Management of Climatic Extreme Events in Lakes and Reservoirs for the Protection of Ecosystem Services
European Joint Doctorate Innovative Training Network GA 722518

POLICY BRIEFING NOTE 1

Exploring the effects of climate extremes in lakes using high frequency data

AUTHORS: Eleanor Jennings[1], Malgorzata Golub[1], Harriet Wilson[1], Alexa Hoke[1], Jorrit P. Mesman[2], Julio A. A. Stelzer[2], Bas W. Ibelings[2], Michael W. Thayne[3], Rita Adrian[3], Hans-Peter Grossart[4], Ana Ayala[5], Donald C. Pierson[5].

1. Centre for Freshwater and Environmental Studies, Dundalk Institute of Technology, Ireland.
2. Department F.A. Forel for Environmental and Aquatic Sciences and Institute for Environmental Sciences, University of Geneva, Geneva, Switzerland.
3. Department of Ecosystem Research, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, and Department of Biology, Chemistry and Pharmacy, Freie Universität Berlin, Berlin, Germany.
4. Department of Ecosystem Research, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, and University of Potsdam, Germany.
5. Limnology, Department of Ecology and Genetics, Uppsala University, 752 36 Uppsala, Sweden.

INTRODUCTION

Changes in the local weather are fundamental drivers of change in lake ecosystems. Recently, there has been an increasing focus on the potential effects of climate extremes, such as storms and heatwaves, on lakes and reservoirs. These events are projected to become even more intense, frequent and prolonged due to climate change. This policy briefing note describes new advances in understanding the implications of such climate extremes for lakes and reservoirs based on an assessment of high frequency datasets undertaken in the MANTEL European Joint Doctorate Innovative Training Network.

BACKGROUND

- Lake water columns commonly stratify into discrete layers during warmer weather, with a layer of warmer water in the upper part of the lake and cooler waters below.
- Cooling air temperatures, for example in autumn, will generally lead to a breakdown of the layer structure and mixing of the water column. High winds speed or rainfall, for example in storms, can also result in a mixing of these layers.
- This layering structure has implications for lake processes that are relevant to water quality. Toxic algal blooms are more likely to occur when there is strong stratification. The water in the bottom layer can also become depleted in oxygen, potentially liberating phosphorus from the sediment. Storms can mix the stratified layers and bring sediment and nutrients from deeper waters to the surface.
- The patterns of stratification are classified based on how lakes de-stratify over the annual cycle. This can be seasonal, for example, only where lakes stratify during warmer weather in summer (‘monomictic’), or during ice cover in winter (‘dimictic’), or where a lake has shorter alternating periods of stratification and mixing (‘polymictic’).
- Automated high frequency monitoring systems using sensors provide information on changes in lakes at short time scales for example minutes to hours. These datasets allow the effects of storms and mixing to be monitored and better understood.
- This policy brief describes advances in our knowledge of the impacts of storms on lakes and reservoirs using such data as part of MANTEL.

BACKGROUND

Automatic systems have been used to monitor lakes since the 1970s, but the technology became more widely used once more sophisticated data control and communications systems became available in the 1990s[1,2]. Commonly used and reliable sensors now include: 1. those measuring water temperature profiles, which provide essential information on lake thermal stratification and mixing, 2. sensors measuring dissolved oxygen, and 3. sensors for measuring chlorophyll *a* and phycocyanin, which provide data on algal blooms[2]. Amongst the challenges facing those operating such systems, such as this one on Lake Erken in Sweden (Figure 1), are the management of the large data sets, and quality control and assurance. These data, however, provide essential information on short and long term changes in water temperature and quality. Many of the participants in MANTEL run such stations, or have access to these data, allowing new and relevant information to be collected on the effects of climate extremes on lakes.

Figure 1: **Automatic monitoring station on Lake Erken (Sweden).**

OVERVIEW OF THE ADVANCES IN OUR KNOWLEDGE

There have been **four** outputs from MANTEL researchers and colleagues that have increased our understanding of how storms and mixing affect processes in lakes:

1. There are a range of calculation methods that have been used in the literature to measure the depth of the upper layer of a stratified lake. This layer is also referred to as the mixed layer, or 'epilimnion'. However, to date there has been no in-depth comparison of these methods. Wilson and others[3] used multi-year data from two lakes (Like Erken in Sweden and Lough Feeagh in Ireland) to undertake such a comparison of methods. They found a large degree of variability between the outputs from the five methods. While there was no prescribed rationale for selecting a given method, the method which performed best was one that defined the epilimnion depth as the shallowest depth where the density was 0.1 kg m^{-3} more than the surface density. This comparison will be useful in informing models and other researchers and managers on an appropriate method for their own lake.

2. Climate warming is causing changes in lake stratification, such as longer summer stratification and reduced ice cover in winter. An ultimate consequence of global warming could be a transition to a very different pattern of mixing in a given lake, for example, from dimictic to monomictic, or from polymictic to monomictic (see **BACKGROUND** above). Mesman and colleagues[4] developed a conceptual model to investigate the role of physical, chemical, and biological feedbacks that could happen during a shift in a lake mixing pattern in deep lakes (lakes as lakes that stratify for at least a season). These processes are described in Fig. 2. The study also assessed three types of potential shifts in stratification: 1. a lake going from polymictic to seasonally stratified, 2. from dimictic to monomictic, and 3. from lakes that do stratify to 'meromictic' (a rarer type, that are always stratified), or 'oligomictic' (lakes that only rarely mix). The paper provided new understanding on shifts to different but stable mixing regimes, and the implications of such shifts, including the potential for internal feedback mechanisms.

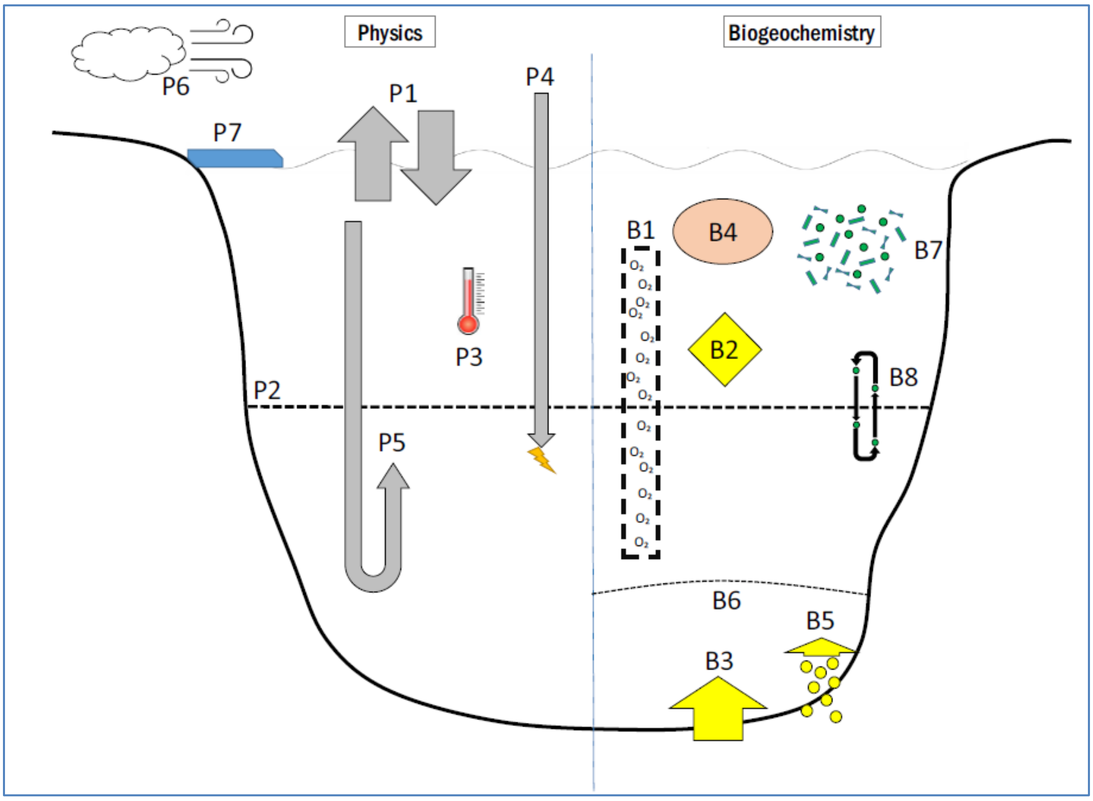

Fig. 2. Overview of the physical and biogeochemical components and processes for P (physical) and B (biogeochemical) processes. Energy fluxes at the air–water interface (P1) = the interaction between climate and the lake. Stratification (P2) is formed primarily by higher water temperatures (P3) in the surface layers compared to bottom. Light penetration into the lake waters (P4) causes heating of surface layers but is also essential for phytoplankton growth. Deep-water mixing (P5) can occur due to cooling. Wind stress (P6) promotes mixing and deepening of the mixed layer. Ice cover (P7) affects surface heat fluxes and reduces the effects of wind on the lake. Oxygen concentration (B1) is linked to many chemical and biological processes in the lake. Nutrient concentrations (B2) in the mixed layer are essential for the growth of phytoplankton. Nutrients and other solutes can be released from the sediment during stratification when oxygen in deeper waters is depleted (B3). Coloured dissolved organic matter (CDOM, B4) reduces light penetration in the water column. Greenhouse gases can be emitted from the sediment (B5). If the deep-water layers of a lake are heavier than the overlying water due to high solute content, the lake becomes meromictic (B6). Phytoplankton (B7) grows through consumption of nutrients and light in the upper zone of the lake where there is light. Some cyanobacteria can control their buoyancy (B8) and can use this to form a maximum concentration in the metalimnion, or middle layer, of the lake.

3. Bacteria play a critical role in lake ecosystems, yet little research has been done to determine how they are affected by extreme weather events such as mixing following a storm or an extreme drought. A study on a lake on the North Atlantic coast of Ireland (Lough Feeagh) used a combination of genetic sequencing and high frequency data from the deepest point of the lake to explore the bacterial community composition[5] in response to extreme weather events. The bacteria were separated into i) those attached to suspended particles (particle-associated), and ii) those that were free-living in the water. Two named storms, six high discharge events, and one drought occurred during the sampling period. These extreme weather events had variable impacts. The particle-associated bacteria were found to be more likely to respond to physical changes such as mixing, while the free-living bacteria responded more directly to changes in nutrient and carbon concentrations. Overall, physico-chemical changes following the extreme weather events were short-lived and the bacterial community stable, suggesting that the bacteria were relatively resilient to such extremes.

4. Research on the resistance and resilience of lake ecosystems has gained momentum in recent years given that extreme wind storms are increasing in duration, intensity, and frequency. Extreme wind storms can strongly influence short-term variation in lake ecosystem functioning. In conjunction with other extreme climatic events, watershed and lake processes are simultaneously affecting antecedent lake conditions, which may shape the resistance and resilience landscape prior to storm exposure. To determine whether storm characteristics or previous lake conditions were more important for explaining variation in lake ecosystem resistance and resilience, the authors analysed the effects of 25 extreme wind storms on various biological and physiochemical variables in a shallow lake. The authors found that previous lake conditions were more important (relative importance = 67%) than storm characteristics (relative importance = 33%) in explaining variation in lake ecosystem resistance and resilience. The most important previous lake conditions were turbidity, water

column stability, percent oxygen saturation, light conditions, and soluble reactive silica concentrations. In addition, they found that storm characteristics were all similar in their relative importance and results suggest that resistance and resilience decrease with increasing storm duration, mean precipitation, wind intensity, and time between storms. These results could inform management practices that make shallow lake ecosystems more resilient following extreme storm events. How resistance and resilience is affected following extreme storm events in lakes of different types, depths and location is, however, still an important area for inquiry.

ABOUT MANTEL

MANTEL (Management of Climatic Extreme Events in Lakes & Reservoirs for the Protection of Ecosystem Services) was an EU funded Maire Skłodowska Curie Action (MSCA) European Joint Doctorate Innovative Training Network (2017-2021, Grant Agreement 722518) that focused on training a cohort of Early Stage Researchers to investigate the effects of the climate extremes on water quality, providing training in state-of-the art technology, data analysis and modelling, and linking to the water management sector.

REFERENCES

1. Marcé R, George G, Buscarinu P, Deidda M, Dunalska J, de Eyto E, Flaim G, Grossart H-P, Istvanovics V, Moreno-Ostos E et al.. 2016. Automatic high frequency monitoring for improved lake and reservoir management. Environmental Science & Technology. 50:10780-10794. doi.org/10.1021/acs.est.6b01604

2. Jennings, E. de Eyto E., Laas, A., Pierson, D., Mircheva, G., Naumoski, A., Clarke, A., Healy, M., Šumberová, K., and Langenhaun D. 2017. The NETLAKE metadatabase—a tool to support automatic monitoring on lakes in Europe and beyond. Limnology and Oceanography Bulletin. DOI: 10.1002/lob.10210.

3. Wilson, H.L., Ayala, A.I., Jones, I.D., Rolston, A., Pierson, D., de Eyto, E., Grossart, H.P., Perga, M-E, Woolway, R.I., Jennings, E. (2020) Variability in epilimnion depth estimations in lakes. *Hydrology and Earth System Sciences*, 24: 5559–5577. DOI: 10.5194/hess-24-5559-2020.

4. Mesman, J.P., Stelzer, J.A.A., Dakos, V., Goyette, S., Jones, I.D., Kasparian, J., McGinnis, D.F., Ibelings, B.W. (2021) The role of internal feedbacks in shifting deep lake mixing regimes under a warming climate. Freshwater Biology, 00: 1– 15. DOI: 10.1111/fwb.13704.

5. Hoke, A., Woodhouse, J., Zoccarato, L., McCarthy, V., de Eyto, E., Calderó-Pascual, M., Geffroy, E., Dillane, M., Grossart, H.P., Jennings E., (2020) Impacts of Extreme Weather Events on Bacterial Community Composition of a Temperate Humic Lake. *Water*, 12(10): 2757. DOI: 10.3390/w12102757.

6. Thayne, M.W., Kraemer, B., Mesman, J.P., Ibelings, B.W., Adrian, R. (2021) Antecedent lake conditions shape resistance and resilience of a shallow lake ecosystem following extreme wind storms. *Limnology and Oceanography,* DOI: 10.1002/lno.11859.

CONTACT AND FUNDING DETAILS

Policy brief and MANTEL coordinator: Prof. Eleanor Jennings
eleanor.jennings@dkit.ie

MANTE website: https://www.mantel-itn.org

MANTEL (2017-2021) was financed under the European Union’s Horizon 2020 Research and Innovation Programme under the Marie Skłodowska-Curie Actions Grant Agreement No. 722518.