Can small changes in water retention time reduce the severity of algal blooms in lakes, providing mitigation of climate change impacts? A proof of concept using Loch Leven as a case study.

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Summary

A lake response model, PROTECH, has been used to explore whether small changes in flushing rate could be used to mitigate climate change effects on lochs and reservoirs. We have used Loch Leven, a large, shallow, well monitored loch in the lowlands of Scotland as case study. Climate change effects can produce unexpectedly large algal blooms at a time when nutrient inputs to a water body appear to have remained stable. This report documents initial results from testing 30 different flushing scenarios on the timing and maxima of cyanobacterial blooms in Loch Leven, using 2019 as a baseline. The results suggest that the peak in chlorophyll *a* levels associated with these blooms could be reduced by up to 39% if relatively small changes in the flushing rate are implemented. Such changes appear to have little effect on the timing of the chlorophyll *a* maxima and almost no effect on water levels. It is recommended that options for mitigating algal blooms through small changes in flushing rates are explored further.

Introduction

Climate change is already affecting many lochs and reservoirs across Scotland, causing changes in water temperatures, hydrological regimes and nutrient budgets. These, in combination, affect the sustainable use of these waterbodies for recreation, tourism and water supply, and/or as a suitable habitat for plants and wildlife that are of conservation importance. Questions are now being raised about whether current loch and reservoir management practices, many of which have been in place for decades, are still fit for purpose under a changing climate and whether changes in policy, or its implementation, might be needed to ensure the successful mitigation of the adverse effects of climate change in the future.

This research is an initial proof of concept study to investigate whether manipulating the flushing rates of lakes and reservoirs could be used to mitigate climate change and eutrophication impacts where options for reducing nutrient inputs to these types of waterbody are limited and their responses to such measures are slow. By applying a scenario based modelling approach to Loch Leven, a well monitored loch in the Scottish lowlands, we have undertaken an initial exploration of the extent to which changes in the rate at which water is discharged from the outflow could help to reduce the likelihood of algal blooms, especially of cyanobacteria, during the summer months.

Site description

Loch Leven is a large, shallow, eutrophic lake with a surface area 13.4 km^2, mean and maximum depths 3.9 m and 25.5 m, respectively, and an average volume of about 50,000,000 m^3. It is located in the lowlands of east central Scotland. Its catchment drains an area of 145 km^2 and the loch has an annual water retention time of about 5 months (Bailey-Watts & Kirika, 1999). Over the last 50 years, long term records have shown that the loch has been warming due to climate change, with an average annual increase in water temperature of about 0.35 degrees centigrade per decade (Figure 1), most of which has occurred since 1990.

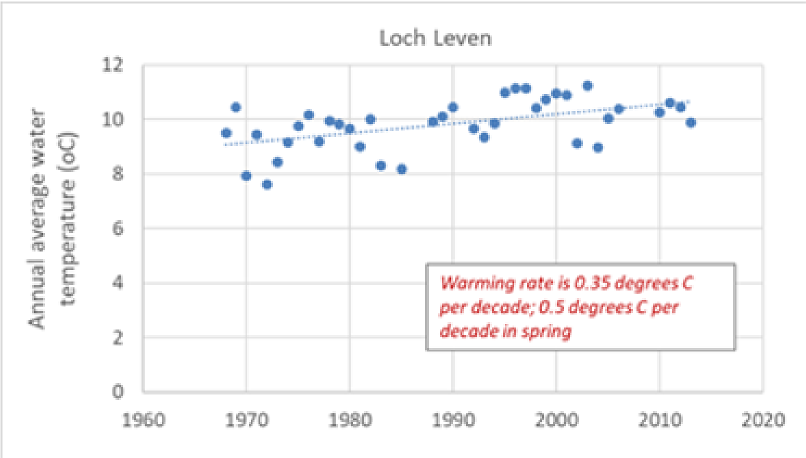


Figure 1 Annual average water temperatures at Loch Leven since 1968.

Despite a 60% reduction in phosphorus (P) inputs to the loch since the mid-1980s (May et al., 2012), and very little evidence of any increase since then (May et al., 2017), algal blooms have become more common again in recent years. During the summers of 2018 and 2019, in particular, dense algal blooms occurred (Figure 2). These comprised mainly cyanobacteria, resulting in Perth and

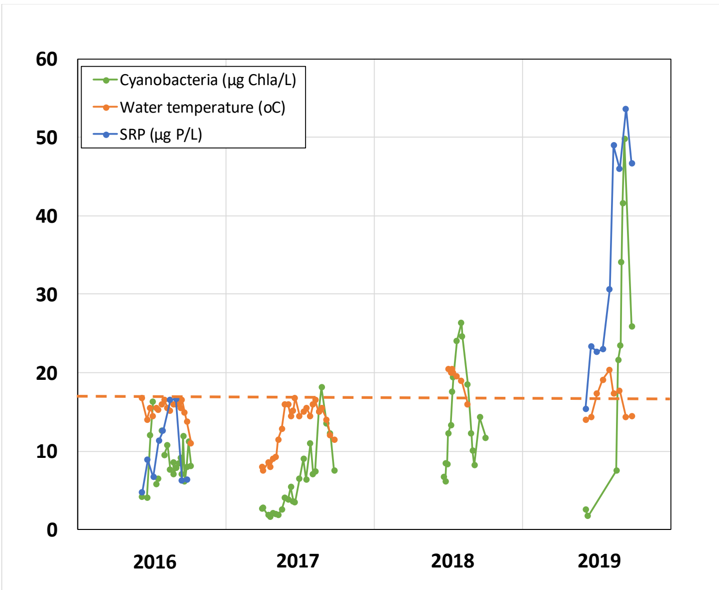


Figure 2. Monitoring data from Loch Leven suggesting that the cyanobacterial blooms of 2018 and 2019 occurred when the when temperatures exceeded 17°C, i.e. went above the orange broken line.

Kinross Council's Environmental Health department erecting signs warning visitors of the dangers of coming into contact with the water.

There has been much discussion about the potential causes of the algal blooms in 2018 and 2019. Theories range from increased P inputs to the loch from new housing developments and/or combined storm overflows to the potential effects of climate change. Although detailed analyses are incomplete, at present, Figure 2 strongly suggests that the algal bloom in 2019 was probably caused by a significant release of soluble reactive phosphorus (SRP) from the loch sediments when the water temperature rose above 17°C for a prolonged period.

Methods

The method used in this study comprised fitting a lake model (PROTECH) to Loch Leven using the best available data and testing a range of potential management scenarios to determine their effectiveness at reducing the magnitude of the algal bloom that developed in 2019. These comprised theoretically manipulating the flushing rate by different amounts, over different periods of time and at different times of year. The flushing scenarios used in the study are summarised in Table 1. The changes in outflow volume indicated correspond to 5%, 10% and 15% increases over the periods shown.

Table 1. Flushing scenarios tested

Outflow volume	Start dates	Duration (days)
x1.05	Day numbers 160, 170, 180, 190, 200	10
		20
x1.1		10
		20
x1.15		10
		20

PROTECH model description

The lake model, PROTECH, has been developed and tested on a wide range of lakes and reservoirs around the world over the last two decades (Elliott et al., 2000; Lewis et al., 2002; Elliott & Thackeray, 2004; Elliott et al., 2005; Elliott el al., 2007). The fundamental core of the biological component of PROTECH (Reynolds et al., 2001; Elliott & Thackeray, 2004) is a basic state variable equation that determines the daily change in the chlorophylla concentration ($\Delta X/\Delta t$, $\mu g\ L^{-1}\ d^{-1}$) of each algal species:

$$\Delta X/\Delta t = (r' - S - G - D).X \qquad \text{(Equation 1)}$$

where:

- r' is growth rate defined as a proportional increase (per 24 hours)
- S is loss due to settling out from the water column
- G is loss associated with *Daphnia* grazing, assuming that species >50 µm are not grazed
- D is loss due to dilution
- X is the initial starting value of each algal species (μg chlorophyll*a* $L^{-1}\ d^{-1}$)

The growth rate (r′ d^{-1}) is further defined by:

r′ = min{r′(θ,I), r′P, r′N, r′Si} (Equation 2)

where:

- r′(θ,I) is growth rate due to temperature and daily photoperiod
- r′P, r′N and r′Si are the growth rates determined by P, N and Si concentrations, respectively

The r′ values relate to the morphology of each algal species. For each species, the initial starting value (X) is modified on a daily time-step to predict change in the chlorophyll*a* concentration in the water column (see Reynolds et al., 2001, for details).

Driving and validation data

The driving and validation data for the initial calibration of PROTECH were taken from 2005, when very detailed information on nutrients and flows were collected for most of the major inflows to the loch. These measurements included stream discharges and associated soluble reactive phosphorus (SRP), nitrate-nitrogen (N) and silica (Si) concentrations collected at 8-daily intervals. In-lake SRP, N, Si and chlorophyll*a* concentrations, and water temperature were measured at 14 day intervals over this period and phytoplankton species biovolume was recorded monthly. In addition, for 2019, total and cyanobacterial chlorophyll*a* concentrations were measured every few days using a BBE Algae torch (https://www.bbe-moldaenke.de/en/products/chlorophyll/details/algaetorch.html).

Daily meteorological data for 2005 (cloud cover, air temperature, air humidity, wind speed) were compiled from records collected at a meteorological station located at Leuchars Airfield, 35 km

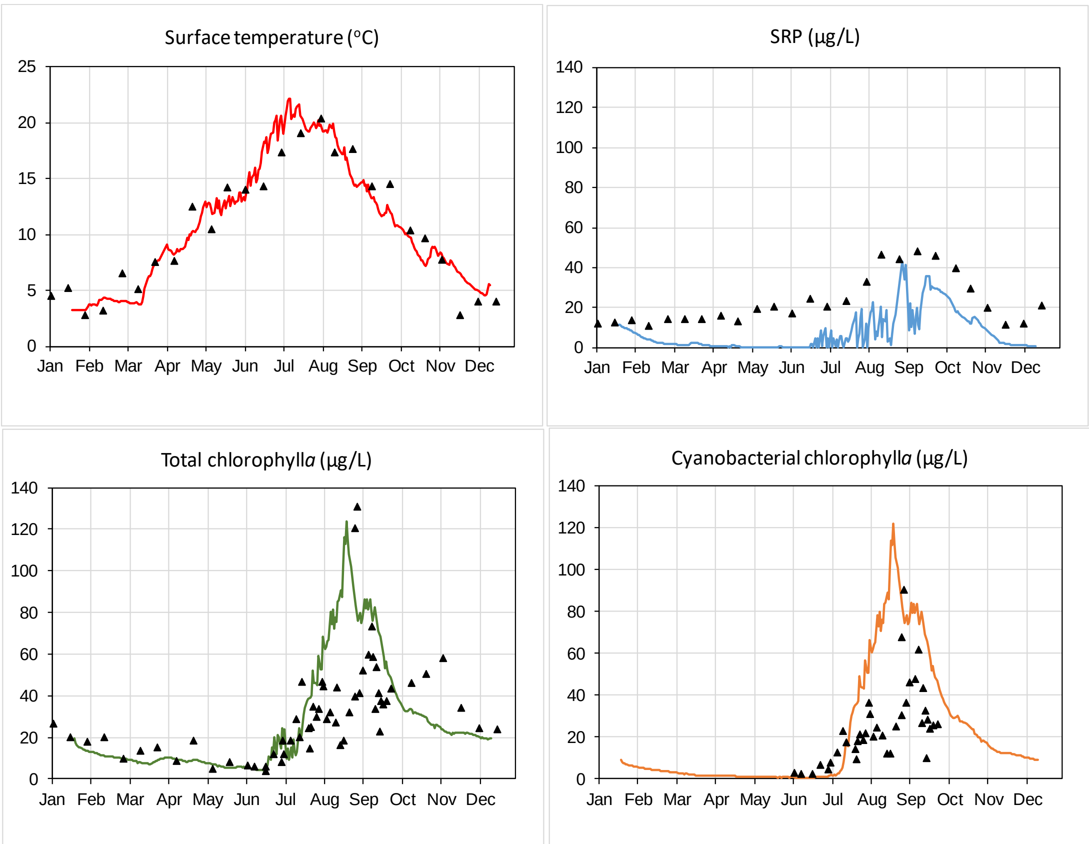


Figure 3. Validation of PROTECH model output (solid line) in terms of fit to 2019 data (black triangles).

north-east of the lake. Wind speeds were corrected to reflect local conditions by applying a 20% reduction to the wind speeds measured at RAF Leuchars (see Smith, 1973).

For the current study, the model developed and validated by Elliott & Defew (2012) was updated to reflect the situation observed in Loch Leven in 2019 by adding a release of SRP from the sediments to the driving data. This was equivalent to 4.5 µg P L^{-1} d^{-1} between day numbers 170 and 260, which equated to an internal sediment P release of about 18.4 tonnes per year. In addition, the Elliott & Defew (2012) model was improved by adding more detailed bathymetric data derived from the survey of Kirby (1971).

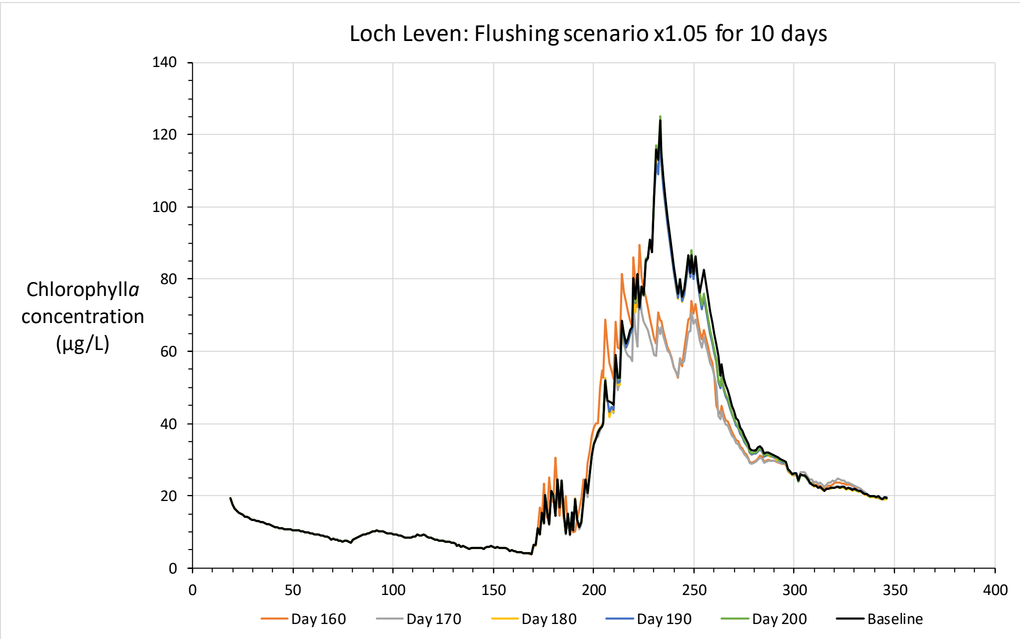
Results

Model validation

To validate the model, its output was compared to the data on water temperature, SRP concentration and algal biomass collected during 2019 (Figure 3). Chlorophyll*a* validation data for the total algal population, and for the cyanobacterial component, were created by combining the fortnightly data from the long-term monitoring programme with more frequent data collected using the BBE Algae torch. On the basis of the graphs shown in Figure 3, and the good fit obtained between the predicted water levels and the measured values (not shown), the simulation was considered adequate for use as a baseline on which scenario testing could be based.

Impact of different flushing regimes on chlorophyll*a* concentrations

Examples of the modelled impacts of the different flushing regimes tested on in-loch concentrations of total chlorophyll*a* and cyanobacterial chlorophyll*a* are shown in Figures 4 & 5 for the two extremes, i.e. a 5 percent increase in discharge to the outflow for 10 days and a 15% increase in discharge to the outflow for 20 days.



~~Figure 4.~~ *The effect on total chlorophyll*a* concentration of a 5% increase in discharge from the outflow for 10 days from the start dates shown*

Figure 3 shows, clearly, that increasing the outflow volume by about 5% for 10 day periods starting at days 160 and 170 reduced the size of the algal bloom considerably while, in contrast, starting on days 180, 190 and 200 did not. For the latter scenarios, the size of the algal bloom differed very little from that of the baseline (normal) data.

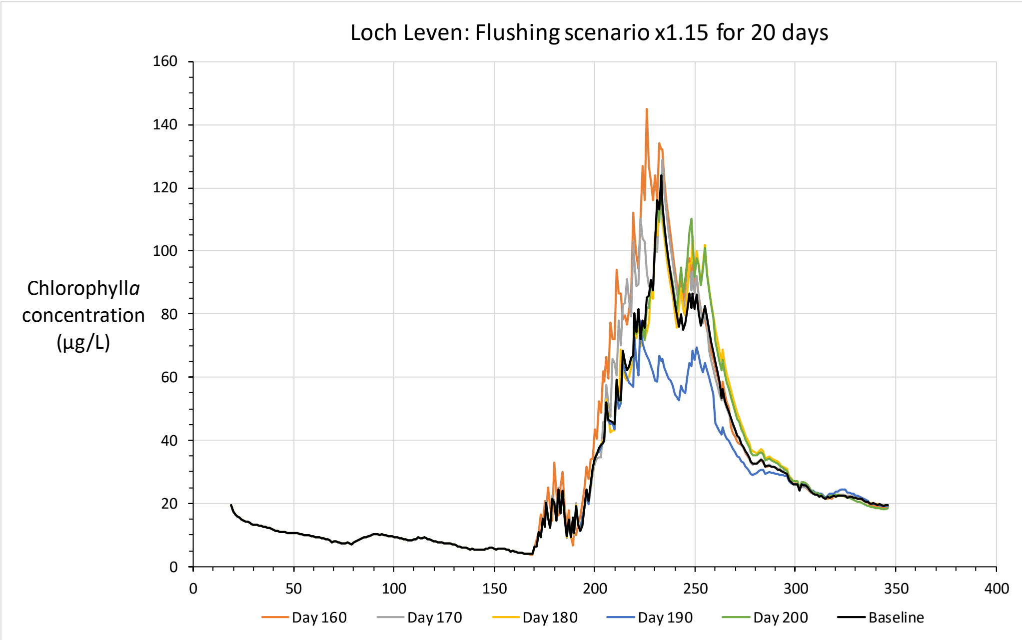


Figure 5. The effect on total chlorophyll<u>a</u> concentration of a 15% increase in discharge from the outflow for 20 days from the start dates shown

Figure 5 shows that the results were very different when the outflow volume was increased by 15% for 20 days, with the different starting dates delivering very different results. For example, the lowest chlorophyll*a* concentrations resulted from starting the increased flow regime on day 190 and the highest chlorophyll*a* concentrations resulted from starting on day 160. In fact, starting on day 160 actually increased the size of the algal bloom making it even more severe than it had been originally, i.e. in the baseline data.

Similar results were found for the cyanobacterial chlorophyll*a* concentrations because most of the algae during the bloom period were cyanobacteria. So, these data are not shown.

Impact on size of chlorophyll*a* peaks

Overall, the loch appeared to be very sensitive to even relatively small changes in its hydrological regime, suggesting that this could provide a possible means of mitigating the algal blooms that now seem to be occurring in response to climate change. Tables 2 & 3 show the effects of the different flushing scenarios tested on the predicted size of the bloom maxima. It is clear that some scenarios were more effective than others at reducing the size of the algal bloom, with some reduced the bloom maxima by up to 39% while others increased the bloom maxima by up to 18%. So, it is very important to determine ways of selecting the correct approach to achieve the required outcome.

In general, smaller increases in flushing seemed to be more effective if they began on earlier start dates whereas larger changes in flushing were more effective when combined with later start dates.

Starting at day 200, i.e. 33 days before the peak of the algal bloom in the baseline data, was completely ineffective at reducing the size of the algal bloom under any of the flushing scenarios.

Table 2. Magnitude and direction of change in maximum total chlorophylla concentrations under different flushing regimes.

		Flushing scenario					
		x1.05 & 10 days	x1.05 & 20 days	x1.1 & 10 days	x1.1 & 20 days	x1.15 & 10 days	x1.15 & 20 days
Start date	Baseline	0%	0%	0%	0%	0%	0%
	Day 160	-28%	-31%	+9%	+1%	-24%	+17%
	Day 170	-37%	-36%	-26%	-34%	-28%	+4%
	Day 180	-2%	-37%	-39%	-36%	-36%	-2%
	Day 190	-2%	-2%	-37%	-39%	-39%	-37%
	Day 200	+1%	-2%	-3%	-1%	-1%	0%

Table 3. Magnitude and direction of change in maximum cyanobacterial chlorophylla concentrations under different flushing regimes.

		Flushing scenario					
		x1.05 & 10 days	x1.05 & 20 days	x1.1 & 10 days	x1.1 & 20 days	x1.15 & 10 days	x1.15 & 20 days
Start date	Baseline	0%	0%	0%	0%	0%	0%
	Day 160	-28%	-31%	+9%	+1%	-24%	+18%
	Day 170	-37%	-37%	-26%	-35%	-28%	+4%
	Day 180	-2%	-37%	-39%	-38%	-37%	-1%
	Day 190	-2%	-2%	-37%	-39%	-39%	-37%
	Day 200	1%	-2%	-3%	-1%	-1%	+1%

Impact on the timing of chlorophylla peaks

In the baseline data, the peak of the algal bloom occurred at day 233. Table 4 shows the impact on this of the different flushing scenarios in terms of the number of days earlier (-) or later (+) that it occurred. In many cases, there was no change ('0') but, in most other cases, the bloom occurred up to 10 days earlier. However, a 10% increase in outflow for 20 days and a 15% increase in outflow for 10 days starting at day 180 delayed the peak of the bloom by about 16 days.

Table 4. Change (in days) in the timing of the chlorophylla peak under different flushing scenarios.

		Flushing scenario					
		x1.05 & 10 days	x1.05 & 20 days	x1.1 & 10 days	x1.1 & 20 days	x1.15 & 10 days	x1.15 & 20 days
Start date	Baseline	0	0	0	0	0	0
	Day 160	-10	-10	-10	0	-10	-7
	Day 170	-10	-10	-10	-10	-10	1
	Day 180	0	-10	-10	+16	+16	0
	Day 190	0	0	-10	-10	-10	-10
	Day 200	0	0	0	0	0	0

Effects on water level

An important concern when changing the flushing rate of a loch is the effect on the water level as increase in water level can cause flooding and decreases in water level can affect the ecology of the lake, e.g. by exposing macrophyte beds or fish spawning grounds to desiccation. Figure 6 shows that increasing the level of discharge from the outflow by 5% over the range of start dates tested had

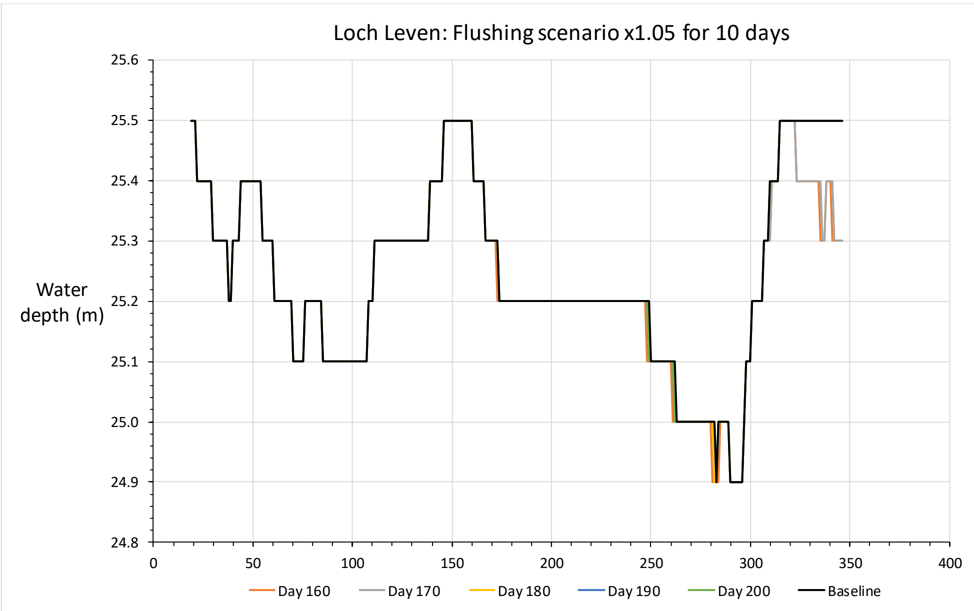


Figure 6. Effect on water level of a 5% increase in discharge from the outflow for 10 days from the start dates shown

little effect on the overall water level (depth). However, Figure 7 shows that if 15% increases in outflow are implemented earlier in the year (e.g. days 160 and 170) water levels may fall to a lower level earlier in the year than with a lower level of flushing or a later start date. In general, however, the loch level still remained within its normal (baseline) operational limits, even under the most extreme scenarios tested.

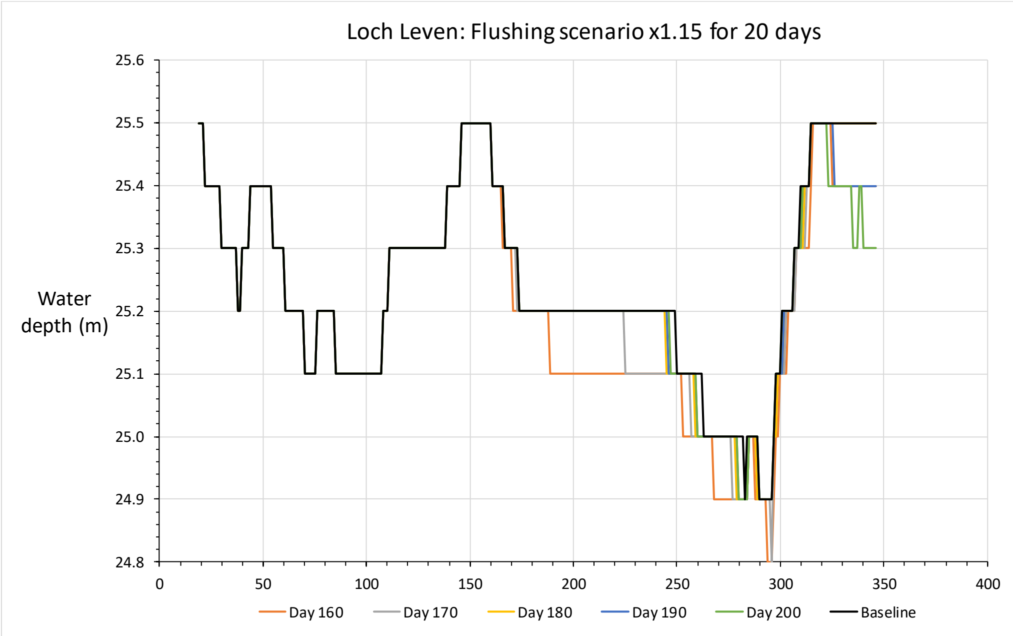


Figure 7. Effect on water level of a 15% increase in discharge from the outflow for 20 days from the start dates shown

Discussion

There is well documented evidence that changes in flushing rates affect the magnitude of cyanobacterial blooms in lochs and reservoirs (Elliott & Defew, 2012). However, to date, there has been little exploration of the management potential that small changes in flushing rate offer in terms of reducing the magnitude of algal blooms, especially those caused by temperature related sediment P releases.

The results of this study suggest that, with relatively small changes in the level of discharge (or abstraction) from a waterbody, it may be possible to reduce the size of a bloom considerably (up to 39% in this case study) without changing the water level significantly. This is important because changes of water level are known to affect risk of flooding and the availability of suitable habitat for aquatic plants and fish (May & Spears, 2012).

The results show, quite clearly, that, if everything else remains unchanged, the effectiveness of these management interventions is determined by their timing in terms of start date and duration. However, it is important to note that these results are based on a single years' inflow data which remained unchanged. So, there is now a need to explore the potential impacts of these interventions on the size of algal blooms under different inflow conditions, e.g. dry summer *cf.* wet summer. The results given above are simply a proof of concept, not an exploration of the impact of all possible scenarios under all possible conditions.

Implications for management

The results of this study suggest that small changes made to the flushing rate of lochs and reservoirs have the potential to reduce the water retention time sufficiently to reduce algal blooms by as much as 40%. Increasing flushing rates by increasing inflow volumes is difficult to achieve, due to the extra water required, but reducing water retention time by increasing outflow volumes would be relatively easy to achieve in systems where the outflow from the waterbody can be regulated by dams or sluice gates.

The benefits of achieving lower cyanobacteria levels in Scottish lochs and reservoirs would be to increase in their recreational and amenity value and reduction water treatment costs to remove algal toxins and substances that cause taste and odour problems in water supplies. It has been estimated that improving the water quality status of Scottish lochs adds about £1,500 per hectare per year to their value (Glenk et al., 2011). From this it can be estimated that the value of a single loch, such as Loch Leven, in terms of its recreational and amenity value would increase by about £2m if problems caused by cyanobacterial blooms were reduced. For lakes that are used for water supply, the costs of water treatment to remove algal toxins and decomposition products were estimated to be about £21.4m per year for the UK by Pretty et al. (2003). This equates to a present day value of about £30m, a cost that would be reduced significantly if algal blooms were less common.

Decisions on how to implement such changes would need to take into account a wide range of, often site specific, factors that could be affected by changes in water retention time and levels of discharges from the outflow. These include maintaining environmental flows downstream of the waterbody, ensuring that water level changes do not have an adverse effect on the ecology of the waterbody, and the need to maintain levels of abstraction for water supply purposes or of flows to support power generation. So, any decisions to make such changes would need to be taken by all of those involved in the governance of the waterbody, including environmental regulators, conservation bodies and water users. However, the results outlined above suggest that it may be beneficial to explore this potential approach to reducing algal blooms in more detail.

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