water

MDPI

Editorial

The Effects of Global Climate Change on Water Level and Salinity: Causes and Effects

Erik Jeppesen [1,2,3,4,*], Meryem Beklioğlu [1] and Egor Zadereev [5,6]

1 Limnology Laboratory, Department of Biological Sciences and Centre for Ecosystem Research and Implementation, Middle East Technical University, Ankara 06800, Türkiye; meryem@metu.edu.tr
2 Sino-Danish Centre for Education and Research, University of Chinese Academy of Sciences, Beijing 101408, China
3 Institute of Marine Sciences, Middle East Technical University, Mersin 33731, Türkiye
4 Institute for Ecological Research and Pollution Control of Plateau Lakes, School of Ecology and Environmental Sciences, Yunnan University, Kunming 650500, China
5 Institute of Biophysics, Krasnoyarsk Research Center, Akademgorodok, 660036 Krasnoyarsk, Russia; egzadereev@gmail.com
6 Institute of Fundamental Biology and Biotechnology, Siberian Federal University, Svobodniy 79, 660041 Krasnoyarsk, Russia
* Correspondence: ej@ecos.au.dk

Temperature and precipitation patterns are changing considerably worldwide because of global climate change [1]. Semi-arid and arid climate zones will experience much less net precipitation and runoff. Moreover, increasing water abstraction is expected due to the need for the provision of food and water for a growing population. These changes will lead to substantial water level decreases and the salinization of inland freshwater in dry climate zones, while waters in areas with higher future precipitation or those affected by runoff from melting glaciers may show a reverse pattern. The magnitude of future changes may have major effects on the structure, functioning, and biodiversity of inland aquatic ecosystems [2–5]. Global warming also leads to rising sea levels, and thus, coastal seawater intrusion, further accelerated by an expected higher frequency and duration of extreme storms. However, little is known about the effects that such changes may have on inland and coastal lake ecosystems. Only a few studies have been conducted in such systems; to date, focus has been directed towards the effects on freshwater lakes [6].

Different approaches have and can be used to gain new insight, including compiling field data, including monitoring on a regular basis, historical information can be obtained from paleoecological studies or remote sensing, causal relationships by experimental studies at various scales, and modeling can help to predict effects of changes in key drivers. This Special Issue of *Water* provides examples of the effects of salinization based on a variety of these approaches. Two of the studies [7,8] took a field observational approach. In [7], salinity–eutrophication interactive effects on the food web were studied in 20 lakes of different salinity (from freshwater to hypersaline) and nutrient status (from oligotrophic to eutrophic) located in southern Siberia. Specifically, the seasonal dynamics of zooplankton, phytoplankton, and water quality parameters were determined and a pronounced bottom-up effect of nutrients was identified, which induced an increase in the biomass of phytoplankton and zooplankton and a decline in water quality. With respect to salinity, a decrease in the species abundance of zooplankton above 3 g L^{-1} salt and the disappearance of fish at 10 g L^{-1} salt were detected. With the disappearance of fish, an increase in zooplankton biomass occurred, as well as a change in the size distribution of phytoplankton particles with an increase in the proportion of cladocerans of the zooplankton. Similar findings were identified in a study of Tibetan lakes [9], except in the control of phytoplankton. The interactive effects of salinity and eutrophication strongly depended on the size and depth of the lakes, and it was concluded that small shallow lakes will be

Citation: Jeppesen, E.; Beklioğlu, M.; Zadereev, E. The Effects of Global Climate Change on Water Level and Salinity: Causes and Effects. *Water* **2023**, *15*, 2853. https://doi.org/10.3390/w15152853

Received: 2 August 2023
Accepted: 3 August 2023
Published: 7 August 2023

the most vulnerable to the joint effect of increased salinity and eutrophication, with the degradation of ecosystem functioning and water quality at moderate salinities of 3–20 g L^{-1}. In the second study [8], the interactive effects of nutrients and salinity on phytoplankton assemblages were elucidated in a four-season investigation of eight lakes in Yunnan Plateau (southwest China), covering a wide range of salinities (conductivities), eutrophic states, and water depths. The species number, density, and biomass of phytoplankton showed stronger seasonal dynamics in shallow lakes than in deep lakes, all being, as expected, higher in the warm season. A unimodal relationship with salinity was observed, peaking at 400–1000 μS cm^{-1}. These results further indicate a shift from mainly phosphorus to nitrogen limitations of phytoplankton growth, with increasing phosphorus concentrations, and the two dominant taxa (cyanobacteria and chlorophytes) revealed different patterns, with chlorophytes generally dominating at low total nitrogen and cyanobacteria levels at high total nitrogen and salinity, suggesting a synergistic effect of nitrogen and salinity on cyanobacterial dominance.

Combining different approaches may strengthen the conclusions about effects. Ref. [10] combined palaeolimnological data (including sedimentary parameters, diatoms, and plant macrofossils) with environmental monitoring data (for the last ~40 years) to assess environmental changes over the last 100 years in Kilen, a brackish lake in northwest Jutland, Denmark. The palaeolimnological data indicated that the lake has been nutrient rich for the last 100 years, with eutrophication peaking from the mid-1980s to the late-1990s. Lake recovery over the last 20 years has been driven by reductions in phosphorus (P) and nitrogen (N) loading from the catchment, and improvements in lake water clarity; recently, reductions in macrophyte cover have occurred. Reduced salinity after 2004 also changed the composition of the dominant macrophyte community within the lake. The low N:P ratio indicates that, in summer, the lake is predominately N-limited, likely explaining why previous management, mainly focusing on P reduction measures, had only a modest effect on the water quality of the lake. The study demonstrated the power of using a combined approach (monitoring with sediment analyses) to understand environmental changes in saline lakes. Likewise, Ref. [11] combined historical data on ecosystems as well as meteorological, remote sensing, and ground-truth data to elucidate the effects of changes in the temperature and precipitation of the Burdur Closed Basin (BCB), located in the southwest of Türkiye, on changes in lake water surface areas and land use, as well as the potential effects on waterbird and fish communities. The BCB includes several types of aquatic ecosystems supporting high biodiversity, including one Ramsar site, six Important Bird Areas, and a considerable richness of native and endemic fish species. A water budget was calculated to elucidate water availability in the basin over the last few decades, and future conditions were predicted based on rainfall and temperature forecasts using climate models. The Standardized Precipitation–Evapotranspiration Index (SPEI) was used to relate the lake water surface area to precipitation and temperature changes in the basin. Crop-farming irrigation in the BCB has increased notably since 2004, leading to intensive water abstraction from the lakes and their inflows, as well as from ground water, to meet the increased demand for irrigation. Water abstraction from the lakes, lake inflows, and the groundwater in the basin has substantially increased the water loss in the catchment. Remotely sensed data on lake surface areas show a major shrinkage of shallow lakes in the last 40 years. Moreover, the largest lake in the basin, Lake Burdur, lost nearly half of its surface area, which is concerning because the shallower areas are those most suitable for supporting high levels of biodiversity. Climate model simulations predict that from 2070, the BCB will face long-term moderate-to-severe dry periods, and this, in addition to increased demand for water for irrigation, may accelerate drying of these lakes in the near future, with devastating effects on the lake ecosystems and their biodiversity. Similar results are available from the Konya basin in Central Anatolia, Türkiye [12].

Observational data and modeling are key to elucidating the effects of stressors on lake ecosystems; however, they are not efficient in providing causal relationships. To this end, control experiments are needed. Most experimental studies on the effects of salinization have been conducted in laboratories, often with only a single or several organisms in focus, while large-scale outdoor experiments at ecosystem-scale are scarce [5]. Ref. [13] established comprehensive and similar experimental mesocosm facilities in two different climate zones in Türkiye, specifically designed to simulate the effects of salinization and climate change on shallow lake ecosystems. In total, 24 mesocosms (diameter 2 m, height 1.8 m, and volume 5 m^3) were established at each location, designed to replicate shallow lake characteristics in arid landscapes. The mesocosms were composed of high-density polyethylene due to this material's resistance to high salinities and UV exposure. The mesocosms were buried at 1 m depth, and the exposed walls were insulated to minimize heat exchange. To prevent stratification, the water in each mesocosm was circulated using an aquarium pump. To provide dynamic heating for temperature increase simulations, selected mesocosms were heated according to measurements made in reference to non-heated mesocosms. All the mesocosms were equipped with a microprocessor-based controller, temperature sensors, and a logging system. Each mesocosm received 30 cm sediment to simulate a realistic sediment biogeochemistry and redox gradient, and they were inoculated with biota from lakes and surface sediment from lakes with contrasting salinities (same at both places), leading to highly synchronized experiments at the two locations. To illustrate the use of the facilities, summary results from two case study experiments are presented: (1) a salinity gradient experiment comprising 16 salinity levels (range: 0–50 g L^{-1}); and (2) a heatwave experiment where two different temperature regimes (no heatwave and +6 °C for two weeks) were crossed with two salinity levels (4 and 40 g L^{-1}). Both experiments demonstrated a significant role of salinization modulated by climate on the structure and function of lake ecosystems. The authors finally provide some recommendations for the best practices for mesocosm experiments to be conducted under saline/hypersaline conditions.

The papers in this Special Issue collectively illustrate the multi-faceted approaches that have and can be used to elucidate the effects of water level and salinity changes induced by the global climate change and their ecosystem effects on inland and coastal lakes that are highly vulnerable to changes in salinity.

Author Contributions: E.J., M.B. and E.Z. wrote this Editorial jointly. All authors have read and agreed to the published version of the manuscript.

Funding: E.J. and M.B. were funded by the Tübitak program BIDEB2232 (Project 118C250). E.Z. was supported by the State Assignment of the Ministry of Science and Higher Education of the RF (project No. 0287-2021-0019).

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Intergovernmental Panel on Climate Change (IPCC). *Climate Change 2021—The Physical Science Basis*; Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK, 2023. [CrossRef]
2. Wurtsbaugh, W.A.; Miller, C.; Null, S.E.; DeRose, R.J.; Wilcock, P.; Hahnenberger, M.; Howe, F.; Moore, J. Decline of the World's Saline Lakes. *Nat. Geosci.* **2017**, *10*, 816–821. [CrossRef]
3. Jeppesen, E.; Beklioğlu, M.; Özkan, K.; Akyürek, Z. Salinization Increase Due to Climate Change Will Have Substantial Negative Effects on Inland Waters: A Call for Multifaceted Research at the Local and Global Scale. *Innovation* **2020**, *1*, 100030. [CrossRef]
4. Zadereev, E.; Lipka, O.; Karimov, B.; Krylenko, M.; Elias, V.; Pinto, I.S.; Alizade, V.; Anker, Y.; Feest, A.; Kuznetsova, D.; et al. Overview of Past, Current, and Future Ecosystem and Biodiversity Trends of Inland Saline Lakes of Europe and Central Asia. *Inland Waters* **2020**, *10*, 438–452. [CrossRef]
5. Cunillera-Montcusí, D.; Beklioğlu, M.; Cañedo-Argüelles, M.; Jeppesen, E.; Ptacnik, R.; Amorim, C.A.; Arnott, S.E.; Berger, S.A.; Brucet, S.; Dugan, H.A.; et al. Freshwater salinisation: A research agenda for a saltier world. *Trends Ecol. Evol.* **2022**, *37*, 440–453. [CrossRef] [PubMed]
6. Jeppesen, E.; Brucet, S.; Naselli-Flores, L.; Papastergiadou, E.; Stefanidis, K.; Nõges, T.; Nõges, P.; Attayde, J.L.; Zohary, T.; Coppens, J.; et al. Ecological Impacts of Global Warming and Water Abstraction on Lakes and Reservoirs Due to Changes in Water Level and Related Changes in Salinity. *Hydrobiologia* **2015**, *750*, 201–227. [CrossRef]

7. Zadereev, E.; Drobotov, A.; Anishchenko, O.; Kolmakova, A.; Lopatina, T.; Oskina, N.; Tolomeev, A. The Structuring Effects of Salinity and Nutrient Status on Zooplankton Communities and Trophic Structure in Siberian Lakes. *Water* **2022**, *14*, 1468. [CrossRef]
8. Wang, Y.; Jiang, X.; Li, Y.-L.; Yang, L.-J.; Li, Y.-H.; Liu, Y.; Zhou, L.; Wang, P.-Z.; Zhao, X.; Wang, H.-J.; et al. Interactive Effects of Nutrients and Salinity on Phytoplankton in Subtropical Plateau Lakes of Contrasting Water Depths. *Water* **2023**, *15*, 69. [CrossRef]
9. Lin, Q.; Xu, L.; Hou, J.; Liu, Z.; Jeppesen, E.; Han, B.P. Responses of trophic structure and zooplankton community to salinity and temperature in Tibetan lakes: Implication for the effect of climate warming. *Water Res.* **2017**, *124*, 618–629. [CrossRef] [PubMed]
10. Lewis, J.P.; Ryves, D.B.; Søndergaard, M.; Lauridsen, T.L.; Johansson, L.S.; Tserenpil, S.; Rasmussen, P.; Jeppesen, E. Nutrients and Saltwater Exchange as Drivers of Environmental Change in a Danish Brackish Coastal Lake over the Past 100 Years. *Water* **2023**, *15*, 1116. [CrossRef]
11. Çolak, M.A.; Öztaş, B.; Özgencil, İ.K.; Soyluer, M.; Korkmaz, M.; Ramírez-García, A.; Metin, M.; Yılmaz, G.; Ertuğrul, S.; Tavşanoğlu, Ü.N.; et al. Increased Water Abstraction and Climate Change Have Substantial Effect on Morphometry, Salinity, and Biotic Communities in Lakes: Examples from the Semi-Arid Burdur Basin (Turkey). *Water* **2022**, *14*, 1241. [CrossRef]
12. Yılmaz, G.; Çolak, M.A.; Özgencil, İ.K.; Metin, M.; Korkmaz, M.; Ertuğrul, S.; Soyluer, M.; Bucak, T.; Tavşanoğlu, Ü.N.; Özkan, K.; et al. Decadal Changes in Size, Salinity, Waterbirds, and Fish in Lakes of the Konya Closed Basin, Turkey, Associated with Climate Change and Increasing Water Abstraction for Agriculture. *Inland Waters* **2021**, *11*, 538–555. [CrossRef]
13. Özkan, K.; Korkmaz, M.; Amorim, C.A.; Yılmaz, G.; Koru, M.; Can, Y.; Pacheco, J.P.; Acar, V.; Çolak, M.A.; Yavuz, G.C.; et al. Mesocosm Design and Implementation of Two Synchronized Case Study Experiments to Determine the Impacts of Salinization and Climate Change on the Structure and Functioning of Shallow Lakes. *Water* **2023**, *15*, 2611. [CrossRef]