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An unusually dense bloom of the cyanobacterium *Gloeotrichia echinulata* in Loch Watten, a Scottish highland loch, during July 2023

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Loch Watten is a large (surface area 373 ha), very shallow (mean depth 2.6 m, maximum depth 3.7 m), high alkalinity, low altitude loch in Caithness, north mainland Scotland, with a predominantly improved and rough grassland catchment area of 5,578 ha (Fig. 1). There are two inflows to the north of the loch with an outflow to the Wick River in the south of the loch, draining for about 12 km to the North Sea at Wick.

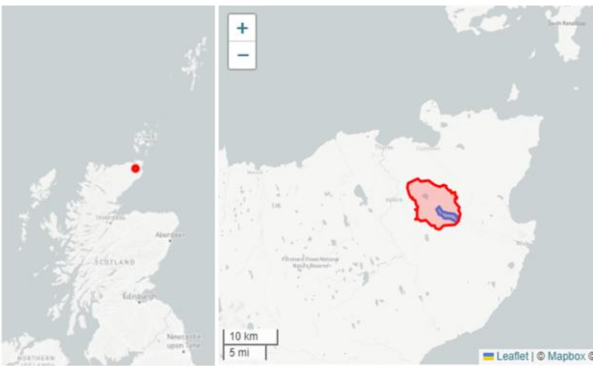

Fig. 1. Location and catchment of Loch Watten, Scotland. Lake polygon geometry in Great Britain is based on Ordnance Survey data and contains public sector information licensed under the Open Government Licence v3.0 (Hughes *et al.*, 2004).

Loch Watten is monitored regularly by the Scottish Environment Protection Agency (SEPA) for several determinands as part of the EU Water Framework Directive (WFD) requirements, with data available from 2002 onwards. No data or very limited data were available between 2020 and 2022. Although the ecology of the loch is reported as being at ‘Good’ ecological status, with the phytoplankton biological quality element also at ‘Good’ status, the overall ecological status is ‘Moderate’, due to a downgrade for total phosphorus (TP).

Total phosphorus concentrations indicated a discernible increase in concentrations over 2002-2019, although in the period 2012-present concentrations fluctuated seasonally but have not shown a discernible further increase (Fig. 2A). The average TP concentrations for 2018 and 2019 were 57.63 µg L^{-1} TP and 59.5 µg L^{-1} TP respectively, highlighting ‘Moderate’ status under WFD and very close to the ‘Moderate/Poor’ ecological class WFD boundary which is 62 µg L^{-1} TP. Peaks in TP were generally visible during winter periods (2013, 2014 - highest 0.2 mg L^{-1} TP, and 2016), but peaks were also recorded during May and August 2016, November 2017 and in March 2018 and 2019. Minima were generally observed over spring and summer.

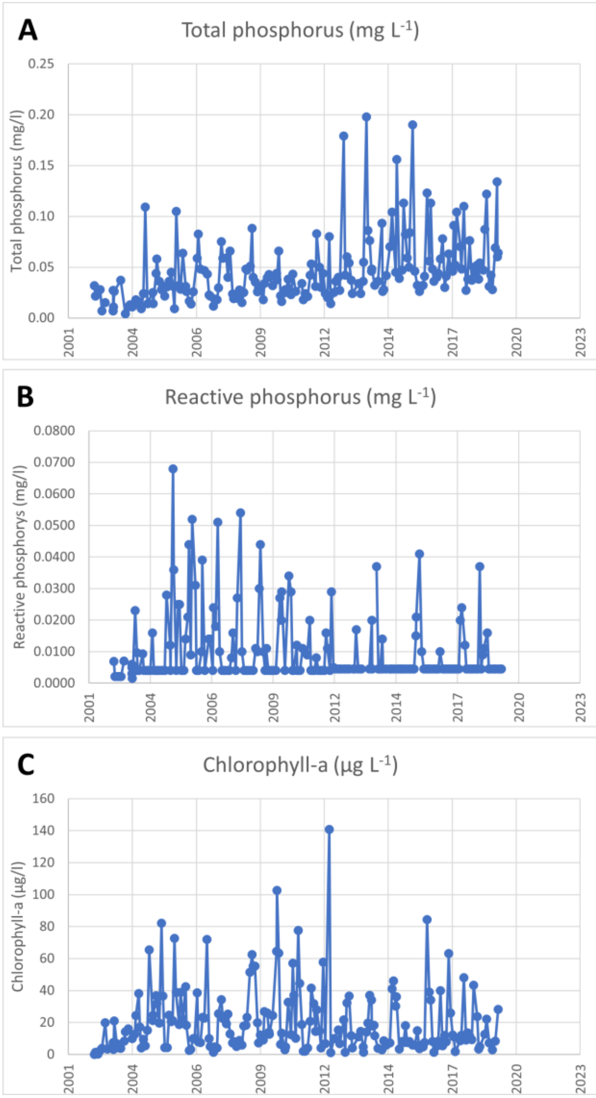

Fig. 2. Total phosphorus (A), reactive phosphorus (B) and chlorophyll-a (C) 2002-2019, Loch Watten, Scotland.

Reactive phosphorus concentrations indicated a slight decrease in concentrations over the same period (2002-

2019) with peaks also recorded in winter and late summer (Fig. 2B).

Spring and summer pulses may be indicative of nutrient re-release from sediments back into the overlying water. During the main phytoplankton growing period in late summer/autumn concentrations were at the limit of detection, potentially highlighting P-limitation for phytoplankton. Other factors may also limit phytoplankton growth. Potential for nitrogen limitation may be assessed using combination of several thresholds; when total oxidised N are <10 mg L^{-1}, dissolved inorganic N <25 μg L^{-1}, nitrate N concentrations <5 μg L^{-1}, and N:P ratios <16 and <10. Examining such trends in Loch Watten (not shown) highlighted periods in late summer when the TON:TP ratios were <10 and total oxidised N concentrations <0.1 mg L^{-1}, with no periods when nitrate concentrations were <5 μg L^{-1}. These may also suggest N-limitation during late summer in Loch Watten.

Phytoplankton biomass as measured by chlorophyll-a highlighted a seasonal pattern with peaks during spring and autumn, with no discernible change in phytoplankton biomass over the period 2002-2019 (Fig. 2C). Maximum chlorophyll-a of 140 μg L^{-1} was recorded during June 2012, but recent maxima were lower (43 μg L^{-1} in August 2018) with average concentrations of 17 μg L^{-1} chlorophyll-a in 2018 and 14 μg L^{-1} chlorophyll-a in 2019, respectively.

Although there are no details on which phytoplankton groups dominated during spring, available phytoplankton data over the growing season only (July-September) from 2015, 2017 and 2019 highlighted green algae *Coelastrum* spp., *Pediastrum* spp. and *Botryococcus* spp., and cryptophytes *Cryptomonas* spp. and *Rhodomonas* spp. as dominant taxa. Cyanobacteria *Anabaena* spp. and *Aphanizomenon* spp. were also abundant, with *Gloeotrichia* recorded as present and abundant.

In 24th July 2023 reports were received by SEPA of a large amount of foam at Loch Watten (Fig. 3). A water sample was subsequently taken and submitted to SEPA laboratory for analysis. The sample was received three days later. Large visible dark olive macroscopic colonies, mostly 1 mm in diameter were evident (Fig. 4). Microscopic examination identified these as a cyanobacterium - *Gloeotrichia echinulata* - with a recorded biomass of 12,348 mm^3 L^{-1} (550x10^6 cells mL^{-1}, 22,919 colonies mL^{-1}). Signs of the bloom breaking down were evident three days later (Fig. 5). *G. echinulata* were also recorded on the 28th July 2023 approximately 12 km downstream of Loch Watten in the Wick River, floating towards the sea.

G. echinulata is a nitrogen fixing, filamentous cyanobacterium forming spherical colonies which may reach many mm in diameter. It has been frequently recorded in analysis carried out by SEPA across Scotland (Krokowski, 2022) as part of the guidance for assessing and minimising risk to public health as outlined by the Scottish Government (Scottish Government, 2012).

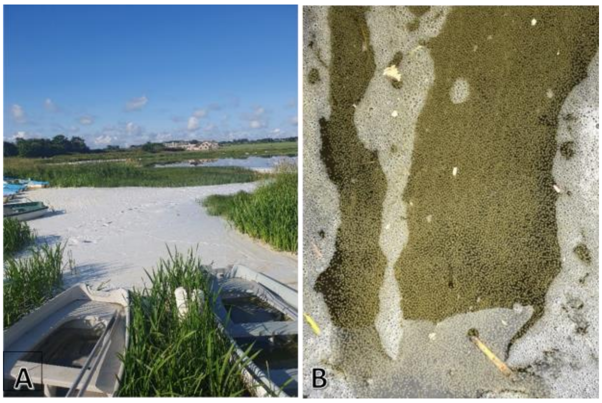

Fig. 3. Extensive *Gloeotrichia echinulata* foam coverage at Loch Watten, Scotland, 24th July 2023. (A) Whipped-up foam. (B) Macroscopic colonies in water. (Photos: E. Summers)

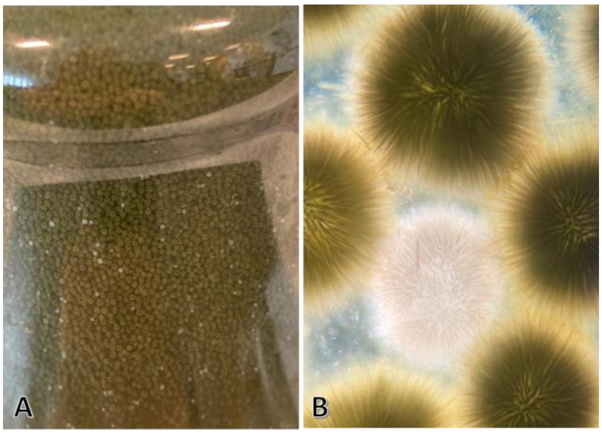

Fig. 4. *Gloeotrichia echinulata* photographed 27th July 2023. (A) Large colonies, including white colonies, in sample bottle received in SEPA laboratory. (B) Microscopic view of colonies. Colonies shown are *ca.* 0.75–1.0 mm in diameter. (Photo: J. Krokowski)

Fig. 5. Signs of bloom breaking down, Loch Watten, Scotland, 27th July 2023. (Photo: M. Nicolson)

Four *Gloeotrichia* species have been recorded from the British Isles in fresh and slightly brackish waters (John *et al.*, 2011), with solely *G. echinulata* recorded from freshwater lochs in Scotland. It is unlikely *G. echinulata* would survive in a river environment such as Wick River due to high flow velocity. However, other *Gloeotrichia* species, such as *G. natans*, have been commonly found in a variety of aquatic habitats, including rivers, where *G.* cf. *natans* was found growing on rocks (Gabyshev *et al.*, 2023).

Mainly dark-green olive colonies were observed. However, there were a few white colonies. These are called "ghost colonies" (C.C. Carey, pers. comm.) and are likely to be senescing due to viruses, grazing, or other mortality events.

A summary of global cyanobacterial poisonings, including those attributed to *Gloeotrichia* is provided by Svircev *et al.* (2019), highlighting cyanobacteria to have the potential to produce a large variety of secondary metabolites, including hepatotoxins, neurotoxins, cytotoxins, dermatoxins, enzyme inhibitors and antimicrobial compounds, which pose a threat to human and animal health. *Gloeotrichia* was shown to be not lethally toxic to mice from studies by Leeuwangh *et al.* (1983), whereas the first detected report of cyanotoxin microcystin-LR from *Gloeotrichia* was provided by Carey *et al.* (2007). On this occasion, toxicity testing carried out on bloom material from Lake Watten highlighted that material was non-toxic (C. Edwards, pers. comm.).

G. echinulata colonies form through radial arrangement of filaments and look like hairy balls, clearly visible and relatively distinct to the naked eye. *Gloeotrichia* form specialised cells – akinetes – which settle on sediments following the end of their growth period and possesses a unique life strategy as they can subsequently germinate from sediments during the following summer. Carey *et al.* (2008) highlighted recruitment from shallow (2 m) sediments but not deep (>5 m) sediments, highlighting an important transfer pathway of nutrients (especially P) from sediments to open water (Karlsson-Elfgren *et al.*, 2003). Germination is triggered by light, followed by growth on the sediment before colonies develop gas vesicles and can float upwards towards the surface (Barbiero, 1993), where they can form dense growths, i.e. blooms. Once in the open water, *Gloeotrichia* can utilise the internally stored, sediment-derived P for their growth, and this recruitment of P-rich colonies was calculated to account for two thirds of the total internal P loading between mid-July and mid-August in studies by Istvánovics *et al.* (1993), and represented an important transfer pathway for P.

Pitois *et al.* (1997) detailed a *Gloeotrichia* bloom in Antermony Loch near Auchenreoch, East Dunbartonshire in central Scotland, during August 1994. Antermony Loch is a small (14 ha), shallow loch with mean depth 4.1 m. Peaks of 10,000 cells mL^{-1} were recorded in Antermony Loch with highest levels of particulate inorganic and particulate organic P recorded when the bloom reached its maximum density. This contrasts with a *G. echinulata* concentration recorded in Loch Watten in July 2023 of $550x10^6$ cells mL^{-1} . Studies in the U.S.A. (Pratt & Holme, 2016) recorded maximum concentrations of over 1,000 colonies L^{-1} in high-nutrient systems, with concentrations at some recorded as between 192 and 250 colonies L^{-1}. Variability between the years was attributed to weather patterns and the authors also suggested increase in *Gloeotrichia* in lower-nutrient systems in the U.S.A. could be due to climate change. This contrasted with 22,919 colonies mL^{-1} recorded from Loch Watten during July 2023.

In Scotland, with increasing warmer temperatures, particularly in shallow and very shallow lochs, effects of climate change on water quality of standing waters may include an increase in algal blooms with higher risk of potentially harmful cyanobacterial blooms and toxins (May *et al.*, 2022).

To help provide a comprehensive picture of cyanobacteria occurrence in Scotland, visible blooms should be reported to SEPA and Local Authorities and the *Bloomin' Algae* app (available at: https://www.ceh.ac.uk/our-science/projects/bloomin-algae) should be used to help record bloom incidence.

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