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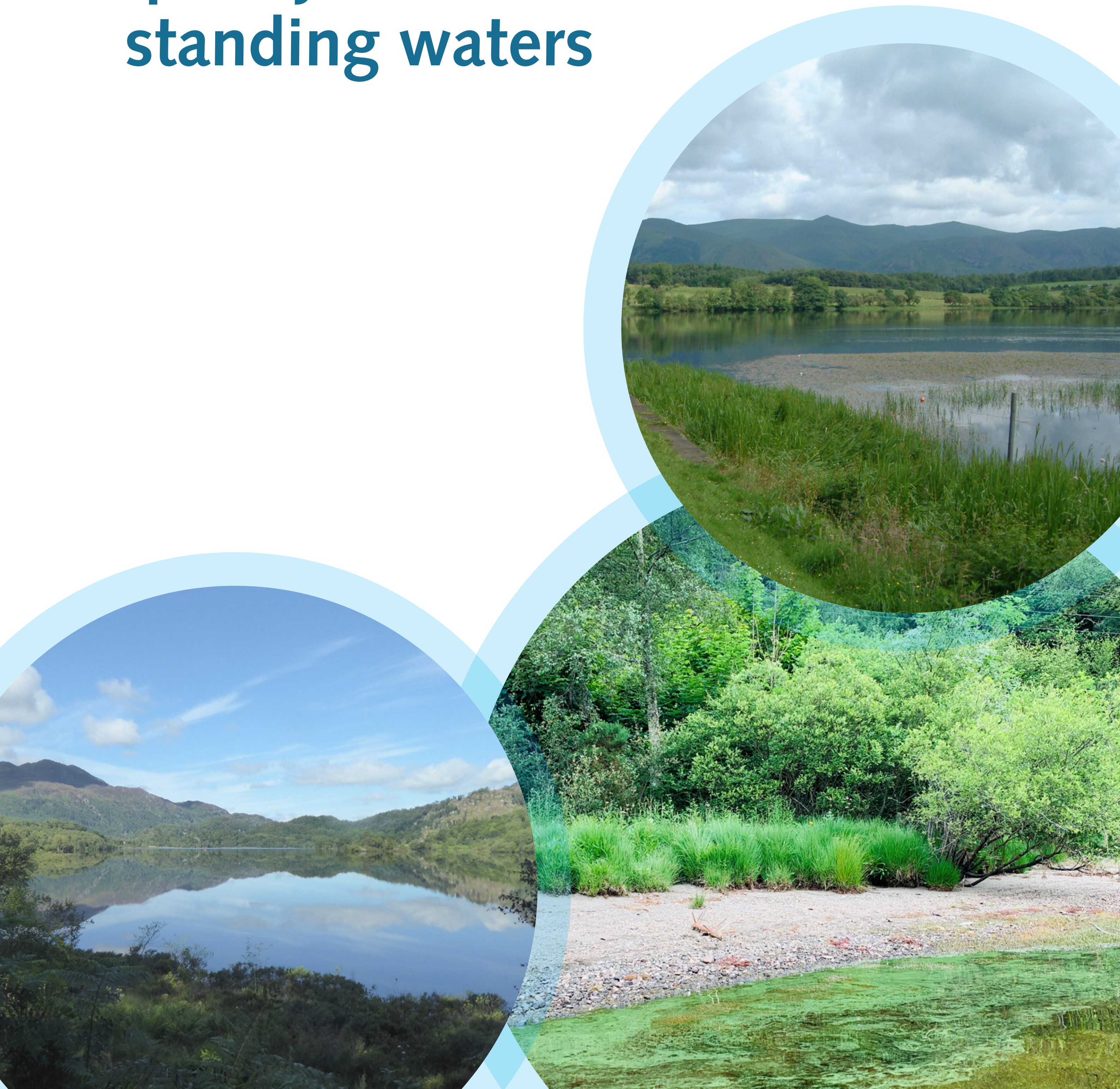
Assessing climate change impacts on the water quality of Scottish standing waters



CREW CENTRE OF EXPERTISE FOR WATERS

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Linda May, Philip Taylor, Iain D. M. Gunn, Stephen J. Thackeray, Laurence R. Carvalho, Peter Hunter, Mairéad Corr, Anne J. Dobel, Alanna Grant, Gemma Nash, Emma Robinson and Bryan M. Spears.

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Cover photographs courtesy of:
Bottom-left image: Loch Achray in the Trossachs, Stirlingshire (Linda May, UK CEH);
Bottom-right image: Evidence of algal bloom on Loch Lubnaig in the Trossachs, Stirlingshire (Pauline Lang, CREW); **Top-right image**: Gartmorn Dam in Clackmannanshire (Iain Gunn, UK CEH).

Contents

Glossary

Adaptation:	Taking action to prepare for, or adjust to, the current and/or future effects of climate change
Algae:	Group of mostly aquatic, microscopic plants that have no true roots, stems, leaves or multicellular reproductive structures
Alkalinity:	Buffering capacity of a water body; a measure of its ability to maintain a fairly stable pH level
Bathymetry:	Depth characteristics of lochs
Benthic:	Zone at the bottom of a waterbody
Bloom:	Proliferation of algal or cyanobacterial cells, often seen as a surface scum
Blue-green algae:	Commonly used synonym for cyanobacteria (see below) which can produce chemicals harmful to animal and human health
Catchment:	Area of land from which water drains into a waterbody; also known as a watershed or drainage basin
CHESS-SCAPE	Future climate data set derived from UK Climate Projections 2018 (UKCP18) that provides projections of several climate variables to 2080 at 1 km spatial resolution and time steps ranging from daily to decadal averages
Chlorophyll-*a*:	Green pigment in plants that converts light energy into chemical energy (photosynthesis); often used as a surrogate measure of algal abundance in standing waters
Climate change:	Changes to the local or global climate, usually attributed to increased levels of greenhouse gases in the atmosphere
Cyanobacteria:	Microscopic photosynthetic bacteria, or blue-green algae (BGA), which may form visible surface blooms in the water column or shoreline scums when present in high concentrations
Diatoms:	Microscopic algae with a silica cell wall, commonly found in standing waters
Epilimnion:	See thermal stratification
Eutrophic:	Description of water enriched with nutrients
Eutrophication:	Process of nutrient enrichment in aquatic ecosystems
Evapotranspiration:	Combined term used to describe water lost as vapour from a soil or open water surface (evaporation) and that lost from the surface of a plant, mainly *via* its stomata (transpiration)
Flushing rate:	Time taken to replace the entire volume of a standing water; the inverse of water retention time
Humic loch/reservoir:	Description of a standing body of water with brown, acidic water
Hydrological extremes:	Extreme hydrological conditions such as droughts and floods
Hypolimnion:	See thermal stratification
Lake/Loch:	Area of standing water surrounded by land; for the purposes of this project, this includes lochs, reservoirs and locally important still waters greater than 1 ha in area
Limnology:	Study of inland waters
Littoral zone:	Shallow water around the shores of a body of standing water that rooted plants can colonise
Nitrogen:	Chemical element required by biological organisms for growth; often referred to as a nutrient
Nutrient limitation:	A process through which a biological process, such as algal growth, is controlled by a lack of nutrient availability
Oligotrophic:	Description of water containing a low concentration of nutrients
Palaeolimnology:	Study of the history and development of freshwater ecosystems, especially lochs, by reconstructing past environments from chemical, physical or biological properties of their sediments

Phenology:	Study of the seasonal occurrence of animals and plants in relation to their environment
Phosphorus:	Chemical element required by biological organisms for growth; often referred to as a nutrient
Photosynthesis:	Process by which green plants use chlorophyll to convert sunlight, water and carbon dioxide into oxygen and chemical energy
Phytoplankton:	Plant plankton that form the basis of many aquatic food webs
Plankton:	Small or microscopic aquatic organisms that drift in the water column
Pond:	A small body of still or standing water formed naturally or by artificial means; smaller than a loch or reservoir
RCP:	Representative Concentration Pathways (RCPs) are a method of capturing assumptions about economic, social and physical changes to our environment that will influence climate change within a set of future change scenarios; there are 4 RCPs available within the UKCP18/CHESS-SCAPE datasets used in this project. These are RCP2.6, RCP4.5, RCP6.0 and RCP8.5, where the number represents the radiative forcing targets for 2100 in watts per square metre ($W\ m^{-2}$); each RCP pathway gives a good indication of the overall level of warming that is likely to occur under each scenario
RCP ensemble member:	Each RCP contains four ensemble members (01, 02, 03, 04); member 01 is the default parameterisation of the Hadley Centre Climate model and the others provide an estimate of climate model uncertainty
Reactive phosphorus:	Also known as orthophosphate, a soluble form of phosphorus that can be taken up by algae
Redox:	A chemical reaction in which the oxidation state of atoms is changed
Reservoir:	Enlarged natural or artificial standing waterbody created using a dam
Residence time:	The average time that water (or a dissolved substance) spends in a particular standing water; also called retention time
Retention time:	See residence time
Silica:	A chemical element required for growth by diatoms
Standing water:	Stationary or relatively still inland fresh waters, i.e., lochs, reservoirs or ponds
Thermal stratification:	Change in the temperature at different depths in a standing water due to the change in water density with temperature; this creates three distinct layers – the epilimnion (upper warm layer); the metalimnion (middle layer); and the hypolimnion (cool bottom layer)
Thermocline:	See thermal stratification
Total oxidisable nitrogen:	The sum of nitrate and nitrite concentrations in water
Trophic asynchrony:	Phenological mismatch occurs when interacting species change the timing of phases in their life cycles at different rates
Turbidity:	A measure of suspended material in a waterbody that affects water clarity
Zooplankton:	Animal plankton (including small crustaceans and rotifers) that typically feed on algae

Executive Summary

Background

In their summary of the up-to-date evidence of observed climate change trends in the UK over recent decades, the UK Climate Change Committee (2021) highlighted the following patterns of change:

- *Warmer average air temperatures*. The UK's annual average air temperature has risen by about 0.6°C over the period 1981-2000. This equates to a rise of almost 0.3°C per decade since the 1980s.
- *Changed temperature extremes*. The average duration of heatwaves (periods with more than three days in excess of 25°C) has increased over time, with summers as hot as in 2018 (the warmest summer on record) expected to occur in one year in four in the future.
- *Changed rainfall extremes*. Heavy rainfall events have increased across the UK, although the association with human-induced climate change is still difficult to distinguish from inter-annual variability within the observational record.

The UK Climate Change Committee (2021) has also summarised the major changes expected in the UK's climate by 2050. These include the following projected scenarios:

- *Warmer and wetter winters*: By 2050, the UK's average winter is expected to be c. 1°C warmer (0.5°C cooler – 2.5°C warmer uncertainty range) and c. 5% wetter (10% drier – 20% wetter uncertainty range) than the averages recorded between 1981 and 2000.
- *Hotter and drier summers*: By 2050, the UK's average summer could be c. 1.5°C warmer (0°C – 3°C uncertainty range) than between 1981 and 2000 and around 10% drier (30% drier – 5% wetter uncertainty range). The intensity of summer rainfall (when it occurs) is expected to increase, and changes in evapotranspiration and water demand are expected to result in water supplies becoming less reliable (Afazal et al., 2015).

If global warming reaches 4°C above pre-industrial levels by 2100, then further significant changes in UK climate would be expected by 2050.

Scotland, like the rest of the world and UK as a whole, is facing an unprecedented climate change crisis. Amongst other impacts, this is affecting the quality of its standing waters[1]. There is now an urgent need for evidence (UK Climate Change Committee, 2022) to evaluate climate-related risks and inform fit for purpose climate change adaptation strategies that can be created and implemented in Scotland without delay. These will safeguard the integrity, biodiversity and sustainable use of the water environment, for people and for nature.

Currently, we have focused on compiling the key information needed to assess and understand climate change impacts on the water quality of Scottish standing waters. However, outputs from this project may help steer direction of future work aimed at strengthening evidence to inform the prioritisation, collaborative development, and implementation of climate change mitigation and/or adaptation strategies urgently needing to be embedded and delivered in Scotland.

Aim, Research Questions and Key Findings

Against this background of climate change scenarios, the overall aim of this project was to compile and assess the key evidence required to improve our understanding of climate change impacts on the water quality of Scottish standing waters at national, regional and local scales. The project focussed on the interactions between climate change, the drivers of eutrophication problems and their impacts. We synthesised information from the literature, expert opinion and monitoring data, using statistical analyses and visualisation (mainly mapping) combined with climate change scenario modelling to meet project objectives. Six strategic water research questions (RQs) have been addressed. Our key findings (KFs) are summarised below:

RQ1: Is there evidence of a causal link between climate change impacts and water quality issues in Scottish standing waters at national, regional and local scales?

- **KF1.1: Climate change is affecting the water quality of Scottish standing waters, specifically in relation to algal blooms, at multiple scales; mostly through increases in air temperatures and changes in rainfall patterns.**
    - o Increases in rainfall, especially high rainfall events, will increase the delivery of pollutants (such as sediment and nutrient run-off) to standing waters from their catchments; this will cause nutrient enrichment (eutrophication) problems such as algal blooms – especially of cyanobacteria.
    - o Decreases in rainfall, including an increase in droughts, reduce the flushing rates of lochs and reservoirs and, potentially, their water levels; this will encourage algal blooms and result in habitat degradation and loss of biodiversity.

[1]For the purpose of this project, these are defined as lochs, reservoirs and locally important still waters, excluding those that are temporary, of less than 1 ha in area or less than 1 m in depth, using the criteria in Annex 1 of the SSSI site selection guidelines (2018).

- o Increases in air temperature leads to an increase in water temperature that favours the development of algal (particularly of cyanobacteria) blooms in standing waters during the typical growing season of April to September; a reduction in the availability of nitrogen and silica as temperatures rise will allow cyanobacteria to outcompete other types of phytoplankton.

- **KF1.2: Increases in Scottish loch and reservoir temperatures are closely related to changes in air temperatures; rapid and extensive climate change-driven warming of these standing waters has already occurred in recent years and is expected to continue increasing.**
  - o Between 2010 and 2019, average water temperatures of Scottish lochs and reservoirs, between April and September, increased 1.2 times faster than corresponding air temperatures.
  - o Based on monitoring data collected between 2015 and 2019, 97% of Scottish lochs and reservoirs experienced an increase in temperature over this period, with most (88%) warming by between 0.25°C and 1.0°C per year and a small number (9%) increasing by 1.0°C to 1.3°C per year.
  - o Standing waters are more likely to experience blooms of algae and cyanobacteria as water temperatures increase if there are sufficient nutrients (mainly nitrogen and phosphorus) available to support their growth.

- **KF1.3: Water temperature increases in many lochs and reservoirs have already been recorded; standing waters are projected to get warmer in the south and east of Scotland but this climate-related risk will spread further and reach all parts of Scotland by 2040.**
  - o Climate-driven temperature changes are already occurring over multiple timescales, and are evident in decadal scale trends, seasonal changes and shorter-lived extreme events.
  - o Short periods of extremely high water temperatures ('lake heatwaves') are likely to increase in occurrence, exacerbating the adverse effects of long-term warming; however these are expected be less intense in deeper lakes than shallower standing waters.
  - o Lake heatwaves are likely to push aquatic ecosystems beyond the limits of their resilience, posing a threat to their biodiversity and related benefits they provide to society; this is especially true where low connectivity to other freshwaters mean that species will need to adapt within.

RQ2: What are the main types of climate-driven water quality impacts identified in Scottish standing waters under current and projected climate change scenarios?

- **KF2.1: Climate change will increase the risk of algal blooms developing in Scottish lochs and reservoirs – especially potentially harmful cyanobacteria.**
  - o Increases in nutrient inputs and reductions in flushing rates, combined with warmer water temperatures, will increase the likelihood that blooms of algae and potentially harmful cyanobacteria will occur; their duration of occurrence may also expand.
  - o Low flushing rates associated with higher water temperatures will increase the risk of nutrients being released from the sediments, fuelling sudden increases in algal growth.
  - o High flushing rates will deliver more nutrients to standing waters from their catchment but, at the same time, limit the rate of accumulation of algae and cyanobacteria in the water due to an increase in losses from the outflow.

- **KF2.2: Increases in algal blooms are often associated with a higher risk of potentially harmful toxins from cyanobacteria being released into the water; the likelihood of this occurring will increase with warmer temperatures and lower flushing rates.**
  - o Algal blooms, especially of cyanobacteria, reduce the amenity value of standing waters by increasing the risk of people and animals experiencing adverse effects on their health and welfare when visiting affected water bodies.
  - o Increases in harmful algal blooms (likelihood and duration of occurrences) would prevent water quality targets being met for water supply and/or safe recreational use, leading to higher water treatment costs and/or restrictions on visitor access.
  - o Further challenges in protecting public and animal health (e.g., recast Drinking Water Directive; revised Scottish Government guidance on cyanobacteria also known as blue-green algae in inland and inshore waters), as well as preventing failure to meet or restore water quality targets (e.g., EU Water Framework Directive), will increase if cyanobacterial blooms become more common.
  - o Increases in algal blooms will impede statutory environmental objectives being met within policy/regulatory relevant timescales, have an adverse impact on biodiversity and reduce the capacity of water managers to deliver water quality improvements or maintain effective compliance measures that prevent further deterioration.

RQ3: Which areas, locations and types of Scottish standing waters are currently most to least at risk of developing water quality issues due to climate change impacts at national, regional and local scales?

- **KF3.1: Currently, all types of Scottish standing waters in all areas and locations are at high risk of climate change impacts.**
  - The average April to September surface water temperatures of lochs and reservoirs across Scotland showed that, between 2015 and 2019, 97% of these waterbodies had warmed year on year.
  - Maps of average April to September water temperatures between 2015 and 2019 showed a general increase in temperatures across the whole of Scotland over this period.
  - Most lochs and reservoirs increased by 0.25 to 1.0°C per year between 2015 and 2019, but at four sites (i.e., Loch Achray, Loch Lubnaig, Loch of Girlsta, Loch Sgamhain) water temperatures increased by between 1.0 and 1.3°C per year.
- **KF3.2: Different types of lochs and reservoirs will respond differently to climate change impacts, with some more likely to develop water quality issues than others.**
  - Although all lochs and reservoirs are warming, shallow and very shallow systems are likely to be more sensitive to climate extremes than deeper waterbodies because of their higher surface area to volume ratio.
  - High concentrations of cyanobacteria were found to be rare in deep lochs and reservoirs, and those with 'humic' (coloured) water, although humic lochs tended to have a higher number of algal blooms than clear water lochs.
  - As water temperatures increased, high concentrations of cyanobacteria occurred across the whole range of alkalinity types; however, these were more likely to occur in lochs and reservoirs with medium alkalinity.
  - Reservoirs are more likely to be affected by climate change than waterbodies with a more natural hydrological regime because higher levels of abstraction under low rainfall conditions will exacerbate the combined effects of less water coming in from the catchment and higher evaporation rates.

RQ4: Which areas, locations and types of Scottish standing waters are likely to experience exacerbated water quality risks under projected climate change scenarios?

- **KF4.1: Water temperatures across different types of lochs and reservoirs are already warming in most places; this climate-driven trend is projected to further increase from south to north, with an exacerbated water temperature situation expanding to all parts of Scotland by 2040.**
  - Maps of projected water temperatures indicate that climate change impacts will be seen in lochs and reservoirs across the whole of Scotland.
  - Average April to September air temperatures are projected to rise by about 2.5°C between 2020 and 2080; because loch and reservoir temperatures appear to be increasing by 1.2 times the rate of increase in air temperature, this equates to a corresponding increase of about 3°C in Scottish standing waters by 2080.
  - As water temperatures increase, deeper lochs and reservoirs are likely to experience changes in the depth and duration of thermal stratification, with earlier onset and longer periods of stratification causing changes in oxygen concentrations.
  - Decreases in oxygen concentrations will cause an increase in the release of sediment bound nutrients and other contaminants (such as manganese) into the overlying water; the increase in nutrients, especially phosphorus, will fuel sudden increases in potentially toxic algae and cyanobacteria.
  - It should be noted, however, that it is not possible to predict these climate change impacts precisely due to the widely recognised uncertainties surrounding climate change predictions; so, these results should be viewed with caution even though the relationships between the climate change data and the loch and reservoir temperature data have been validated for 2010 – 2019.
  - Further research is necessary to establish the relationships between climate change and water quality as the response of standing waters is complex and will be determined by the interaction of multiple factors. A key gap in our current knowledge is how climate change will affect the delivery of nutrients to a water body form its catchment – even with warmer temperatures, algal blooms cannot develop if there are insufficient nutrients available to support their growth.

RQ5: What factors contribute to the risk of water quality issues from climate change impacts in Scottish standing waters at national, regional, and local scales?

- **KF5.1: Climate change driven increases in water temperature and nutrient availability, and reductions in flushing rates, will increase the risk of water quality issues developing in Scottish lochs and reservoirs**.
  - The likelihood of algal blooms, especially of cyanobacteria, will increase as mean monthly water temperatures rise above 17°C; this temperature threshold for water quality impacts has been recognised across Europe and is not unique to Scotland, although the underlying reason for this is uncertain at present.
  - Maps showing changes in the frequency with which average monthly water temperatures are likely to exceed 17°C over time suggest that climate change will result in all Scottish lochs and reservoirs experiencing algal blooms by 2080, unless algal growth is nutrient limited.
  - Nutrient releases from the bottom sediments of lochs and reservoirs will be more likely to occur under climate change due to more frequent deoxygenation at the sediment/water interface; in combination with higher water temperatures, these increases in nutrient availability will lead to an increase in algal blooms.
  - Changes in zooplankton community composition are likely to occur when mean monthly water temperatures exceed 14°C; this will affect aquatic biodiversity – especially in relation to species, such as fish, that depend on these organisms as a source of food.
  - Shifts in the seasonal timing of biological communities will occur under the projected climate change scenarios; where this causes a mismatch in the timing between algal communities and their zooplankton grazers, algal blooms will be more likely to occur.
  - The lack of zooplankton data for Scottish standing waters, especially in the spring/early summer when the zooplankton induced clear water phase is most likely to be adversely affected, makes this difficult to evidence.
  - A key gap in our understanding is the time that biological communities will take to undergo an evolutionary adaption to climate change, and whether this will be fast enough to avoid the catastrophic loss of key species – especially of zooplankton, which play a pivotal role in maintaining good water quality in standing waters.
- **KF5.2: Scottish loch and reservoir sensitivity factors will affect the risk of water quality issues developing due to climate change impacts.**
  - The statistical modelling of the loch and reservoir monitoring data showed that, at national scale, the causal relationships between chlorophyll-*a* concentrations and total phosphorus concentrations or water temperature are masked by variations among lochs and reservoirs in terms of their patterns of response.
  - Responses are likely to be more complex when climate change interacts with other pressures, especially where impacts cascade through connected ecological systems.
  - High levels of cyanobacteria are most common in shallow and very shallow lochs, especially those with medium alkalinity levels; these should be prioritised for mitigation purposes.
  - Humic lochs appear to be more prone to high biomass events than clear lochs; the reason for this is unclear.

RQ6: What factors need to be considered for mitigating climate-driven risks to water quality under current and projected climate change scenarios?

- **KF6.1: A whole system approach needs to be taken to mitigate future climate change impacts on standing waters.**
  - Mitigation of climate-driven risks to water quality under current and projected climate change scenarios needs to take a whole system approach, focusing on improved catchment management and sustainable use of water resources; this is a key policy requirement of, for example, the recast Drinking Water Directive (rDWD) and EU Water Framework Directive (WFD).
  - Where climate change impacts cannot be controlled by mitigation, adaptation may need to be considered.
  - Standing waters are subject to multiple interacting pressures that need to be taken into account when interventions are planned.
  - Site-specific analyses may be needed to inform management interventions aimed at reducing, or adapting to, climate change impacts.
  - Categorising lochs into typologies on the basis of depth or other physical characteristics may be insufficient to inform choices about management interventions; shallow and very shallow systems with high nutrient content should be prioritised first in terms of restorative or preventative management, because these are at highest risk of developing water quality problems.

- **KF6.2: An integrated catchment-based approach needs to be taken for setting water quality targets and planning interventions.**
  - o Statistical analysis of long-term monitoring data should be used to determine which site-specific combinations of TP concentration, flushing rate and water temperature would enable chlorophyll-*a* targets to be met.
  - o Where long term data are not available, site or type specific modelling should be used to identify where interventions can be targeted most cost effectively to achieve water quality targets into the future in un-monitored standing waters.
  - o Catchment based interventions, such as sustainable nature-based (or nature-inspired) solutions, should be considered.

Research Undertaken

This evidence-based review of the impacts of climate change on Scottish standing waters comprised (**1**) a review of published and unpublished literature to explore the likely effects of climate change on standing waters[2] in Scotland, (**2**) a survey of expert opinion to gain an insight into stakeholder perceptions of the impacts of climate change and (**3**) the development of a series of climate change scenarios for all standing waters in Scotland and their catchments. These climate change scenarios were validated against measured data where the time series overlapped and used to create projections of climate change impacts on standing waters to 2080. Available monitoring data were examined to identify water quality parameters that have already been affected by environmental pressures that are likely to change under future climate change scenarios, including loch and reservoir temperatures and flushing rates. Statistical analyses were undertaken to explore links between climate change drivers and impacts, especially in relation to water temperature and the likelihood of eutrophication problems leading to algal blooms. The results are presented as graphs, maps and tables, as appropriate.

Key Recommendations

As a result of this current project analysis, our key recommendations are outlined as follows:

Policy recommendations

The global envelope of climate change is currently affecting, and is projected to further impact on, standing water quality, especially in relation to increasing water temperatures and algal blooms. As part of an informed strategic and coordinated response to the climate crisis, Scotland needs to consider developing, revising, operationalising, and implementing a combination of broad, dynamic, and targeted policy changes for embedding a proportionate response to climate-driven impacts on people, policy, and the water environment across multiple scales, now and into the future. This is made clear from the recent UK Climate Change Committee (2022) Report to Scottish Parliament.

- **Global Climate Change Impacts – Adaptive National Water Policy Perspectives:** The policy gap between global and national understanding of the impacts of systemic climate change on water temperatures and changing rainfall patterns needs to be closed. Failure to address this issue and monitor for key indications of climate-related risks will undermine the development and implementation of adaptive water policy and management practices intended to mitigate complex interactions that affect water use and nutrient run off at regional and local scales.
- **National Climate Change Impacts – Adaptive Regional and Catchment Water Policy Perspectives:** Water policy and management practices need to be adapted to take into consideration national climate-driven risks on the quality of standing waters at regional and catchment scale in Scotland (e.g., River Basin Management Planning (RBMP); Third Land Use Strategy). These climate change impacts will be mediated through shifts in catchment and in-lake processes such as flushing rates, water levels, and nutrient inputs. In combination, these which exacerbate the future risk of algal blooms and may compromise Scotland's ability to meet statutory goals and regulatory targets within given timelines. Revision of current nutrient criteria for Scottish lochs and reservoirs may need to be considered, in conjunction with other policy-based and nature-based solutions, as a potential climate change mitigation/adaptation strategy, to support desirable legislative outcomes under different climate scenarios. For example, EU Water Framework Directive (WFD) targets for Scottish standing waters may need to be reviewed, and mitigation/adaptation climate strategies mobilised so that good ecological status can be achieved, prevent further deterioration and guide restorative action. It is anticipated that revision of nutrient standards and regulatory compliance permitting/assessment may need to consider climate-related risk in the future. This current analysis of climate-related water quality issues illustrates links between the twin climate and biodiversity crises colliding and being interwoven. This could form a significant contribution to the forthcoming Scottish Biodiversity Strategy (SBS; expected during 2022). This work could also lead to a re-assessment of the Scottish Government's

[2]These include lochs and reservoirs.

favourable condition targets for protected sites – particularly Special Areas of Conservation and Sites of Special Scientific Interest. It is also noted that the recast Drinking Water Directive (rDWD) will require the creation of Catchment Risk Assessments for all drinking water catchments to encourage greater source control of pollutants (known in the Directive as Hazards and Hazardous Events) i.e., a prevention-led approach for addressing climate change interactions with these catchment factors than reactively managing potential impacts (e.g., algal blooms) on public health with expensive treatment.

- **Regional Climate Change Impacts – Adaptive Local Water Policy Perspectives:** There is an urgent need to update the publication 'Cyanobacteria (Blue-Green Algae) in Inland and Inshore waters: Assessment and Minimisation of Risks to Public Health – Scottish Government Revised Guidance (2012)' in relation to climate change impacts by capturing new evidence that has emerged from this current analysis. This policy review would help protect the amenity value of locally important still waters (e.g., for recreational and wellbeing purposes), and reduce climate-driven water quality risks to public and animal health, whilst climate change mitigation/adaptation needs are being met through other policy routes.

Future monitoring recommendations

The recent UK Climate Change Committee (2022) Report to Scottish Parliament makes clear that 'Scotland lacks effective monitoring and evaluation systems meaning that changes in aspects of many climate-related risks are largely unknown'. Therefore, the existing monitoring network for Scottish lochs and reservoirs urgently needs to be reviewed with a focus on developing an integrated approach for detecting climate change impacts, at pace and scale, whilst including focussed use of new scientific innovations and adaptive resource capabilities. For example:

- Monitor water temperatures in Scottish standing waters at an accuracy of approximately 0.1°C to provide early warning that water quality issues are likely to develop.
- Monitor total and cyanobacterial chlorophyll-*a* concentrations using handheld devices that provide instantaneous data on accumulation of algal blooms, especially cyanobacteria.
- Measure nutrient inputs from catchments, including high temporal resolution gauging of inflows where site specific problems need to be addressed.
- Collect data on precipitation and wind speed to better represent the multi-faceted nature of climate change drivers and their impacts (e.g., storm-driven mixing events, "pulses" of polluted run-off during high rainfall events).
- Develop and monitor indicators of climate change impacts on ecosystem state, processes, and services.
- Explore the potential role of diverse monitoring approaches (e.g., earth observation, in-situ sensors, molecular techniques) for detecting and understanding climate change impacts.
- Consider how different data "streams", especially earth observation data, can be integrated to improve our ability to detect and forecast change.
- Support citizen science initiatives which can provide useful surveillance monitoring data (e.g., Bloomin' Algae app) for assessing climate change impacts on Scotland's water resources.

Further research recommendations

We have assessed that climate change is currently affecting the water quality of Scottish standing waters. We have also projected it will continue happening without urgent intervention to establish pace and scale of mitigation/adaptation strategies needed to course-correct an exacerbated warming situation in the future. This new evidence offers a significant contribution towards strategic climate change needs identified by the recent UK Climate Change Committee (2022) Report to Scottish Parliament. Yet there is still much to be learned about the extent, complexity, rate, and interactions of climate-related risks to water resources in Scotland. We have initially scratched the surface through this current analysis, and as such, there are potential opportunities to explore and understand this evidence in more depth through further analysis. The following research activities are recommended to make best use of the new information that is now available:

- A more in-depth analysis of the SEPA lochs and reservoirs monitoring dataset should be undertaken to improve our understanding the current impacts of climate change on standing waters, how these have developed over time and how they relate to waterbody structure and function.
- More research is needed to provide a better understanding of the links between climate change impacts at the catchment scale and their effects on downstream waterbodies, especially in relation to the propagation of the impacts of extreme climatic events such as storms, heatwaves, floods, and droughts. Existing lake and catchment models would need to be upgraded and linked together to achieve this.
- Further research is needed to understand the extent of climate change impacts on the ecological functioning of Scottish standing waters, especially

when ecosystems and biodiversity are likely to reach the point of no return (or tipping point), and *how* we can mitigate for this sort of potentially catastrophic collapse.

- There is a precise need to better understand why, and specifically what, ecosystem changes are generally triggered across Scotland and in wider Europe when mean monthly water temperatures exceed 17°C and favour the development algal blooms, especially cyanobacteria; as well as the important role of zooplankton as naturally occurring 'ecosystem engineers' or 'nature-based solutions' that maintain the good water quality of standing waters for example through grazing pressure. We also need to understand the capacity of zooplankton communities to undergo evolutionary adaptation fast enough to prevent a climate change induced ecological crisis.
- Probing connectivity in Scottish standing waters between the climate and biodiversity crises with modelled outputs examined against a broader context of biodiversity typology and classification system-based approaches (e.g., Duigan et al., 2006).

Potential future phase(s) of work recommendations

- **Delivery Purpose and Implementation Needs:** Potential future phase(s) of work should specifically consider addressing the factors that drive algal blooms and engaging sustainable system-based approaches for mitigation of, or adaptation to, current and future climate change impacts on the water quality of Scottish standing waters. This is in the interest of (**1**) delivering maximal water-related benefits for people and the environment; (**2**) co-creating effective solutions and supporting intended climate change adaptation outcomes; and (**3**) strengthening the evidence needed to inform coordinated adaptive management and strategic delivery responses by key stakeholders. Such responses may involve revising existing or developing new and innovative policy-based changes to, management strategies including the integration of nature-based solutions where feasible. These may involve targeting intervention by effective (e.g., response types or site-specific) approaches in a less data-intensive and more readily deployable way.
- **Prioritisation and Engagement Needs:** If required then further analysis should focus on identifying which lochs, reservoirs, and locally important still waters should be prioritised within a climate change mitigation and/or adaptation strategy. By actively engaging a broad range of individuals and organisations in knowledge-exchange opportunities, it should develop tailored approaches and management practices capable of reducing the risk of climate-driven impacts on the water quality of Scottish standing waters across multiple scales. Such outreach activities will need to engage with the primary beneficiaries, such as staff from strategic to operational levels across key stakeholder organisations including the Scottish Government and its environmental conservation and regulatory agencies (e.g., NatureScot, SEPA, DWQR), and water managers (e.g., Scottish Water). Outreach and engagement activities with representatives of the wider water community (e.g., public interest, local authorities, national park authorities, Fisheries Trusts and District Salmon Fishery Boards, anglers, Scottish Freshwater Group members) could include the creation of data visualisations, infographics, and storyboards to illustrate climate change impacts in an accessible way to empower others to become involved in shaping climate action.
- **Evidence-based Needs:** Given additional evidence needs, mapping and modelling tools to project the risk of algal blooms into the future need to be developed to help forecast which areas, locations and types of Scottish standing waters are most vulnerable or sensitive to bloom formation and the impacts of climate change at the national scale. This should be complemented by a more in-depth exploration of climate-driven risk (e.g., in relation to different water uses). Potentially, site-specific studies would help to identify effective management strategies for reducing or reversing climate change impacts on waterbodies at local to catchment scales. Scenario-based modelling approaches should be employed to examine the potential effectiveness of management interventions aimed at mitigating climate change impacts, especially catchment-based solutions such as land use change and nutrient neutrality-based approaches.

1 Introduction

1.1 Background and scope

In their summary of the up-to-date evidence of observed climate change trends in the UK over recent decades, the UK Climate Change Committee (2021) highlighted the following patterns of change:

- *Warmer average air temperatures.* The UK's annual average air temperature has risen by about 0.6°C over the period 1981-2000. This equates to a rise of almost 0.3°C per decade since the 1980s.
- *Changed temperature extremes.* The average duration of heatwaves (periods with more than three days in excess of 25°C) has increased over time, with summers as hot as in 2018 (the warmest summer on record) expected to occur in one year in four in the future.
- *Changed rainfall extremes.* Heavy rainfall events have increased across the UK, although the association with human-induced climate change is still difficult to distinguish from inter-annual variability within the observational record.

The UK Climate Change Committee (2021) has also summarised the major changes expected in the UK's climate by 2050. These include the following projected scenarios:

- *Warmer and wetter winters*: By 2050, the UK's average winter is expected to be c. 1°C warmer (0.5°C cooler – 2.5°C warmer uncertainty range) and c. 5% wetter (10% drier – 20% wetter uncertainty range) than the averages recorded between 1981 and 2000.
- *Hotter and drier summers:* By 2050, the UK's average summer could be c. 1.5°C warmer (0°C – 3°C uncertainty range) than between 1981 and 2000 and around 10% drier (30% drier – 5% wetter uncertainty range). The intensity of summer rainfall (when it occurs) is expected to increase, and changes in evapotranspiration and water demand are expected to result in water supplies becoming less reliable (Afazal et al., 2015).

If global warming reaches 4°C above pre-industrial levels by 2100, then further significant changes in UK climate would be expected by 2050.

Scotland, like the rest of the world and UK as a whole, is facing an unprecedented climate change crisis. Amongst other impacts, this is affecting the quality of its standing waters[3]. There is now an urgent need for evidence (UK Climate Change Committee, 2022) to evaluate climate-related risks and inform fit for purpose climate change adaptation strategies that can be created and implemented in Scotland without delay. These will safeguard the integrity, biodiversity and sustainable use of the water environment, for people and for nature.

Our changing climate is already affecting many standing waters across Scotland in the wake of the warmest decade on record (2011-2020). A particular concern is algal blooms and their related impacts. In recent years, these have become increasingly common in Scottish standing waters due to the combined effects of nutrient enrichment and climate change, and their complex interactions (e.g., warmer surface temperatures, shifts in seasonality and prevailing weather conditions, changes in flushing rate, and hydrological extremes such as floods and droughts) which may exacerbate the risk of water quality issues. Algal blooms, especially of cyanobacteria (blue-green algae), can reduce the amenity value of these standing waters, increase public health risk and water treatment costs, impede statutory environmental objectives from being met within policy/regulatory relevant timescales, and affect biodiversity and the capacity of water managers to deliver water quality improvement targets or maintain effective measures that prevent further deterioration. The effects of climate change on the factors that increase the risk of algal blooms developing are the main focus of this project.

The increasing importance of these climate change impacts on water quality issues in Scottish standing waters is reflected in revised and recent legislation, policy goals, statutory commitments and policy decisions at European, national, regional and local scales. These include:

- Climate Change Committee (2021). Independent Assessment of UK Climate Risk: Advice to Government for the Third Climate Risk Assessment (CCRA3)
- Climate Change (Scotland Act 2009) and Scottish Government Climate Emergency Response Statement (2019)
- Controlled Activities Regulations (Regulations) (2005)
- Cyanobacteria (Blue-Green Algae) in Inland and Inshore waters: Assessment and Minimisation of Risks to Public Health – Scottish Government Revised Guidance (2012)
- Defra (2018). A Green Future; Our 25 Year Plan to Improve the Environment
- Scottish Biodiversity Strategy post 2020 – Statement of Intent
- EU Habitats Directive (1992)
- EU Water Framework Directive (2000)

[3]For the purpose of this project, these are defined as lochs, reservoirs and locally important still waters, excluding those that are temporary, of less than 1 ha in area or less than 1 m in depth, using the criteria in Annex 1 of the SSSI site selection guidelines (2018).

- EU recast Drinking Water Directive (2021)
- Scottish Government land use strategy policy and future agri-environment support (2021) – e.g., Land Use - getting the best from our land strategy 2021-2026
- The State of Nature 2019 – The State of Nature partnership
- The Urban Waste Water Treatment (Scotland) Regulations 1994 and The Urban Waste Water Treatment (Scotland) Amendment Regulations 2003

1.2 Project objectives and research questions

The overall aim of this project was to compile and assess the key evidence required to improve our understanding of climate change impacts on the water quality of Scottish standing waters[4] at national, regional and local scales. The project focussed on the interactions between climate change, the drivers of eutrophication problems and their impacts. We synthesised information from the literature, expert opinion and monitoring data, using statistical analyses and visualisation (mainly mapping) combined with climate change scenario modelling to meet two project objectives and address the six strategic water research questions outlined below:

Objective 1 aimed to establish and deliver a preliminary evidence-base to enable the evaluation of the extent to which:

1.1. Climate change impacts are driving current and future risk of water quality issues arising in Scottish standing waters.

1.2. Climate change impacts on water quality are mediated through catchment management practices, in-loch processes and other interacting factors (e.g., prevailing weather; hydrological extremes) under current and projected climate change scenarios.

Objective 2 aimed to use expert opinion and best available evidence (from outputs from Objective 1 such as literature review, data exploration and modelling), to address the following key strategic water research questions:

Drivers and Impacts

1. Is there evidence of a causal link between climate change impacts and water quality issues in Scottish standing waters at national, regional and local scales?
2. What are the main types of climate-driven water quality impacts under current and projected climate change scenarios?

[4]These include lochs and reservoirs.

Risk

3. Which areas, locations and types of Scottish standing waters are currently most to least at risk of developing water quality issues due to climate change impacts at national, regional and local scales?
4. Which areas, locations and types of Scottish standing waters are likely to experience exacerbated water quality risks under projected climate change scenarios?

Factors

5. What factors contribute to the risk of water quality issues from climate change impacts in Scottish standing waters at national, regional and local scales?
6. What factors need to be considered for mitigating climate-driven risks to water quality under current and projected climate change scenarios?

1.3 Report structure

In this report, we have synthesised and summarised the results of 7 interdisciplinary technical appendices to answer the six water strategic research questions (see **Box 1**). These have been combined and published on the CREW website as a standalone project output for those needing more information about the research approaches used and evidence-base supporting our overall key findings and recommendations.

Box 1 The 7 technical appendices combined and published as a standalone project output.

- ***Appendix 1 –*** *Literature Review*
- ***Appendix 2 –*** *Survey of Expert Opinion*
- ***Appendix 3 –*** *Development of climate change scenarios from CHESS-SCAPE Future Climate dataset*
- ***Appendix 4 –*** *Exploration of SEPA monitoring data*
- ***Appendix 5 –*** *Relationship between chlorophyll-a concentrations and environmental factors that area likely to be affected by climate*
- ***Appendix 6 –*** *Site-specific effects of total phosphorus, air temperature and retention time on chlorophyll-a concentration in Loch Leven*
- ***Appendix 7 –*** *The potential for using remote sensing to monitor climate change impacts on water quality in Scottish standing waters*

2 Methods

2.1 Literature Review

A literature review was undertaken to collate and synthesise all available published and unpublished literature on the potential impacts of climate change on standing waters, especially in relation to Scotland. This followed the code of best practice established by Collins et al. (2015); a rapid scoping review was used to identify and summarise the available evidence, rather than conducting a full systematic review. Relevant literature was identified using web-based sources of information, such as Web of Science and Google Scholar. Priority was given to studies conducted within the UK, especially Scotland, but international literature from similar climatic zones was also consulted.

Evidence was gathered using three Web of Science (WoS) searches conducted on the 27th and 28th October 2021, using the following search terms and covering the period 2000 to 2021:

1. Climate change drivers: *(lake* OR loch* OR "standing water" OR pond* OR reservoir* OR lough*) AND (Scotland OR UK OR "northern Europe") AND ("air temperature" OR rainfall OR wind)* [1,456 references]
2. Primary impacts of climate change: *(lake* OR loch* OR "standing water" OR pond* OR reservoir* OR lough*) AND (Scotland OR UK OR "northern Europe") AND (flood* OR drought* OR "flushing rate" OR "water level" OR "ice cover"* [1,608 references]
3. Secondary impacts of climate change: *(lake* OR loch* OR "standing water" OR pond* OR reservoir* OR lough*) AND (Scotland OR UK OR "northern Europe") AND (eutrophication OR "algal bloom*" OR "invasive species" OR "oxygen level*" OR stratification OR turnover)* [1,279 references]

An additional literature search was carried out using Google Scholar and the search terms "climate change" and "Scottish lochs", to check for any peer-reviewed articles not found on WoS and any relevant unpublished literature that would not have been listed by WoS. This yielded 399 results, most of which had already been discovered in the WoS searches; however, some additional reports were found. These references were supplemented by information from the following sources: citations within these publications; our own knowledge of relevant published and unpublished reports; and additional information provided by Project Steering Group (PSG) members and other stakeholders. Please refer to Appendix 1 if more detailed information is needed.

Evidence from the literature review was compiled and summarised in an Excel spreadsheet, as a separate deliverable output, that provides a framework for addressing the overall project ask.

2.2 Survey of expert opinion

Expert opinion on the perceived impacts of climate change on Scottish standing waters was gathered from Scotland, other parts of the UK and beyond using an online survey based on questions agreed with Project Steering Group (PSG) members. These were distributed to members of a wide range of academic institutions, regulatory bodies, conservation agencies and policymakers who were not involved in this project directly. The survey was undertaken during November 2021. Please refer to Appendix 2 if more detailed information is needed.

The opinion of participants was sought on the following issues:

- Current and future impacts of climate change (rainfall, temperature, wind) on standing water ecosystems, especially in terms of nutrients, algal and cyanobacterial blooms, and other ecological responses.
- Current and future effects of climate change on water use (recreation, water supply etc.) and on Scotland's ability to meet regulatory and policy requirements.

We approached a wide pool of key individuals and organisations from across Scotland and beyond to take part in the expert opinion survey. Eleven responses were received by the project deadline. While we recognise the potential limits and uncertainties associated with extrapolating evidence from such a small dataset; the results have provided some useful insight into expert opinion for the current analysis and informed recommendations for potential future phase(s) of work.

2.3 Development of climate change scenarios

The climate change data (Robinson et al., 2022) used in this project were derived from the CHESS-SCAPE dataset; they comprised values for air temperature and rainfall at 1km resolution, with a monthly time-step. The data spanned December 1980 to November 2080, with the first 30 years being hindcast.

To project climate change into the future, it is necessary to make assumptions about the economic, social and physical changes to our environment. Representative Concentration Pathways (RCPs) are a method of capturing those assumptions within a set of future change scenarios (Met Office, 2018; van Vuuren et al., 2011). There are four RCPs available within the CHESS-SCAPE datasets (RCPs 2.6, 4.5, 6.0 and 8.5), where each number represents the radiative forcing targets for 2100 (W m^{-2}). The increase in global mean surface temperatures (averaged over 2081-2100), estimated for each RCP pathway, give a good indication of the overall level of warming expected under each scenario: 1.6°C for RCP2.6; 2.4°C for RCP4.5; 2.8°C for RCP6.0; and 4.3°C for RCP 8.5 (IPCC, 2018). Hausfather & Peters (2020) showed that RCP6.0 is probably the most likely of the four, so this scenario was chosen for use in this project.

Each RCP includes four ensemble members (01, 02, 03, 04), with member 01 being the default parameterisation of the Hadley Centre Climate model, and the others allow an estimate of climate model uncertainty. Member 01 sits close to the ensemble mean and has been used across all RCPs in this study.

Monthly air temperature data were extracted from the CHESS-SCAPE dataset for the centre points (centroids) of all Scottish standing waters for 1981-2080.

Not all rainfall is converted into run off from the catchment into standing waters; some is lost through evapotranspiration. To correct the rainfall data for evaporation and transpiration losses and calculate runoff, potential evapotranspiration (*PETI*) was calculated using the method developed by Robinson et al. (2017b), with all values based on the evaporative demand of the atmosphere over short grass. Runoff, or hydrologically effective rainfall (*EffRain*; m), was calculated from monthly precipitation data (*PR*; m) and potential evapotranspiration (*PETI*) as follows:

$EffRain = PR - PETI$

The data were extracted as mean values for each catchment.

Evapotranspiration varies with land cover. For this analysis, 1km resolution Land Cover Map (LCM 2015) data were used to provide this information. Each land cover class was assigned a ‘crop coefficient’ (*Kc*), with seasonal values approximated from three main sources of information (FAO, 1998; Nistor et al., 2015; Corbari et al., 2017) using an approach adapted from Richardson et al., 2018. Seasonal *Kc* values were then used to calculate an annual mean value, which was then used to calculate Actual Evapotranspiration (*AET*) as follows:

$AET = PETI * Kc$

Water retention time (RT; years) is a sensitivity factor that affects the impact of environmental change on the water quality of standing waters. This was calculated, for each loch, from *EffRain*, waterbody volume (*VolLake*; m^3), and catchment area (*CatchArea*; m^2) as follows:

$RT = VolLake / (CatchArea * EffRain)$

The data were compared with results obtained using measured flow data from the National River Flow Archive (NRFA) at 38 lake/loch outflow sites across the UK, averaged over the ten-year period 2004-13. For each RCP, a correction factor was derived to enable a validated set of retention times to be calculated from *EffRain* for each waterbody. All linear regressions had an R^2 of >0.9 and a slope >0.96, with the intercept set at 0.

To establish a relationship between the air temperatures derived from CHESS-SCAPE data and the loch and reservoir temperatures measured by SEPA, the two sets of data were compared for two 5-year periods, 2010-2014 and 2015-2019. These periods were split because the latter included some notable periods of warm weather and associated loch and reservoir warming events. Relationships between these variables were strong (R^2 >0.7) over both time periods, indicating the suitability of this approach for predicting loch and reservoir surface temperatures from modelled air temperatures. Please refer to Appendix 3 if more detailed information is needed.

2.4 Exploration of monitoring data

Monitoring data for Scottish standing waters were provided by the Scottish Environment Protection Agency (SEPA). The SEPA data comprised loch and reservoir monitoring data collected between 1989 and 2019, although the earlier years had many missing values which restricted their use in some of the analyses. Although the data included physical and chemical determinands from 175 lochs and reservoirs (amounting to 629,303 values), only data for total phosphorus (TP), total oxidisable nitrogen (TON), silicate, chlorophyll-*a*, pH, oxygen saturation and surface temperature were included in this study (142 sites; Table 1). It should be noted that the measured data were for surface temperatures only; no depth profile data were included within the SEPA dataset.

Surface water temperature data with a limit of resolution of at least 0.5°C were available for 142 (Table 1) lochs and reservoirs, but there were many gaps in the data especially during the winter months and in July and/or August. For the loch and reservoir temperature mapping, data were selected where there were at least four monthly data values between April and September, with no two missing values in consecutive months. The data were then summarised as April to September average water temperatures for each year between 2005 and 2019; any April to September average water temperature based on less than five monthly values was excluded from the analyses.

Table 1 List of lochs and reservoirs for which SEPA monitoring data were available; those designated as Heavily Modified Waterbodies (⁺HMWBs) for water supply highlighted in blue, hydropower in green, navigation in grey, flood protection in pink, biodiversity purpose in amber. ⁺HMWBs where the impoundment/abstraction is a significant consideration for this specific project. There are a few other examples that have a water supply abstraction, but they are not HMWBs, and their hydrology status is high, so impacts are minimal (I. Milne, SEPA, *pers. comm.*).

SEPA WBID	Name	SEPA WBID	Loch name	SEPA WBID	Name
100342	Butterstone Loch	100278	Loch Fitty	100003	Loch of Girlsta
100322	Castle Loch	100242	Loch Freuchie	100008	Loch of Harray
100294	Castle Semple Loch	100229	Loch Frisa	100012	Loch of Kirbister
100295	Cobbinshaw Reservoir	100303	Loch Garasdale	100225	Loch of Lintrathen
100313	Daer Reservoir	100190	Loch Garry	100235	Loch of Lowes
100276	Gartmorn Dam	100134	Loch Garve	100185	Loch of Skene
100287	Hillend Reservoir	100113	Loch Glascarnoch	100004	Loch of Spiggie
100300	Kilbirnie Loch	100275	Loch Glashan	100136	Loch of Strathbeg
100271	Lake of Menteith	100288	Loch Gorm	100005	Loch of Swannay
100112	Loch a' Bhraoin	100331	Loch Grannoch	100027	Loch of Toftingall
100238	Loch a' Phuill	100034	Loch Hempriggs	100141	Loch Olabhat
100097	Loch Achall	100019	Loch Hope	100162	Loch Olaidh Meadhanach
100140	Loch Achilty	100187	Loch Insh	100274	Loch Ore
100264	Loch Achray	100261	Loch Katrine	100084	Loch Osgaig
100199	Loch an t-Seilich	100326	Loch Ken	100167	Loch Ruthven
100270	Loch Ard	100334	Loch Kinder	100121	Loch Scadabhagh
100227	Loch Arienas	100192	Loch Kinord	100020	Loch Scarmclate
100197	Loch Arkaig	100198	Loch Laggan	100144	Loch Sgamhain
100259	Loch Avich	100223	Loch Laidon	100078	Loch Sgiobacleit
100585	Loch Awe	100099	Loch Langabhat	100208	Loch Shiel
100241	Loch Ba	100145	Loch Leathan	100065	Loch Shin
100228	Loch Bà	100209	Loch Lee	100260	Loch Sloy
100118	Loch Bad an Sgalaig	100269	Loch Leven	100039	Loch Stack
100042	Loch Badanloch	100194	Loch Lochy	100074	Loch Stranndabhat
100168	Loch Beinn a' Mheadhoin	100257	Loch Lomond	100180	Loch Tarff
20553	Loch Borralan	100029	Loch Loyal	100233	Loch Tay
100316	Loch Bradan	100258	Loch Lubnaig	100284	Loch Thom
100092	Loch Brora	100131	Loch Luichart	100110	Loch Tollaidh
100017	Loch Calder	100091	Loch Lurgainn	100256	Loch Tralaig
100133	Loch Carabhat	100327	Loch Maberry	100033	Loch Urghag
100166	Loch Chill Donnain Uarach	100109	Loch Maree	100139	Loch Ussie
100265	Loch Chon	100018	Loch Meadie	100108	Loch Vaich
100178	Loch Cluanie	100048	Loch Merkland	100266	Loch Venachar
100143	Loch Damh	100100	Loch Migdale	100079	Loch Veyatie
100324	Loch Dee	100030	Loch Mòr Bharabhais	100022	Loch Watten
100215	Loch Doilet	100035	Loch More	100157	Loch Lochindorb
100314	Loch Doon	100182	Loch Morlich	100329	Lochrutton Loch
100155	Loch Druidibeag	100160	Loch Moy	100330	Milton Loch
100268	Loch Drunkie	100202	Loch Muick	100338	Mochrum Loch
100176	Loch Dùn na Cille	100125	Loch nan Eun	100332	Penwhirn Reservoir
100161	Loch Duntelchaig	100070	Loch nan Ritheanan	100226	Rescobie Loch
100251	Loch Earn	100043	Loch Naver	100290	Roughrigg Reservoir
100272	Loch Eck	100246	Loch Nell	100307	St Mary's Loch
100224	Loch Eigheach	100156	Loch Ness	100296	Strathclyde Loch
100206	Loch Eilt	100328	Loch Ochiltree	100336	White Loch
100107	Loch Eye	100007	Loch of Boardhouse	100333	Woodhall Loch
100292	Loch Fad	100000	Loch of Cliff		
100119	Loch Fada	100236	Loch of Clunie		

April to September water temperature values were averaged over the three 5-year periods 2005-2009, 2010-2014 and 2015-2019, as well as over 2010-2019, and the derived values were plotted against similarly summarised climate change data for RCP 6.0 air temperatures. A relationship was derived between the air temperature values derived from CHESS-SCAPE and the water temperature values from the monitoring data, which was then used to predict loch and reservoir water temperature (*LochTemp*; °C) from air temperature (*AirTemp*; °C) into the future (Figure 1). This equation was:

LochTemp = 1.2033 x Air temp – 0.7697; R2 =0.3874

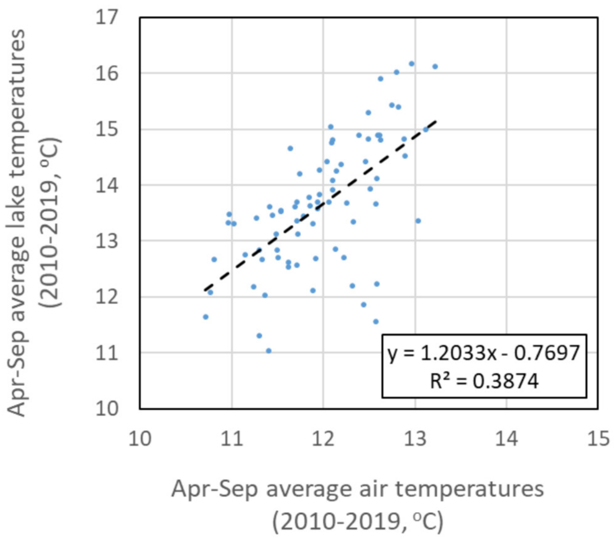

Figure 1 Relationship between RCP 6.0 modelled air temperatures and measured loch and reservoir water temperatures, averaged over April-September 2010-2019. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

To estimate the rate at which lochs and reservoirs warmed between 2015-2019, a linear correlation was applied to the annual average April to September values for each loch or reservoir over this period. As above, lochs and reservoirs were selected only if they had at least four monthly data values between April and September in any given year, with no two missing values in consecutive months, and annual mean April to September values for at least four of the five years. The slope of the line was used to estimate the rate of warming (°C per year) of each loch, and values were considered useable only if the associated regression line had a $R^2 > 0.3$.

Relationships between cyanobacterial biomass, total phosphorus concentrations and water temperature were explored for different loch and reservoir types (Table 2). Analyses were based on SEPA monitoring data from 62 lochs sampled between June and October, and from 2009 to 2012 (237 data points). Most of these data (229 data points) were collected between July and September. The data were explored visually, using bubble plots.

Table 2 Loch and reservoir depth, alkalinity and water colour types (typologies defined from WFD-UKTAG, 2014)

Depth type	**Mean depth (m)**
Very shallow (VS)	< 3m
Shallow (S)	3 – 15
Deep (D)	> 15
Alkalinity type	**Value (μEq L^{-1})**
High (HA)	> 1000
Moderate (MA)	200 - 1000
Low (LA)	< 200
Marl (M)	Limestone catchment
Water colour type	**Value (mg L^{-1} Pt)**
Clear (C)	< 30
Humic (H)	≥ 30
Polyhumic (PH)	≥ 30
Unknown (U)	N/A

Please refer to Appendix 4 if more detailed information is needed.

2.5 Relationship between chlorophyll-*a* concentrations and environmental factors across multiple lochs

Chlorophyll-*a* is an important proxy indicator of water quality responses to environmental pressures such as nutrient inputs and climate. It also acts as an indicator of whether water is suitable for recreational use or water supply, and of turbidity relating to algal or cyanobacterial blooms that reduce light penetration and suppress underwater plants.

Relationships between chlorophyll-*a* concentrations and environmental factors that are likely to be affected by climate change were investigated using a range of statistical models applied to the SEPA loch and reservoir monitoring data (2000-2019). Changes in monthly chlorophyll-*a* concentrations (summer months, July-September) in response to total phosphorus (TP) concentrations, water temperatures and retention times were explored. Information on the required variables were available for 133 lochs.

Before applying the models, chlorophyll-*a* concentrations; TP concentrations; and retention times estimated from the CHESS-SCAPE data were 'transformed' by taking the natural logarithm (Log_e) of the original values and 'standardised' by subtracting the mean and then dividing the result by the standard deviation. Water temperature was standardised but not transformed. Transformation and standardisation reduced skew in the variables prior to modelling, and ensured that model residuals were distributed approximately normally and showed constant variance. All predicted retention times of >100 years (i.e., those that appeared to be infinite due to lack of rainfall) were capped at 100 years. Please refer to Appendix 5 if more detailed information is needed.

Transformed and standardised mean summer (July to September) TP concentrations, water temperatures, and retention times for each month were included in the model, as were interaction terms:

$$\gamma = \beta_O + \beta_1\chi_{TP} + \beta_2\chi_{Temp} + \beta_3\chi_{Retention} + \beta_4\chi_{TP\ x\ Temp} + \beta_5\chi_{TP\ x\ Retention} + \beta_6\chi_{Temp\ x\ Retention} + \beta_7\chi_{TP\ x\ Temp\ x\ Retention} + \delta_{LakeID} + \delta_{year} + \varepsilon_{,} \quad \gamma \sim (0,\sigma_l^2), \quad \varepsilon \sim (0,\sigma_r^2)$$

where γ is the response of interest (chlorophyll-*a*), β_0 is the intercept term, and β_1, β_2, and β_3 are model parameters for TP concentration, water temperature and retention time terms, respectively. The model parameters for the interaction terms are β_4 (TP and temperature), β_5 (TP and retention time), β_6 (temperature and retention time) and β_7 (TP, temperature and retention time). δ_{LochID} and δ_{year} are the random effect terms for loch identification code and year, respectively, that allow the response to vary on the intercept for individual lochs and years. Finally, ε is the overall error term with a mean of zero and unknown variance (estimated during model fitting). Due to convergence issues, the random effect of month was excluded from the models.

Manual backwards selection based on Akaike Information Criterion (AIC) values was used to remove "unimportant variables" and arrive at the most parsimonious model, i.e., the simplest model that explains the most variability statistically. This resulted in four fixed effects (*mean.temp, TP, retention.time, mean.temp*retention.time*) and two random effects (*Loch.ID; Year*) being selected for the final model:

*Chlorophyll-a = mean.temp + TP + retention.time + mean.temp*retention.time + (1/Loch.ID) + (1|Year)*

2.6 Site-specific effects of total phosphorus concentration, air temperature and retention time on chlorophyll-*a* levels

Monitoring data from Loch Leven, collected by UKCEH as part of its UKSCAPE project, offers a unique time series of consistent data collected from a single sampling site at more or less fortnightly intervals between 1967 and 2017. These data were used to create a case study that demonstrates how interactions among phosphorus, temperature, and retention time affect the amount of algae and cyanobacteria (measured as chlorophyll-*a*) a waterbody develops. Please refer to Appendix 6 if more detailed information is needed.

2.6.1 Data processing

Chlorophyll-*a* concentration in the water column has been used as a proxy for algal and cyanobacterial biomass, and TP concentration in the water column as a proxy for nutrient enrichment. Chlorophyll-*a* and TP concentrations for the period 1989 to 2019 were extracted from the UKCEH Loch Leven Long-Term Monitoring dataset, and processed to create monthly averages. Data for air temperature and retention time at Loch Leven were abstracted from the climate change dataset described in Section 2.3. For the linear modelling, monthly retention times in excess of 100 years were capped at that value (n = 33 of 372 monthly values). Data for each variable were processed to produce average spring (March to May), summer (June to August), autumn (September to November) and annual (January to December) values for each year. This produced values for all seasons in all years and for all variables, except summer 2007 for retention time.

2.6.2 Pairwise linear modelling approach

The approach used in this study follows that described in Spears et al. (2022a), but with model selection forced systematically to predict the response variable (chlorophyll-*a* concentration) as a function of TP and either temperature or retention time. Individual pairwise models were constructed to aid visualisation of the interactions described below, allowing the hypothesis that climate stressors will interact with nutrient stressors to moderate chlorophyll-*a* concentration to be tested. All response variables were modelled with Gaussian errors and all models were fitted by maximum likelihood using the R lm function. Prior to model fitting, response variables and covariates were transformed using Box-Cox transformations, offset by a small value to ensure all values were greater than zero.

This approach was applied systematically for seasonal and annual conditions, to produce models with combinations of predictor variables such as TP and air temperature, and TP and retention time. Model residuals were checked for normality and constant variance. Predicted variation in chlorophyll-*a* concentration for each stressor pair was visualised using 'heat maps,' which depict the intensity of response along a blue (low) to red (high) gradient. The gradients of response and predictor variables included were constrained to the model input data. A reference value of 30 µg L^{-1} chlorophyll-*a* concentration was added to each heat map for reference only.

2.7 Climate change projections

Climate change projections for loch and reservoir temperatures were calculated using the regression equation derived in Section 2.4, making the assumption that the same relationship between air and loch temperatures would hold into the future. While this cannot be proven, having been derived from a 15-year period of measured water temperature records, it seemed reasonable to assume that this will be the case.

3 Results

3.1 Literature Review

Standing freshwaters are an important part of the Scottish landscape; there are 25,159 individual waterbodies with surface areas of greater than 0.1 ha in Scotland (UKLakesPortal). Their relative importance is emphasised by the fact that Scotland possesses 69% of the standing waters found in Great Britain by number, 79% by total surface area and 91% by volume (Smith and Lyle, 1979). Scottish standing waters include a diverse range of natural waterbody types, such as peaty pools, mountain corrie lochs, expansive shallow lowland basins and large deep valley lochs, as well as artificially created reservoirs (Lyle and Smith, 1994). In total, standing waters cover about 2% of the land area of Scotland, with the largest concentration being in the west and north-east Highlands (Lyle and Smith, 1994).

Standing waters can be influenced directly through climatic forcing or variation at the air-water interface, and indirectly via climatic effects on their catchments (Schindler, 2001). Climate change drivers have been conceptualised as energy transfers (e.g., heat, irradiance and wind mixing) and mass transfers (e.g., rainfall, solutes and suspended solids) to receiving waters (Leavitt et al., 2009). Climate change, together with growing human populations and global economies, are all likely to control the influx of energy to freshwater ecosystems in the future (Leavitt et al, 2009, Williamson et al., 2009). Muir et al. (2012) state that, in Scotland, climate change will most likely affect standing water hydrological cycles by altering water temperature and rainfall patterns, especially intensities and extremities. The ecological response of individual lakes to these climate change impacts depends on their relative sensitivity or resilience, as determined by their site-specific characteristics.

Woolway et al. (2020a) reviewed the global response of physical lake variables to climate change, including decreases in winter ice cover and increases in lake surface temperatures. These modified lake mixing regimes and accelerated evaporation losses, which in turn, if not balanced by increases in rainfall or runoff, caused decreases in water levels and surface area. The authors concluded that these responses would have knock on effects on water quantity and quality, and the provision of ecosystem services.

Table 3 summarises the main physical and environmental aspects of Scottish standing waters that are likely to be affected by climate change and its likely consequences (Gunn et al., 2021). These are reviewed in more detail below and include the water quality and biological impacts of climate change (direct and indirect), especially nutrient concentrations and algal blooms.

Impacts on flushing rate

The speed at which inflowing water passes through a standing water is expressed as its flushing rate (*lake volume ÷ inflow volume*; per year) (Winter, 2003). Flushing rate critically affects the sensitivity of a standing water to environmental change and is a key component of the lake models that are used widely to predict nutrient concentrations and algal standing crop from nutrient inputs (e.g., Dillon and Rigler, 1974; OECD, 1979; Vollenweider, 1975). Hydrological extremes (e.g., floods and droughts) affect the flushing rate of a standing water, thereby affecting its water level, inputs of nutrients and sediments from the catchment, and its responses to those inputs. Flooding increases water flow, leading to increases in surface area and volume (especially in shallow lakes), changes in habitat availability in the littoral zone, and reductions in the sensitivity of lakes to other pressures such as nutrient enrichment. In contrast, droughts – combined with the increases in evaporative losses from the water surface that result from lower levels of humidity and increases in air temperatures – often reduce flushing rates, causing a fall in water levels and volumes. Reductions in flushing rates will increase the sensitivity of a standing water to other pressures such as abstraction, acidification, nutrient enrichment and invasive species (Jones et al., 2013; Whitehead et al., 2009). Shallow lakes are particularly susceptible to such changes (George et al., 2007). During severe droughts, standing waters may become disconnected from surrounding waterbodies, causing loss of connectivity and a reduction in water quality and amenity value (Dobel et al., 2020).

Globally, the effects of changing climate on water flow through catchments are predicted to vary geographically (Milly, 2005) and seasonally (Nijssen et al., 2001). Laizé et al. (2017) computed likely future flows in pan-European rivers for baseline conditions (period 1961-1990) and for different combinations of climate and socio-economic scenarios (2040-2069). They showed that climate change is likely to alter flow regimes, leading to new types of rivers with implications for water flow through downstream standing water habitats. Within Scotland, depletion of river flows in summer would decrease flushing rates, suggesting that a further reduction in nutrient inputs would be needed to avoid consequent increases in algal blooms. Muir et al. (2012) illustrate this with some Scottish loch and reservoir types. For example, small shallow lochs and reservoirs within large catchments, which are more typical of south-east Scotland, are likely to be more sensitive to reductions in summer rainfall than larger lochs and reservoirs. This is in contrast to the large deep lochs that are more characteristic of the north-west of Scotland. These are less likely to respond to changes in flushing rate but may be more sensitive to other climate induced changes, such as longer periods of thermal stratification reaching greater depths, which can lead to deoxygenation of the hypolimnion and stress in sensitive fish populations (Arvola et al., 2010).

Loch Leven, a shallow loch in south-east Scotland, provides a good example of how changes in summer flushing rate can affect water quality. Lower flushing rates are likely to be linked to a greater accumulation of phosphorus in the loch sediments (Spears et al., 2012), which are then likely to be released, periodically, fuelling problematical cyanobacterial blooms (Carvalho et al., 2011; Elliott, 2010). In addition, Carvalho et al. (2012) found a clear climate change impact at this site, arising from an inverse relationship between summer rainfall and chlorophyll-*a* concentrations, a proxy measure of phytoplankton abundance. In wet summers, Loch Leven has very low chlorophyll-*a* concentrations due to enhanced flushing (Bailey-Watts et al., 1990); whereas, in dry summers, high concentrations of chlorophyll-*a* are often recorded (Spears, 2007a). Low flushing rates can indirectly affect algal species composition and succession (Bailey-Watts et al., 1990; Carvalho et al., 2011; Elliott, 2010; Jones et al., 2011; Reynolds et al., 2012), for example *via* changes in temperature regime and nutrient availability.

Increases in cyanobacterial populations caused by reduced flushing rates may be less marked if growth is limited by other factors such as light and nutrient availability (Elliott, 2012a). An increase in the nutrient enrichment of standing waters with cyanobacterial blooms can also cause a greater risk to public health and loss of amenity value (e.g., Carvalho et al., 2013; Cox et al., 2018; Facciponte et al., 2018). In general, cyanobacterial populations tend to increase during warm dry summers, then fall rapidly if a high rainfall event then flushes them out of the loch. These processes are all natural phenomena that occur in response to variations in rainfall and runoff. The underlying mechanisms responsible for the link between algal biomass and flushing rate have been investigated using PROTECH, a numerical model that predicts the accumulation of algal biomass in lochs in response to inputs of nutrients, light and thermal energy (Elliott et al., 2010; Reynolds et al., 2001). Using this model, Elliott and Defew (2012) simulated changes in the 2005 Loch Leven phytoplankton community in response to a combination of water temperatures and flushing rates, and found that some bloom-forming algal taxa were negatively affected by increases in water flow (e.g., *Aphanocapsa*; a type of cyanobacteria), while others were enhanced (e.g., *Stephanodiscus*; a diatom). Others were found to respond more to changes in water temperature, with some (e.g., *Aulacoiseira*; a diatom) responding positively to increased temperatures and others (e.g., *Asterionella*; a diatom) responding negatively to increases in water temperatures.

Impacts on water level

Changes to water levels in standing water are caused by a variety of hydrological factors, including floods, droughts, abstraction and changes in evaporation rates (Woolway et al., 2020a). These may occur seasonally, weekly, or even daily under some circumstances (Smith et al., 1987). The overall water balance of a standing water (i.e., inflow volume minus abstraction, evaporative losses and outflow) affects its water level. Where losses are greater than inflow volumes, loch shores can become exposed, whereas the reverse situation can cause high water levels and flooding of marginal areas. Muir et al. (2012) highlighted that, in Scotland, climate change will tend to increase variability in rainfall patterns, resulting in more extreme flood and drought events that affect surface and groundwater flows. This will, in turn, change standing water flow regimes; affect loch-landscape connectivity; and alter shoreline complexity and habitat structure (Wantzen et al., 2008). As lochs are relatively closed systems, changes in water level will affect biological communities across the entire waterbody, especially around the shoreline. At low water levels, previously inundated areas become dry and exposed; and at high water levels, previously dry and exposed areas can become inundated. Shallow standing waters are more vulnerable than deeper standing waters, because small changes in water level represent a much larger proportion of their total surface area and volume (George et al., 2007). In deep, seasonally stratified lochs, the impacts of water level fluctuations are restricted mainly to changes in the littoral zone (Smith et al., 1987).

Although the biota of many standing waters have evolved life cycles that accommodate natural water level fluctuations, extreme or unusually timed fluctuations are likely to impair ecosystem functioning. Such changes, especially those associated with a significant lowering of water level with consequent loss of volume, can have serious detrimental impacts on plant and invertebrate communities, especially around the shoreline. Littoral areas can become exposed and desiccated leading to significant losses amongst the littoral macroinvertebrate community (e.g., Arvoviita and Heiki, 2008; Baumgartner et al., 2008; White et al., 2008). This in turn affects species that depend on these organisms as a food supply (e.g., aquatic birds and fish). Exposure of littoral areas during droughts can also prevent their use by fish as spawning and nursery areas (Winfield, 2004). In general, loch biota with relatively short lifespans and generation

Table 3. Summary of potential impacts of climate change on Scottish standing waters (adapted from Gunn et al., 2021).

Change	Affected by	Consequences
Flushing rate	rainfall/runoff/evaporation rates/abstraction	• changes in water quality, e.g., eutrophication/ blooms of algae and cyanobacteria • increased sensitivity to other (multiple) pressures including acidification, abstraction & invasive species • changes in connectivity
Water level	rainfall/runoff/evaporation rates/abstraction/ bathymetry/rate & duration	• changes in loch/reservoir morphology • changes in ecosystem functioning • changes in habitat diversity, e.g., loss of littoral plants, invertebrate habitat and fish spawning/nursery sites • changes in greenhouse gas emissions • changes in species diversity and increased vulnerability to invasive species
Nutrient delivery	runoff (diffuse sources)/dilution (point sources)/internal release (sediment sources)	• changes in nutrient concentrations and ecological responses
Sediment delivery	runoff (diffuse sources)/sediment disturbance	• changes to water clarity affecting nutrient concentrations, habitat quality, fish egg survival and fish
Water temperature	rainfall/flushing rate/water level/temperature/ bathymetry	• changes to water temperatures, e.g., higher water temperatures leading to increased likelihood of algal blooms (if in combination with increased nutrients) • changes in stratification pattern, e.g., affect flushing rate because epilimnion behaves like a shallow loch and hypolimnion is not flushed • reduced habitat volume for fish; changes in zooplankton species composition • changes in seasonal timing of population peaks and densities • impacts on biogeochemical cycling • heat stress to biota/low oxygen conditions • general degradation of biota
Deoxygenation	flushing rate/temperature/organic decomposition & respiration/bathymetry	• changes to water temperatures/stratification, e.g., higher water temperatures leading to increased risk of algal blooms (if combined with increased nutrients), reduced habitat volume for fish and changes in zooplankton species composition. • changes in timing of population peaks and densities. Impacts on biogeochemical cycling. • heat stress to biota/low oxygen conditions; general degradation of biota

times (days to weeks), such as open water (planktonic) communities and benthic invertebrates, tend to be less affected by water level changes than biota with longer lifespans and generation times (months to years), such as aquatic plants and fish. Excessive or prolonged drawdown or flooding of lochs may cause significant losses in biota, leading to a reduction in structural diversity or, in some cases, the complete destruction of aquatic communities if physiological limits are exceeded. This may cause a regime shift from an aquatic plant-dominated to an algal-dominated system (Reynolds et al., 2012). Examples of such impacts are often seen in lochs managed for water supply (e.g., Loch Doon, Thirlmere) (Jones et al., 2013), where drought impacts may be amplified by the need for higher levels of abstraction to meet increasing demands for water.

Water level decline and elevated evapotranspiration are universal driving processes; however, water chemistry responses can be site-specific (Webster et al., 1996), with groundwater-fed streams having a greater impact on their water chemistry than catchment geology (Webster et al., 2000). Mosley (2015) observed that, in European lakes and reservoirs, drought conditions caused increases in dissolved organic carbon, inorganic nutrients, pH, salinity, turbidity and redox metals, and decreases in dissolved oxygen concentrations, resulting in lower habitat and recreational value. These water chemistry responses can be more prominent in deeper, stratifying waterbodies than in shallow waters, where changes in water chemistry are only manifested during post-drought re-filling (Baldwin et al., 2008). In lochs and reservoirs served predominantly by surface water, hydrological disconnection during droughts could result in increased evapo-concentration, causing an increase in salinity and nutrient concentrations. Changes in shoreline habitat may also result in an increase in greenhouse gas emissions, because emissions from exposed sediments increase during drying and re-wetting (Kosten et al., 2018). In shallow standing waters, reduced water levels can also promote wind induced sediment disturbance, leading to increased turbidity (Mosley, 2015).

Impacts on nutrient and sediment delivery

Changes in the hydrological inputs to standing waters also affect the delivery of water-borne substances from the catchment, such as nutrients and sediments. In general, more than 80% of nutrient inputs to a loch are delivered in just a small number of high rainfall events with comparatively little being delivered under low rainfall conditions (Jordan et al., 2012; Sharpley, 2008). Variation in rainfall also affects the timing of delivery, which in turn affects the response of the standing water. However, it can be very difficult to differentiate between responses caused by increases or decreases in nutrient inputs, and those caused by increases or decreases in waterbody retention time. For example, Defew et al. (2013) found that, within the Loch Leven catchment, if nutrients from external sources were supplied diffusely, the level of input tended to reflect the variation in inflow (and thus flushing) rates, especially during high rainfall events. However, if nutrients were from point or internal sources, their inputs would remain almost constant as rates of flow changed, with nutrient concentrations tending to increase as flushing rates decreased (Elliott et al., 2009).

A warmer climate may also enhance acidification and nutrient enrichment by increasing the release of nitrogen from soil organic matter into runoff (Wright and Schindler, 1995). Futter et al. (2009) modelled the effects of changing climate (and nitrogen deposition) on nitrogen dynamics in Lochnagar, and found that a warmer and drier climate would result in less runoff and a much-reduced snowpack. Futter et al. (2009) indicated that surface water nitrate concentrations would be expected to increase under climate change, but were not likely to return to or exceed historical levels even if nitrogen deposition levels remained constant.

Although not the primary focus of this literature review, it should be noted that concentrations of dissolved organic matter (DOM) in UK upland drinking waters have been rising over recent decades, largely as a consequence of organic matter becoming more soluble as soils recover from the effects of acid rain (Monteith et al., 2021). With predicted future warming, any trend towards drier summers would likely result in significantly higher DOM concentrations (particularly in water draining, peat-dominated catchments), while DOM concentrations in catchments with more coverage by freely draining organic soils are likely to be more sensitive to fluctuations in rainfall (Monteith et al., 2021). This has led to concerns that this could cause even higher concentrations of DOM to reach UK water treatment works, increasing treatment costs (Ritson et al., 2014).

Impacts on water temperature

Lake surface water temperatures are warming worldwide, with Pilla et al. (2020) reporting an average rate of increase of +0.37°C decade^{-1} from their study of 102 lakes. However, temperature trends vary over space and time, with some evidence suggesting that surface water temperatures are rising more rapidly than air temperatures (e.g., Pilla et al., 2020). From a small study of 10 European lakes (including Loch Leven), evaluation of 50 years of observational data from 1966 to 2015 showed that annual maximum lake surface temperatures had increased at an average rate of +0.58°C decade^{-1}, which was similar to the observed increase in annual air temperature of +0.42°C decade^{-1} (Dokulil et al., 2021). In contrast, however, Pilla et al. (2020) found little change in average deep-water temperatures in lakes, although there was a high degree of variability across the 102 lakes investigated. This variability could not be explained by surface water temperatures or the thermal stability of lakes, so it is likely that long-term trends in the thermal structure of deep-water lakes are driven by external factors, such as local to regional climate patterns or external anthropogenic influences.

Normally the temperature of standing waters – other than very small and shallow lakes – follows seasonal trends, often showing small, short-term variations that can be related to significant or extreme weather events, such as heat waves or storm events (Climate Change Committee, 2021). Inflows, rainfall and mixing by winds are all variably influential, depending on the relative hydrology and morphometry of the lake concerned. Shallow lakes and lakes with shallow thermoclines (regions of rapid temperature change) are the most susceptible to warming (George et al., 2007), while in deeper waterbodies higher water temperatures tend to lengthen the period of thermal stratification and deepen the thermocline (Hassan et al., 1998). In the UK, there are two types of lake thermal regime: warm monomictic and dimictic lakes. Warm monomictic lakes include large deep lakes (such as Loch Ness) that never fall below 4°C, the temperature of maximum water density. Dimictic lakes, on the other hand, are characterised by water temperatures passing through 4°C twice a year (in spring and autumn) and, if deep enough, may undergo thermal stratification in the summer.

Battarbee et al. (2002) indicated that it is easier to detect evidence of climate change in arctic or alpine lakes, where warming is more pronounced and where its effects are not masked by other types of human activity (e.g., pollution). Identifying the effect of climate change on standing waters affected by nutrient enrichment is more difficult, because increasing water temperatures tend to produce similar symptoms to those of cultural eutrophication, i.e., increased algal productivity/oxygen stress in the hypolimnion and accelerated nutrient recycling (Moss et al., 2011). Also, nutrient loading can be enhanced by climate mediated changes in catchment hydrology and soil biochemistry (e.g., Moore et al, 2010; Pierson et al., 2010).

Through its effect on water density, temperature change also influences the timing of lake mixing and stratification, essentially altering the length of the growing season (e.g., earlier onset). This causes profound effects throughout the ecosystem (Woolway et al., 2021a), drastically altering the structure and function of the waterbody by affecting biogeochemical processes between the sediments and open water (Spears et al., 2007b), as well as the biology of phytoplankton (i.e., increasing likelihood of cyanobacterial blooms), zooplankton and fish. Increasing water temperature and stratification can lead to heat stress on biota and hypoxia in deeper waters due to increased respiration; this can lead to a general degradation in the biota. In the case of droughts, an extreme lowering of water levels may reduce the volume of the hypolimnion, affecting fish that require relatively low water temperatures and increasing the risk of fish kills due to anoxic conditions. Some of the UK's rarest fish, such as vendace (*Coregonus albula*) and Arctic charr (*Salvelinus alpinus*), are likely to be affected most (Elliott and Bell, 2011; Jones et al., 2008). When rates of oxygen transport across the thermocline are low compared to rates of decomposition and respiration, oxygen consumption can lead to anoxia at depth – a process that may be stimulated by nutrient enrichment and climate change (Foley et al., 2012).

Woolway et al. (2021a) investigated changes in lake stratification phenology across the Northern Hemisphere (including the English Lake District) between 1901 and 2099, using a lake-climate model ensemble and long-term observational data. Under high-greenhouse gas-emission scenarios, it was predicted that the period of stratification will be extended by 33.3 ± 11.7 days by the end of the current century (Woolway et al., 2021a). This will have knock on effects on nutrient mineralisation and phosphorus releases from lake sediments, with a likely misalignment of lifecycle events causing irreversible changes in lake ecosystems. Stratification may also be affected by other larger-scale processes, such as those driven by changes in the Gulf Stream (George and Taylor, 1995), the North Atlantic Oscillation (George et al., 2004) and, potentially, the jet-stream (Strong and Maberly, 2010). Energy, surface heating and water transparency can also determine the patterns of vertical mixing that occur, affecting many of the biogeochemical processes that are known to regulate key lake functions (Jones et al., 2005; Persson and Jones, 2008). These coupled processes can drive water quality and the ecological structure and function of lakes (Spears et al., 2012), regulate the delivery of nutrients and other pollutants to downstream systems (Spears et al., 2007a), and contribute to global scale climate regulating processes (Maberly et al., 2013). Drivers of these processes are related to a mosaic of interacting physicochemical and biogeochemical drivers that vary in space and time (Spears et al., 2007b), most of which are sensitive to various combinations of external and in-lake hydrological processes.

Impacts on water chemistry

Although the solubility of dissolved oxygen decreases with increasing water temperature, long-term lake trajectories have proven difficult to predict (Jane at al., 2021). The concentration of dissolved oxygen in standing waters is important as it helps to regulate biodiversity, nutrient biogeochemistry, greenhouse gas emissions and drinking water quality (Jane at al., 2021). Increasing temperatures can strengthen stratification, causing a reduction in the volume of the hypolimnion and increasing the risk of hypoxia in bottom waters (Baldwin et al., 2008). As a result, the biogeochemical processes in bed sediments can influence water chemistry, resulting in elevated concentrations of dissolved iron, manganese, phosphorus, and ammonium, and reduced concentrations of nitrates. Similarly, an increase in other redox sensitive metals and metalloids are likely, leading to degradation of water quality and recreational value (Jirsa et al., 2013). The production of the greenhouse gases methane and nitrous dioxide may also be elevated under reducing bed sediment conditions (Tranvik et al., 2009).

Oxygen concentrations and water temperatures near the sediments are strongly affected by in-lake hydrological processes and are, in turn, important drivers of the biological and chemical processes that liberate nutrients from lake sediments. During stratification, surface and deep waters are largely isolated from each other, although some vertical mixing continues to occur through vertical diffusion across the thermocline and/or the mixing of hypolimnetic waters as the epilimnion deepens. Mackay et al. (2014) have shown that the rate of vertical diffusion and the number and size of entrainment events are affected by atmospheric forcing, causing changes to deep-water anoxia, phosphorus accumulation in the hypolimnion and fluxes of phosphorus into the epilimnion.

In a recent analysis of temperature and dissolved oxygen profiles from 393 temperate lakes (over period 1941-2017), Jane et al. (2021) found that there was a widespread trend towards lower dissolved oxygen concentrations in surface and deep standing water habitats. They concluded that oxygen losses in warming lakes may be amplified by enhanced decomposition and stronger thermal stratification, or by oxygen increasing as a result of enhanced primary production. The decline in oxygen concentrations of surface waters was primarily associated with reduced solubility under warmer water temperatures; although dissolved oxygen concentrations in surface waters increased in some highly productive warming lakes, probably owing to increasing production of phytoplankton. In contrast, Jane et al. (2021) associated oxygen decline in deep waters with stronger thermal stratification and loss of water clarity, but not with changes in gas solubility, *per se*.

Effects of water temperature on algal blooms

With climate change modelling predicting increases in summer water temperatures as air temperatures increase, there is likely to be an associated prolongation of periods of thermal stratification, especially in relatively deep standing waters, leading to increases in the biomass, frequency and intensity of cyanobacterial blooms (Moss et al., 2003). In one such deep Scottish lake system, Loch Lomond, Krokowski (2007) found that surface water temperatures had increased from 9°C in 1987 to 13-14°C in 2005, and that the phytoplankton biomass and abundance were strongly correlated to water temperatures. Through modelling the 2005 Loch Leven phytoplankton community in response to a combination of water temperatures and flushing rates, Elliott and Defew (2012) found that some genera responded positively to increased temperature (e.g., Aulacoseira) and some negatively (e.g., Asterionella), while other species were more affected by increased water flows.

Bennion et al. (2012) also showed that in Loch Leven there had been several changes in the recent fossil record, indicating shifts in the lake diatom species assemblages that could be attributed to climatic controls; e.g., the presence of *Aulacoseira granulata* and *Aulacoseira granulata var. angustissma* seemed to show seasonality and coincided with warmer temperatures. Krokowski et al. (2012), reviewing the potential effects of climate change on the incidence of cyanobacteria in Scottish lochs, indicated that temperature rises in combination with increased nutrient runoff from surrounding catchments (as would be associated with predicted increases in rainfall) would result in increases in phytoplankton biomass. Modelling has also predicted that, with water temperature warming, there is an increased likelihood of phytoplankton being dominated by cyanobacteria, creating more intense and frequent cyanobacterial blooms (Wagner and Adrian, 2009). Krokowski et al. (2012) also highlighted the potential threat of increased summer water temperatures, leading to invasion by warm-water cyanobacterial species spreading into Scottish standing waters from the tropics and displacing native cold-water species, as has occurred already in some northern European water bodies (Wiedner et al., 2007). Jones et al. (2020), in a national screening assessment of threshold-based climate change impacts on UK fresh waters, identified such water temperature effects on algal blooms as being one of the key impacts of climate change on lakes. These authors also found that above a mean monthly water temperature of 17°C in summer, and in combination with elevated nutrient levels, harmful algal blooms were more likely to occur, leading to a decrease in water quality and adverse effects on ecosystem services that are dependent on good water quality (Figure 2).

Jones et al. (2020) justified the use of such a temperature threshold on the basis that lake temperatures are likely to warm as air temperatures rise, with an associated increase in water column stability due to stronger thermal stratification. Such warming stimulates the growth of phytoplankton species capable of forming blooms, particularly favouring harmful cyanobacterial blooms; as does the improved underwater light climate that results from increased water column stability (Elliott, 2012a, 2012b; Elliott et al., 2010; Ho et al. 2019; Paerl and Huisman 2008; Richardson et al. 2018).

Cyanobacterial growth rates frequently reach their maximum, or exceed those of other phytoplankton, above a water temperature of 25°C (Jöhnk et al., 2008; Paerl and Huisman, 2008). However, the temperature at which bloom formation occurs is often much lower due to other factors such as nutrient availability (total inputs and resultant concentrations) and lake morphology. Recent studies by UKCEH (Carvalho et al., 2013; Van der Spoel, 2019) have also suggested a mean monthly water temperature of 17°C as a threshold value above which blooms are more likely to occur in the UK if sufficient nutrients are available to support primary production. Changing water colour can also moderate the temperature effect in different ways: it is indicative of organic inputs that that can supply additional nutrients, but also limits the availability of underwater light. Nutrients and water colour are frequently quantified as concentrations, but it is important to recognise that total inputs (amount) of material entering standing waters and the flow volumes in which they are delivered are also important.

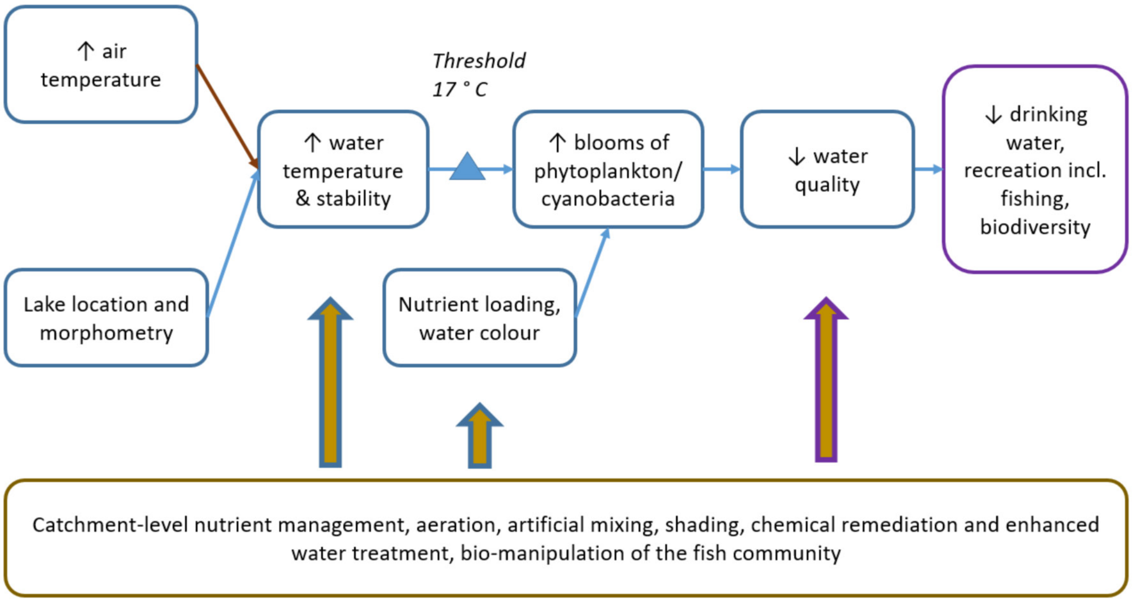

Figure 2 Impact chain for temperature effects on phytoplankton and cyanobacterial blooms in lakes. Purple box shows socio-economic or biodiversity endpoint; brown box shows potential adaptation measures (Source: Jones et al., 2020).

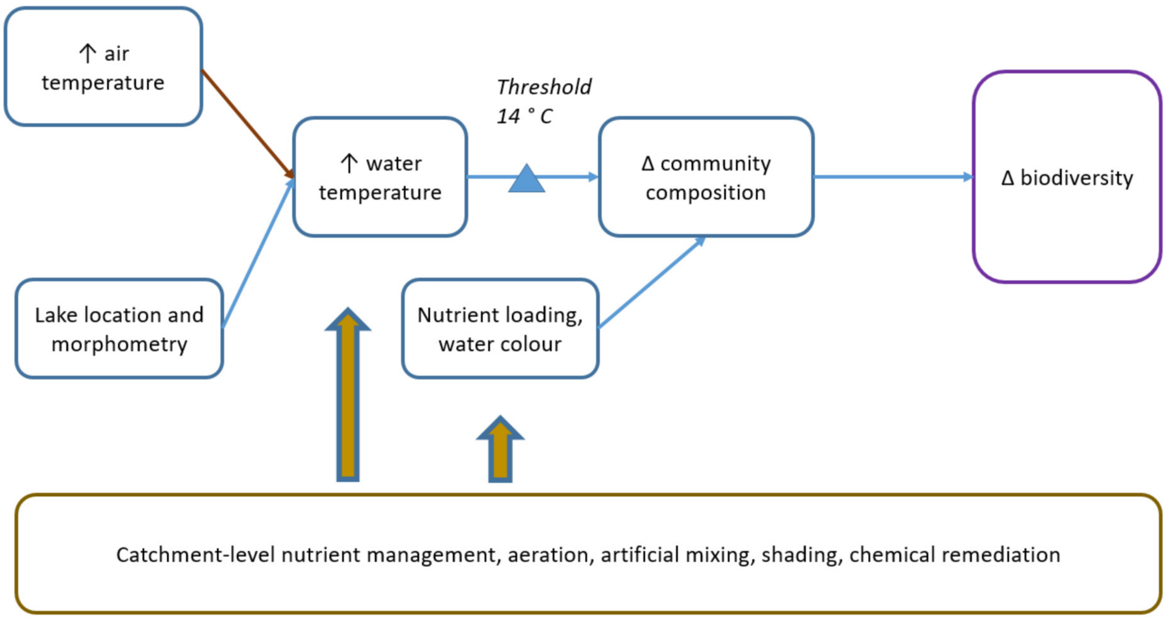

Figure 3 Impact chain for temperature effects on zooplankton species composition in lakes. Purple box shows biodiversity endpoint; brown box shows potential adaptation measures (Source: Jones et al., 2020).

Effects of changes in water temperature on zooplankton

Increases in water temperature can also lead to changes in the species composition of the planktonic herbivore community (Bruel et al., 2018). In Loch Leven, warmer spring temperatures have had a positive effect on water quality by increasing the level of grazing by Daphnia on the algae. This results in a decrease in spring chlorophyll-*a* concentrations and an associated improvement in water quality during May and June (Carvalho et al., 2012). Jones et al. (2020), in a national screening assessment of threshold-based climate change impacts on UK fresh waters, identified such water temperature effects on zooplankton composition as being one of the key impacts of climate change on lakes. Jones et al. (2020) derived a summer mean monthly water temperature threshold of 14°C for impacts on zooplankton composition (Bruel et al., 2018), as summarised in Figure 3.

Warming water can stimulate the growth of filamentous phytoplankton, including cyanobacteria (Paerl and Huisman, 2008), thus affecting food quality and, thereby, favouring different species of zooplankton grazers. Furthermore, warming may enhance fish predation on zooplankton, changing which species dominate the community (Gyllström et al., 2005). Changes in nutrient loading can also interact with these effects by influencing the quantity and quality of food available to grazers. Climate change may also alter the seasonal timing of phytoplankton and zooplankton blooms, causing desynchronisation of species interactions with potential implications for food-webs (Thackeray et al., 2013; Samplonius et al., 2021).

Heatwaves

As well as projected long-term increases in global average air temperatures, climate models suggest a future increase in the frequency and severity of extreme temperature conditions (Climate Change Committee, 2021). Such temperature extremes include lake heatwaves - periods of extremely warm surface water temperatures. A recent example of the impact of lake heatwaves on lake surface water temperatures was recorded in European lakes during May-October 2018, when the modelled mean and maximum lake surface temperatures were found to be 1.5°C and 2.4°C warmer than the base-period average (1981-2010) (Woolway et al., 2020b). Further analysis using satellite data and modelling of hundreds of lakes worldwide from 1901 to 2099 showed that, globally, lake heatwaves are likely to increase in intensity and duration (Woolway et al., 2021b). This modelling indicated that surface heatwaves will be longer-lasting but less intense in deeper lakes (up to 60 metres deep) than in shallower lakes, and predicted that during the twenty-first century heatwaves will begin to extend across multiple seasons, with some lakes reaching a permanent heatwave state. Woolway et al. (2021b) indicated that such heatwaves are likely to exacerbate the adverse effects of long-term warming in lakes and exert a widespread influence on their physical structure and chemical properties. They also suggested that these lake heatwaves could alter the lake biota by pushing aquatic species and ecosystems to the limits of their resilience, threatening biodiversity and the key ecological and economic benefits that lakes provide to society.

Storm events

Severe storms are another type of extreme event that can have major effects on standing waters (Jennings et al., 2021). Such storms influence lakes principally by increasing inputs of terrestrial material derived from catchments during heavy rainfall, and through increased mixing of the water column by high winds (Woolway et al., 2018). Woolway et al. (2018) studied the impacts of one such event, Storm Ophelia, on Windermere in 2017; this storm caused a great upwelling of deep, cold, oxygen poor water in Windermere, which then flowed into the outflow. The study indicated that the response of standing waters to an extreme weather event of this type may have important effects downstream that are not immediately apparent at the lake surface – suggesting that climate change effects may be propagated through the drainage network.

The impacts of storm events are contingent on many things, including the features of the storm itself and the attributes of the water bodies and catchments affected. In the case of lake phytoplankton, such extreme events can restructure communities and affect their dynamics, resulting in altered ecological functioning (e.g., carbon, nutrient and energy cycling) in the short- and long-term, but this will be dependent on how resilient a particular standing water is to such impacts (Stockwell et al., 2020). For example, lake phytoplankton communities may be more vulnerable to an extreme wind event if it comes shortly after another storm, or if periods of drought alternate with periods of intense rainfall. Conversely, an extreme wind event may not have much impact on a phytoplankton community if the lake was already fully mixed (Stockwell et al., 2020). The main factors that need to be considered for mitigating climate change impacts on water quality of Scottish standing waters are summarised in Table 4.

Table 4 Summary of the main factors that need to be considered for mitigating climate change impacts on water quality of Scottish standing waters.

Factor	Affected by	Considerations for mitigation of climate change impacts on water quality of Scottish standing waters
Flushing rate	rainfall/runoff/evaporation rates/abstraction	• increase flushing rates during periods of low rainfall • reduced inputs of terrestrial material from catchments by improving management practices that reduce soil erosion and nutrient runoff
Water level	rainfall/runoff/evaporation rates/abstraction/ bathymetry/rate & duration	• avoid reductions in water level wherever possible by actively managing these to increase resilience, especially in shallow waters • consider options for managing stratification
Nutrient/ sediment delivery	runoff (diffuse sources)/dilution (point sources)/internal release (sediment sources)/sediment disturbance	• changes high rainfall events very important as these will deliver majority of nutrients and sediment into standing waters; very little delivered under low flow conditions – timing will affect response of standing waters • increase in storminess and associated high winds will lead to physico-chemical extremes in standing waters due to increased mixing of the water column
Water temperature change	rainfall/flushing rate/water level/temperature/ bathymetry	• at mean monthly temperatures of >17°C, algal blooms (especially of cyanobacteria) are likely to increase in frequency if sufficient nutrients are available • changes in zooplankton community likely to occur above mean monthly temperature of 14°C with knock-on effects on removal of algae by grazers; this will affect water quality • strengthened thermal stratification will lead to trends of lower dissolved oxygen concentrations, increasing the likelihood of releases of sediment-bound nutrients and contaminants into the overlying water • increased frequency of heatwaves likely to exacerbate the adverse effects of long-term climate change
Changes in seasonal timing of biological communities	changes in seasonal warming patterns	• increased likelihood of trophic mismatches, e.g., between predators and prey, leading to changes in plankton population interactions and threats to ecosystem functioning • shifts in species ranges
Climate change complexities	multiple interacting stressors	• need to consider multiple interacting stressors, not climate change alone, in determining resilience of individual standing waters to climate change • need to improve measures of climate change resilience at catchment scale by developing and diversifying indicators of impacts

3.2 Survey of expert opinion

A survey of expert opinion was undertaken in November 2021 to understand the perceived effects of climate change on Scottish standing waters. Eleven replies were received from scientists (50%), policy makers (30%) and environmental regulators (20%), with all respondents expressing concern about climate change impacts on a wide range of standing waters. These included lochs (100%), reservoirs (55%), locally important still waters (73%), and ponds and other small waterbodies (18%).

When asked what they believe are the main types and directions of change in environmental and ecological parameters under climate change at present, most respondents thought that temperature would increase (82%) but fewer respondents expected an increase in inputs of sediments (73%), nutrients (36%) or other forms of pollution (18%) from catchments. In terms of within waterbody responses, concerns were expressed about increases in algal blooms (91%), nutrient enrichment (54%) and sediment disturbance (46%). Many respondents expressed concern about a decrease in biodiversity (73%), especially in relation to rare or sensitive species (64%). When asked about their expectations of future climate change impacts, the responses received were very similar to those given for the current situation.

Concerns about other types of water quality issues were also raised. These included:

- increases in water colour
- longer periods of stratification
- less resilience to introduced or invasive non-native species
- less ice cover
- greater variation in water levels, especially in reservoirs

In terms of the impacts of climate change on the use of Scottish standing waters, most respondents expected water quality to decrease now (64%) and in the future (100%), leading to higher water treatment costs now (64%) and in the future (91%). Although recreational use of standing waters was thought to have increased already (55%), fewer respondents (46%) expected this to continue into the future. Some (18%) believed that this was already affecting human health and well-being, whereas 46% of respondents expected animal health and well-being to be adversely affected now and in the future. Overall, there was a general feeling that recreational visits to standing waters would increase under climate change, but that water quality would decrease. Concerns were raised that climate change had increased the risk of contact with potentially harmful algal blooms.

When asked whether climate change impacts would affect Scotland's ability to meet water quality objectives for standing waters, 64% of respondents thought that it would decrease our capacity to meet statutory environmental objectives within policy/regulatory relevant timescales. Concerns were raised by 46% of respondents that water managers would be less able to achieve water quality improvement targets or prevent further deterioration.

When asked to indicate the perceived level of risk of standing waters in different parts of Scotland developing water quality issues due to climate change, the responses suggested that rural (55%), urban (46%), lowland (46%) and upland (27%) standing waters were already believed to be at medium to high risk of such impacts and that this was expected to continue. Regarding the future impacts of climate change, the perceived level of risk to standing waters in rural and upland areas was considered to be higher than the current situation, while risks to urban and lowland standing waters were considered to be lower.

Regionally, most respondents considered standing waters in the southern, western and central parts of Scotland to be at higher risk of developing water quality issues under current climate change conditions than those in the north and east. Level of risk was perceived to be greater under future climate change scenarios across all areas of Scotland.

Survey participants were asked to consider the level of risk that different types of standing waters had already developed water quality problems due to climate change. While large and deep waters were considered to be at relatively low risk by some respondents (32%), about 39% considered the level of risk across all types of standing waters to be medium to high at present and into the future.

Participants were asked to indicate which, if any, policies relevant to their organisations would be difficult to comply with in the future due to the impacts of climate change on standing waters. EU Habitats and Water Framework Directives were judged at most risk of non-compliance, with 55% and 64% of respondents, respectively, raising concerns. A further 46% of respondents were concerned about compliance with Scottish Government guidance on cyanobacteria, and 27% of respondents raised concerns about compliance with wastewater treatment regulations, the EU Drinking Water Directive and the Scottish Government's Climate Emergency Response statement. Only a small number of respondents (18%) were concerned about compliance with the Scottish Government's land use strategy and the Climate Change (Scotland) Act 2009.

When participants were asked which environmental factors relating to climate change impacts were likely to contribute most to the risk of water quality issues developing in Scottish standing waters, 100% thought that changes in water temperature would cause the most problems and 91% were concerned about the impacts of changes in rainfall and the size and frequency of extreme events. Changes in flushing rates and wind were deemed to be of less concern, having been selected as important by only 36% and 18% of respondents, respectively.

Of the three approaches suggested as possible adaptation options for reducing the impacts of climate change on standing waters, nature-based solutions were selected by 100% of participants, with policy-based solutions (91%) and coordination of planning and management options (73%) being a little less popular. Overall, the survey responses showed that most respondents were concerned about the potential impacts of climate change on all standing waters, across all areas of Scotland. The main concerns were about the increasing incidence of algal blooms, which were expected to reduce recreational use and affect animal and human health/welfare. Concern was also expressed about increased treatment costs where water supply reservoirs were affected.

3.3 Exploration of monitoring data

Figure 4 and Figure 5 and show annual average April to September measured water temperature values recorded in Scottish lochs and reservoirs between 2015 and 2017, and 2018 and 2019, respectively. Over this period, summer air temperatures across the UK were some of the warmest on record with 2017 and 2018 being ranked[5] by the UK MetOffice as the 5th and 7th warmest summers on record since 1884.

It is clear from the water temperature data available that there is considerable interannual variability among years, with some years being much warmer than others. It is important to recognise that these short-term variations exist when looking for longer term trends that are likely to have been caused by climate change. However, in general, the data suggest that almost all (97%) of the Scottish lochs and reservoirs monitored warmed considerably over that period, with one having increased by 1.3°C per year since 2015 (Figure 4 - Figure 7). Several lochs (Loch Doon, Loch Ken, Mochrum Loch, St Mary's Loch) appeared to have cooled by up to 0.6°C per year, although the reason for this is unclear. For example, it could be that the potential extent of climate-driven changes in surface water temperatures are influenced by different water resource pressures (e.g., hydro scheme reservoir) and/or catchment-related uses (e.g., forestry), but this would require further investigation.

Figure 8 shows key determinands within the SEPA data records that show a positive or negative correlation with water temperature; three of the 142 lochs examined are shown as examples. The first is silicate, which is an essential nutrient for diatoms and a small number of other algae. The inverse correlation between silica concentrations and water temperature in the examples shown suggests that diatoms are likely to be unable to sustain viable populations at temperatures above 15°C. Taking 1 mg Si L^{-1} as being the level below which lack of silica availability starts to limit diatom growth, the SEPA data suggest that about 67% of monitored lochs are currently silica limited in summer. With climate change, the level and temporal extent of Si limitation is likely to increase.

Availability of dissolved nitrogen (expressed as total oxidisable nitrogen; TON) also becomes severely reduced in many lochs at temperatures above about 15°C. If a TON:RP (reactive phosphorus) ratio of < 10 is taken to indicate N limitation (as suggested by Maberly et al., 2020), the monitoring data suggest that about 90% of lochs are already N-limited when the temperature rises above 15°C. The higher temperatures associated with climate change are likely to lengthen the period over which N-limitation is likely to occur in the future. Nitrogen limitation will tend to limit the growth of all algae apart from some species of cyanobacteria that can fix nitrogen from the atmosphere.

Increases in N and Si limitation as temperatures rise would be expected to result in cyanobacteria outcompeting other algal species, as long as there is sufficient phosphorus available to support growth. There was no indication within these data that phosphorus availability is strongly affected by water temperature; although in some lochs and reservoirs it is likely to be released from the sediments in the summer months.

The graphs in Figure 8 also show that dissolved oxygen concentrations (expressed as percent saturation) and pH increase with increasing water temperature. This is likely, to some extent, to affect rates of biogeochemical processes in the lochs and reservoirs in which this situation occurs; however, it is more likely that changes in pH and oxygen concentrations will affect aquatic biota. It is feasible that all of the situations outlined above will become more common over longer periods under climate change, because the water temperature of Scottish lochs will be increasing according to current climate change projections (Figure 6).

Analysis of the relationships between cyanobacterial biovolume (biomass), total phosphorus concentrations and water temperature for different loch and reservoir types (Figure 9) were based on SEPA monitoring data from 62 lochs sampled between June and October, 2009 – 2012. In general, the highest cyanobacterial biovolumes occurred at higher TP concentrations (i.e., >20 µg L^{-1}, noting that

[5]https://www.metoffice.gov.uk/about-us/press-office/news/weather-and-climate/2019/state-of-the-uk-climate-2018 [Accessed 13 March 2022]

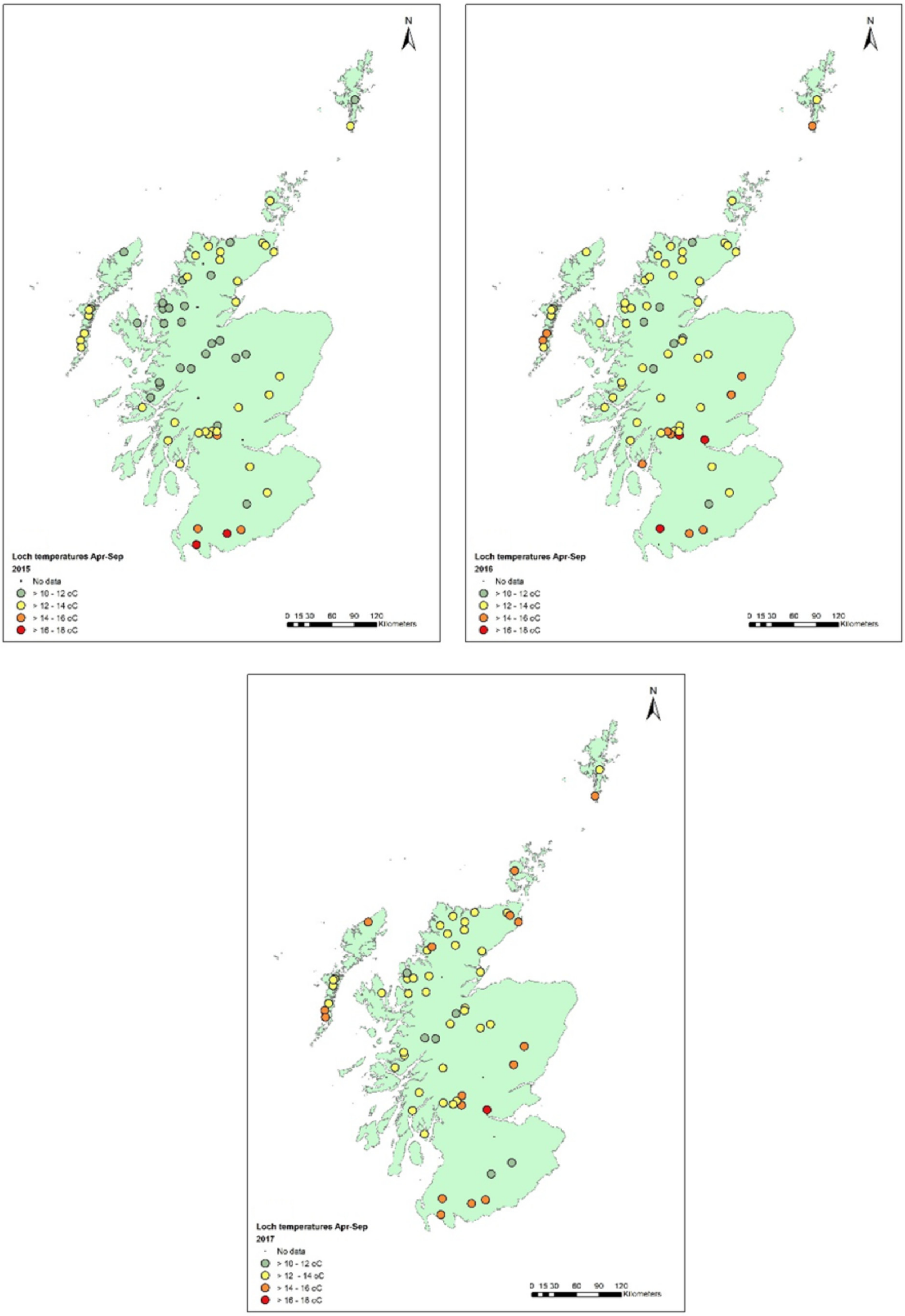

Figure 4 Variation in average measured loch and reservoir water temperatures across Scotland, April – September 2015-2017.

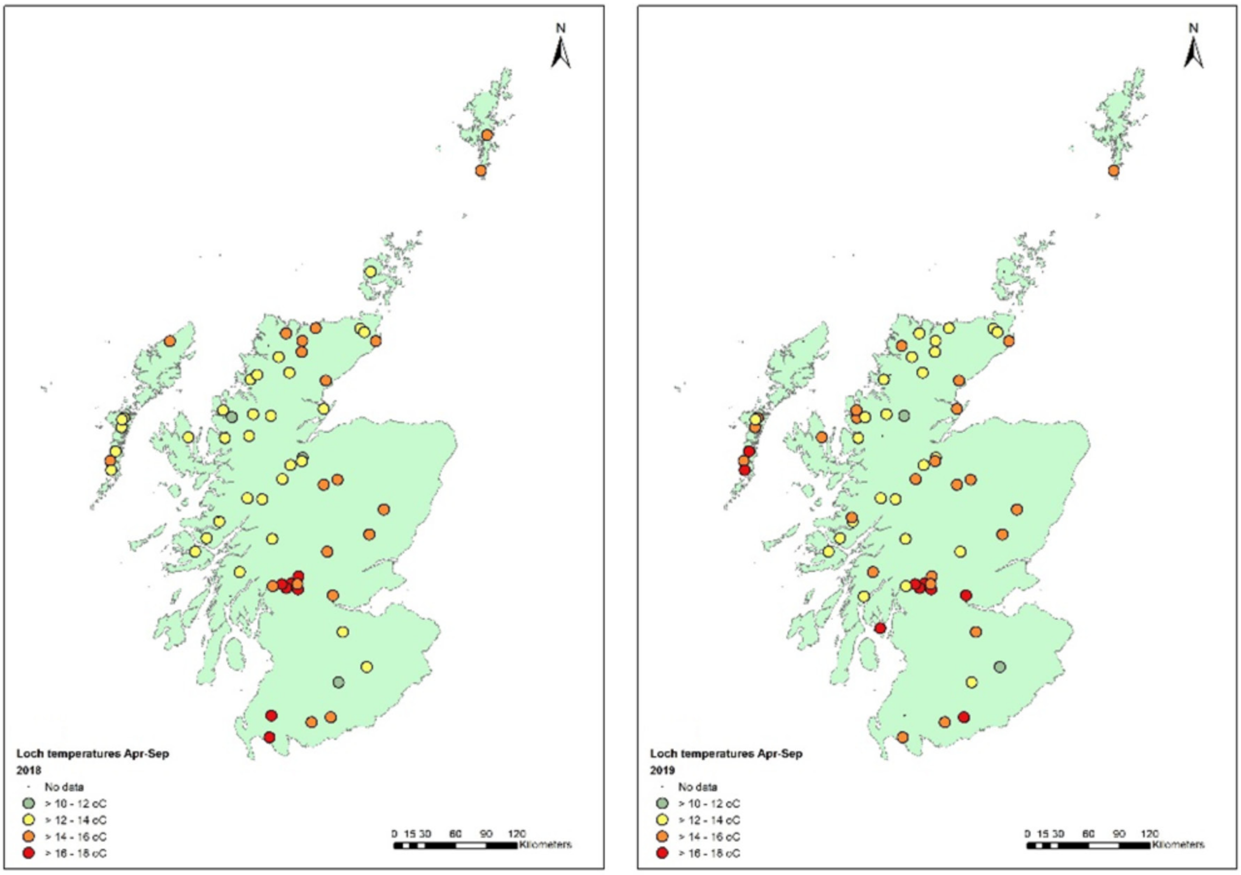

Figure 5 Variation in average measured loch and reservoir water temperatures across Scotland, April – September 2018-2019. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

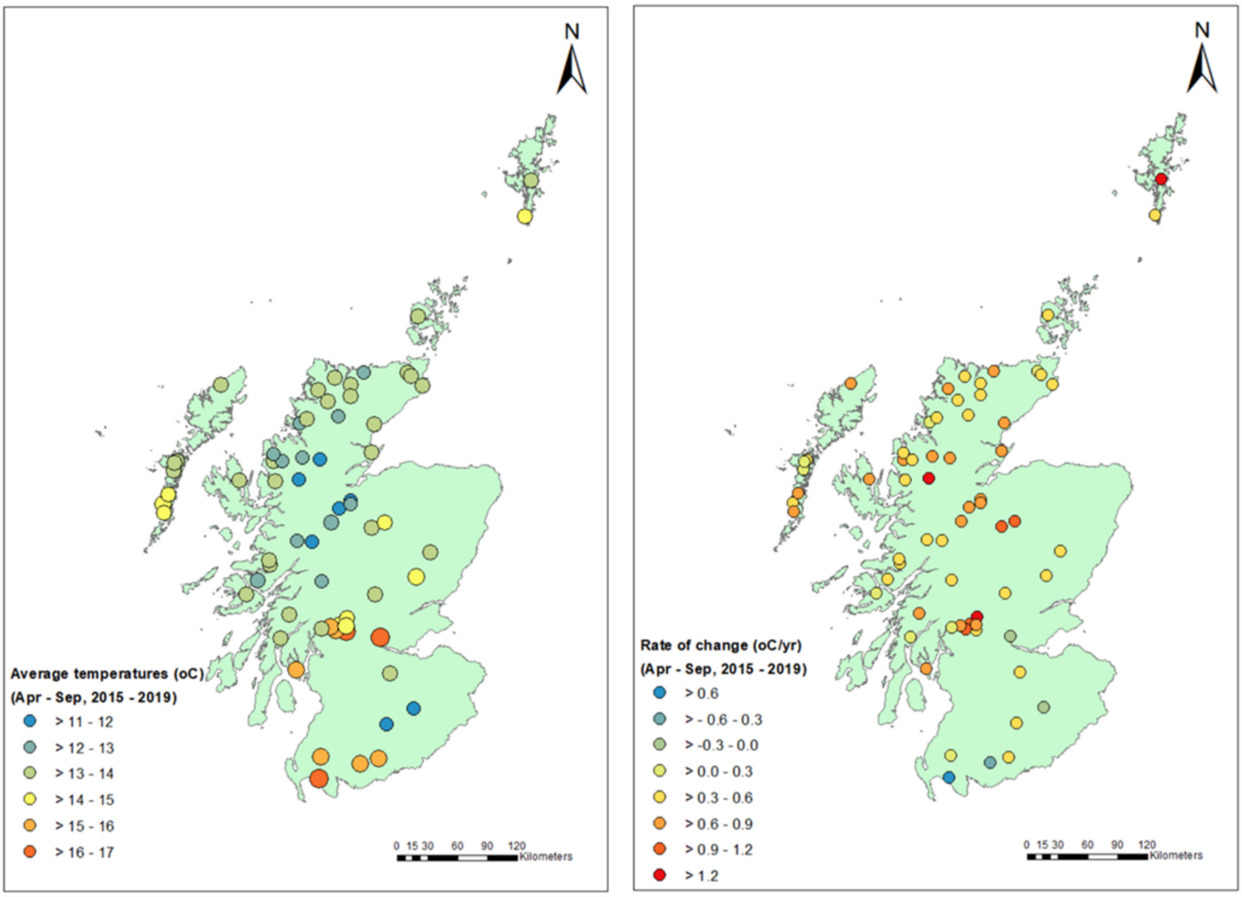

Figure 6 Average measured water temperatures (°C; left panel) and change in average water temperature (°C per year; right panel) for each monitored loch and reservoir, April – September 2015-2019. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

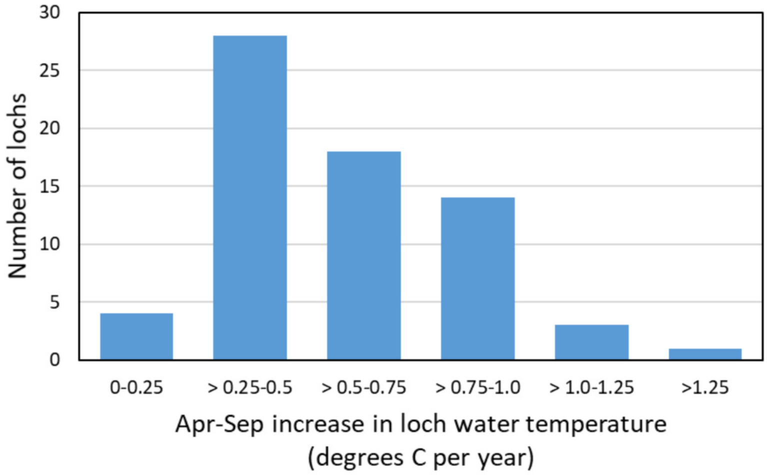

Figure 7 Number of lochs within each category of temperature rise, based on measured data collected between April and September, 2015-2019. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

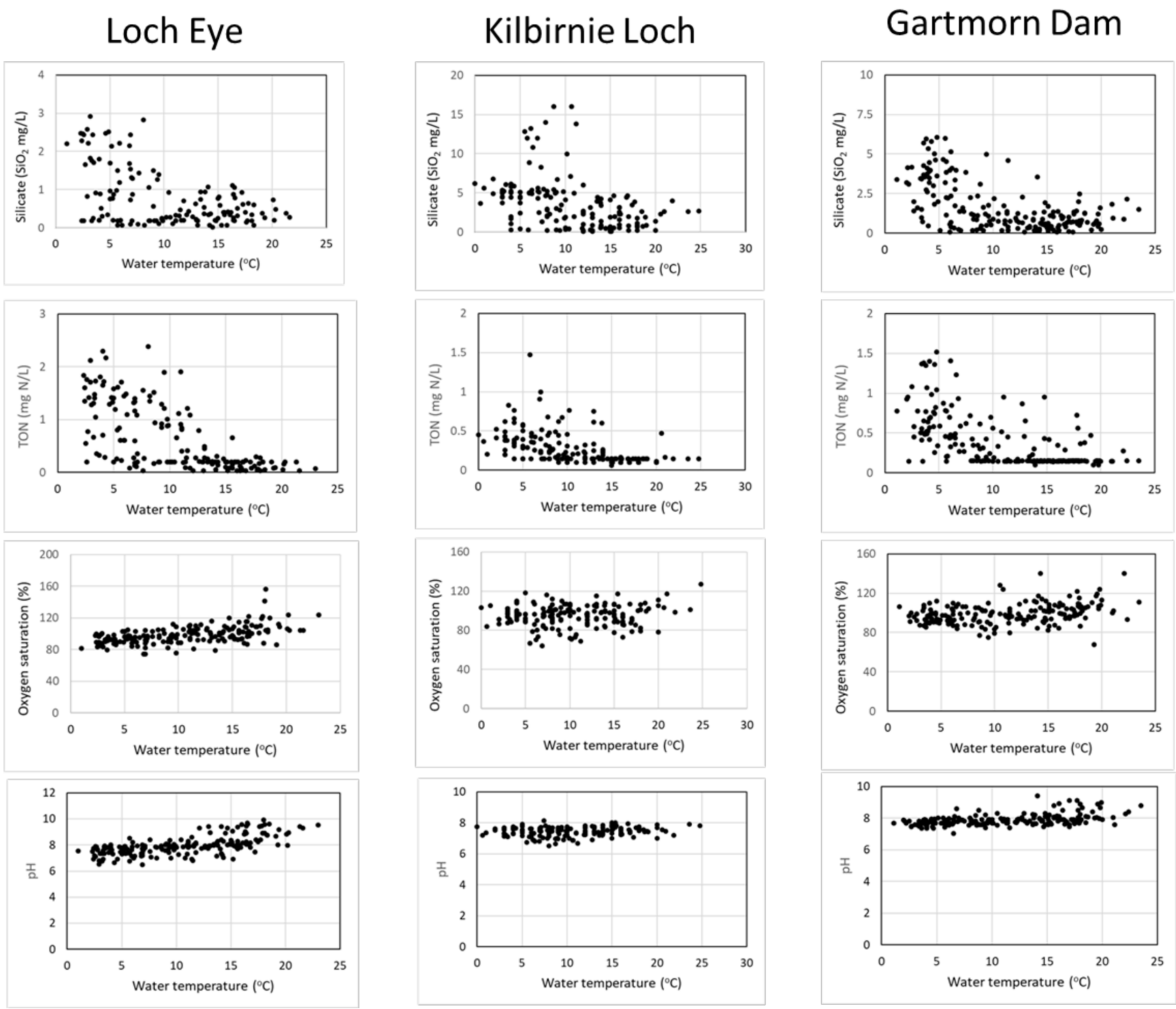

Figure 8 Examples of chemical water quality parameters that show a relationship with water temperature.
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Log_e (20) = 3) and at temperatures above 14°C (Figure 9).

When these data were examined according to loch and reservoir type (see Table 2), the following patterns emerged:

1. high concentrations of cyanobacteria were found to be most common in shallow and very shallow lochs and reservoirs
2. high concentrations of cyanobacteria were not recorded in deep or very humic lochs and reservoirs
3. humic lochs and reservoirs tended to have more high biomass events than clear lochs
4. high concentrations of cyanobacteria were observed across all alkalinity types, but were especially common in lochs and reservoirs with medium alkalinity

It should be noted, however, that that many deep lochs are still prone to surface blooms, even in winter, as has been observed in the Bloomin' Algae[6] records. This is due to the large area of water over which buoyant algae cells typically accumulate down wind.

3.4 Modelling the relationship between chlorophyll-*a* concentrations and environmental factors

A Linear Mixed Effects model with Gaussian errors was used to investigate the variability in mean monthly chlorophyll-*a* concentrations in Scottish lochs and reservoirs in summer, and indicated that this was best explained by monthly mean TP concentrations. However, variability in chlorophyll-*a* concentrations in relation to environmental factors was best explained by splitting the data into depth-types (Table 2) and developing type-specific models. These indicated the following relationships for the different loch and reservoir types:

1. *Very shallow lochs and reservoirs*: Chlorophyll-*a* concentrations were best explained by TP concentrations; climatic variables did not have a significant effect. This fits with general ecological theory and process understanding, which indicates that internal food web interactions and aquatic plants have a strong role in structuring ecosystems in very shallow systems
2. *Shallow lochs and reservoirs*: All of the variables explored significantly affected chlorophyll-*a* concentrations, but they also showed significant interactions. This made it difficult to visualise or describe, in simple terms, the relationships between chlorophyll-*a* concentrations and individual environmental factors. In general, TP and retention time had strong, positive relationships with chlorophyll-*a* concentrations, and temperature had a weaker, negative relationship.
3. *Deep lochs and reservoirs*: All of the variables explored significantly affected chlorophyll-*a* concentrations, as did the interaction between temperature and retention time. In general, TP had a significant positive effect on chlorophyll-*a* concentrations and mean water temperature had a positive effect in highly flushed lochs, but this relationship became negative at lower flushing rates.

It should be noted, however, that the results obtained may be affected by the relatively small number of examples of very shallow and deep loch and reservoir types included in the analyses. It is recommended that, of the models developed, only that for shallow lochs is suitable for investigating the future impacts of climate change on chlorophyll-*a* concentrations. The deep lochs model should be applied with caution, because much of the variability in chlorophyll-*a* concentrations that was observed could not be explained by the variables considered. However, the performance of this model could probably be improved by including data on other variables in the modelling process. Factors such as water colour, alkalinity, nitrogen availability, and aquatic plant, fish and zooplankton population densities are all likely to have important effects on chlorophyll-*a* concentrations, too. If such additional data were available for a subset of "data-rich" waterbodies, then additional multi-site modelling could be run in the next phase of this work. In addition, development of individual loch and reservoir models – such as those developed for Loch Leven – would overcome some of these issues because water colour and alkalinity do not vary greatly within any particular waterbody, and this would lessen the number of confounding effects that are obscuring the impacts of climatic drivers.

3.5 Modelling of site-specific effects of total phosphorus, air temperature and retention time on chlorophyll-*a* concentration

Interpretation of linear models for Loch Leven

The results of the systematic linear modelling analysis are presented in Table 5, in Figure 10 (annual model) and Figure 11 (seasonal models). Total phosphorus concentration explained the greatest variation in chlorophyll-*a* concentration across all models and pairwise models were statistically significant for TP *cf*. temperature and TP *cf*. retention time for annual, spring and summer models, but not for autumn.

[6]Bloomin' Algae is a Citizen Science app for reporting the presence of harmful algal blooms of blue-green algae.

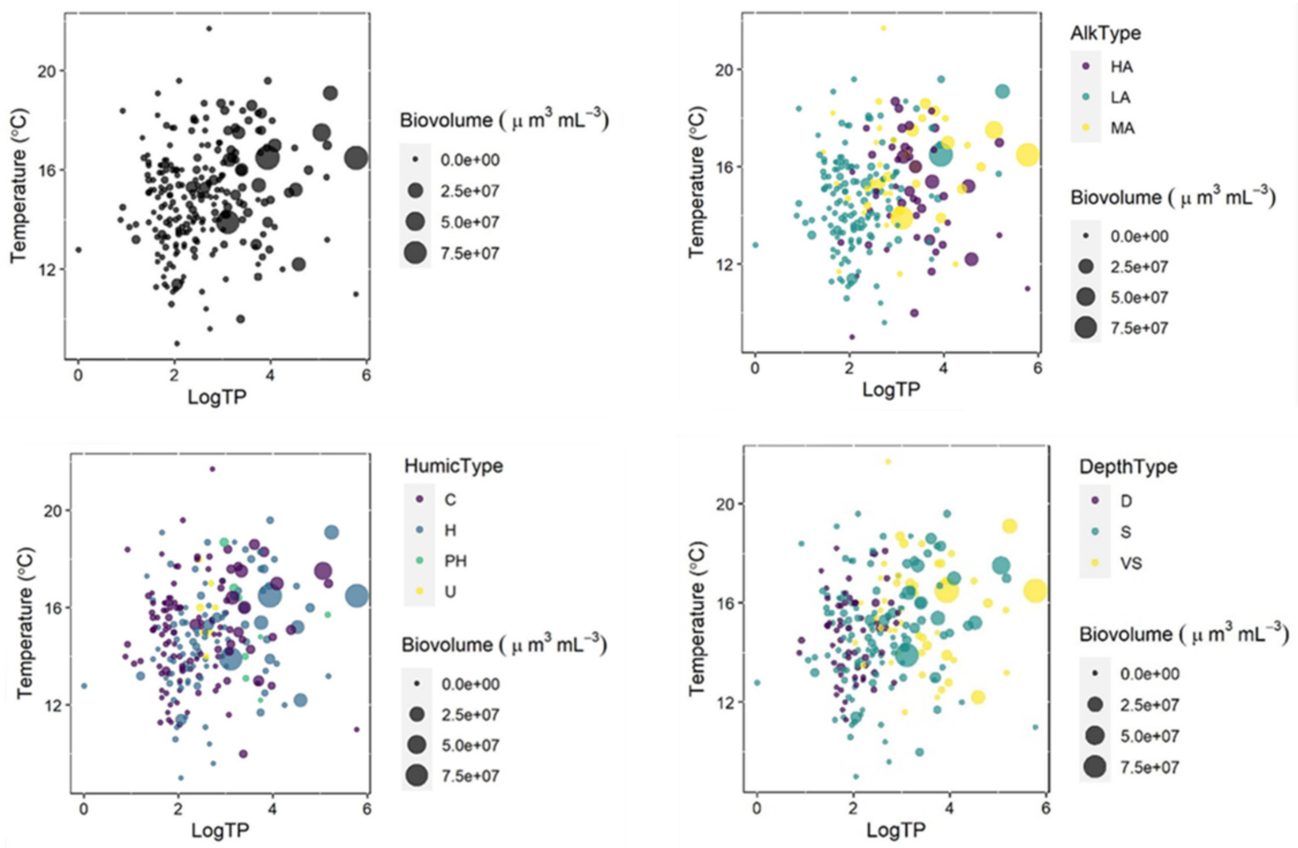

Figure 9 Relationship between cyanobacterial biovolume, Log_e total phosphorus (TP) concentrations and water temperature in all Scottish lochs and reservoirs with sufficient data (top left) and in lochs and reservoirs with different typologies (alkalinity type [AlkType) – top right; humic type – bottom left; depth type – bottom right). Abbreviations are: HA = High Alkalinity; LA = Low Alkalinity; MA = Medium Alkalinity; C = clear; H = Humic; PH= Polyhumic; U = Unknown; D = Deep; S = Shallow; VS = Very Shallow. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

Effects of total phosphorus and temperature on chlorophyll-*a* vary with season

Expected chlorophyll-*a* concentrations increase towards the right hand side of each heat map, confirming that TP is an important predictor of this response in all models (Table 5). However, the change in chlorophyll-*a* concentration with temperature varies with season along the TP axis. For TP cf. temperature in spring and autumn, the effect of TP on chlorophyll-*a* level is predicted to reduce at higher temperatures (i.e., from 6°C to >10°C in spring and from about 7°C to 11°C in autumn). This suggests an interaction effect in autumn whereby the effect of temperature appears to reverse under low TP concentrations. In contrast to spring and autumn, summer chlorophyll-*a* concentrations are highest at high TP concentrations and high temperatures, especially above about 80 µg L^{-1} and 14°C. As suggested above, the effects of temperature on chlorophyll-*a* concentration may be positive or negative, which can be explained by increases in grazing rates with temperature (i.e., negative relationship observed previously in spring) or increasing phytoplankton production (positive relationship in summer) under warmer conditions. Our analysis suggests that both processes play an important role in moderating the dominant TP vs. chlorophyll-*a* relationships in Loch Leven. The annual heat map (Figure 10) represents the net effects of both processes (and perhaps of other temperature sensitive processes as yet unidentified) where chlorophyll-*a* concentrations are lowest and highest at the upper end of the temperature gradient and at opposite ends of the TP gradient.

Effects of total phosphorus and retention time on chlorophyll-*a* vary with season

Higher retention times appeared to dampen the effects of TP on chlorophyll-*a* concentrations (at high TP concentrations) in spring and summer. This effect appears to be strongest at > 50 µg TP L^{-1} and at retention times of less than about 3 years. In contrast, high retention times were predicted to exacerbate the effects of higher TP concentrations in autumn, especially above 60 µg TP L^{-1} and at retention times of more than 0.5 years. As with the contrasting seasonal effects of temperature, retention time may also exhibit negative and positive effects on the phytoplankton community. As outlined above, positive effects of retention time on phytoplankton biomass (i.e., increasing chlorophyll-*a* concentration with decreasing flushing rate/increasing retention time) may indicate a decrease in the removal of nutrients and phytoplankton from the loch. In contrast, a negative effect (e.g., increasing chlorophyll-*a* with increasing flushing rate/decreasing retention time) may indicate increasing nutrient loading from the catchment. Again, the annual heat map (Figure 10) represents the net effects of these seasonal conditions and suggests an overall increase in chlorophyll-*a* concentrations at high retention times, but only when annual mean TP concentrations are high.

The approach demonstrated here offers visualisation of the effects of paired nutrient and climate change stressors on chlorophyll-*a* concentration in Loch Leven. The analysis targeted temperature and retention time, only, although UKCEP18 RCP outputs for wind speed may come on-line in the future, to expand the list of climate change stressors. Additionally, indicators of zooplankton grazing rates, inorganic nitrogen concentrations and modelled catchment nutrient loading would strengthen the modelling approach for Loch Leven. It is likely that a combination of these stressors beyond simple pairwise comparisons, for example, using the Linear Mixed Effects (LME) Modelling framework, will significantly improve model performance, thereby strengthening predictive capacity.

Implications of results from a climate change management perspective

The approach demonstrated here offers visualisation of the effects of paired nutrient and climate change stressors on chlorophyll-*a* concentration in Loch Leven. The analysis targeted temperature and retention time, only, although UKCEP18 RCP outputs for wind speed may become available in the future to expand the list of climate change stressors. Additionally, indicators of zooplankton grazing rates, inorganic nitrogen concentrations and modelled catchment nutrient loading would strengthen the modelling approach. It is likely that a combination of these stressors beyond simple pairwise comparisons,

Table 5 Summary of loch typology and linear model coefficients for Loch Leven for the 1989 to 2019. maod – metres above ordinance datum; WFD – European Water Framework Directive; HA – high alkalinity; LA – low alkalinity; VS – very shallow; S – shallow; D – deep. All data extracted from UK Lakes Portal 9th Sep. 2022 (https://eip.ceh.ac.uk/apps/lakes/). * to the left and right of season indicates model p values for TP x Temperature and TP x Retention time, respectively. *** $p < 0.001$; ** $p > 0.001 < 0.05$; * $p > 0.05 < 0.1$. Underscored values indicate p values for individual effects of <0.05. Chl – mean chlorophyll-*a* concentration of the season indicated. TP – mean total phosphorus for the season indicated; T – mean air temperature for the season indicated; Ret – mean retention time for the season indicated. MRsq – multiple R squared value; ARsq – adjusted R squared value. Model coefficients are based on transformed data.

Name	Mean depth (m)	Grid Reference	Elevation (maod)	Surface area (ha)	WFD Lake type	
Loch Leven	4.5	NO14720146	106	1371	HAS	
Pairwise Linear Model Coefficients						
Chl	TP x T			TP x Ret		
Chl	TP	T	TPxT	TP	Ret	TPxRet
Ann	***0.65	-0.20	0.15	0.74***	0.07	0.07
	MRsq: 0.61 ARsq: 0.57			MRsq: 0.57 ARsq: 0.52		
Spr	**0.63	-0.17	-0.17	0.70***	0.06	-0.13
	MRsq: 0.52 ARsq: 0.46			MRsq: 0.49 ARsq: 0.43		
Sum	***0.80	-0.05	0.09	0.79***	-0.17	-0.03
	MRsq: 0.67 ARsq: 0.62			MRsq: 0.67 ARsq: 0.64		
Aut	0.36*	-0.05	-0.11	0.39**	0.05	0.14
	MRsq: 0.17 ARsq: 0.07			MRsq: 0.18 ARsq: 0.09		

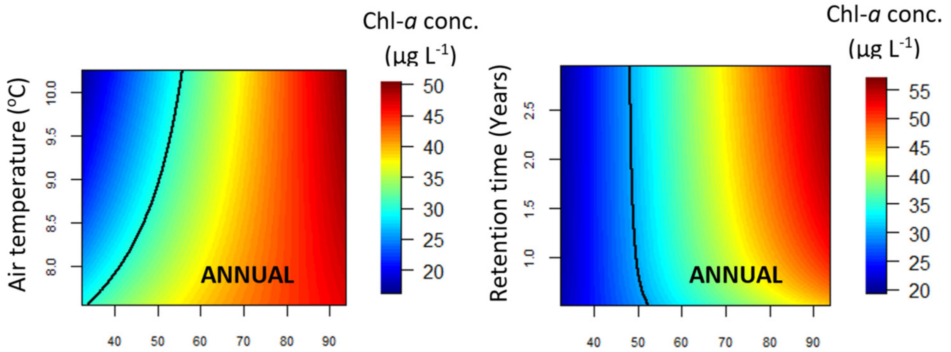

Figure 10 Heat maps showing effects predicted by linear models of annual mean total phosphorus (TP) concentration and air temperature (left panel), and annual mean TP concentration and retention time (right panel), on expected response in annual mean chlorophyll-*a* concentration in Loch Leven, 1989 to 2019. Black line: arbitrary reference value of 30 µg L^{-1} chlorophyll-*a*.

for example, using the Linear Mixed Effects (LME) Modelling framework would significantly improve model performance, thereby strengthening predictive capacity.

Addressing limitations in the approach for application across other Scottish lochs and reservoirs

A similar analysis to that conducted here for Loch Leven could be conducted for other Scottish Lochs where sufficient water quality monitoring data are available. We used data that span 1989 to 2019 and are derived from analytical and sample collection methods that were consistent and of high quality. Exploration of the SEPA water chemistry data for other lochs and reservoirs highlighted some quality issues, specifically for TP concentration, that raised concerns about inconsistencies within data collected before 2002. This would constrain the period of observation for other lochs. In addition, monitoring frequency was variable across lochs and reservoirs before and after 2002, with a lower frequency of data in August and during winter months. This may further constrain application of this approach to other lochs and reservoirs to including assessments of growing seasons (e.g., April to September), only, to ensure comparability of data across sites. It was for these reasons that, in this first instance, we focused our analysis on demonstrating the approach using the longer and more consistent Loch Leven data. On a positive note, the climate change stressor data produced within this project represents a consistent data resource with which similar analyses could be conducted across other sites. However, first, there is a need to develop this statistical approach further to address data quality issues and ensure comparability of stressor effects across data from different lochs and reservoirs.

The need to capture the effects of extreme events in climate change scenarios

Spears et al. (2021 and 2022a) proposed that LMEs can be used to estimate the probability of failing a given chlorophyll-*a* target to inform future management interventions. An important caveat to this is that future projections using LMEs, or similar multi-variate empirical modelling approaches, should be constrained theoretically to the gradient of the measured data. Climate change scenarios for Loch Leven using UKCP18 RCP Scenario 6.0 (Figure 12) indicate that future temperatures are at least within the range of measured temperatures in our models, and so future projections are feasible at least at this site, for this scenario, and for temperature.

However, retention time projections indicate an increase in the occurrence of extreme events (e.g., drought conditions, indicated by very high retention times; Figure 12). For our models, values in excess of 100 years were removed for computational purposes. So, our models should represent extreme wet conditions well, but are likely to underrepresent extremely dry conditions. An alternative modelling approach will be necessary to specifically capture the responses of chlorophyll-*a* concentration to extreme events, especially where they are rare in historical data. Consideration should be given to developing climate change scenarios that include

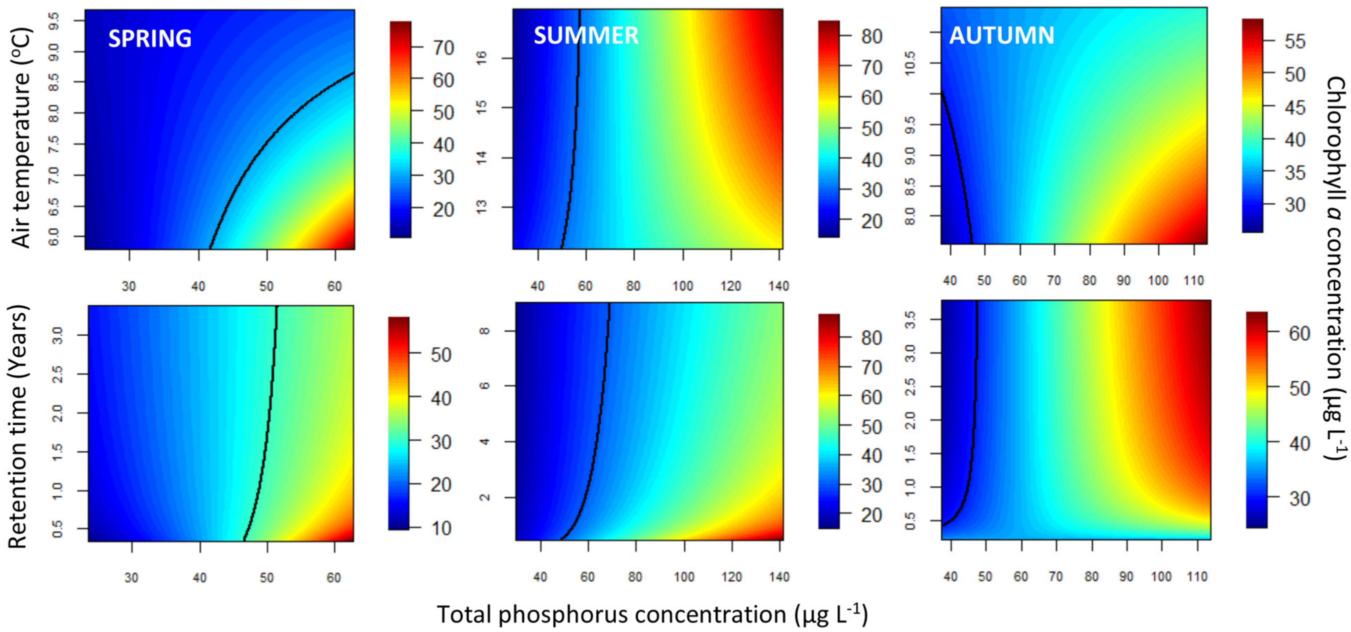

Figure 11 Heat maps showing effects predicted by linear models of total phosphorus (TP) concentration and air temperature (top panels), and TP concentration and retention time, on expected response in chlorophyll-*a* concentration (bottom panel) for spring (March - May), summer (June - August), and autumn (September - November) in Loch Leven, 1989 and 2019. Black line: arbitrary reference value of 30 µg L^{-1} chlorophyll-*a*.

indicators of the intensity and duration of extreme events beyond the threshold values indicated in the literature review, and also include temperature, wind and retention time as stressors.

Combining process based and empirical modelling to inform climate change management

A combination of process based and empirical modelling is likely to be necessary to unpick the complex processes moderating interactions between climate change stressors and nutrient stressors in Scottish lochs and reservoirs that are exemplified above for Loch Leven. For example, the lake process based lake models PROTECH and PCLake, which have been applied previously to Loch Leven, allow the prediction of ecological responses beyond simple indicators of phytoplankton biomass.

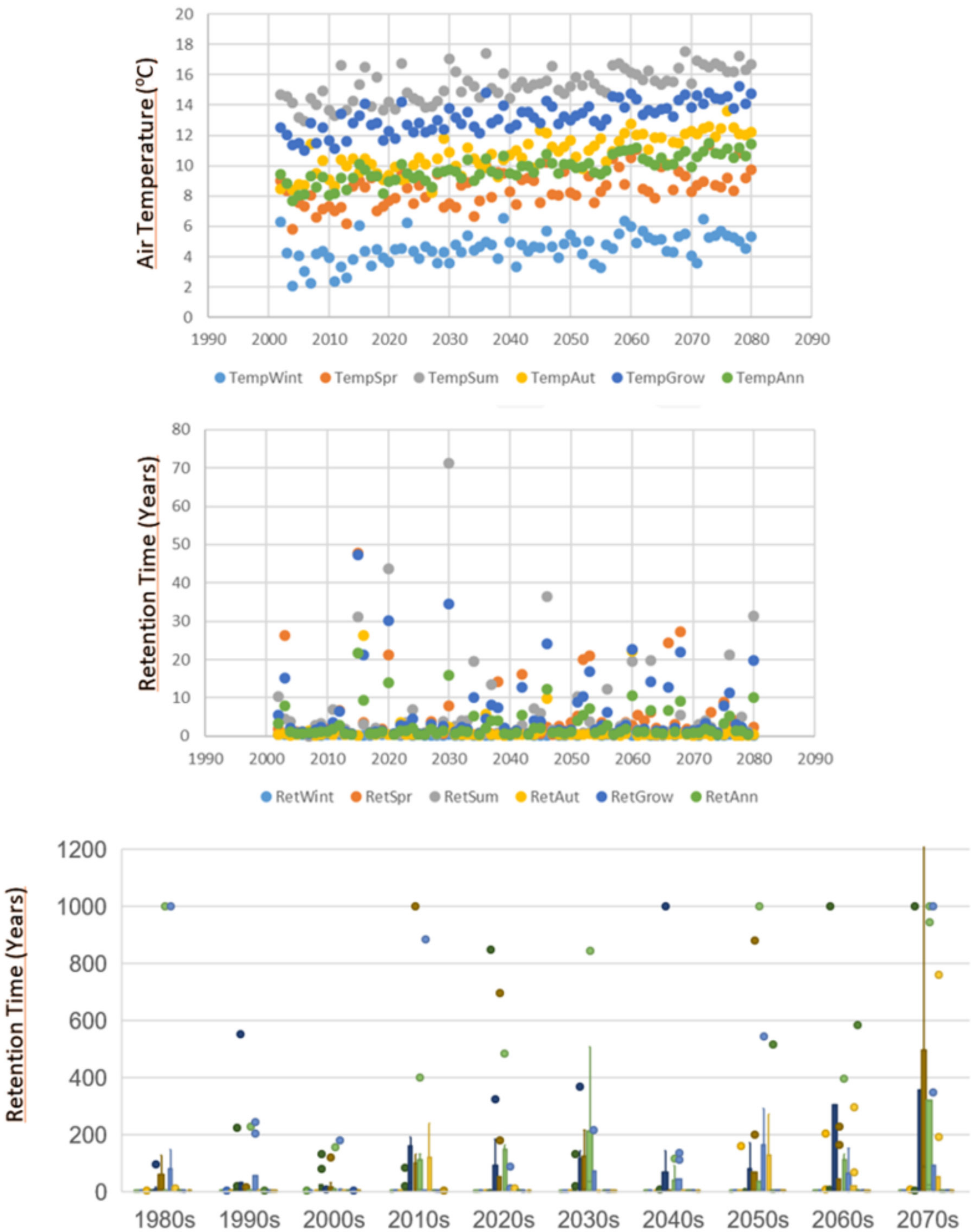

Figure 12 Long-term UKCP18 RCP6.0 climate change projections for seasonal air temperature (upper panel) and retention time (middle panel; monthly values >100 years removed for consistency with linear modelling approach) at Loch Leven between 2001and 2080 for winter (Dec - Feb), spring (Mar - May), summer (June - Aug), autumn (Sep - Nov), annual (all calendar months), 'growing' season (Apr – Sep).

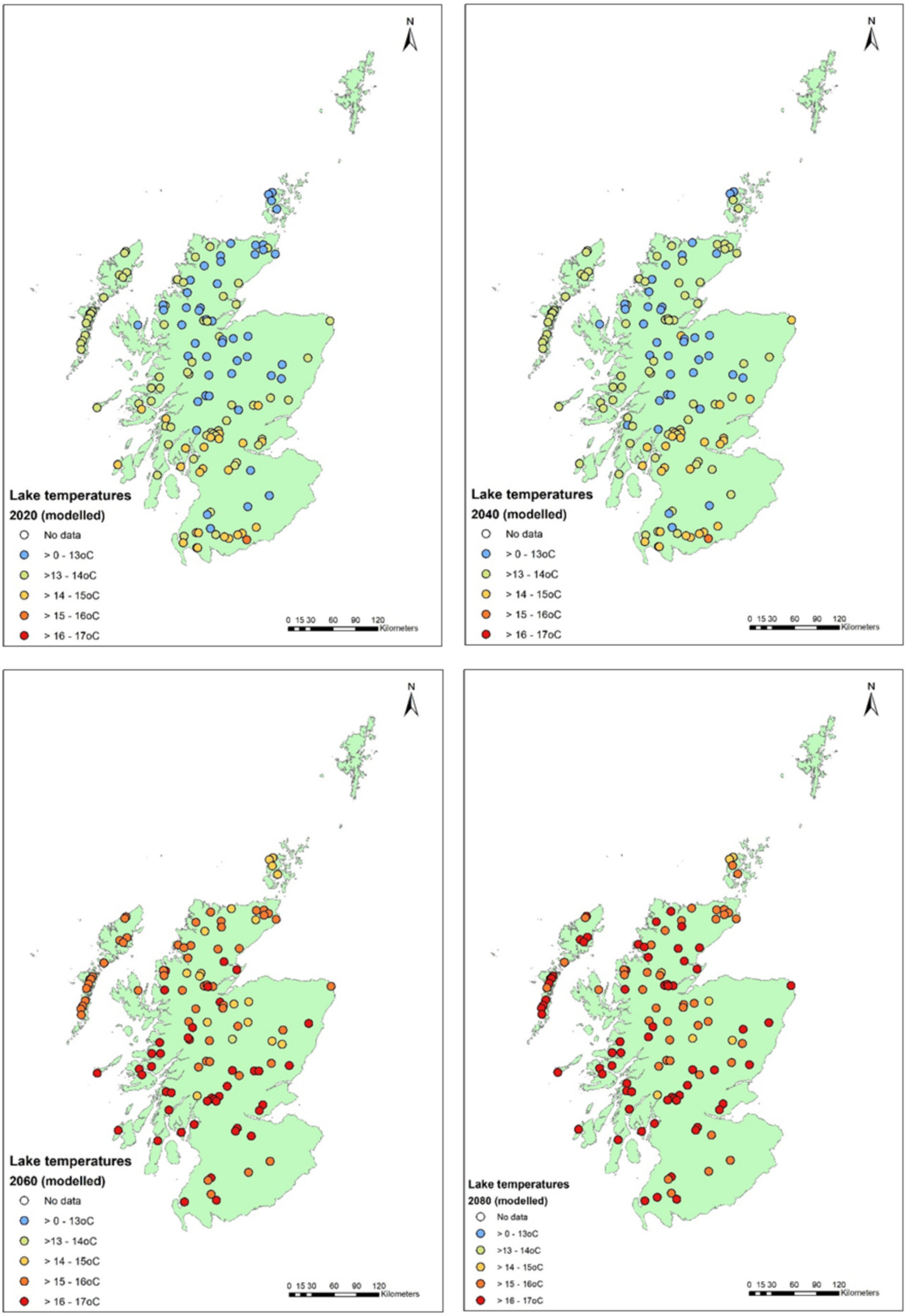

Figure 13 Modelled loch and reservoir water temperatures across Scotland for 2020, 2040, 2060 and 2080 based on projections derived from CHESS-SCAPE climate change data for RCP6.0, ensemble member 01 which is considered to be the most likely climate change scenario. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

Figure 14 Change in number of months per year that lochs and reservoirs across Scotland are likely to exceed an average monthly water temperature of more than 17°C under climate change; these water bodies will be at high risk of developing algal blooms during those months if flushing rates are relatively low and there are sufficient nutrients available to support their growth. *© UKCEH. Contains SEPA data © Scottish Environment Protection Agency and database right 2021. All rights reserved.*

Using the lake model, PROTECH, Elliott et al. (2008) predicted that chlorophyll-*a* concentration in Loch Leven is controlled by P load from the catchment, but that the relative abundance of the dominant cyanobacteria species in Loch Leven, the nitrogen fixing *Anabaena* sp., will be highest when N load is low in the model. Elliott and Defew (2012) predicted that cyanobacteria abundance would increase with nutrient loading during storm events, but not in response to warming, whereas chlorophyll-*a* was predicted to be lowest at low retention times and highest at high retention times. The results on retention time are in general agreement with our linear models for spring and summer. However, we also detected temperature effects that were not predicted in the PROTECH model. The PCLake model offers broader scope with respect to ecosystem scale responses across the food web, especially in relation to the sediment nutrient processes that are likely to be important in shallow lochs and reservoirs, such as Loch Leven. Assessment of empirical models could inform the development of scenarios that would enable process-based models to explore, for example, the revised setting of nutrient targets to avoid undesirable, or promote desirable, effects of climate change stressors. This approach should be considered in the context of a Climate Change Management Planning Framework for Scottish Lochs to inform the selection of potential management interventions based on the probability of their effectiveness, and based on agreed future climate change scenarios.

3.6 Climate change projections

The projected loch and reservoir temperatures derived from the CHESS-SCAPE climate change data under are shown in Figure 13. The mapped data suggest an increasing trend in water temperatures from 2020 to 2080, with average April to September values exceeding 16°C in most lochs and reservoirs by 2060. It is not possible to predict these climate change impacts precisely, due to uncertainties in the underlying climate change data. However, the RCP scenario used to generate these data (i.e., RCP 6.0, ensemble 1.0) is considered to be the most realistic of those available, and the relationship between the modelled loch and reservoir temperatures and the measured have been validated over the period 2010 to 2019. Nevertheless, given the inherent uncertainty associated with climate change projections, these results should be viewed with caution.

The average monthly water temperature threshold above which lochs and reservoirs are considered to be at high risk of developing risk algal or cyanobacterial blooms is 17°C. Figure 14 shows where loch and reservoir temperatures were above that threshold value in 2020, and will exceed that threshold value by 2040, 2060 and 2080. The likelihood of threshold exceedance increases over time to such an extent that, by 2080, half of all waterbodies are expected to be above that temperature threshold for one month a year and the other half for at least two months per year. Although the likelihood of algal blooms occurring in these systems is also affected by nutrient availability (which controls growth) and flushing rate (which controls losses from the outflow), factors that are difficult to quantify at present, it should be of considerable concern to water managers and environmental conservation/regulatory agencies that loch and reservoir temperatures in most areas of Scotland will be at high risk of developing algal blooms during 1-2 months per year if sufficient nutrients are available.

4 Discussion

The literature review identified a number of common factors in relation to climate change impacts on standing waters. The first is that the effects of climate change are already apparent and are expected to intensify. Many of the climate pressures on standing waters are mediated through their catchments, but climate change also has multiple direct and indirect effects on the physical, chemical and biological properties of the standing waters themselves.

Change seems to be occurring over multiple timescales, including decadal scale trends, seasonal changes and shorter-lived extreme events. Shallow lochs and reservoirs are more vulnerable to extreme climatic events than deeper lochs and reservoirs, because they have a larger proportion of their surface area affected. It is likely that impacts will be more marked on reservoirs due to the increased frequency and magnitude of drawdown events.

Shallow standing waters, particularly in south-east Scotland, are expected to be more sensitive to lower rainfall and reduced flushing rates than deeper lochs and reservoirs and more likely to develop algal blooms as a consequence. Deeper lochs and reservoirs, which are more characteristic of north-west Scotland, are less likely to be affected by changes in flushing rate, but may be more sensitive to other climate induced changes such as thermal stratification. Earlier onset and longer periods of thermal stratification will lead to changes in oxygen concentrations and carbon levels, resulting in increased releases of sediment bound nutrients and contaminants into overlying water.

Algal blooms, especially of cyanobacteria, are likely to increase when water temperatures exceed a monthly mean water temperature threshold of 17°C in summer. In addition, changes in the composition of the zooplankton community is likely to occur above a monthly mean water temperature threshold of 14°C. This will have knock-on effects on biodiversity, the level of grazing pressure on the phytoplankton community and water quality.

Changes in seasonal timing of biological communities and shifts in species ranges will occur under the climate change scenarios that are being projected. However, it is not always easy to attribute observed changes to climate change alone, as Scottish standing water systems are affected by multiple interacting stressors. Complexities are likely to arise when climate change interacts with other pressures and when impacts cascade through connected ecological systems.

Analysis of the SEPA monitoring data suggests that there is a strong relationship between air temperature and water temperature in Scottish standing waters, and that standing waters waterbodies are warming about 1.2 times faster than air temperatures. The data also show that cyanobacterial biomass in these waters increases with temperature and phosphorus concentration, with the highest cyanobacterial biovolumes occurring at TP concentrations above 20 µg L^{-1} if water temperatures rise above 14°C. These responses depend on loch and reservoir type, to some extent, with high levels of cyanobacteria being most common in shallow and very shallow lochs. In addition, this study found that humic lochs were more prone to high biomass events than clear lochs, and that high levels of cyanobacteria were especially common in medium alkalinity lochs.

When the national scale data were analysed using statistical models, any relationships between chlorophyll-*a* concentration and total phosphorus concentrations or water temperature seemed to be masked by variations among lochs and reservoirs in terms of their responses. This suggests that site specific analyses will be needed to inform management interventions aimed at reducing, or adapting to, climate change impacts either at sites already modelled or priority sites elsewhere. The results of this study suggest that, even by categorising lochs and reservoirs into typologies on the basis of depth or other physical characteristics, it may be difficult to generalise about likely responses to inform choices about management interventions. It is possible that standing waters may need to be grouped by response types instead, but this still needs to be explored. These response types should include bot waterbody and catchment typologies, such as nutrient concentrations and inputs (loads). In this study, the value of taking a site-specific approach has been demonstrated using Loch Leven as a case study. Here, statistical analysis of long-term data has been used to determine which site-specific combinations of TP concentration, flushing rate and water temperature would enable chlorophyll-*a* targets to be met.

Although not used in this study, the ability to generate internally consistent, and potentially long-term, water quality time-series from remote sensing data holds significant potential for monitoring the effects of climate change on water quality in Scotland into the future (see also Appendix 7). The utility of satellite data for climate studies will increase as the length of the observation record grows. Current data archives from the Sentinel-2 mission (5 years with two satellites) are arguably too short for the reliable detection of long-term climate change effects on water quality at the moment. But the data can already be used to explore, for example, more recent intra- or inter-annual trends, or the effects of climate extremes such as heatwaves and drought on the proliferation of algal blooms. The recurrence of algal blooms (rather than the quantitative estimation of chlorophyll-*a*) can also be identified using Landsat data, which does permit analyses to be extended back to the mid-1980s (e.g., Ho et al., 2017).

In general, the results from the expert survey showed that most respondents were concerned about the potential impacts of climate change on all types of standing waters across all areas of Scotland. The main issues raised were in relation to increases in algal blooms, which are expected to reduce recreational use waterbodies and affect the health and welfare of people and animals. Concern was also expressed about increased treatment costs where water supply reservoirs were affected. These opinions are closely aligned with the evidence gathered from the literature review, analysis of the monitoring data and the modelling work that was undertaken in this study.

5 Conclusions

Our key findings below are framed in response to the six strategic water research questions that this research addressed.

RQ1: Is there evidence of a causal link between climate change impacts and water quality issues in Scottish standing waters at national, regional and local scales?

- **KF1.1: Climate change is affecting the water quality of Scottish standing waters, specifically in relation to algal blooms, at multiple scales; mostly through increases in air temperatures and changes in rainfall patterns.**
    - Increases in rainfall, especially high rainfall events, will increase the delivery of pollutants (such as sediment and nutrient run-off) to standing waters from their catchments; this will cause nutrient enrichment (eutrophication) problems such as algal blooms – especially of cyanobacteria.
    - Decreases in rainfall, including an increase in droughts, reduce the flushing rates of lochs and reservoirs and, potentially, their water levels; this will encourage algal blooms and result in habitat degradation and loss of biodiversity.

- Increases in air temperature leads to an increase in water temperature that favours the development of algal (particularly of cyanobacteria) blooms in standing waters during the typical growing season of April to September; a reduction in the availability of nitrogen and silica as temperatures rise will allow cyanobacteria to outcompete other types of phytoplankton.

- **KF1.2: Increases in Scottish loch and reservoir temperatures are closely related to changes in air temperatures; rapid and extensive climate change-driven warming of these standing waters has already occurred in recent years and is expected to continue increasing.**
    - Between 2010 and 2019, average water temperatures of Scottish lochs and reservoirs, between April and September, increased 1.2 times faster than corresponding air temperatures.
    - Based on monitoring data collected between 2015 and 2019, 97% of Scottish lochs and reservoirs experienced an increase in temperature over this period, with most (88%) warming by between 0.25°C and 1.0°C per year and a small number (9%) increasing by 1.0°C to 1.3°C per year.
    - Standing waters are more likely to experience blooms of algae and cyanobacteria as water temperatures increase if there are sufficient nutrients (mainly nitrogen and phosphorus) available to support their growth.

- **KF1.3: Water temperature increases in many lochs and reservoirs have already been recorded; standing waters are projected to get warmer in the south and east of Scotland but this climate-related risk will spread further and reach all parts of Scotland by 2040.**
    - Climate-driven temperature changes are already occurring over multiple timescales, and are evident in decadal scale trends, seasonal changes and shorter-lived extreme events.
    - Short periods of extremely high water temperatures ('lake heatwaves') are likely to increase in occurrence, exacerbating the adverse effects of long-term warming; however these are expected be less intense in deeper lakes than shallower standing waters.
    - Lake heatwaves are likely to push aquatic ecosystems beyond the limits of their resilience, posing a threat to their biodiversity and related benefits they provide to society; this is especially true where low connectivity to other freshwaters mean that species will need to adapt within.

RQ2: What are the main types of climate-driven water quality impacts identified in Scottish standing waters under current and projected climate change scenarios?

- **KF2.1: Climate change will increase the risk of algal blooms developing in Scottish lochs and reservoirs – especially potentially harmful cyanobacteria.**
    - Increases in nutrient inputs and reductions in flushing rates, combined with warmer water temperatures, will increase the likelihood that blooms of algae and potentially harmful cyanobacteria will occur; their duration of occurrence may also expand.
    - Low flushing rates associated with higher water temperatures will increase the risk of nutrients being released from the sediments, fuelling sudden increases in algal growth.
    - High flushing rates will deliver more nutrients to standing waters from their catchment but, at the same time, limit the rate of accumulation of algae and cyanobacteria in the water due to an increase in losses from the outflow.

- **KF2.2: Increases in algal blooms are often associated with a higher risk of potentially harmful toxins from cyanobacteria being released into the water; the likelihood of this occurring will increase with warmer temperatures and lower flushing rates.**
    - Algal blooms, especially of cyanobacteria, reduce the amenity value of standing waters by increasing the risk of people and animals experiencing adverse effects on their health and welfare when visiting affected water bodies.
    - Increases in harmful algal blooms (likelihood and duration of occurrences) would prevent water quality targets being met for water supply and/or safe recreational use, leading to higher water treatment costs and/or restrictions on visitor access.
    - Further challenges in protecting public and animal health (e.g., recast Drinking Water Directive; revised Scottish Government guidance on cyanobacteria also known as blue-green algae in inland and inshore waters), as well as preventing failure to meet or restore water quality targets (e.g., EU Water Framework Directive), will increase if cyanobacterial blooms become more common.
    - Increases in algal blooms will impede statutory environmental objectives being met within policy/regulatory relevant timescales, have an adverse impact on biodiversity and reduce the capacity of water managers to deliver water quality improvements or maintain effective compliance measures that prevent further deterioration.

RQ3: Which areas, locations and types of Scottish standing waters are currently most to least at risk of developing water quality issues due to climate change impacts at national, regional and local scales?

- **KF3.1: Currently, all types of Scottish standing waters in all areas and locations are at high risk of climate change impacts.**
  - o The average April to September surface water temperatures of lochs and reservoirs across Scotland showed that, between 2015 and 2019, 97% of these waterbodies had warmed year on year.
  - o Maps of average April to September water temperatures between 2015 and 2019 showed a general increase in temperatures across the whole of Scotland over this period.
  - o Most lochs and reservoirs increased by 0.25 to 1.0°C per year between 2015 and 2019, but at four sites (i.e., Loch Achray, Loch Lubnaig, Loch of Girlsta, Loch Sgamhain) water temperatures increased by between 1.0 and 1.3°C per year.
- **KF3.2: Different types of lochs and reservoirs will respond differently to climate change impacts, with some more likely to develop water quality issues than others.**
  - o Although all lochs and reservoirs are warming, shallow and very shallow systems are likely to be more sensitive to climate extremes than deeper waterbodies because of their higher surface area to volume ratio.
  - o High concentrations of cyanobacteria were found to be rare in deep lochs and reservoirs, and those with 'humic' (coloured) water, although humic lochs tended to have a higher number of algal blooms than clear water lochs.
  - o As water temperatures increased, high concentrations of cyanobacteria occurred across the whole range of alkalinity types; however, these were more likely to occur in lochs and reservoirs with medium alkalinity.
  - o Reservoirs are more likely to be affected by climate change than waterbodies with a more natural hydrological regime because higher levels of abstraction under low rainfall conditions will exacerbate the combined effects of less water coming in from the catchment and higher evaporation rates.

RQ4: Which areas, locations and types of Scottish standing waters are likely to experience exacerbated water quality risks under projected climate change scenarios?

- **KF4.1: Water temperatures across different types of lochs and reservoirs are already getting warmer in most places; this climate-driven trend is projected to further increase from south to north, with an exacerbated water temperature situation expanding to all parts of Scotland by 2040.**
  - o Maps of projected water temperatures indicate that climate change impacts will be seen in lochs and reservoirs across the whole of Scotland.
  - o Average April to September air temperatures are projected to rise by about 2.5°C between 2020 and 2080; because loch and reservoir temperatures appear to be increasing by 1.2 times the rate of increase in air temperature, this equates to a corresponding increase of about 3°C in Scottish standing waters by 2080.
  - o As water temperatures increase, deeper lochs and reservoirs are likely to experience changes in the depth and duration of thermal stratification, with earlier onset and longer periods of stratification causing changes in oxygen concentrations.
  - o Decreases in oxygen concentrations will cause an increase in the release of sediment bound nutrients and other contaminants (such as manganese) into the overlying water; the increase in nutrients, especially phosphorus, will fuel sudden increases in potentially toxic algae and cyanobacteria.
  - o It should be noted, however, that it is not possible to predict these climate change impacts precisely due to the widely recognised uncertainties surrounding climate change predictions; so, these results should be viewed with caution even though the relationships between the climate change data and the loch and reservoir temperature data have been validated for 2010 – 2019.
  - o Further research is necessary to establish the relationships between climate change and water quality as the response of standing waters is complex and will be determined by the interaction of multiple factors. A key gap in our current knowledge is how climate change will affect the delivery of nutrients to a water body form its catchment – even with warmer temperatures, algal blooms cannot develop if there are insufficient nutrients available to support their growth.

RQ5: What factors contribute to the risk of water quality issues from climate change impacts in Scottish standing waters at national, regional, and local scales?

- **KF5.1: Climate change driven increases in water temperature and nutrient availability, and reductions in flushing rates, will increase the risk of water quality issues developing in Scottish lochs and reservoirs.**
  - The likelihood of algal blooms, especially of cyanobacteria, will increase as mean monthly water temperatures rise above 17°C; this temperature threshold for water quality impacts has been recognised across Europe and is not unique to Scotland, although the underlying reason for this is uncertain at present.
  - Maps showing changes in the frequency with which average monthly water temperatures are likely to exceed 17°C over time suggest that climate change will result in all Scottish lochs and reservoirs experiencing algal blooms by 2080, unless algal growth is nutrient limited.
  - Nutrient releases from the bottom sediments of lochs and reservoirs will be more likely to occur under climate change due to more frequent deoxygenation at the sediment/water interface; in combination with higher water temperatures, these increases in nutrient availability will lead to an increase in algal blooms.
  - Changes in zooplankton community composition are likely to occur when mean monthly water temperatures exceed 14°C; this will affect aquatic biodiversity – especially in relation to species, such as fish, that depend on these organisms as a source of food.
  - Shifts in the seasonal timing of biological communities will occur under the projected climate change scenarios; where this causes a mismatch in the timing between algal communities and their zooplankton grazers, algal blooms will be more likely to occur.
  - The lack of zooplankton data for Scottish standing waters, especially in the spring/early summer when the zooplankton induced clear water phase is most likely to be adversely affected, makes this difficult to evidence.
  - A key gap in our understanding is the time that biological communities will take to undergo an evolutionary adaption to climate change, and whether this will be fast enough to avoid the catastrophic loss of key species – especially of zooplankton, which play a pivotal role in maintaining good water quality in standing waters.
- **KF5.2: Scottish loch and reservoir sensitivity factors will affect the risk of water quality issues developing due to climate change impacts.**
  - The statistical modelling of the loch and reservoir monitoring data showed that, at national scale, the causal relationships between chlorophyll-*a* concentrations and total phosphorus concentrations or water temperature are masked by variations among lochs and reservoirs in terms of their patterns of response.
  - Responses are likely to be more complex when climate change interacts with other pressures, especially where impacts cascade through connected ecological systems.
  - High levels of cyanobacteria are most common in shallow and very shallow lochs, especially those with medium alkalinity levels; these should be prioritised for mitigation purposes.
  - Humic lochs appear to be more prone to high biomass events than clear lochs; the reason for this is unclear.

RQ6: What factors need to be considered for mitigating climate-driven risks to water quality under current and projected climate change scenarios?

- **KF6.1: A whole system approach needs to be taken to mitigate future climate change impacts on standing waters.**
  - Mitigation of climate-driven risks to water quality under current and projected climate change scenarios needs to take a whole system approach, focusing on improved catchment management and sustainable use of water resources; this is a key policy requirement of, for example, the recast Drinking Water Directive (rDWD) and EU Water Framework Directive (WFD).
  - Where climate change impacts cannot be controlled by mitigation, adaptation may need to be considered.
  - Standing waters are subject to multiple interacting pressures that need to be taken into account when interventions are planned.
  - Site-specific analyses may be needed to inform management interventions aimed at reducing, or adapting to, climate change impacts.
  - Categorising lochs into typologies on the basis of depth or other physical characteristics may be insufficient to inform choices about management interventions; shallow and very shallow systems with high nutrient content should be prioritised first in terms of restorative or preventative management, because these are at highest risk of developing water quality problems.

- **KF6.2: An integrated catchment-based approach needs to be taken for setting water quality targets and planning interventions.**
    - o Statistical analysis of long-term monitoring data should be used to determine which site-specific combinations of TP concentration, flushing rate and water temperature would enable chlorophyll-*a* targets to be met.
    - o Where long term data are not available, site or type specific modelling should be used to identify where interventions can be targeted most cost effectively to achieve water quality targets into the future in un-monitored standing waters.
    - o Catchment based interventions, such as sustainable nature-based (or nature-inspired) solutions, should be considered.

6 Key Recommendations

As a result of this current project analysis, our key recommendations are outlined as follows:

Policy recommendations

The global envelope of climate change is currently affecting, and is projected to further impact on, standing water quality, especially in relation to increasing water temperatures and algal blooms. As part of an informed strategic and coordinated response to the climate crisis, Scotland needs to consider developing, revising, operationalising, and implementing a combination of broad, dynamic, and targeted policy changes for embedding a proportionate response to climate-driven impacts on people, policy, and the water environment across multiple scales, now and into the future. This is made clear from the recent UK Climate Change Committee (2022) Report to Scottish Parliament.

- **Global Climate Change Impacts – Adaptive National Water Policy Perspectives:** The policy gap between global and national understanding of the impacts of systemic climate change on water temperatures and changing rainfall patterns needs to be closed. Failure to address this issue and monitor for key indications of climate-related risks will undermine the development and implementation of adaptive water policy and management practices intended to mitigate complex interactions that affect water use and nutrient run off at regional and local scales.
- **National Climate Change Impacts – Adaptive Regional and Catchment Water Policy Perspectives**: Water policy and management practices need to be adapted to take into consideration national climate-driven risks on the quality of standing waters at regional and catchment scale in Scotland (e.g., River Basin Management Planning (RBMP); Third Land Use Strategy). These climate change impacts will be mediated through shifts in catchment and in-lake processes such as flushing rates, water levels, and nutrient inputs. In combination, these which exacerbate the future risk of algal blooms and may compromise Scotland's ability to meet statutory goals and regulatory targets within given timelines. Revision of current nutrient criteria for Scottish lochs and reservoirs may need to be considered, in conjunction with other policy-based and nature-based solutions, as a potential climate change mitigation/adaptation strategy, to support desirable legislative outcomes under different climate scenarios. For example, EU Water Framework Directive (WFD) targets for Scottish standing waters may need to be reviewed, and mitigation/adaptation climate strategies mobilised so that good ecological status can be achieved, prevent further deterioration and guide restorative action. It is anticipated that revision of nutrient standards and regulatory compliance permitting/assessment may need to consider climate-related risk in the future. This current analysis of climate-related water quality issues illustrates links between the twin climate and biodiversity crises colliding and being interwoven. This could form a significant contribution to the forthcoming Scottish Biodiversity Strategy (SBS; expected during 2022). This work could also lead to a re-assessment of the Scottish Government's favourable condition targets for protected sites – particularly Special Areas of Conservation and Sites of Special Scientific Interest. It is also noted that the recast Drinking Water Directive (rDWD) will require the creation of Catchment Risk Assessments for all drinking water catchments to encourage greater source control of pollutants (known in the Directive as Hazards and Hazardous Events) i.e., a prevention-led approach for addressing climate change interactions with these catchment factors than reactively managing potential impacts (e.g., algal blooms) on public health with expensive treatment.
- **Regional Climate Change Impacts – Adaptive Local Water Policy Perspectives:** There is an urgent need to update the publication 'Cyanobacteria (Blue-Green Algae) in Inland and Inshore waters: Assessment and Minimisation of Risks to Public Health – Scottish Government Revised Guidance (2012)' in relation to climate change impacts by capturing new evidence that has emerged from this current analysis. This policy review would help protect the amenity value of locally important still waters (e.g., for recreational and wellbeing purposes), and reduce climate-driven water quality risks to public and animal health, whilst

climate change mitigation/adaptation needs are being met through other policy routes.

Future monitoring recommendations

The recent UK Climate Change Committee (2022) Report to Scottish Parliament makes clear that 'Scotland lacks effective monitoring and evaluation systems meaning that changes in aspects of many climate-related risks are largely unknown'. Therefore, the existing monitoring network for Scottish lochs and reservoirs urgently needs to be reviewed with a focus on developing an integrated approach for detecting climate change impacts, at pace and scale, whilst including focussed use of new scientific innovations and adaptive resource capabilities. For example:

- Monitor water temperatures in Scottish standing waters at an accuracy of approximately 0.1°C to provide early warning that water quality issues are likely to develop.
- Monitor total and cyanobacterial chlorophyll-*a* concentrations using handheld devices that provide instantaneous data on accumulation of algal blooms, especially cyanobacteria.
- Measure nutrient inputs from catchments, including high temporal resolution gauging of inflows where site specific problems need to be addressed.
- Collect data on precipitation and wind speed to better represent the multi-faceted nature of climate change drivers and their impacts (e.g., storm-driven mixing events, "pulses" of polluted run-off during high rainfall events).
- Develop and monitor indicators of climate change impacts on ecosystem state, processes, and services.
- Explore the potential role of diverse monitoring approaches (e.g., earth observation, in-situ sensors, molecular techniques) for detecting and understanding climate change impacts.
- Consider how different data "streams", especially earth observation data, can be integrated to improve our ability to detect and forecast change.
- Support citizen science initiatives which can provide useful surveillance monitoring data (e.g., Bloomin' Algae app) for assessing climate change impacts on Scotland's water resources.

Further research recommendations

We have assessed that climate change is currently affecting the water quality of Scottish standing waters. We have also projected it will continue happening without urgent intervention to establish pace and scale of mitigation/adaptation strategies needed to course-correct an exacerbated warming situation in the future. This new evidence offers a significant contribution towards strategic climate change needs identified by the recent UK Climate Change Committee (2022) Report to Scottish Parliament. Yet there is still much to be learned about the extent, complexity, rate, and interactions of climate-related risks to water resources in Scotland. We have initially scratched the surface through this current analysis, and as such, there are potential opportunities to explore and understand this evidence in more depth through further analysis. The following research activities are recommended to make best use of the new information that is now available:

- A more in-depth analysis of the SEPA lochs and reservoirs monitoring dataset should be undertaken to improve our understanding the current impacts of climate change on standing waters, how these have developed over time and how they relate to waterbody structure and function.
- More research is needed to provide a better understanding of the links between climate change impacts at the catchment scale and their effects on downstream waterbodies, especially in relation to the propagation of the impacts of extreme climatic events such as storms, heatwaves, floods, and droughts. Existing lake and catchment models would need to be upgraded and linked together to achieve this.
- Further research is needed to understand the extent of climate change impacts on the ecological functioning of Scottish standing waters, especially *when* ecosystems and biodiversity are likely to reach the point of no return (or tipping point), and *how* we can mitigate for this sort of potentially catastrophic collapse.
- There is a precise need to better understand why, and specifically what, ecosystem changes are generally triggered across Scotland and in wider Europe when mean monthly water temperatures exceed 17°C and favour the development algal blooms, especially cyanobacteria; as well as the important role of zooplankton as naturally occurring 'ecosystem engineers' or 'nature-based solutions' that maintain the good water quality of standing waters for example through grazing pressure. We also need to understand the capacity of zooplankton communities to undergo evolutionary adaptation fast enough to prevent a climate change induced ecological crisis.
- Probing connectivity in Scottish standing waters between the climate and biodiversity crises with modelled outputs examined against a broader context of biodiversity typology and classification system-based approaches (e.g., Duigan et al., 2006).

Potential future phase(s) of work recommendations

- **Delivery Purpose and Implementation Needs**: Potential future phase(s) of work should specifically consider addressing the factors that drive algal blooms and engaging sustainable system-based approaches for mitigation of, or adaptation to, current and future climate change impacts on the water quality of Scottish standing waters. This is in the interest of (**1**) delivering maximal water-related benefits for people and the environment; (**2**) co-creating effective solutions and supporting intended climate change adaptation outcomes; and (**3**) strengthening the evidence needed to inform coordinated adaptive management and strategic delivery responses by key stakeholders. Such responses may involve revising existing or developing new and innovative policy-based changes to, management strategies including the integration of nature-based solutions where feasible. These may involve targeting intervention by effective (e.g., response types or site-specific) approaches in a less data-intensive and more readily deployable way.
- **Prioritisation and Engagement Needs**: If required then further analysis should focus on identifying which lochs, reservoirs, and locally important still waters should be prioritised within a climate change mitigation and/or adaptation strategy. By actively engaging a broad range of individuals and organisations in knowledge-exchange opportunities, it should develop tailored approaches and management practices capable of reducing the risk of climate-driven impacts on the water quality of Scottish standing waters across multiple scales. Such outreach activities will need to engage with the primary beneficiaries, such as staff from strategic to operational levels across key stakeholder organisations including the Scottish Government and its environmental conservation and regulatory agencies (e.g., NatureScot, SEPA, DWQR), and water managers (e.g., Scottish Water). Outreach and engagement activities with representatives of the wider water community (e.g., public interest, local authorities, national park authorities, Fisheries Trusts and District Salmon Fishery Boards, anglers, Scottish Freshwater Group members) could include the creation of data visualisations, infographics, and storyboards to illustrate climate change impacts in an accessible way to empower others to become involved in shaping climate action.
- **Evidence-based Needs**: Given additional evidence needs, mapping and modelling tools to project the risk of algal blooms into the future need to be developed to help forecast which areas, locations and types of Scottish standing waters are most vulnerable or sensitive to bloom formation and the impacts of climate change at the national scale. This should be complemented by a more in-depth exploration of climate-driven risk (e.g., in relation to different water uses). Potentially, site-specific studies would help to identify effective management strategies for reducing or reversing climate change impacts on waterbodies at local to catchment scales. Scenario-based modelling approaches should be employed to examine the potential effectiveness of management interventions aimed at mitigating climate change impacts, especially catchment-based solutions such as land use change and nutrient neutrality-based approaches.

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