^{-1} (1,000 mg m^{-3}) and 2 mg L^{-1} (2,000 mg m^{-3}) of total phosphorus were implemented for Grasmere and Ambleside WwTW respectively, and UV treatment was established at Ambleside and Tower Wood WwTW.
- In AMP4 (2005 - 2010), annual average permit discharges of total phosphorus were further reduced to 0.6 mg L^{-1} (600 mg m^{-3}) for Grasmere, 1 mg L^{-1} (1,000 mg m^{-3}) for Ambleside and Tower Wood WwTW, and 1.5 mg L^{-1} (1,500 mg m^{-3}) for Hawkshead WwTW.
- In AMP5 (2010 - 2015), spills from Elterwater PS were reduced to fewer than 30 per year, and the annual average permit discharge for Hawkshead WwTW was reduced to 1 mg L^{-1} (1,000 mg m^{-3}) of total phosphorus.
- In AMP6 (2015 - 2020), the last significant WwTW upgrades occurred which included enhanced UV treatment at Tower Wood WwTW to reduce phosphorus loads to current technical achievable standards, improvements at Ambleside and Grasmere WwTW, and spill reduction (to less than 30 spills per year) from Glebe Road PS. Ambleside, Tower Wood, Grasmere and Outgate WwTW also received tighter annual average permit discharges of 0.5 mg L^{-1} (500 mg m^{-3}), 0.25 mg L^{-1} (250 mg m^{-3}), 0.3 mg L^{-1} (300 mg m^{-3}), and 2 mg L^{-1} (2,000 mg m^{-3}) of total phosphorus respectively.

Most recently, £41 million of investment was announced in 2023 to further reduce spills from four assets (Ambleside WwTW storm overflow, Near Sawrey WwTW storm overflow, Elterwater PS, Hawkshead PS) in the catchment by 2030 (S. Platts-Kilburn, *personal communication*, 27 February 2024). Modelling by the Environment Agency indicates that this should reduce the total phosphorus load by 4% in the

North Basin and 8% in the South Basin (Environment Agency, 2023), detailed in section 2.1.5 of the State of Windermere report (Harper, 2024).

Conditions in Windermere vary with depth, across the lake surface, around the lake shoreline, and over time. Therefore, it is important to take a large-scale and multi-season view of lake health over the long-term. Long-term data on the lake's biology and water chemistry are crucial for recommending future management strategies to improve the overall health of the lake and its catchment (Maberly & Elliott, 2012). It may not ever be 'restored' in the sense of returning it to some predetermined historical state, but threats can be mitigated to improve conditions and protect the lake for future generations.

Previous research, management and restoration activities have generally considered Windermere and connected lakes and rivers in isolation when a catchment view should be taken (Dudgeon *et al.*, 2006). The exception being Windermere Reflections which took a catchment-based approach. This 3-year partnership programme consisted of 19 projects, including tree planting and river restoration, footpath and cycle route creation, heritage surveys, arts events and initiatives to encourage sustainable choices reducing environmental impact. There were also free courses and numerous volunteering opportunities (Clarke & Anteric, 2014). Changes in Windermere over time have been described by Talling *et al*. (1986) and Pickering (2001), with brief mention of other waterbodies and watercourses in the catchment. The introduction to a Special Issue of *Freshwater Biology* in 2012 (Maberly & Elliott, 2012) then a subsequent review in *Ecological Informatics* (Maberly *et al.*, 2018) synthesised the ecological insights that have been gained from long-term monitoring and research on the lakes in Windermere's catchment, but this effort has not been repeated since. Management and restoration of Windermere and the wider Leven catchment will require sustained commitment and engagement from local stakeholders as well as support from partner organisations at a national level and from local and national government through tighter policies and legislation (Pickering, 2001).

1.2. Current activities to improve and understand lake health

The Love Windermere partnership was formed in 2022 and originally comprised 10 partner organisations, each with a stake in Windermere, whether that be scientific, cultural and/or economical. The partnership currently comprises nine organisations; Environment Agency, Lake District National Park Authority, Lake District Foundation, National Trust, South Cumbria Rivers Trust, National Farmers Union, Westmorland and Furness Council, United Utilities and Cumbria Local Enterprise Partnership. The partnership aims to take a scientific and evidence-based approach to better understand the complex and interdependent pressures facing Windermere and prioritise effective solutions to improve the condition of the lake. The partnership operates as seven workstreams which aim to develop and implement projects and activities that will achieve positive environmental or socioeconomic goals.

The FBA and UKCEH have been monitoring the lake at least fortnightly since 1945, including water chemistry and dynamics of phytoplankton, zooplankton and fish populations. Blelham Tarn, Esthwaite Water, Grasmere (1968-2018), Bassenthwaite (1990 - 2018) and Derwent Water (1990 - 2018) are or were also tested for water chemistry, including surface temperature, surface oxygen saturation, Secchi depth, alkalinity (calcium carbonate and pH), ammonium, nitrate, soluble reactive phosphorus, total phosphorus, dissolved reactive silica and phytoplankton chlorophyll *a*. Water samples are based on a sample integrated from 0 to 5 m (1945 - 1962), 0 to 10 m (1962 - 1964) or 0 to 7 m (1964 onwards) (Maberly & Elliott, 2012; Maberly *et al*., 2018). Phytoplankton counts as well as crustacean zooplankton and fish (pike *Esox lucius*, perch *Perca fluviatilis*, and Arctic charr with gill nets or traps, and gill nets for whole fish community) sampling were previously part of this monitoring as well. These data are available on the Environmental Information Data Centre (EIDC).

High-frequency, automatic monitoring buoys in each basin of Windermere as well as Esthwaite Water and Blelham Tarn collect data on air temperature, solar radiation, wind speed and lake temperature profile every 4 minutes from which hourly averages are calculated (Maberly *et al*., 2018). These data are also archived on the EIDC. More comprehensive water quality assessments of Windermere, Esthwaite Water and Blelham Tarn alongside other Cumbrian lakes are undertaken seasonally every 5 years by UKCEH and collaborators, i.e. the UKCEH Lakes Tour (Hall *et al*., 1992, 1996; Parker *et al*., 2001; Maberly *et al*., 2006, 2011c, 2016; Mackay *et al*., 2023). Furthermore, UKCEH manages a citizen science app, Bloomin' Algae, for opportunistic reporting of the presence of potentially harmful algal blooms (i.e. cyanobacteria or blue-green algae). These reports as well as those reported directly to the Environment Agency are used to update Citizen Space during the bathing water season. UKCEH also supports PhD students conducting research, including the planktonic food web in Windermere, and changes in nutrient concentrations and phytoplankton biomass, paleolimnology, and plankton community composition and trophic interactions in Esthwaite Water.

The Environment Agency monitors 24 sampling locations for Water Framework Directive (WFD) assessment (results for individual parameters on the Water Quality Archive and classifications on the Catchment Data Explorer) and 4 designated bathing waters for Bathing Water Directive (BWD) assessment (results and classifications on Swimfo). The Environment Agency also conducts farm inspections, and has remote monitoring stations on Windermere and the surrounding lakes and rivers for daily monitoring of water quality (ammonium, cyanobacteria, chlorophyll, conductivity, dissolved oxygen, pH, temperature, and turbidity), rainfall, river level, river flow and groundwater level (see Hydrology Data Explorer). Additionally, the Environment Agency supported the development of the Source Apportionment Geographical Information System (SAGIS), which can help inform understanding of sources of nutrients and chemicals at catchment scale and identify measures to improve water quality in rivers, lakes and estuaries. SAGIS was applied to phosphorus inputs in the Leven catchment in November 2023 (Environment Agency, 2023).

The FBA has been taking daily measurements of surface water temperature, rainfall and water level on Windermere's west shore since 1933. In 2022, the FBA started the Big Windermere Survey (BWS) with Lancaster University, which is a citizen science investigation of the sources of nutrient and bacterial inputs around the lake shore and wider catchment in order to inform targeted action on the ground. Parameters measured are temperature, pH, electrical conductivity, nitrite, nitrate, ammonia, total oxidised nitrogen, total phosphorus, total dissolved phosphorus, soluble reactive phosphorus, particulate phosphorus, dissolved organic phosphorus, silica, dissolved organic carbon, total coliforms, *E. coli* and intestinal enterococci. Each site surveyed is given an indicative 'classification' based upon the WFD and BWD using a slightly modified approach to the Environment Agency. These classifications are used to provide context to the results for volunteers and should not be interpreted as formal classifications, which are based on repeated monitoring over several years. Results (published on Cartographer) show that phosphorus concentrations in Windermere are generally at levels that would be classed as 'Good' phosphorus status under the WFD. However, concentrations vary throughout the year and local hotspots of nutrient enrichment are observed in each season. Other lakes in the catchment also face similar challenges. Levels of faecal indicator bacteria are generally low across all seasons, but there tend to be hotspots with increased concentrations in summer and autumn, and mainly within Windermere.

The BWS complements existing monitoring by UKCEH, the Environment Agency and South Cumbria Rivers Trust (SCRT). The latter trains citizen scientists to undertake Riverfly surveys (the FBA hosts this national programme), electrofishing, and walk-over surveys as well as water chemistry testing when possible. In addition, SCRT undertakes a number of practical restoration activities with volunteers and other stakeholders, including reedbed creation/restoration, riverbank fencing to prevent ingress of sediments and nutrients from agriculture, septic tank and private package treatment plant education and awareness, and INNS management. The charity is currently trialling a novel technology for removal of phosphorus from compliant septic tank effluents and private package treatment plant effluents.

The Lake District National Park Authority (LDNPA) and National Parks Partnerships are collaborating with Palladium on Revere. In the LDNP, this project aims to look at nature-based solutions to mitigate phosphorus inputs to Windermere that could be sustainably financed. The first phase of this project, which modelled the nature-based solutions that would deliver enough phosphorus reduction for Windermere to achieve 'Good' phosphorus status under WFD, has been completed. The second phase will ground truth the modelling, undertake research with landowners and land managers to understand how to deliver nature-based solutions, and identify buyers of these solutions (the ecosystem service that intercepts phosphate) in the form of water quality credits, which together will inform the nature finance model for long term income to deliver riparian woodlands and constructed wetlands. This is due to be completed in 2024 and provide the capability for the third phase that will deliver the required interventions.

United Utilities are investing £41 million over the next 7 years into reducing spills from four of their assets (Ambleside WwTW storm overflow, Near Sawrey WwTW storm overflow, Elterwater PS, Hawkshead PS). The company has also deployed real-time water quality monitoring sondes on Cunsey Beck and Esthwaite Water which provide high-resolution monitoring, including real-time phosphorus concentrations.

The Cumbria Innovative Flood Resilience (CiFR) programme is looking at nature-based solutions and blended finance to improve flood resilience. The programme is validating natural flood management in areas where modelling has shown this will mitigate flood risk, monitoring the impact of the intervention on flood risk and water quality, and improve understanding of the landscapes in which natural flood management makes the greatest difference to flood risk. A pilot in Grasmere will develop synergies and maximise opportunities for stakeholders to work together that could be replicated in other areas of the Leven catchment.

Beyond the activities of Love Windermere partners and collaborators, Ambleside Action For A Future (AAFAF) is a network of local residents working together to mitigate climate and environmental breakdown and build community resilience. They ran a citizen science project testing phosphate concentration in the River Rothay and Stock Ghyll above and below Ambleside WwTW from March to September 2023. The Lakes Aquarium test water from Windermere every week by the Lakeside Hotel & Spa for pH, nitrite, nitrate, ammonia, and phosphate.

These data have provided and will continue to provide insights into how the lake has responded to natural changes, human impacts and actions taken to improve it over weeks, seasons, years, and decades. In addition to on the ground, monitoring and research activities, there are community networks and campaigns promoting awareness of local issues. Friends of the Lake District aim to protect and enhance the natural beauty of landscapes in the Lake District for the benefit of local communities, visitors, wildlife and habitats. Save Windermere are campaigning for removal of all treated and untreated sewage discharges from Windermere and its catchment.

1.3. Science planning and support for Windermere

The Lake District was designated as a National Park in 1951 and the LDNP became a UNESCO World Heritage Site in 2017, but Windermere has no specific protection. Windermere is subject to several pieces of environmental legislation, namely the European Union Water Framework Directive, Bathing Water Directive, and Urban Wastewater Treatment Directive. The WFD requires Member States to protect and, where necessary, restore waterbodies in order to reach 'Good' status, including water chemistry and ecology. The BWD requires Member States to monitor and assess bathing waters to disseminate information actively and promptly to the public on bathing water quality during the bathing season (15 May – 30 September), including identifiable notices banning or advising against bathing where necessary.

Both pieces of legislation are enforced by the Environment Agency, with results published on the Catchment Data Explorer and Swimfo respectively. Within the Leven catchment, there are 24 sampling locations for WFD assessment and 4 designated bathing waters for BWD assessment. The UWWTD requires Member States to collect and treat wastewater, and secondary treatment of all discharges, from urban areas with more than 2,000 people. More advanced treatment is required for urban areas with more than 10,000 people in catchments with sensitive waters. Performance of treatment plants and receiving waters must be monitored, and appropriate controls for sewage sludge disposal and reuse, and treated wastewater reuse, must be in place.

Within the Leven catchment, there are over 20 Sites of Special Scientific Interest (SSSI) as designated by Natural England (Pickering, 2001), with aquatic SSSIs including Blea Tarn, Elterwater, Little Langdale Tarn, Blelham Tarn, Claife Tarns, Esthwaite Water and Skelghyll Beck. The Joint Nature Conservation Committee (JNCC) have classified one Special Area of Conservation (SAC) in the form of Yewbarrow Woods SAC, and Esthwaite Water is the only Ramsar Site, i.e. wetland of international importance designated under the Ramsar convention. There are no locations classified as Special Protection Areas (SPA) by the JNCC or designated as Areas of Outstanding Natural Beauty (AONB) by Natural England (NB: AONB have been rebranded as 'National Landscapes' as of 22 November 2023). However, the River Leven feeds into Morecambe Bay, which is a SAC, SPA, Ramsar Site, and has designated bathing waters. National Nature Reserves (NNRs) established by Natural England include Blelham Bog NNR, North Fen NNR and Rusland Moss NNR. Site designations/classifications for the UK can be viewed using MAGIC. Over 250 UK Biodiversity Action Plan (UKBAP) species are present in Cumbria, including 18 fish, 3 amphibians, 6 reptiles, 29 birds and 14 mammals (Cumbria Wildlife Trust, 2009). UKBAP species of particular relevance to Windermere include Arctic charr, Atlantic salmon (*Salmo salar*), brown trout (*Salmo trutta*), river lamprey (*Lampetra fluviatilis*), and European eel (*Anguilla anguilla*). Additionally, the slender naiad (*Najas flexilis*) is found in Esthwaite Water; the only site where the species is found in England.

Legislative monitoring and protection for Windermere largely comes from the overarching WFD and BWD which offer some support for monitoring and subsequent management, but Environment Agency efforts are ultimately based on risk prioritisation where resource is limited. Additional monitoring is currently undertaken by research organisations (e.g. UKCEH, Lancaster University) and scientific charities (e.g. FBA, SCRT), but could cease at any time subject to organisational goals, grant funding and staff resource. Efforts for Windermere pale in comparison to other international lakes of importance (e.g. Laurentian Great Lakes, Lake Tahoe, Lake Winnipeg, Lake Annecy, Lake Geneva, Lake Bouget) around the world which have partnerships/consortia tasked solely with their research, monitoring and management, specific protective legislation, and government funding (Hymanson & Collopy, 2010; Jacquet *et al.*, 2014; Scott, 2015).

1.4. Approach taken to construct the WISP

Key to selection and implementation of research, management and restoration projects and activities is the scientific evidence base to enable effective yet adaptive management whilst maximising available resources. To our knowledge, this integrated science plan represents the first endeavour to coordinate science planning for Windermere and the wider Leven catchment.

The WISP was constructed by the FBA in collaboration with a range of regulatory authorities, scientific charities, private businesses and research organisations (i.e. the Love Windermere Data, Science & Evidence workstream) to identify and refine the scientific information needs for Windermere and the wider Leven catchment. The main purpose of the WISP is to identify monitoring and research needs to address key uncertainties and information gaps that challenge stakeholders (including commercial operators, regulatory agencies, communities and recreational users) working in the Leven catchment based on an assessment of the issues Windermere faces. Current and future monitoring and research needs will guide future works and help maximise the information gained from science investments.

In most cases, the Leven catchment (excluding the River Leven downstream of Newby Bridge to Morecambe Bay, already the focus of the local Catchment Based Approach group, coordinated by South Cumbria Rivers Trust) encompasses the entire geographic scope of this science plan, but where appropriate, the scope is broadened to consider factors that can influence conditions or future management within the catchment, e.g. climate change.

The plan presents the results of efforts to organise and describe the scientific evidence needed to inform adaptive management to maintain and improve conditions in Windermere and the wider Leven catchment. Partners and collaborators also have their own organisational goals, projects and activities that will contribute to or run parallel to this science plan, including routine and regulatory monitoring, modelling and digital development, improvements to infrastructure, citizen science, volunteer projects, advocacy and education work, and on-the-ground delivery programmes.

The plan includes four sections describing knowledge gaps, monitoring and research needs, and recommended aims and objectives for the theme areas of water quality, climate, people, and monitoring. The Love Windermere Data, Science & Evidence (DSE) workstream have identified relevant subthemes (e.g. nutrient inputs are one subtheme under the water quality theme area) and the management issues and information needs associated with these (e.g. understanding the internal phosphorus load to the lake is one information need under the nutrients subtheme). For each subtheme, remaining uncertainties and knowledge gaps are identified, and activities that would address these uncertainties and knowledge gaps are outlined. The current state of knowledge on each theme area is reviewed and summarised in corresponding sections of the State of Windermere report (Harper, 2024).

There are three common drivers of the recommendations presented in each section:

- Increasing understanding of the environmental and anthropogenic factors and processes (and their interactions) operating within Windermere and the wider Leven catchment.
- Developing the tools and knowledge to predict future ecological conditions in Windermere and permit comparisons among alternative scenarios.
- Providing information for future management decisions aimed at restoring natural processes and reducing anthropogenic impacts in the Leven catchment that strike the right balance for nature and people.

Each section concludes with a presentation of near-term research priorities which are based on input received from other Love Windermere workstreams and members of local communities, as well as the best professional judgment of the DSE workstream. Several factors can influence the applicability of near-term research priorities, e.g. changing stakeholder priorities, funding levels, and the emergence of new issues, new information, or new technologies. Therefore, the WISP should be considered as a living document where the research priorities are reviewed and revised regularly to ensure they reflect the changing information needs and evolving priorities of stakeholders responsible for the health of Windermere. Love Windermere partners share the responsibility to continually revisit and update this document in the future.

1.5. WISP implementation

Clear direction and stakeholder commitment are essential to successful delivery and advancement of the WISP. Science provides objective and verifiable means of generating new information to address uncertainties and knowledge gaps. However, meeting the ongoing information needs of and providing timely information in useful formats to stakeholders will require scientific practices and principles to be organised and implemented as an integrated science plan encompassing monitoring, research, and data application. Efforts need to be coordinated with appropriate allocation of resources to each aspect of the plan.

Production of the WISP alone will not ensure continuous scientific monitoring, research and data application to deliver the information required to address the issues outlined in the State of Windermere report (Harper, 2024). Dedicated support for and protection of Windermere is vital, but commitment from stakeholders is crucial to move from planning to implementation. Scientific organisations are ready and willing to do the work, but stakeholders responsible for the health of Windermere and the wider Leven catchment will need to establish the funding, resources, infrastructure and governance required to implement the WISP. Further engagement and partner dialogue will be needed to overcome the complex environmental and socioeconomic obstacles to this implementation.

The WISP includes recommendations for four topics of importance to Windermere and the wider Leven catchment: water quality, climate, people, and monitoring. The recommendations differ in scope and breadth because the number and complexity of issues vary, as does the current state of knowledge on different themes. Past efforts to obtain knowledge in each of the theme areas have not been equal, and so different levels of investment are needed to fill knowledge gaps. For example, environmental parameters indicative of water quality have been consistently recorded for over 80 years, whereas information on the number of residents within, and visitors to, the Leven catchment over time is patchy. Consequently, research needs for the theme area of water quality are well-defined in comparison to the theme area of people. Differences in the scientific evidence base hinder efforts to understand and quantify interactions between pressures and biological, chemical and socioeconomic trends. Therefore, continued commitment to resource and fund all four theme areas is needed to balance the scientific evidence base.

1.6. Target audience for the WISP

The target audience for the WISP includes regulatory agencies, scientific organisations, commercial operators, private businesses, communities and recreational users that have a role in the protection and management of Windermere and the wider Leven catchment. It is hoped this plan is of particular use to individuals responsible for deciding if and how new funding should be awarded to scientific activities.

2. Water Quality

The current state of knowledge on the theme area of water quality in Windermere is reviewed and summarised in section 2.1 of the State of Windermere report (Harper, 2024).

2.1. Knowledge gaps

Nutrient inputs to the lake, both in terms of internal and external loads, are a key knowledge gap. Phosphorus can come from a myriad of sources, including WwTW, septic tanks, private package treatment plants, storm overflows, misconnections, agriculture, wildlife, food items, and household products. Nitrogen originates from the same sources as well as the atmosphere but has received very little consideration in debates around nutrient levels in Windermere to date. Its role relative to phosphorus needs to be better understood (Wurtsbaugh *et al.*, 2019). It is possible that there is a greater negative impact of nutrient inputs over winter due to higher rainfall and associated increases in river discharge as well as surface water and groundwater runoff (Heron, 1961; Reynolds *et al.*, 2012; Watts *et al.*, 2015). Most phosphorus currently in the lake sediment is likely to have arrived during storm events (Whitehead *et al.*, 2009). In addition to lake sediment, nutrient concentrations in terrestrial soils delivered to the lake via runoff are unknown.

An accurate nutrient budget, including contemporary estimates of source apportionment (for WwTW, storm overflows, septic tanks, private package treatment plants, rural land, urban sources, industry, and wildlife), internal loading and potential external loading from other sources, is urgently needed. The messaging on nutrient levels and what is the most relevant baseline needs to be carefully considered. A long-term view, possibly spanning several thousand years, is needed to put current nutrient levels into context of different baselines (McGowan *et al.*, 2012).

Faecal material inputs are only formally assessed for *Escherichia coli* and intestinal enterococci concentrations, as described in the Bathing Water standards protocols (Department of the Environment, Department of Health and Social Security, 1982), at the four designated bathing water sites on Windermere (Millerground Landing, Rayrigg Meadow, Fell Foot, Lakeside YMCA) from May to September. There is a need to assess these inputs across greater spatial and temporal scales as well as identifying the source(s) (e.g. human, livestock, wildlife) to inform management. Other emerging pathogens should also be considered for inclusion in the Environment Agency's future threats list. There are a number of pathogens that are present in Windermere in addition to *Escherichia coli* and intestinal enterococci that can impact human health, e.g. *Klebsiella* sp., *Salmonella* sp. and *Vibrio* sp., *Citrobacter* sp., *Enterobacter* spp., *Aeromonas veronii* bv. *sobria*, *Aeromonas hydrophila*, *Stenotrophomonas maltophilia*, *Serratia* sp., *Cryptosporidium* and *Mycobacterium avium* subsp. *paratuberculosis* (Rhodes *et al.*, 2012). The impacts of other pollutants, such as pharmaceuticals, chemicals (including forever chemicals), plastics and heavy metals, entering freshwater systems via drinking water and wastewater on biological and human health are also unknown (Reid *et al.*, 2018; Fielding *et al.*, 2020).

A better understanding of the ecology of Windermere and the impacts of different pressures on its biodiversity is needed as this essentially drives the functioning and resilience of the lake. Ultimately, a whole food web approach, encompassing all aspects of life from phytoplankton to vertebrates, to monitoring and management needs to be taken (Maberly *et al.*, 2018). Greater knowledge on the performance of nature-based solutions which support wildlife whilst tackling water quality issues will be key. For example, reed bed restoration may help marginally with phosphorus uptake but significantly with nitrogen uptake and biodiversity net gain (Rushworth, 2014; O'Keefe *et al.*, 2015), and increased tree planting could have multiple natural flood management benefits, including reducing flows, soil runoff and nutrient delivery to waterbodies (Hankin *et al.*, 2017).

2.2. Research needs

The utmost priority in terms of Windermere's water quality is a contemporary nutrient budget as well as greater knowledge on nutrient cycling and the biological response to nutrient inputs.

In 2023, the Environment Agency undertook an investigation into phosphorus source apportionment within the Leven catchment using SAGIS with SIMulation of CATchments (SIMCAT) modelling tools to update the estimate of 30% from WwTW to 70% from inflowing streams produced in 2009 (Maberly 2009). Currently, it is estimated that 52% of phosphorus in Windermere's North Basin is associated with point sources (i.e. sewage from WwTW, storm overflows, septic tanks and private package treatment plants) whereas 48 % is associated with diffuse sources (i.e. rural and urban land use). In the South Basin, 59 % of phosphorus is associated with point sources and 41 % with diffuse sources. The modelling predicted that improvements required from United Utilities by the Environment Agency to the Glebe Road PS storm overflow in Windermere and at Ambleside, Grasmere, Outgate and Tower Wood WwTW have resulted in a 31% and 30% reduction in phosphorus inputs to the North Basin and South Basin respectively from pre-2020 to post-2020. This equates to a reduction in total phosphorus load of ~3,000 kg yr^{-1}. Total phosphorus concentrations have decreased by ~26% and ~33% in the North Basin and South Basin respectively between pre-2020 and post-2020. The modelling predicted that planned improvements to storm overflows at Ambleside, Hawkshead, Langdale and Near Sawrey WwTW will further reduce phosphorus inputs by 8% to the North Basin and by 4% to the South Basin post-2030. Further reductions could be achieved by improvements to point sources for other lakes like Grasmere. However, a number of uncertainties remain around the latest estimates.

The internal phosphorus load of the lake and the potential rate of phosphorus release over time from the sediment remains unquantified. Numbers and locations of septic tanks, private package treatment plants, misconnections, and wildfowl also need to be established to accurately quantify the loads they contribute. These parameters were based on published research data for the source apportionment modelling and adjusted during calibration to match current lake conditions. The data used to derive phosphorus loadings from rural land use for the modelling originates from the 2010 agricultural census survey and thus may be out-of-date and the resolution too coarse. Local knowledge of rural land use and more recent census survey or land use data (e.g. UKCEH Land Cover Maps) could improve the models and reduce uncertainty around results. Limited data are available for storm overflow discharges, thus additional sampling and subsequent data would reduce uncertainty around these results. More research on the impacts of climate change on the lake is needed, including the individual and cumulative effects of changing rainfall, river flow, and temperature. Finally, only scenarios for improvements to United Utilities discharges were modelled, but changes resulting from improvements to other sectors should also be assessed.

At the time of writing, UKCEH are working with the Environment Agency to conduct an evidence review of nutrient cycling (including diffuse inputs) in Windermere. This will include a review of the available information on sediment enrichment and internal loading, a review of lake restoration best practices and lessons learned with a focus on nutrient inputs. It will also outline options for investigation of internal nutrient loading, to address key knowledge gaps. Depending on the outcomes and available funding, a field investigation of internal nutrient loading may be undertaken. However, there are a number of uncertainties with sediment core contributions and this sampling method is very expensive and difficult to extrapolate for a large lake like Windermere.

If the internal load can be quantified, it then needs to be placed in context of the total load of the lake within the nutrient budget. This information would allow stakeholders to understand whether the lake sediment has a significant impact on phosphorus load in relation to other sources, and the potential legacy effects. Unlike the more productive lakes in the catchment, Windermere has not been anoxic in recent decades (Hall *et al.*, 1992, 1996; Parker *et al.*, 2001; Maberly *et al.*, 2006, 2011c, 2016; Mackay *et al.*, 2023) so high rates of phosphorus release from the sediment are unlikely, but the redox situation is a function of productivity, heavy metal loading and climate (Talling *et al.*, 1986; Whitehead *et al.*, 2009). Regardless of whether internal phosphorus load is a significant contributor to the overall phosphorus load of the lake or not, the external phosphorus inputs and load to the lake need to be addressed first to avoid further oxygen depletion and potential future phosphorus release from the lake sediment (Wurtsbaugh *et al.*, 2019).

In order to target management interventions to deliver the greatest reduction in nutrient inputs, the effectiveness of available interventions (e.g. reed bed restoration, septic tank soakaways) to reduce inputs from different sources (e.g. septic tanks, storm overflows, agriculture) needs to be assessed. Success can be measured as reduction in kilograms, but should also be considered in terms of the response of biological communities, for example, macroinvertebrates are highly responsive to changes in water quality with composition changing in favour of pollution-sensitive or pollution-tolerant species depending on environmental conditions (Hatton-Ellis, 2008). 'Good' phosphorus status and 'Good' overall ecological status under the WFD needs to be consistently achieved for Windermere in each cycle of WFD monitoring, and not fluctuate as they have in the past. Phosphorus status was 'Moderate' in the South Basin from 2013 to 2019, and 'Moderate in the North Basin in 2019. Overall ecological status has been 'Moderate in both basins since 2013, and the North Basin was actually classed as 'Poor' in 2014. WFD classifications can also be complex to communicate to the general public, so there is a need for other metrics of success focused on areas of public interest, e.g. outdoor swimming, angling.

Examining changes in biodiversity over the long-term in response to different stressors will be fundamental to understanding changes in lake health over time (Maberly *et al.*, 2018). Identification of biological indicator species that respond to pressures such as eutrophication will allow progress towards management interventions to be monitored and provide a metric that the public can engage with (Siddig *et al.*, 2016). Positive indicators could be vulnerable species, such as Arctic charr, salmon, river lamprey, European eel, water vole (*Arvicola amphibius*), otter (*Lutra lutra*), white clawed crayfish (*Austropotamobius pallipes*) or freshwater pearl mussel (*Margaritifera margaritifera*), and negative indicators could be INNS, such as roach, ruffe, bream (*Abramis brama*), signal crayfish (*Pacifastacus leniusculus*), crayfish plague (*Aphanomyces astaci*) or Canada geese. Changes in the detection and distribution of these species could inform management, for example, further movement of roach from Windermere's South Basin to the North Basin would be indicative of deteriorating water quality in the North Basin which was previously a refuge for Arctic charr (Winfield *et al.*, 2012). However, it is important that multiple indicator species across a range of taxonomic groups that have been found to exhibit cause-effect relationships with underlying processes of interest are selected and used alongside other metrics (e.g. occupancy, abundance) for this approach to be effective (Siddig *et al.*, 2016).

More broadly, determining ecological thresholds for species, communities or habitats (i.e. the point or zone at which there is rapid change from one ecological condition to another due to a change in one or more key factors) that would act as an early warning system could inform how and when management should respond to monitoring results. If a biological community with unique function(s) is associated with certain conditions, then changes to this community should necessitate examination of what conditions have changed and corrective management. Alternatively, if certain habitats support biologically diverse, functional and resilient communities, then change in the percentage cover of these habitats may necessitate intervention, e.g. reedbeds may facilitate colonisation or recovery of associated species and thus a biologically diverse community (Rushworth, 2014). The challenge is identifying the threshold(s), which requires long-term data of sufficient spatial and temporal resolution to make links between anthropogenic pressures and observed ecological responses that can be distinguished from natural variability (Huggett, 2005; Capon *et al.*, 2015).

Biological assessments should take a whole food web approach, including high-profile sensitive species (e.g. Arctic charr) and INNS (e.g. roach), which is feasible using environmental DNA (eDNA) analysis in conjunction with complementary tools (Hänfling *et al.*, 2016; Lawson Handley *et al.*, 2019). A current assessment of fish populations is urgently needed to understand how native species (e.g. Arctic charr) are faring in response to anthropogenic pressures and INNS, e.g. roach, ruffe (Di Muri *et al.*, 2022). Sediment eDNA in particular offers the opportunity to create biological time series' spanning several hundred years (Thorpe *et al.*, 2023), which could capture the pre-Victorian era, Victorian industry and tourism, expansion of agriculture and infrastructure, through to present day. The timing, frequency and intensity of algal blooms (including cyanobacteria) must be quantified to assess change over time in response to nutrient inputs, climate change, and local weather patterns. Better monitoring and forecasting of algal blooms is needed to minimise hazards to human health as well as health of pets, livestock, and wildlife (McGowan, 2023). Biological assessment will also be key to understanding the role of emerging contaminants, such as drugs, chemicals, plastics and heavy metals, both in isolation or combination with nutrients, faecal pollution, and land use change (Reid *et al.*, 2018; Albini *et al.*, 2023).

Development of Microbial Source Tracking would allow sources of faecal pollution to be identified for more effective management (Harwood *et al.*, 2014). If humans were the predominant source, action should be targeted at mains and non-mains drainage systems. If livestock were the predominant source then agricultural and animal husbandry practices must be improved. However, developing this approach requires landowner buy-in to provide faecal samples from farms within the catchment in order to test specificity and sensitivity of selected markers for potential animal sources in the area (Ballesté *et al.*, 2020). It also requires intensive sampling of the river network and lake to be able to pinpoint the location of the faecal material source (Jardé *et al.*, 2018).

Obtaining the understanding to establish appropriate metrics must begin with site-scale investigations into the response patterns of biodiversity to environmental and anthropogenic changes (including interactions between different factors and species) and to validate Microbial Source Tracking. When this understanding has been achieved at a local scale, it can be applied at regional scale to inform management throughout the Leven catchment.

2.3. Aims and objectives

2.3.1. Nutrients

Over the next 5 years:

- Stakeholders should aim to produce a more accurate nutrient budget. This work is currently underway through projects with the Environment Agency and UKCEH as mentioned above, but also through the LDNPA and Palladium collaborative project Revere. In the LDNP, this project aims to look at nature-based solutions to mitigate phosphorus inputs to Windermere that could be sustainably financed. The first phase of this project, which modelled the nature-based solutions that would deliver enough phosphorus reduction for Windermere to achieve 'Good' phosphorus status under WFD, has been completed and the second phase, which will ground-truth the modelling, is ongoing and due to be completed in 2024.
- Although the internal phosphorus load is likely to be less than the external phosphorus load to the lake, and the rate of phosphorus release in Windermere will not be as high as other lakes that are anoxic or severely oxygen depleted, establishing the internal load, how much this contributes to total load, and rate of phosphorus release from the sediment will be key to a revised nutrient budget for Windermere.
- The benefits when nutrients from a given source are reduced by a certain amount need to be articulated to local communities and businesses to inspire others to take action in their personal lives.

In the longer-term, once contributions from different sources have been identified and more accurately quantified:

- Stakeholders need to quantify reductions in nutrient load from different sources to improve the WFD phosphorus status and/or deliver specific benefits.
- The effects of different interventions to reduce nutrients at different scales should be modelled, e.g. how does 1 ha of wetland influence nutrient reduction.
- The best use of resources for nutrient reduction should be identified, e.g. investment in land management vs. spill reduction from storm overflows.
- Interactions between climate and nutrient inputs/reduction need to be investigated (e.g. how do extreme events influence nutrient inputs and mitigation in place to reduce inputs).
- Whether reductions in nutrient inputs from point sources in the catchment are offset by increased release of phosphorus from sediment due to temperature increase and oxygen reduction needs to be addressed.
- The amount of sediment generated by different land uses (e.g. farming vs. forestry) needs to be quantified.
- There should be exploration of whether sediment focusing (i.e. where water turbulence moves sediment to deeper parts of a lake) occurs in Windermere to determine whether this impacts stratification and leads to more phosphorus release and changes in environmental parameters in certain areas.
- The impacts of nutrient reduction on the ecology and functioning of the lake need to be identified.
- Public expectations around what can be done and what the endpoints of restoration could look like needs to be managed and effectively communicated. For example, tackling internal nutrient loading would take several decades and millions of pounds.
- Legislation and enforcement of permits for septic tanks and private package treatment plants should be tightened.

2.3.2. Biological monitoring

Over the next 5 years:

- A contemporary biological baseline for Windermere and the wider Leven catchment needs to be established, taking a whole food web approach.
- Routine biological monitoring (potentially using non-invasive and less field-intensive methods such as eDNA analysis and hydroacoustics) should be implemented and consistently resourced. Target taxa should include fish, other vertebrates, macroinvertebrates, zooplankton, phytoplankton, and bacteria.
- Systematic monitoring for algal blooms must be established to quantify changes in phytoplankton community composition and abundance of different species as well as timing, frequency, and intensity of bloom events over time.

In the longer-term:

- Abundance information should be obtained to understand whether species are stable, increasing or declining in response to water quality pressures and inform appropriate management. For example, information on distribution and abundance of non-native roach would enable creation of a management programme.
- A biological time-series using the sediment record should be established to identify how much the present-day biological community differs to historic biological communities, and identify potential baselines for ecological restoration.
- The use of indicator species to prompt management intervention and assess subsequent progress should be evaluated, beginning with an examination of whether any species reliably exhibit cause-effect relationships with underlying processes of interest, e.g. nutrient enrichment, temperature.
- The use of ecological thresholds to prompt management intervention should be evaluated, beginning with an examination of whether any species, communities of habitats are exhibiting rapid change in response to one or more pressures.
- The role of emerging contaminants (and their interactions with other pressures) on the ecology of the lake must be better understood.

2.3.3. Bathing water quality

Over the next 5 years:

- Stakeholders need to find out what water-users, especially outdoor swimmers, want to know about bathing water quality.
- More communication and engagement activities are needed to educate residents and visitors on available data and information on bathing water quality as well as the potential risks of entering the water, and how these can be mitigated.

In the longer-term:

- Water testing needs to be expanded beyond *Escherichia coli* and intestinal enterococci to include emerging pathogens.
- Microbial Source Tracking should be developed and implemented across the catchment.

3. Climate

The current state of knowledge on the theme area of climate in Windermere is reviewed and summarised in section 2.2 of the State of Windermere report (Harper, 2024).

3.1. Knowledge gaps

Climate change influences water quantity and quality both directly through water temperature and weather patterns but also indirectly by compounding other pressures, such as nutrient enrichment (i.e. warmer temperatures promote algal growth and reduce oxygen availability) and INNS, i.e. warmer temperatures allow INNS to expand their distribution and colonise new habitats (Winfield *et al.*, 2008; Elliott, 2012). A better understanding of independent and interacting effects of climate change on the lake is needed. Assessing long-term changes in climate, including temperature, rainfall, wind speed, drought periods, nutrient deposition, air pollution, and frequency of extreme events, will be key (Watts *et al.*, 2015). The impacts any changes have had on nutrient inputs and water residence times, and subsequently algal growth, and whether there is a seasonal pattern is largely unknown. Extreme events, specifically storms, could cause surges in nutrients inputs to and increased water mixing in Windermere with the potential to alter phytoplankton communities and resuspend sediment (Woolway *et al.*, 2018). The frequency and intensity of droughts dictates water supply and will influence power generation and/or agriculture in different parts of the UK, but the effects of drought on UK freshwaters have not been well-studied. Short summer droughts are projected to increase which could worsen acidification, but uncertainty in climate models means longer droughts are also possible (Watts *et al.*, 2015). Droughts would likely exacerbate the problems Windermere already faces, through longer duration and intensity of thermal stratification, lower dissolved oxygen concentrations (both in surface water and at depth), and increases in nutrients, turbidity, salinity, algal biomass, and sediment resuspension as a result of reduced flushing and greater productivity (Mosley, 2015). Studies of other large and deep Cumbrian lakes could help tease apart patterns in impacts of climate on Windermere (Maberly & Elliott, 2012).

3.2. Research needs

It will be crucial to increase monitoring effort to produce adequate input data for models that would enable forecasting (Page *et al.*, 2018), and to obtain a better understanding of interactions between climate and other variables (Watts *et al.*, 2015). Statistical modelling using existing long-term data from UKCEH would allow relationships between temperature and other variables to be examined over time. The direction of change and actions to mitigate impacts could then be identified.

Understanding interactions between environmental parameters (e.g. hydrology and temperature) will be key to gaining insight into what conditions to expect in the future. Specifically, what variables influence flow into lakes and overall water quality. Work on Blelham Tarn (Foley *et al.*, 2012) and Elterwater (Olsson *et al.*, 2022) has already illuminated interactions between temperature and other environmental parameters.

Air quality is equally as important as water quality. The UKCEH is investigating atmospheric deposition, particularly nitrogen, in the uplands of the Lake District through the UK Upland Waters Monitoring Network. However, the role of greenhouse gas emissions on local climate and nutrient cycling still needs to be understood.

The combined effect of nutrient loading and temperature on algal bloom events could be examined using PROTECH (Phytoplankton RespOnses To Environmental CHange) modelling (Elliott, 2012). Flood risk has previously been assessed by the Environment Agency under different climate scenarios. A similar approach could be taken with PROTECH modelling for different weather and environmental conditions, for example, different temperature scenarios could be modelled to perform a sensitivity analysis for water quality whilst also looking at growth and timing of phytoplankton. However, this would be dependent on having the necessary input data hence the need for improved monitoring. In addition to PROTECH, there are catchment models, such as the UKCEH Future Flows which models flow conditions under different climate scenarios. The Inter-Sectoral Impact Model Intercomparison Project (ISIMIP) can also be used for lake modelling using physical variables where climate models are run across grid cells around the world.

Ultimately, the Love Windermere partnership needs to investigate how to increase resilience of Windermere to climate change. It is unclear whether mitigation and remediation works currently taking place (e.g. riparian habitat creation) will be up to the task. Expected and ongoing climate changes will make Windermere and other lakes much more sensitive to water quality decline than they were in the past (Watts *et al.*, 2015). Management and restoration action is needed to maintain the status quo but will need to go further to achieve improvement, including addressing emerging issues.

3.3. Aims and objectives

Over the next 5 years:

- Stakeholders should create a conceptual model of climate impacts on the lake and catchment, grounded in current evidence, to include:
    - The multi-faceted nature of climate change (temperature, precipitation, and flow regimes).
    - Episodic extremes (storms, flooding, drought) and long-term trends.
    - Interactions between climate and other pressures, e.g. nutrients from the catchment, atmospheric deposition, and land use.
    - Possible climate-related facilitation of INNS.

Data and models can then be "mapped" onto the conceptual framework. Some impacts (e.g. temperature, stratification timing and duration) could be investigated now, but some will require new data and approaches. Similar to water quality, more communication and engagement activities are needed to convey climate impacts (and any proxies used) to local residents and businesses as well as tourists.

In the long-term:

- Data analysis and modelling are needed to establish the evidence for the impacts in the conceptual framework.
- Forecasting capabilities must be developed (e.g. water temperature, thermal stratification and algal blooms) to pre-empt events on the lake.
- Climate adaptation options need to be developed for Windermere and the wider catchment to increase resilience. These may include habitat creation/management and chemicals to slow down rainfall and increase water retention of soil. In Grasmere, the CiFR programme is looking at natural land management schemes to reduce flooding in rural areas, including sourcing sondes to look at the impacts of schemes on water quality and flow.
- Communication and engagement activities on climate adaptation messaging will be key to inspire local residents and businesses as well as tourists to take individual action.

4. People

The current state of knowledge on the theme area of people in Windermere is reviewed and summarised in section 2.3 of the State of Windermere report (Harper, 2024).

4.1. Knowledge gaps

Perhaps the most widely suspected but least quantified cause of water quality deterioration is people and their activities. High visitor numbers during school holidays and summer months are likely to increase nutrient and faecal material inputs from mains and non-mains drainage relative to times of year when mainly the resident population is present. Summer months are also when phytoplankton production is greatest due to light availability and warm temperatures. Therefore, phytoplankton will readily use any additional nutrients resulting in larger blooms. However, numbers of residents and visitors have not been examined in relation to nutrient or faecal indicator bacteria concentrations to quantify their impact. In addition to this core pressure, the impact of recreational activities (e.g. hillwalking, climbing, paddling, outdoor swimming, boating) of both residents and visitors and the roads used to access them in terms of pollution/damage (e.g. littering, fuel spills, air contaminants, soil erosion, riverbank degradation) and wildlife disturbance (e.g. light, noise) has been qualitatively reported on Windermere (Talling *et al.*, 1986; Pickering, 2001), but not quantitatively assessed. Land use change (including types of farming, forestry, industry, transportation and residences) is known to influence water quality (McGowan *et al.*, 2012), but the distribution of land use types throughout the Leven catchment and the role they each play are less well understood. Finally, there is a need to create and grow local knowledge networks to ensure effective knowledge exchange and build the evidence base around Windermere, for example, local anglers are likely to have the most current information on fish stocks (Shephard *et al.*, 2023).

4.2. Research needs

At the most fundamental level, the people carrying capacity for a catchment like that of Windermere's needs to be understood in order to improve infrastructure to increase carrying capacity if required, i.e. number of visitors currently exceeds what the catchment can support. If improvements to infrastructure cannot be made, then development of new hotels, B&Bs, hostels, campsites and caravan sites may need to cease to minimise additional visitors to the catchment, or a 'visitor revenue income' may need to be implemented to support restoration activities or maintenance of mains and non-mains drainage systems. There has been some work on historic human influence on the catchment (McGowan *et al.*, 2012; Moorhouse *et al.*, 2014, 2018) but parish records are deficient for certain years.

Following on from this, the impact of influxes and outfluxes of visitors on non-mains drainage needs to be quantified to make non-mains drainage more resilient to future change. Data on the number of properties with septic tanks and which of these are holiday lets would be needed. Permitted non-mains drainage systems have more data and initial work on these suggests that 50% of properties with septic tanks may be holiday lets as opposed to local owners (SCRT, *personal communication*). However, this is a rough estimate and some privately owned properties may be second homes.

Investigations into the potential impacts of human activities (e.g. boating, kayaking, paddle boarding, outdoor swimming, hillwalking, feeding waterfowl) on the chemical and biological quality of freshwater and terrestrial habitats in the Leven catchment are needed. Similarly, the effects of emerging contaminants associated with humans (e.g. road salt, heavy metals, rubber/tyre particles, pharmaceuticals) and domestic animals (e.g. flea/tick treatments) on environmental conditions are largely unknown and need to be quantified (Pickering, 2001; Venohr *et al*. 2018; Gillis *et al*., 2022; Diepens *et al*., 2023)

Finally, stakeholders need to consider ways to expand local knowledge networks by engaging more people with messaging and facilitating feedback, and creating citizen science and volunteering opportunities. Understanding the resident and visitor perception of impacts on Windermere and what the lake should look like and be used for will be key to inform management that will strike the right balance for people and nature.

4.3. Aims and objectives

Over the next 5 years:

- Stakeholders should aim to understand public perception of the lake through a structured questionnaire and in-person events. Information would need to be provided to get people's interpretations (e.g. asking people to correctly identify good- and poor-quality habitat based on pictures) and the outcome would need to be clear, e.g. prioritising what researchers would work on. Separate sections could be included to target different users, e.g. outdoor swimmers.
- More communication and engagement activities should occur to increase awareness on pressures and individual actions that can be taken, e.g. flyers or campaigns around pre-loading septic tanks in preparation for busy periods and emptying requirements, littering, and "check, clean, dry" to prevent spread of INNS.

In the long-term:

- The carrying capacity of the catchment needs to be established to identify improvements to infrastructure or manage visitor numbers.
- The impacts of tourism (i.e. visitor vs. resident population) on nutrient inputs from mains and non-mains drainage need to be quantified to inform targeted management at the right locations and time of year.
- The impacts of different activities (e.g. boating, kayaking, paddle boarding, outdoor swimming), numbers of people partaking in each activity, and associated pollution/damage/disturbance on the biology and chemistry of freshwater and terrestrial habitat in the Leven catchment needs to be identified.
- Long-term changes in land use and land cover should be examined.
- The effects of emerging contaminants associated with humans (e.g. road salt, heavy metals, rubber/tyre particles, pharmaceuticals) and domestic animals (e.g. flea/tick treatments) and whether these are associated with changes in land use or run-off patterns should be researched.
- Public access to data and evidence generated on Windermere and the wider catchment should be facilitated through a user-friendly, interactive platform.

5. Monitoring

The current state of knowledge on the theme area of monitoring in Windermere is reviewed and summarised throughout section 2 of the State of Windermere report (Harper, 2024).

5.1. Knowledge gaps

Although the lake's geology, hydrology and water chemistry have been extensively studied, and long-term records exist for phytoplankton, zooplankton and fish, systematically recorded information on other taxonomic groups is sparse.

Furthermore, funding cuts to monitoring programmes mean that fish populations have not been monitored since 2017, some environmental parameters are no longer recorded, and the frequency of sampling or number of waterbodies sampled has decreased. These cuts threaten the longevity of these programmes and the crucial evidence they generate on lake health.

If anything, more high-frequency data on the catchment and continuous in-lake monitoring is needed in addition to the high-frequency automated monitoring buoys deployed by UKCEH in key lakes (i.e. Windermere North Basin, Windermere South Basin, Esthwaite Water, Blelham Tarn), and the high-frequency sondes deployed by the Environment Agency and United Utilities in key inflowing becks, e.g. Cunsey Beck, Trout Beck, Mill Beck. These efforts focus on surface water but sampling at depth is also needed to understand environmental conditions in the deepest parts of the lake. At present, it is unclear exactly what spatial coverage and timescales are needed to capture variation in individual parameters but current efforts should not be reduced as different approaches currently provide daily, fortnightly, monthly, seasonal or annual insights.

New technologies can enhance existing monitoring by detecting cryptic taxa, automating processes, or providing entirely new information. These include remotely controlled and real-time instruments, eDNA analysis, hydroacoustics, drones and satellite imagery (Jackson *et al.*, 2016). Some of these technologies will be needed to develop new near real-time forecasting and data visualisation tools (e.g. Digital Twins) that would improve lake management by stakeholders, for example, expected date of an algal bloom or lake turnover (Page *et al.*, 2018). However, contemporary baseline assessments of the catchment's biology and water chemistry are needed before this in order to assess change over time in response to management interventions.

5.2. Research needs

Currently, Windermere is sampled for different physical parameters every hour by UKCEH automatic buoys, daily for temperature and hydrological parameters by the Environment Agency and FBA, fortnightly and monthly for physical, biological and chemical parameters by UKCEH, monthly for WFD assessment by the Environment Agency, seasonally each year for the BWS led by the FBA and Lancaster University, and seasonally every 5 years as part of the Lakes Tour (UKCEH with other stakeholders). Irregular sampling is also undertaken by other organisations, such as SCRT, LDNPA, Lakes Aquarium, AAFAF, and Natural England, in different parts of the catchment.

It is unclear whether the spatial and temporal scales of existing monitoring are sufficient for every question identified in this plan. The frequency of data required to assess whether it is safe to swim in the water at specific times of year vs. the long-term health of the lake will be very different. Sondes and automatic buoys are a substantial investment so it may not be possible to deploy more unless forecasting was deemed to be the utmost priority. The BWS began in 2022 and has increased the spatial coverage of lake shoreline and riverbank monitoring in the catchment. If this and the long-running data sets from the UKCEH and Environment Agency continue and any patterns are identified, then stakeholders can begin to fill some of the knowledge gaps outlined in this plan and identify specific locations that should be prioritised for future monitoring. However, this is dependent on funding and staff resource, with the additional challenge of integrating the various datasets given the different temporal and spatial scales and parameters being measured with different equipment. It is also unknown whether additional organisations operating within and outside the Leven catchment have unpublished data that could address some of the research needs in this plan. Governance comes into play as one organisation needs to have oversight and resources to continually collate data and publications as well as synthesise results and integrate data sets.

It is more expensive to include emerging pathogens in routine water quality testing – an investment that likely cannot be justified when their numbers and impact are unknown thus this knowledge gap must be addressed first. However, citizen science represents an opportunity to engage local residents and bolster monitoring activity, for example, the impacts of septic tanks and agriculture could be assessed by volunteers sampling agricultural land and land around septic tanks and freshwaters adjacent to these. The challenge is identifying those properties then engaging with people to participate, especially landowners and farmers who would have easiest access.

Fish monitoring should be restarted and monitoring for other taxa, including native species and INNS, established by using technologies such as eDNA analysis and hydroacoustics (Winfield *et al.*, 2008; Hänfling *et al.*, 2016). However, fish ecologists are still needed to interpret the data. In 2024, the Lake District Charr Recovery and Management (LD-CHARM) project commenced. This project will initially focus on investigating the condition and use of Arctic charr spawning grounds in Windermere, plus investigations on population genetic characteristics of the Windermere population in the context of the wider Lake District (and beyond).

Forecasting is also a topic of particular interest and discussion, with proposals developed for Digital Twinning (a virtual representation of a real system that is constantly updated to accurately represent the current state and behaviour of that system) for freshwater systems. Coding the real-time element is the challenging part of producing a forecasting system that requires investment into data/Artificial Intelligence and digital infrastructure and would likely need to be supported via research grants. Researchers at UKCEH performed a preliminary exercise using data from Esthwaite Water and Windermere, but identified that poor spatial resolution and lack of adequate input data and weather forecasts for upland areas were a barrier (Page *et al.*, 2018). The frequency and resolution of the input data will depend on whether weekly, seasonal, or annual forecasts are required. Nonetheless, with funding, there is a strong digital science staff resource at the UKCEH which could be a valuable asset and provide vital data in future.

5.3. Aims and objectives

Over the next 5 years:

- Existing monitoring should continue to maintain long-term data sets, but this is subject to funding. This data facilitates comparison of trends in both basins of Windermere, and comparison of trends for inflowing tributaries in the catchment and other lakes to Windermere.
- Real-time phosphate monitors should be deployed across the catchment, covering the main tributaries and still waters. These will provide high frequency nutrient data, that are often lacking as key drivers of ecological models (e.g. PROTECH).

In the long-term:

- Stakeholders should submit funding proposals for new projects that would expand the spatial or temporal extent of monitoring, such as Water Quality Digital Twins, fish monitoring, and citizen science sampling for nutrient inputs from agriculture and septic tanks.
- Stakeholders should capitalise on and deploy new technologies wherever possible. United Utilities have deployed real-time water quality monitoring sondes in Esthwaite Water and Cunsey Beck. With funding, it would be possible to automate in-situ eDNA sampling and processing.

6. Conclusions

Nearly 40 years ago, Talling *et al.* (1986) identified six potential sources of change in Windermere: (i) climatic change; (ii) mechanical disturbance or alteration of the lake basin and its outflows; (iii) changing chemical input from the atmosphere plus drainage basin; (iv) changes in the quantity or quality of biological populations; (v) consequent changes in water characteristics; and (vi) biological hazards from introduced toxins, pathogens, predators, or invasive competitors. All have affected Windermere over the past nine decades.

Around 20 years ago, horizon scanning by Pickering (2001) identified the following challenges for lake management: inefficiency of phosphorus stripping, especially during heavy rainfall from WwTW; unquantified storm overflow discharge and impact on nutrient and faecal material inputs; climate change with expected temperature and annual rainfall increases that will have knock-on effects for lake processes and demand for water supply; ecotoxicological effects of emerging contaminants, such as hormones and boat materials; INNS; reedbed decline; and continued human development.

Despite substantial investment in improvements to WwTW, reductions in spills from storm overflows, extensive scientific monitoring and research, practical conservation and restoration efforts, and outreach and engagement activities over the last 20 years, these challenges remain in 2024. Climate change is one of the biggest threats to lake health due to alterations in frequency and intensity of weather patterns that have consequences for physical, chemical and biological processes in the lake and wider catchment. Changing inputs, particularly nutrients, is the other key issue that will continue to influence the future condition of the lake and the catchment for better or worse through knock-on effects for the biological community. INNS and emerging pathogens and contaminants will continue to play an increasingly important role as temperatures rise and human activity increases. The most intense outbreaks of avian influenza in the UK have occurred since 2021, and the disease was detected in wild birds and commercial poultry in the Leven catchment in 2023. Domestic animals transfer pesticides through flea and tick treatments into the environment at concentrations that present a risk to both terrestrial and aquatic ecosystems (Diepens *et al.*, 2023), but this has not yet been investigated in Windermere. Similarly, road run-off contains particles and compounds from tyre wear, dust suppressants, as well as various de-icing salts and metals that can be toxic to aquatic biota (Gillis *et al.*, 2022) but these effects need to be quantified. With a growing human population, residential housing and holiday accommodation developments will continue, converting more of the land to urban and suburban land cover. These pressures will continue to impact the lake in the future, with some potentially irreversible effects, and recovery is likely to be slow even after any interventions.

Key challenges/priorities outlined in this report are summarised in Table 1, with the current situation, key ecological impacts, key pressures and the main practical and research needs listed. The investment required to address these issues in both the short- and long-terms are significant and will require substantial commitment from a wide range of stakeholders for them to be realised.

Table 1: Summary of the status of key ecological impacts and pressures affecting the current state of Windermere. *The current situation and key ecological impacts and pressures are outlined, as well as the main priorities for practical (P) and research (R) activities within the catchment.*

Challenge	Current situation	Ecological impacts	Key pressures	Practical measures (P) and research needs (R)
Nutrient enrichment	Nutrient concentrations remain elevated despite reductions since late 20th Century Phytoplankton biomass, communities and timings of blooms being affected by nutrient enrichment	Increased primary productivity (algae and cyanobacteria) impacting both ecology and human-use of lakes Dissolved oxygen concentrations impacted by increased primary production and the subsequent decomposition of dead algal cells Changing algal communities and timing of blooms affecting the wider food web	Growing human population including tourism and high visitor numbers – human waste and use of products containing nutrients e.g. phosphates in washing products Agricultural inputs Forestry	**R** Better understand and quantify internal nutrient loading from lake sediments **R** Contemporary nutrient budget taking in to consideration all major nutrients (not just phosphorus) **P** Identify and investigate methods for amelioration of diffuse nutrient sources **P** Activities which reduce nutrient and sediment run-off from the land e.g. tree planting, wetland creation, reedbed restoration **P** Deploy real-time phosphate monitors across catchment, covering main tributaries and still waters **P** Communication of benefits of any nutrient reduction to local communities and businesses to inspire individual action **P&R** Identify and quantify nutrient loading from non-mains drainage. Improve private sewerage infrastructure monitoring and enforcement (where necessary) **P&R** Ongoing monitoring of algal communities

Challenge	Current situation	Ecological impacts	Key pressures	Practical measures (P) and research needs (R)
Low dissolved oxygen (DO)	Low DO concentrations at depth due to thermal stratification, lack of mixing and decomposition of organic matter on lake bed Low surface water DO concentrations due to high summer temperatures and the decomposition of inshore "algal scums"	Volume of habitable space decreases for mobile species (e.g. fish) as deep and surface waters become temporarily uninhabitable Chronic stress reduces survival and fitness of species Possibility of internal nutrient loading from lake bed sediments	Nutrient enrichment Climate change (longer periods of stable stratification under warmer weather conditions during summer)	**R** Investigate potential feedback loop of internal phosphorus loading and associated impacts due to low DO **P&R** Continuation of long-term monitoring programmes
Climate change	Surface water temperatures increasing More frequent and extreme weather events e.g. extended dry weather, severe rainfall/flooding Altered wind speeds and directions	More vulnerable, cold water species, e.g. Arctic charr, are particularly affected by the multiple pressures of climate change on water and habitat quality Altered habitats facilitating the spread and success of invasive species More sediment, nutrients and contaminants being delivered to water courses during significant rainfall events Changing thermal stratification affects the distribution of organisms within the water column Shifting seasonal timings of limnological events, affecting interactions between species	Human activity/growing human population Loss/degradation of habitats and natural processes exacerbates effects of extreme weather events	**R** Creation of conceptual model of climate impacts on the lake and the wider catchment with subsequent consideration of climate adaptation options **P** Creation of resources for public engagement activities, and delivery of public engagement events, to increase awareness and understanding **P&R** Continuation of long-term monitoring programmes to provide data for modelling

Challenge	Current situation	Ecological impacts	Key pressures	Practical measures (P) and research needs (R)
Faecal indicator organisms (FIOs)	Statutory monitoring for *E. coli* and intestinal enterococci at the four designated Bathing Waters on Windermere (all currently classed as Excellent status) No monitoring of other organisms or other locations, except as part of the Big Windermere Survey. Sources/pathways not clear	High concentrations can have human health impacts Effects on other species unknown	Wastewater from mains or non-mains sources, particularly if no treatment to kill bacteria before discharge. Agriculture (faecal matter from mammals entering water courses). Wild bird populations.	**R** Better understand sources and pathways of FIOs at greater spatial and temporal scales, potentially using Microbial Source Tracking or modern biomolecular methods. **P** Include monitoring for a wider range of pathogens. **P** Find out what water-users, especially outdoor swimmers, want to know about bathing water quality
Changes to phytoplankton communities	Changes in phytoplankton communities and timing of blooms The possibility of more frequent/intense algal and cyanobacterial blooms Monitoring of blooms currently only opportunistic (Bloomin' Algae) affecting communication with the public about possible health impacts	Blooms can pose health risks to humans, pets and livestock. Severe blooms can impact public water usage. Effects on food web as phytoplankton a primary producer.	Nutrient enrichment Climate change INNS affecting primary consumers (zooplankton)	**P&R** Continuation of long-term monitoring programmes and consideration of new monitoring opportunities to address the need to provide accurate and swift information to the public about bathing water safety **P&R** Contemporary biological baseline established **P&R** Systematic monitoring for algal blooms

Challenge	Current situation	Ecological impacts	Key pressures	Practical measures (P) and research needs (R)
Changes to zooplankton communities	Nutrient enrichment has led to recent species extinctions and a switch from a *Bosmina*- to *Daphnia*-dominated community in the 1940s Changes in timing of zooplankton population growth peaks	Timing of algal blooms (food for zooplankton) changing, leading to altered food availability during key seasonal “windows” Timing of *Daphnia* population spring peak has advanced due to altered phytoplankton growth patterns Impacts on fish recruitment of changing zooplankton-perch spawning synchrony Declining populations because of increased pressure from invasive species, e.g. roach Warmer surface water temperatures affecting zooplankton metabolism and lake thermal stratification impacting zooplankton distribution	INNS Climate change Nutrient enrichment	**P&R** Continuation of long-term monitoring programmes **P&R** Contemporary biological baseline established

Challenge	Current situation	Ecological impacts	Key pressures	Practical measures (P) and research needs (R)
Changes to fish communities	Multiple pressures affecting native fish populations such as timing of food availability, negative effects of invasive species, climate change, habitat degradation etc.	Perch populations negatively affected by earlier zooplankton population peaks; lower food availability for juvenile fish Arctic charr populations at a historic low level due to poor spawning habitat quality, invasive fish species, food competition & climate change effects More INNS (e.g. roach & ruffe), putting pressure on native fish.	Climate change Nutrient enrichment INNS Food availability and competition Declining dissolved oxygen concentrations	**R** Fish monitoring should be reinstated to understand the population dynamics of fish species in Windermere and to identify potential pressures on native species **R** Research should seek to clarify current population size, undertake a population genetics study in the wider Lake District context, identify the extent and condition of current spawning grounds and propose a conservation plan for Arctic charr in Windermere. **P&R** Contemporary biological baseline established
Human use	The Leven catchment is one of the most visited parts of the Lake District National Park with an estimated 7 million visitors in 2019, and a resident population of 14,000 – 17,500 individuals	Introduction of INNS Decrease in biodiversity and species abundance due to habitat disturbance, degradation or loss Changes to community composition, species physiology and ecological functioning Changes to water chemistry	The pressures of use by people are complex but include nutrient enrichment, emerging contaminants associated with humans, physical disturbance and habitat degradation/loss	**R** Investigation into the potential impacts of human activities on the chemical and biological quality of freshwaters within the catchment, including the effects of emerging contaminants and pharmaceuticals **P** Increased engagement with local communities and tourists about practical measures they can undertake to reduce their personal impact and also to gather information about people's aspirations for Windermere.

Several stakeholders have a vested interest in Windermere but no single organisation has the responsibility or legislative power to fund and coordinate lake management and restoration, and there have been no lasting stakeholder partnerships. Current stakeholders include:

- The Environment Agency is responsible for monitoring, maintaining and improving water quality across England and Wales, and sets limits on permitted discharges that prevent deterioration in water quality.
- United Utilities is a supplier of drinking water and responsible for the management, treatment and disposal of wastewater from the public sewerage system.
- The LDNPA is part of the local government in the Lake District and has some, but not all, of the powers and duties of local councils. It aims to conserve and enhance the natural beauty, wildlife and cultural heritage of the LDNP for the wider public through practical restoration, management of recreation, repair and maintenance of rights of way, visitor centres, and ranger assistance and enforcement.
- The National Trust is a major landowner in the Lake District and committed to environmental conservation and habitat improvement. Alongside tenant farmers, the National Trust looks after 20% of the LDNP, including England's deepest lake (Wastwater) and highest mountain (Scafell Pike). The charity restores habitats for nature and conserves the cultural heritage within a dozen historic buildings.
- Westmorland & Furness Council is the local authority which covers the Leven catchment. It is the current owner of the lake bed, influences day-to-day management, and represents the general public.
- Maintenance of major roads is the responsibility of Cumbria Highways, a partnership between Cumbria County Council, Amey and Connect Roads.
- Cumbria Local Enterprise Partnership is a business-led partnership between local authorities and the private sector, whose role is to determine local economic priorities and undertake activities to drive economic growth and the creation of jobs.
- The National Farmers Union is member organisation/industry association for farmers in England and Wales, representing and championing their interests.
- The Lake District Foundation promotes and funds conservation, environmental and cultural heritage projects within the Lake District.
- Friends of the Lake District is committed to protecting and conserving the landscape and natural beauty of the Lake District and Cumbria more broadly.
- The FBA is a charity dedicated to understanding and protecting freshwater environments across the world, and initiated the long-term scientific monitoring on Windermere and other lakes in the Leven catchment in the mid 1900s.
- South Cumbria Rivers Trust is a charity dedicated to conserving and protecting the freshwater habitats and wildlife of the local area.
- Cumbria Wildlife Trust is part of a network of wildlife trusts across the UK, conserving wildlife and managing nature reserves within Cumbria.

- Natural England is responsible for monitoring and managing SSSIs and NNRs.
- Locally, UKCEH monitor and research the water chemistry, limnology and biology of Windermere and other lakes in the Leven catchment. More broadly, the Lake Ecosystems group conducts multidisciplinary research that provides process-based understanding of how lakes function. Results help with the planning, assessment and implementation of whole-lake restoration programmes within the UK and beyond. The wider organisation conducts environmental science across water, land and air to inform policy, commercial innovation and conservation action globally.
- The Graythwaite Estate is one of the largest private estates (5,000 acres) in the LDNP, with lake and woodland habitat, that caters to holidays, experiences and gatherings. The owners strive to minimise impact on the environment and to preserve the local wildlife and landscape.
- Cumbria Tourism is the official tourist board for the county with the aim of promoting tourism in the area.
- Recreation brings organisations such as the Royal Yachting Association, local boating clubs, outdoor and watersports centres, and anglers into the picture. The Lake Use Regulations require that all boats have foul water storage and that wastewater is brought ashore for disposal in to collection points around the lake.
- The public is the biggest end-user of the lake and ultimately the biggest polluter with the greatest potential to drive positive change. A number of residential properties are not connected to the public sewerage system and will be using other means of wastewater treatment.

The Love Windermere partnership was established in 2022 with the aim of bringing about a healthier future for the lake and the surrounding area, balancing the needs of nature, the community and the local economy, by uniting some of the major stakeholders. However, it is not the first attempt at partnership working. In 1999, a Lake District Still Waters Partnership was established with similar aims and partners, including the LDNPA, Environment Agency, Natural England, United Utilities, National Trust, UKCEH and the FBA. The book 'Windermere: restoring the health of England's largest lake' by Pickering (2001) was a major output from this partnership, which encompassed the programmes Bassenthwaite Reflections and Windermere Reflections which were also part of the of the LDNP Partnership. The Still Waters Partnership continued to meet until 2017/2018 but ultimately dissolved due to lack of funding and resource.

The 2011 project Windermere Reflections was a 3-year partnership programme supported by the Heritage Lottery Fund. There were 19 projects bringing long-term benefit to the area and increased understanding of environmental issues within the Leven catchment. The programme ran wide ranging activities, including tree planting and river restoration, footpath and cycle route creation, heritage surveys, arts events and initiatives to encourage sustainable choices reducing environmental impact. There were also free courses and numerous volunteering opportunities. In addition to Heritage Lottery Funding, core funding came from the Environment

Agency, LDNPA, the National Trust, and the University of Cumbria, with delivery partners including SCRT, Nurture Lakeland, Friends of the Lake District and Windermere Rotary (Clarke & Anteric, 2014). The programme left a lasting impact, but a similar effort has not been repeated since.

All individuals and organisations with an interest in Windermere and the wider Leven catchment, whether it be scientific, cultural or economic, need to commit to an integrated approach to manage and improve environmental conditions to benefit people and nature. Any plan will need to consider and accommodate as many interests as possible, and have infrastructure, governance, and funding in place to monitor progress towards objectives to ensure desired results are being seen or facilitate adaptive management. Tighter permits, byelaws, legislation and enforcement of these will be needed. Novel management interventions may need to be considered and trialled, such as floating solar farms (López *et al.*, 2022) and heat pumps (Eggimann *et al.*, 2023) to remove heat from the lake, biomanipulation to control algal blooms (Mehner *et al.*, 2002), and sediment phosphorus capping to minimise internal phosphorus release (Gibbs & Hickey, 2018). However, a strong understanding of lake processes is needed to identify which interventions are most appropriate to trial and for successful implementation; this WISP sets out the shorter- and longer-term scientific priorities to answer some of these questions.

From as early as 1990, there were calls for Windermere to become a UK Long-Term Reference Site for the freshwater environment due to the wealth of long-term data on species and communities that would enable responses to new environmental challenges to be addressed in the future (Elliott, 1990). This is more pertinent now than ever to ensure the continuation of long-term monitoring and research on Windermere and the wider Leven catchment, and confer some level of site-specific protection for the lake.

Windermere and the other lakes, tarns, becks and rivers in the wider Leven catchment are internationally important resources in terms of the ecological, aesthetic, cultural, recreational and economic services they provide. Much of the LDNP's appeal comes from its natural features, and how the water resources are managed in response to the environmental and socioeconomic pressures causing change will influence the quality and character of the LDNP in years to come.

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