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Sediment fingerprinting as an environmental forensics tool explaining cyanobacteria blooms in lakes

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A B S T R A C T

Cyanobacteria (blue-green algae) blooms in water bodies present serious public health issues with attendant economic and ecological impacts. Llyn Tegid (Lake Bala) is an important conservation and amenity asset within Snowdonia National Park, Wales which since the mid-1990s has experienced multiple toxic cyanobacteria blooms threatening the ecology and tourism-dependent local economy. Multiple working hypotheses explain the emergence of this problem, including climate change, land management linked to increased nutrient flux, hydromorphological alterations or changing trophic structure - any of which may operate individually or cumulatively to impair lake function. This paper reports the findings of a sediment fingerprinting study using dated lake cores to explore the linkages between catchment and lake management practices and the emergence of the algal blooms problem. Since 1900 AD lake bed sedimentation rates have varied from 0.06 to 1.07 g cm^{-2} yr^{-1}, with a pronounced acceleration since the early 1980s. Geochemical analysis revealed increases in the concentrations of total phosphorus (TP), calcium and heavy metals such as zinc and lead consistent with eutrophication and a rising pollution burden, particularly since the late 1970s. An uncertainty-inclusive sediment fingerprinting approach was used to apportion the relative fluxes from the major catchment land cover types of improved pasture, rough grazing, forestry and channel banks. This showed improved pasture and channel banks are the dominant diffuse sources of sediment in the catchment, though forestry sources were important historically. Conversion of rough grazing to improved grassland, coupled with intensified land management and year-round livestock grazing, is concluded to provide the principal source of rising TP levels. Lake Habitat Survey and particle size analysis of lake cores demonstrate the hydromorphological impact of the River Dee Regulation Scheme, which controls water level and periodically diverts flow into Llyn Tegid from the adjacent Afon Tryweryn catchment. This hydromorphological impact has also been most pronounced since the late 1970s. It is concluded that an integrated approach combining land management to reduce agricultural runoff allied to improved water level regulation enabling recovery of littoral macrophytes offers the greatest chance halting the on-going cyanobacteria issue in Llyn Tegid.

Introduction

Aquatic ecosystems are exposed to multiple drivers of environmental change including water pollution, drainage and land improvement schemes, engineering pressures, the spread of invasive species and increasingly climatic variability (Adrian, O'Reilly, & Zagarese, 2009; Van Sickle & Paulsen, 2008). All systems have an 'assimilative capacity', or tolerance to chemical, biological or physical perturbations (Jeppensen & Sondergaard, 2007; Utz, Hilderbrand, & Boward, 2009) conditioned in the case of lakes by landscape setting, basin size, food-web structures and environmental history (*cf.* Soranno, Webster, Cheruvelil, & Bremigan, 2009; Rowan, Grieg, Armstrong, Smith, & Tierney, 2011). Accepting that our understanding of the biophysical linkages between perturbation and ecological response remains weak the precautionary principle emphasises protecting the integrity of natural catchment and limnological processes (*cf.* Vaughan et al., 2009).

The mass growth of blue-green algae (cyanobacteria) was first reported on Llyn Tegid during the summer of 1995 and they have recurred sporadically since then, primarily in the spring and summer months. Problems arise when free-floating forms reach the water surface whereupon they can be blown onto the leeward

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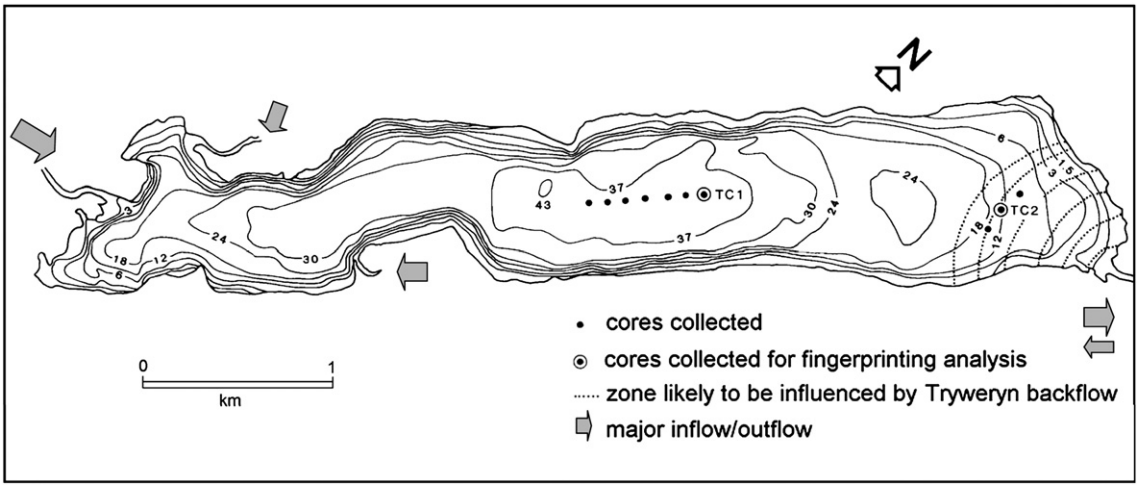

Fig. 1. Llyn Tegid (Lake Bala) core sampling locations.

shore to accumulate as thick unsightly and foul smelling scums. Aesthetic concerns are compounded by the fact that at least 60 cyanobacterial toxins have now been recognised (Bell & Codd, 1994; Carmichael, 1994). In England and Wales the appearance of blue-green algae blooms within a water body requires the Environment Agency to notify owners and local environmental health officers of the problem and to post warning notices instructing the public about the potential hazard. In the case of Llyn Tegid the potential health risks and associated negative publicity have had a significant impact of the local tourism-based economy within Wales' most iconic National Park.

Due to both its high conservation status and recreational importance research was needed to elucidate possible catchment controls on bloom occurrence and develop appropriate management strategies. The importance of sediment-associated transport of nutrients and contaminants is now well established (Thompson, Beard, & Fraser, 1998), but the role of hydromorphological pressures (alterations to the hydrological regime and physical habitats of the lake) has been comparatively overlooked (Rowan et al., 2006). This work thus sought to use a sediment fingerprinting approach (Fox & Papanicolaou, 2008; Peart & Walling, 1986; Rowan, Goodwill, & Franks, 2000) to reconstruct the patterns of sediment supply over time linked to changing land management practices in the catchment and hydraulic engineering within the lake. Analysis of lake cores provides the basis for the environmental reconstruction beyond the very limited and recent instrumented record from monitoring stations in the basin (*cf.* Foster & Lees, 1999).

To date much of the work in sediment fingerprinting has been driven by methodological concerns dealing with the identification of suitable suites of tracers and refining unmixing models (Collins, Walling, Webb, & King, 2010; Davis & Fox, 2009; Small, Rowan, Franks, Wyatt, & Duck, 2004). Here the focus is using sediment fingerprinting as a forensic tool providing the evidence base needed to reconcile multiple working hypotheses explaining the emergence of toxic blue-green algae booms on Llyn Tegid (Lake Bala) since the 1990s and more generally as an exemplar of a sediment-based approaches to '*investigative monitoring,* as required under the EC Water Framework Directive (WFD) for water bodies failing to achieve the target condition class of 'good ecological status' (Rowan et al., 2006). The WFD was introduced across the European Union to maintain or restore all natural water bodies, such as lakes, to at least good ecological status by 2015. Good ecological status prevails when human pressure causes no more than a slight deviation in the composition and abundance of the flora and fauna from their natural condition (Rowan et al., 2011).

Lake and catchment characteristics

Llyn Tegid is the largest natural lake in Wales and is situated in the headwaters of the River Dee. The lake has a surface area of 414 ha and is approximately 5.5 km long (Fig. 1). Depths in excess of 40 m are found along the central axis, with a mean overall depth of 24 m. The main catchment area of approximately 150 km^2 drains five sub-basins namely the Llafar, the Lliw, Dyfrdwy, Twrch and Glyn (Fig. 2). An additional source of water and sediment is derived from the 112 km^2 Afon Tryweryn catchment which enter Llyn Tegid when sluice gates are closed enabling a reverse flow through what is normally the main outflow channel of the lake (indicated on Fig. 1). A series of minor stream systems additionally drain the valley slopes flanking the lake.

Catchment elevations range from 880 m to 160 m at the Llyn Tegid outflow and the physiography is geologically controlled. The Aran Volcanic Group is a thick volcanic sequence with inter-bedded sedimentary rocks forming the mountainous western margins of the catchment. Acid ash-flow tuffs of the Aran Fawddwy Formation outcrop extensively within this area. The southern and eastern areas of the catchment are characterised by dissected plateaux composed of Ordovician-aged argillaceous rocks such as the Nant Hir, Glyn Gower and Allt Dhu mudstones and siltstones. Llyn Tegid was formed in a glacially scoured trough.

In the western highlands shallow peaty soils occur over bedrock, while deep blanket peat is found on the rolling interfluves. Free draining soils are found locally on lower ground associated with steep slopes. However most are poorly drained due to the low permeability of their subsoils causing seasonal water-logging and making them susceptible to structural damage by poaching and trafficking (Rudeforth, Hartnup, Lea, Thompson, & Wright, 1984). These problems have encouraged widespread land drainage in pursuit of increased agricultural productivity (Thompson et al., 1998).

Three main types of agricultural land use are recognised within the catchment – improved grassland, rough grazing (moorland) and forestry. These main classes also included a number of intermediate land cover types such as 'semi-improved' grassland (Thompson & Fuller, 1997). Sheep farming dominates the economy, with limited amounts of beef cattle. Sheep typically spend the entire year on the fields or grazing on the high fell where their foraging is supplemented at feeding stations providing silage, hay and concentrates. Cattle tend to remain housed in cattle sheds during the winter months. The rural community is dispersed in farmsteads with exception of the villages of Llangower,