AGU ADVANCING EARTH AND SPACE SCIENCES

Earth's Future

REVIEW ARTICLE
10.1029/2023EF004387

Global Lake Health in the Anthropocene: Societal Implications and Treatment Strategies

Gesa A. Weyhenmeyer[1], Azubuike V. Chukwuka[2], Orlane Anneville[3], Justin Brookes[4], Carolinne R. Carvalho[5], James B. Cotner[6,7], Hans-Peter Grossart[8,9], David P. Hamilton[10], Paul C. Hanson[11], Josef Hejzlar[12], Sabine Hilt[13], Matthew R. Hipsey[14], Bas W. Ibelings[15], Stéphan Jacquet[3], Külli Kangur[16], Theis Kragh[17], Bernhard Lehner[18], Fabio Lepori[19], Ben Lukubye[20,21], Rafael Marce[22], Yvonne McElarney[23], Ma. Cristina Paule-Mercado[12], Rebecca North[24], Keilor Rojas-Jimenez[25], James A. Rusak[26,27], Sapna Sharma[28], Facundo Scordo[29,30], Lisette N. de Senerpont Domis[31], Jonas Stage Sø[17], Susanna (Susie) A. Wood[32], Marguerite A. Xenopoulos[33], and Yongqiang Zhou[34]

[1]Department of Ecology and Genetics/Limnology, Uppsala University, Uppsala, Sweden, [2]Department of Environmental Quality Control, National Environmental Standards and Regulations Enforcement Agency (NESREA), Osun State, Nigeria, [3]Université Savoie Mont Blanc, INRAE, CARRTEL, Thonon-les-Bains, France, [4]School of Biological Science, Environment Institute, The University of Adelaide, Adelaide, SA, Australia, [5]College of Agiculture "Luiz de Queiroz", University of São Paulo, São Paulo, Brazil, [6]Department of Ecology, Evolution and Behavior, University of Minnesota, St. Paul, MN, USA, [7]Department of Biological Sciences, University of Bergen, Bergen, Norway, [8]Department of Plankton and Microbial Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany, [9]Institute of Biochemistry and Biology, Potsdam University, Potsdam, Germany, [10]Australian Rivers Institute, Griffith University, Nathan, QLD, Australia, [11]Center for Limnology, University of Wisconsin-Madison, Madison, WI, USA, [12]Biology Centre of Czech Academy of Sciences, v.v.i., Institute of Hydrobiology, České Budějovice, Czech Republic, [13]Department of Community and Ecosystem Ecology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Berlin, Germany, [14]Centre for Water and Spatial Science, UWA School of Agriculture and Environment, The University of Western Australia, Perth, WA, Australia, [15]Department F.-A. Forel for Environmental and Aquatic Sciences, University of Geneva, Geneva, Switzerland, [16]Centre for Limnology, Chair of Hydrobiology and Fishery, Institute of Agricultural and Environmental Sciences, Estonian University of Life- Sciences, Tartu, Estonia, [17]Department of Biology, University of Southern Denmark, Odense M, Denmark, [18]Department of Geography, McGill University, Montreal, QC, Canada, [19]Institute of Earth Sciences, University of Applied Sciences and Arts of Southern Switzerland, Mendrisio, Switzerland, [20]Department of Biology, Mbarara University of Science and Technology, Mbarara, Uganda, [21]Department of Biology, Emory University, Atlanta, GA, USA, [22]Blanes Centre for Advanced Studies (CEAB-CSIC), Blanes, Spain, [23]Agri-Food and Biosciences Institute, Oceanography and Limnology, Belfast, N. Ireland, [24]School of Natural Resources, University of Missouri, Columbia, MO, USA, [25]Escuela de Biología, Universidad de Costa Rica, San José, Costa Rica, [26]Dorset Environmental Science Centre, Ontario Ministry of the Environment, Dorset, ON, Canada, [27]Department of Biology, Queen's University, Kingston, ON, Canada, [28]Department of Biology, York University, Toronto, ON, Canada, [29]Instituto Argentino de Oceanografía, Universidad Nacional del Sur (UNS)-CONICET, Buenos Aires, Argentina, [30]Departamento de Geografía y Turismo, Universidad Nacional del Sur, Buenos Aires, Argentina, [31]Netherlands Institute of Ecology (NIOO-KNAW), Wageningen, The Netherlands, [32]Cawthron Institute, Nelson, New Zealand, [33]Department of Biology, Trent University, Peterborough, ON, Canada, [34]State Key Laboratory of Lake Science and Environment, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing, China

Key Points:

- Anthropogenic stressors can cause lake health issues that range from thermal, circulatory, respiratory, nutritional and metabolic issues to infections and poisoning
- Lake health varies geographically, with the highest risk of critical conditions occurring in densely populated low-income countries
- There is an urgent need to follow-up the progress of treatments and to make adjustments whenever needed

Correspondence to:
G. A. Weyhenmeyer,
Gesa.Weyhenmeyer@ebc.uu.se

Citation:
Weyhenmeyer, G. A., Chukwuka, A. V., Anneville, O., Brookes, J., Carvalho, C. R., Cotner, J. B., et al. (2024). Global lake health in the Anthropocene: Societal implications and treatment strategies. *Earth's Future*, *12*, e2023EF004387. https://doi.org/10.1029/2023EF004387

Received 23 DEC 2023
Accepted 27 MAR 2024

Author Contributions:
Conceptualization: Gesa A. Weyhenmeyer, Azubuike V. Chukwuka, Orlane Anneville, Justin Brookes, Carolinne R. Carvalho, James B. Cotner, Hans-Peter Grossart, David P. Hamilton, Paul C. Hanson, Josef Hejzlar, Sabine Hilt, Matthew R. Hipsey, Bas W. Ibelings, Stéphan Jacquet, Külli Kangur, Theis Kragh, Bernhard Lehner, Fabio Lepori, Ben Lukubye, Rafael Marce, Yvonne McElarney, Ma. Cristina Paule-Mercado, Rebecca North, James A. Rusak, Sapna Sharma, Facundo Scordo, Lisette N. de Senerpont Domis, Jonas Stage Sø, Susanna (Susie) A. Wood, Marguerite A. Xenopoulos, Yongqiang Zhou
Data curation: Gesa A. Weyhenmeyer, Azubuike V. Chukwuka, Orlane Anneville, Justin Brookes,

Abstract The world's 1.4 million lakes (≥10 ha) provide many ecosystem services that are essential for human well-being; however, only if their health status is good. Here, we reviewed common lake health issues and classified them using a simple human health-based approach to outline that lakes are living systems that are in need of oxygen, clean water and a balanced energy and nutrient supply. The main reason for adopting some of the human health terminology for the lake health classification is to increase the awareness and understanding of global lake health issues. We show that lakes are exposed to various anthropogenic stressors which can result in many lake health issues, ranging from thermal, circulatory, respiratory, nutritional and metabolic issues to infections and poisoning. Of particular concern for human well-being is the widespread lake drying, which is a severe circulatory issue with many cascading effects on lake health. We estimated that ~115,000 lakes evaporate twice as much water as they gain from direct precipitation, making them vulnerable to potential drying if inflowing waters follow the drying trend, putting more than 153 million people at risk who live in close vicinity to those lakes. Where lake health issues remain untreated, essential ecosystem services will decline or even vanish, posing a threat to the well-being of millions of people. We recommend coordinated multisectoral and multidisciplinary prevention and treatment strategies, which need to include a follow-up of the progress and

10.1029/2023EF004387

Carolinne R. Carvalho, James B. Cotner, Hans-Peter Grossart, David P. Hamilton, Paul C. Hanson, Josef Hejzlar, Sabine Hilt, Matthew R. Hipsey, Bas W. Ibelings, Stéphan Jacquet, Külli Kangur, Theis Kragh, Bernhard Lehner, Fabio Lepori, Ben Lukubye, Rafael Marce, Yvonne McElarney, Ma. Cristina Paule-Mercado, Rebecca North, James A. Rusak, Sapna Sharma, Facundo Scordo, Lisette N. de Senerpont Domis, Jonas Stage Sø, Susanna (Susie) A. Wood, Marguerite A. Xenopoulos, Yongqiang Zhou
Methodology: Gesa A. Weyhenmeyer, Azubuike V. Chukwuka, Orlane Anneville, Justin Brookes, Carolinne R. Carvalho, James B. Cotner, Hans-Peter Grossart, David P. Hamilton, Paul C. Hanson, Josef Hejzlar, Sabine Hilt, Matthew R. Hipsey, Bas W. Ibelings, Stéphan Jacquet, Külli Kangur, Theis Kragh, Bernhard Lehner, Fabio Lepori, Ben Lukubye, Rafael Marce, Yvonne McElarney, Ma. Cristina Paule-Mercado, Rebecca North, James A. Rusak, Sapna Sharma, Facundo Scordo, Lisette N. de Senerpont Domis, Jonas Stage Sø, Susanna (Susie) A. Wood, Marguerite A. Xenopoulos, Yongqiang Zhou
Visualization: Gesa A. Weyhenmeyer, David P. Hamilton, Sabine Hilt, Bernhard Lehner, Yongqiang Zhou
Writing – original draft: Gesa A. Weyhenmeyer, Azubuike V. Chukwuka, Orlane Anneville, Justin Brookes, Carolinne R. Carvalho, James B. Cotner, Hans-Peter Grossart, David P. Hamilton, Paul C. Hanson, Josef Hejzlar, Sabine Hilt, Matthew R. Hipsey, Bas W. Ibelings, Stéphan Jacquet, Külli Kangur, Theis Kragh, Bernhard Lehner, Fabio Lepori, Ben Lukubye, Rafael Marce, Yvonne McElarney, Ma. Cristina Paule-Mercado, Rebecca North, James A. Rusak, Sapna Sharma, Facundo Scordo, Lisette N. de Senerpont Domis, Jonas Stage Sø, Susanna (Susie) A. Wood, Marguerite A. Xenopoulos, Yongqiang Zhou
Writing – review & editing: Gesa A. Weyhenmeyer, Azubuike V. Chukwuka, Orlane Anneville, Justin Brookes, Carolinne R. Carvalho, James B. Cotner, Hans-Peter Grossart, David P. Hamilton, Paul C. Hanson, Josef Hejzlar, Sabine Hilt, Matthew R. Hipsey, Bas W. Ibelings, Stéphan Jacquet, Külli Kangur, Theis Kragh, Bernhard Lehner, Fabio Lepori, Ben Lukubye, Rafael Marce, Yvonne McElarney, Ma. Cristina Paule-Mercado, Rebecca North, James A. Rusak, Sapna Sharma, Facundo Scordo, Lisette N. de Senerpont Domis, Jonas Stage Sø, Susanna (Susie) A. Wood, Marguerite A. Xenopoulos, Yongqiang Zhou

an assessment of the resilience of lakes to intensifying threats. Priority should be given to implementing sewage water treatment, mitigating climate change, counteracting introductions of non-native species to lakes and decreasing uncontrolled anthropogenic releases of chemicals into the hydro-, bio-, and atmosphere.

Plain Language Summary Lakes around the world come in an array of sizes, shapes and colors, each telling a unique story of geological history and environmental importance. When lakes are healthy they contribute to the achievement of the global sustainable development goals by providing many important ecosystem services. Lakes are, however, not always healthy. Here, it is shown that lakes can suffer from a large variety of health issues, ranging from thermal, circulatory, respiratory, nutritional and metabolic issues to infections and poisoning. Without improved treatment strategies, many of the health issues may become chronic, affecting millions of people who are dependent on the ecosystem services from the lakes. To prevent and cure lakes from critical health conditions, strategies that are similar to those used in human healthcare should be applied: intervention and preventative actions before health problems occur, regular screening and early identification of lake health issues, and remediation and mitigation efforts at an appropriate scale, spanning from local to global.

1. Introduction

The human population has now reached 8 billion people (United Nations, 2022) all of whom need clean water. Of the approximately 1.4 million unevenly distributed lakes around the world (Figure 1), many play a fundamental role in providing humans with water and food, thereby contributing to the achievement of the 17 global sustainable development goals (SDGs), in particular SDGs 1: no poverty, 2: zero hunger, 3: good health and well-being, 6: clean water and sanitation, and 14: life below water (Ho & Goethals, 2019). If lakes and the organisms living in and around them stay healthy, humans in their vicinity have increased prospects for a healthy life, a concept known as One Health (Adisasmito et al., 2022). There is, however, increasing evidence that many lakes on Earth, including the large ones that provide people with extensive ecosystem services, are no longer healthy, owing to local, regional and global stressors (Jenny et al., 2020).

Defining lake health is challenging. In 1998, the U.S. Environmental Protection Agency described a healthy lake as a lake with clean water, balanced algal growth, adequate oxygen levels and abundance and diversity of fish, bottom-dwelling invertebrates and native plants (Environmental Protection Agency, 1998). This general definition is based on undefined terms like "clean," "balanced," "adequate" and "diversity," where unhealthy conditions might be recognized as algal blooms, fish kills, foams, smells, oil films, litter etc. Many health problems are, however, invisible, such as contamination by disease-causing microorganisms, mercury, persistent organic pollutants or microplastics, among many others. These invisible health problems are usually only detectable by diagnostic tests. There is a wide range of diagnostic tests available, for example, more than 100 variables were measured to assess the health status of hundreds of lakes across Canada (Huot et al., 2019). Performing all of these measurements is costly and consequently not feasible to implement for the majority of the world's lakes. To overcome the lack of data from comprehensive lake sampling programs, there are increasing efforts to retrieve lake and watershed data by the interpretation of satellite images (Alsdorf et al., 2007; Dornhofer & Oppelt, 2016; Huot et al., 2019; Yin et al., 2005).

Over the past decades, many countries have made substantial progress in assessing the health status of their freshwaters and there are even efforts, such as the European Water Framework Directive (https://environment.ec.europa.eu/topics/water/water-framework-directive_en), to harmonize assessments across countries. A variety of authorities regularly update the assessments, for example, the U.S. National Lake Assessment (https://www.epa.gov/national-aquatic-resource-surveys/nla), the Australian Healthy Land and Water program (https://reportcard.hlw.org.au/), the European Environment Agency (https://www.eea.europa.eu/data-and-maps/), and the China National Environmental Monitoring Center (https://szzdjc.cnemc.cn:8070/GJZ/Business/Publish/Main.html). A key concept of lake health assessments is a comparison of the present status to reference conditions, often defined as conditions that prevail in the absence or near absence of human disturbance, and thus corresponding to pre-industrial conditions (Bouleau & Pont, 2015). Although the determination of reference conditions is still highly uncertain and requires more research (Bouleau & Pont, 2015; Noges et al., 2009), the approach to assess deviations from reference conditions has similarities to practices used in the human healthcare. In medical sciences, health can be conceptualized as the capability to react to all kinds

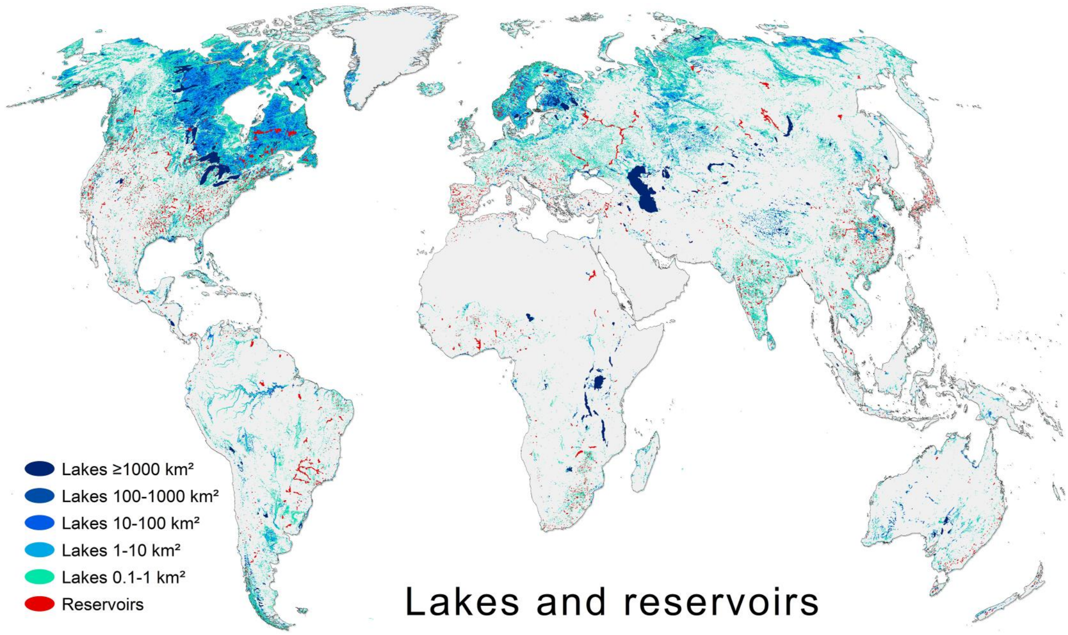

Figure 1. World's distribution of lakes ≥10 ha (0.1 km^2). Approximately 5% of the lakes are reservoirs (only the largest ~7,000 are shown on this map). Data for the map are from LakeATLAS (Lehner et al., 2022). Of the 1,427,688 lakes, 994,072 are located in North America, 54,048 in South America, 281,956 in Europe, 15,964 in Africa, 68,169 in Asia and 13,479 in Oceania.

of environmental stressors with desired emotional, cognitive and behavioral responses, and to avoid undesirable ones (Leonardi, 2018), where the delimitation between desired and undesired responses is given by reference values.

Despite major improvements in the assessment of lake health, especially in high-income countries, there is not yet a global classification system for lake health available and links to human well-being have been postulated but often remain unclear. Here, we introduce a simple classification system which has similarities to the international classification system for human health, developed by the World Health Organization (https://www.who.int/standards/classifications/classification-of-diseases). In our approach, lake health issues are classified into thermal, circulatory, respiratory, nutritional and metabolic issues, infections, poisoning and other harmful disturbances (Figure 2). The choice of using anthropomorphic analogies is based on studies showing that such an approach might enhance connectedness to and protectiveness toward nature (Chan, 2021; Tam et al., 2013).

2. Common Lake Health Issues and Their Societal Implications

In this review, we focus on lake health issues that are widespread, human-induced (including climate change) and that can have major implications for human well-being (Figure 3).

Lake health issues can vary substantially in their severity. In human health, the severity of a disease is commonly assessed by monitoring vital signs. For lakes, vital signs might correspond to measurements of oxygen saturation, nutrient (phosphorus and nitrogen) concentrations, water temperature, pH, and water clarity (e.g., Secchi depth). Using this approach and adopting the concept of ecological status of the European Water Framework Directive, the range of lake health conditions can vary from being excellent to critical (Table 1).

Presently, it is not known how many of the 1.4 million lakes ≥10 ha (0.1 km^2) suffer from one or more health issues, mainly because of undefined reference conditions and missing data on lake physical, chemical and biological conditions. Here, we use rough estimates on the likelihood of lakes to suffer from one or more health issues by analyzing some of the lake and watershed data compiled in LakeATLAS (Lehner et al., 2022), available at https://www.hydrosheds.org/hydroatlas. In LakeATLAS, water bodies with a surface area ≥10 ha (0.1 km^2) are considered, encompassing both lakes and reservoirs, of which less than 200,000 are larger than 1 km^2 (Messager et al., 2016). Their combined surface area covers 2.9×10^6 km^2 which is about 2.0% of the global land area. This

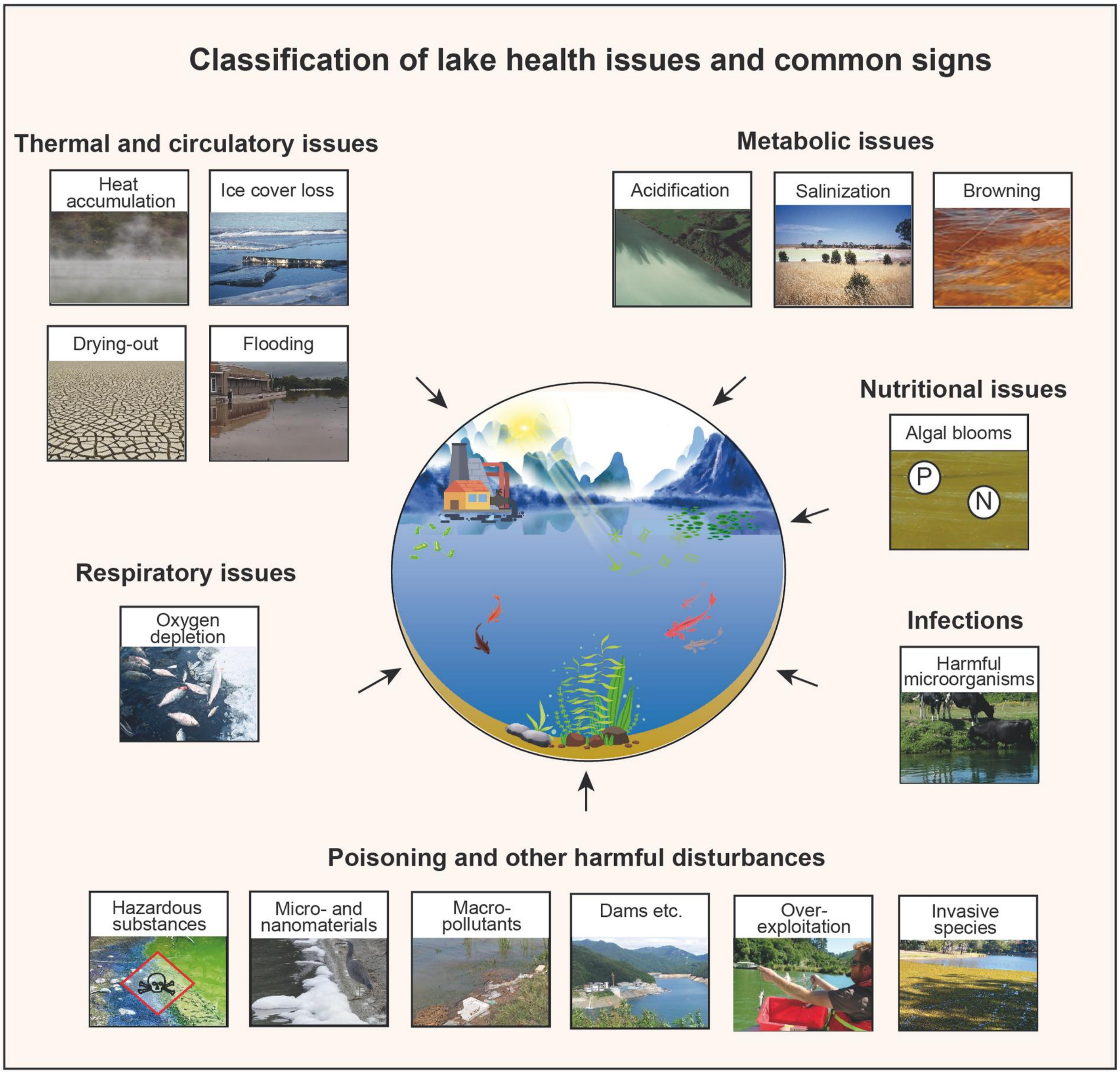

Figure 2. Lakes are living systems that can suffer from a large variety of health issues, similar to humans. A lake has a health issue if conditions deviate from reference conditions, that is, conditions that prevail in the absence or near absence of human disturbance, often referred to as pre-industrial conditions. Many, but not all, of the health issues are visible, demonstrating the importance of applying adequate diagnostic test. Lakes often experience multiple concurrent or serial health issues. The health issue of heat accumulation includes prolonged and intensified thermal stratification as a response to climate change.

selection has been made for reasons of data availability. The total number of lakes on Earth is not exactly known but has been estimated to be around 3.4 million when including those ≥3 ha, based on satellite imagery and deep learning methods (Pi et al., 2022), and around 21 million when including those ≥1 ha, based on extrapolation techniques (Messager et al., 2016). Considering even smaller lakes and ponds, estimates reach between 117 million (Verpoorter et al., 2014) and 304 million lakes (Downing et al., 2006). For the work presented here, we used version 1.0 of LakeATLAS that contains data from a total of 1,427,688 lakes. According to the LakeATLAS database, almost 965 million people live within 3 km of a lake, which is more than 12% of the world's population. A detailed description of available variables, their sources and abbreviations are available in Lehner et al. (2022).

In the following sections we address and classify lake health issues which have been observed in many lakes around the world. By outlining their consequences for human well-being, we demonstrate the need for improved prevention and treatment strategies.

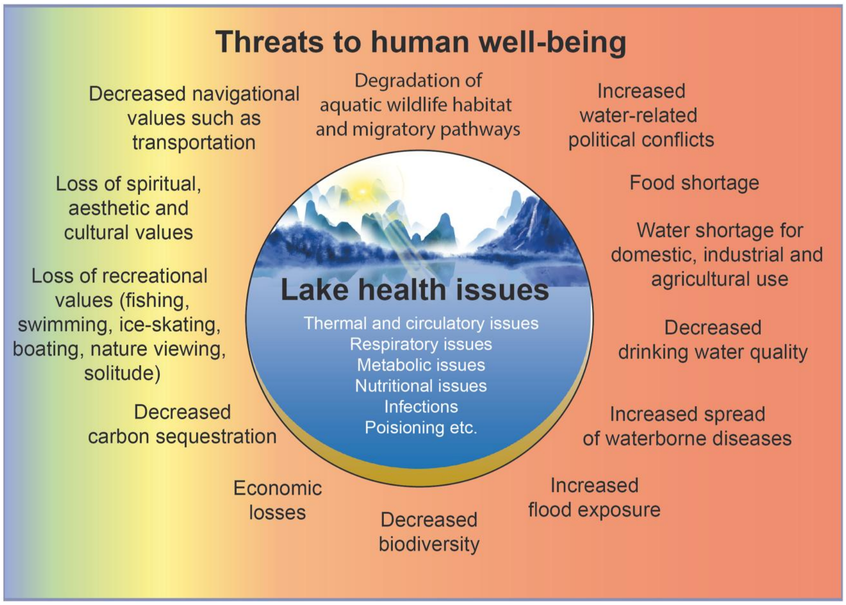

Figure 3. Possible threats to human well-being as a result of lake health issues. The threats differ widely across geographical regions, both in occurrence and severity. Threats that pose the highest likelihood of directly endangering human survival such as water and food shortage, contaminated drinking water, waterborne diseases, water-related wars and floods are highlighted in red in the color gradient.

2.1. Thermal and Circulatory Issues

Climate change has resulted in pronounced changes in thermal stratification and water column mixing in lakes around the world (Adrian et al., 2009). Water column mixing is a key regulator of lake health, as it determines the replenishment of life-sustaining oxygen concentrations (Boehrer & Schultze, 2008). Full water column mixing can occur several times a year in polymictic lakes, during winter in monomictic lakes, during spring and autumn

Table 1
Range and Key Assessment Criteria of Lake Health Conditions

Critical	One or more vital signs such as oxygen saturation, nutrient concentrations, temperature, pH and water clarity of a lake are far outside reference conditions. According to the guidelines given by the European Water Framework Directive, this condition corresponds to a bad ecological and chemical status of a lake.
Serious	One or more vital signs such as oxygen saturation, nutrient concentrations, temperature, pH and water clarity of a lake are clearly outside reference conditions. According to the guidelines given by the European Water Framework Directive, this condition corresponds to a poor ecological and chemical status of a lake.
Fair	One or more vital signs such as oxygen saturation, nutrient concentrations, temperature, pH and water clarity of a lake are outside reference conditions. According to the guidelines given by the European Water Framework Directive, this condition corresponds to a moderate ecological and chemical status of a lake.
Good	All vital signs such as oxygen saturation, nutrient concentrations, temperature, pH and water clarity are close to reference conditions. According to the guidelines given by the European Water Framework Directive, this condition corresponds to a good ecological and chemical status of a lake.
Excellent	All vital signs such as oxygen saturation, nutrient concentrations, temperature, pH and water clarity are fully within reference conditions. According to the guidelines given by the European Water Framework Directive, this condition corresponds to a high ecological and chemical status of a lake.

Note. To judge the severeness of a lake health issue, reference conditions need to be known. The colors correspond to the colors used in the European Water Framework Directive.

in dimictic lakes, or it can be absent in meromictic lakes. With climate change, some lakes have started to shift to a new category of lake circulatory, for example, permanently ice-covered meromictic lakes in the Arctic can nowadays undergo circulation as ice cover is lost (Bégin et al., 2021), dimictic lakes can become monomictic lakes (Shatwell et al., 2016), and circulation in some large lakes that had mixed once in an annual cycle may no longer occur at all, as strengthening vertical density gradients can resist the seasonal cooling and wind turbulence that would normally result in full circulation (Mesman et al., 2021; Sahoo et al., 2016). From a human health perspective, the latter case could be likened to the loss of circulation from a limb; not necessarily life threatening, but severely limiting functional ability. Even some shallow polymictic lakes may change to become monomictic with climate change and therefore lose connectivity of deep waters to atmospheric reaeration when they are stratified. Human activities associated with salts from de-icing roads, connection of coastal canals to lakes and mining activities can also increase the density of water inflows to lakes (Ladwig et al., 2023). This water can accumulate at the lake bottom and make these lakes permanently stratified, with major effects on dissolved oxygen, circulation and nutrition (Boehrer & Schultze, 2008).

Below we focus on four critical widespread thermal and circulatory issues: heat accumulation that includes prolonged and intensified thermal stratification, loss of ice cover, drying-out and flooding.

2.1.1. Heat Accumulation Including Prolonged and Intensified Thermal Stratification

Many lakes accumulate heat as a response to global warming, with an increasing occurrence of heat waves, defined as a period in which lake surface temperatures exceed a local and seasonally varying 90th percentile threshold for at least 5 days relative to a baseline climatological mean (Woolway, Jennings, et al., 2021; Woolway, Sharma, et al., 2021). Direct effects of heat waves can include a loss of habitat (Kraemer et al., 2021), deoxygenation (Jane et al., 2021) and an accelerated growth of potentially harmful lake organisms, for example, disease-causing microorganisms, invasive species and toxin-producing cyanobacteria (Wilk-Wozniak, 2020). Heat waves are commonly associated with prolonged and intensified thermal stratification (Woolway, Jennings, et al., 2021; Woolway, Sharma, et al., 2021). The cascading effects of longer and stronger stratification on chemical and biological processes in lakes with an increasing occurrence of harmful algal blooms and fish kills are well known (Shimoda et al., 2011). As long as global warming proceeds, the duration and intensity of thermal stratification will most likely further increase in lakes around the world (Woolway, Jennings, et al., 2021; Woolway, Sharma, et al., 2021). Such a trend might not only cause new health issues but will most probably also intensify the severity of existing issues.

2.1.2. Ice Cover Loss

The majority of lakes on Earth are still periodically covered by ice. Climate change has, however, caused rapid ice cover loss, which is projected to continue, with another approximately 35,000 lakes losing their seasonal ice cover in a 2°C warmer world (Sharma et al., 2019). Additionally, the quality of ice is changing, resulting in a higher frequency of unstable ice conditions (Weyhenmeyer et al., 2022). Unstable ice conditions can cause substantial economic losses due to delays in winter ice road construction (Hori et al., 2017), as well as cancellations of ice fishing and ice-skating tournaments (Knoll et al., 2019). Under projected warmer climatic conditions, ice is forecasted to be too thin to be safe for winter transportation without engineering adaptation solutions (Woolway et al., 2022). Changes in ice cover and quality also entail direct threats to human health by increasing the occurrence of drownings, especially of small children (Sharma et al., 2020). Furthermore, the rapid decline in lake ice cover can threaten human health by affecting various cultural, recreational and spiritual ecosystem services (Knoll et al., 2019). Additionally, there will be far-reaching ecological consequences because winter conditions strongly influence how lake conditions, dynamics and functionality will unfold over the following seasons (Hampton et al., 2017). Conversely, some of the ecological changes from lake ice cover loss may increase lake ecosystem services, for example, from an increase in lake productivity (Weyhenmeyer et al., 2013).

2.1.3. Drying-Out of Lakes

Severe water exploitation and climate change have caused many lakes around the world to rapidly lose water, resulting in a substantial decline in key lake ecosystem services such as the availability of water for drinking, irrigation and fisheries (Rodell et al., 2018; Vörösmarty et al., 2000). Famous examples of lakes that have rapidly lost water over a relatively short time period with fatal consequences for human well-being are the Aral Sea in Central Asia (Micklin, 1988), Lake Urmia in Northern Iran (Rahimi & Breuste, 2021), Lake Chapala in Mexico (von Bertrab, 2003), Lake Chilwa in Malawi (Njaya et al., 2011), Lake Chad in West Central Africa (Lemoalle et al., 2012), and the Great Salt Lake in the USA (Wurtsbaugh & Sima, 2022). The process of drying-out is analogous to dehydration and potential death for humans. Sustained loss of water security has become a major constraint to socio-economic development and a threat to livelihood in many parts of the world (Liu et al., 2017). Water scarcity can also increase salinity, often making lakes unusable as a water and food resource with direct effects on human well-being (Kafumbata et al., 2014; Wurtsbaugh & Sima, 2022; see also section below on salinization). Despite the well-known ripple effects of drying-out of lakes, many lakes on Earth continue to rapidly lose water (Yao et al., 2023; Zhao et al., 2022). Using global lake and watershed data from LakeATLAS (Lehner et al., 2022), we estimated that about 8% of the worlds' lakes ≥10 ha (i.e., 115,179 out of 1,427,688 lakes) evaporate at least twice as much water as they gain from direct precipitation, which corresponds to an aridity index of ≤0.5 (Zomer et al., 2022; Figure 4a). Lakes that evaporate substantially more water than they directly receive are highly dependent on inflows from upstream or groundwater sources, making them particularly vulnerable to alterations due to climate or human water use change. Such lakes are present across all continents, but they dominate in densely populated low-income countries (Figure 4a). Based on data from LakeATLAS, more than 153 million people live in close vicinity (3 km radius) to a lake with an aridity index ≤0.5. As long as global warming and human water consumption continues to increase, many lakes will continue to lose water and some lakes might even dry-out completely. Globally, the loss of lakes in warm and dry geographical regions might, to some extent, be compensated by the formation of new lakes when permafrost or glaciers melt (Shugar et al., 2020) but these lakes are usually far away from densely populated regions where freshwater is most needed.

2.1.4. Flooding

Lakes around the world suffer not only from drying-out but also from flooding (Tellman et al., 2021), in particular in the tropics where heavy tropical storms increasingly occur under climate change with fatal consequences for the survival of flora and fauna (Reyer et al., 2017). Floods are frequently monitored with data being available and regularly updated in repositories such as the global flood database (https://global-flood-database.cloudtostreet.ai/#), yet predicting their effect on individual lakes remains challenging. Floods often classify as a severe circulatory issue of a lake but flooding can sometimes also be beneficial to replenish aquifers, to reconnect lakes with their natural floodplains and to provide suitable habitat for fish to spawn (Talbot et al., 2018). Here, we fous on extreme flooding events that in the worst case can result in loss of homes, property, livestock and lives. Extreme flooding is not only climate-driven but can also occur when dams break or when they are built, famous examples being the dam building projects in James Bay, Canada (Roebuck & Virginia, 2010) and Three Gorges in China (New & Xie, 2008; see section on hydromorphological modifications below). Extreme flooding events are often a direct threat to lake and human health by substantially increasing contaminant loads, macropollutants and disease-causing microorganisms, in particular when flood water encroaches into agricultural land or when there are overflows from sewers or manufacturing facilities into lakes and reservoirs (Talbot et al., 2018; Zaher & Aly, 2021). The litter washed into lakes and onto shores by a flooding event can substantially impair recreational values of a lake due to unsightly debris and malodor. These tangible threats to lake health may be perceived by lake users as more harmful than invisible threats such as heat accumulation, disease-causing microorganisms, oxygen depletion, acidification, etc. The frequency of lake flooding may increase in the future due to an increase in climate change driven extreme precipitation events or rapid glacial melt (Paprotny et al., 2018). Extreme flooding events might also increase due to an increase in landslides that can result in dam breaks (Fischer et al., 2021). Extreme lake flooding events may, however, also decrease because of improved hydromorphological modifications that can regulate the water flow through the landscape in a more efficient way (see also section on hydromorphological modifications below).

2.2. Nutritional Issues

The nutritional balance of a lake is disturbed when its nutrient concentrations are either too high or too low compared to reference conditions. Such disturbances commonly result in a decline of lake ecosystem services, for example, the productivity of a lake might rapidly decrease due to nutrient deficiency or it might rapidly increase due to nutrient excess, a process which has been known for many decades as eutrophication (Le Moal et al., 2019).

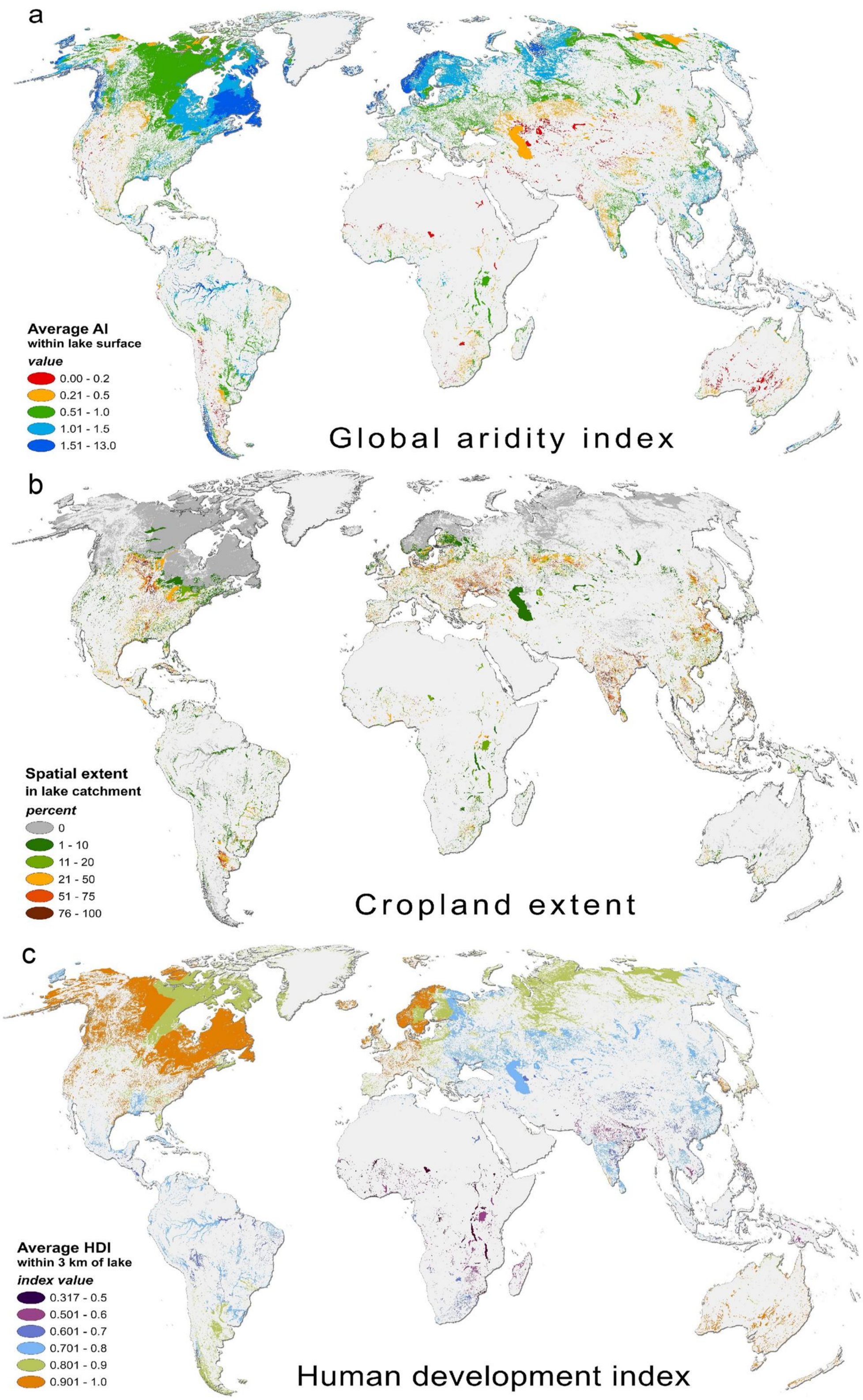
a
Average AI
within lake surface
value
0.00 - 0.2
0.21 - 0.5
0.51 - 1.0
1.01 - 1.5
1.51 - 13.0
Global aridity index
b
Spatial extent
in lake catchment
percent
0
1 - 10
11 - 20
21 - 50
51 - 75
76 - 100
Cropland extent
c
Average HDI
within 3 km of lake
index value
0.317 - 0.5
0.501 - 0.6
0.601 - 0.7
0.701 - 0.8
0.801 - 0.9
0.901 - 1.0
Human development index

Figure 4.

10.1029/2023EF004387

Eutrophication is often associated with phytoplankton blooms which occur when microscopic or filamentous algae or cyanobacteria aggregate and float to the surface and become visible to the naked eye. Algal blooms have been observed for centuries; for example, in 1188 Geraldus Cambrensis reported from a lake in Wales: "*The lake has many miraculous properties—it sometimes turns bright green, and in our days it has been known to become scarlet, not overall, but as if blood were flowing along certain currents and eddies*." Blooms can also involve benthic biofilms of algae and filamentous forms of cyanobacteria in littoral habitats (Vadeboncoeur et al., 2021). Algal blooms might directly threaten human health as certain cyanobacterial strains produce toxins, causing respiratory, gastrointestinal, and dermatological issues (Funari & Testai, 2008). A wide range of symptoms can be triggered by cyanotoxins, with hepatotoxicity (Hernandez & Bessone, 2022) and neurotoxicity (Hinojosa et al., 2019) effects leading to cellular and genomic damage, protein synthesis inhibition and potential carcinogenesis in humans and wildlife (Funari & Testai, 2008). Cyanobacterial blooms have been related to the death of a large variety of organisms (Benayache et al., 2022; Carmichael & Boyer, 2016; Chen et al., 2009; Codd et al., 2015; Lugomela et al., 2006; Trevino-Garrison et al., 2015). Another effect of algal blooms is their contribution to methane production through various pathways, including organic matter degradation and photosynthesis-related processes (Bartosiewicz et al., 2021; Yao et al., 2016) with potential to influence global warming (Bartosiewicz et al., 2021). The key driver for the global expansion and intensification of algal blooms and toxin production is the cultural eutrophication from domestic, industrial and agricultural waste (Carpenter et al., 1998) which is likely exacerbated by climate change. Eutrophication is very common in lakes that have substantial agricultural land in their watersheds (Arbuckle & Downing, 2001; Keatley et al., 2011). Taking more than 75% cropland in a lake watershed as a proxy for a high risk of eutrophication and the development of harmful algal blooms, we found globally that about 0.9% of the 1.4 million lakes ≥10 ha might be eutrophic as a consequence of extensive agricultural acitivities in the watershed, most of them located in India (3,043 lakes). This number increases to 8% when a threshold of more than 20% cropland in the watershed is used, with most lakes located in USA (18,581 lakes; Figure 4b). According to the LakeATLAS database, more than 590 million people live around lakes (3 km radius) which have >20% cropland in the watershed.

2.3. Respiratory Issues

Clear signs of lake respiratory issues are dissolved oxygen concentrations far below reference conditions. Oxygen desaturation in a lake is primarily related to algal blooms, warmer water temperatures, and insufficient water circulation due to stronger and longer stratification (Jane et al., 2023). Among the most severe consequences of oxygen desaturation in a lake is the death of oxygen demanding organisms, with massive fish kills being a sign of critical lake health conditions. Fish kills have been reported from lakes all around the world (Fukushima et al., 2017; Hoyer et al., 2009; Kangur et al., 2016; Ochumba, 1990; Rao et al., 2014; Roelke et al., 2011; Sayer et al., 2016; Smith et al., 2016). Fish kills usually result in the loss of many ecosystem services, the most apparent being a loss in the provision of food from lakes and a loss of recreational value. Fish kills are commonly related to the decay of massive algal blooms in highly eutrophic waters with low flushing rates (Zhou et al., 2015) and subsequent oxygen depletion (Rao et al., 2014). They have also been linked to cyanobacterial toxins (Carmichael & Boyer, 2016), infections (Scott & Bollinger, 2014), acidification episodes (Rosseland, 1986), exceptionally high organic carbon inputs related to browning (Brothers et al., 2014), high rainfall events (Kragh et al., 2020), pollutants, loss of habitat connectivity (Mendoza et al., 2022) or a combination of factors often related to heat waves (Kangur et al., 2013). Fish kills usually generate considerable attention from the public, putting pressure on managers to identify causal factors and implement treatment strategies. Fish kills are expected to increase in a warmer future, especially during heat waves when thermal stratification is expected to intensify and lengthen (Woolway, Jennings, et al., 2021; Woolway, Sharma,

Figure 4. Lake and watershed characteristics of about 1.4 million lakes. Lakes that are shown have a surface area ≥10 ha (0.1 km^2) and include reservoirs. The data are taken from LakeATLAS (Lehner et al., 2022). Panel (a) Global aridity index for lake surface area, defined as the ratio between annual precipitation that falls directly onto the lake surface and potential evapotranspiration from the lake. An aridity index >1 (blue color) represents lakes that receive more water from direct precipitation than they lose through evaporation, whereas an aridity index ≤0.5 (orange and red color) represents lakes that evaporate at least twice as much water as they receive from direct precipitation. Most lakes in Africa and Australia, and many lakes in Central Asia evaporate much more water than they receive. Panel (b) Extent of cropland in lake watersheds. Lakes that have >20% cropland in the watershed (yellow, orange and red color) are regarded as being at high risk of eutrophication and algal blooms. Panel (c) Human development index within 3 km vicinity of a lake. A human development index ≤0.5 (dark purple color) is regarded as being critical to lake health due to the high probability of uncontrolled inputs of untreated sewage and unmanaged waste. Most lakes in Africa and many in Asia are surrounded by people with a low human development index.

et al., 2021), resulting in elevated risk for oxygen depletion (Jane et al., 2021). Globally, oxygen depletion in lakes is spreading quickly, even faster than in the oceans and with no signs of recovery (Jane et al., 2021). Hypoxia is even returning to lakes with good water quality, like observed in Lake Geneva due to milder winters that result in incomplete lake overturn, causing long-term isolation of the deepest part of these lakes from the atmosphere, threathening benthic fauna (Mesman et al., 2021). The loss of dissolved oxygen from deeper waters has important ramifications for lake nutrition, as it is associated with the release of dissolved phosphorus from bottom sediments (Sondergaard et al., 2003), linked to reduction and dissolution of binding metal ions (e.g., iron, manganese) and shutdown of nitrification (Small et al., 2014). Thus, the loss of dissolved oxygen in a lake should be viewed similarly to any impairment in human respiratory function, with potential for far-reaching consequences on health and nutrition.

2.4. Metabolic Issues

Acidification, salinization and browning with elevated energy and ion inputs into lakes can all disturb the metabolic balance of a lake. Because those processes also occur naturally, we only consider them as health issues when pH/acidity, salinity and color/dissolved organic matter are outside of reference conditions. High densities of naturally saline and acid-saline lakes are usually found in regions with extreme aridity and specific geological conditions. Those lakes commonly show high variability of salinity and acidity with seasonal rains, often with high levels of endemism and acting as important bird migration flyovers (Pedler et al., 2014).

2.4.1. Acidification

Mining activities, industrial pollution, atmospheric deposition of sulfur and nitrogen compounds and afforestation can all result in a pH drop to critical levels below 6 or, in the presence of strong nitric and sulfuric acids, even lower (Schindler, 1988). Acidification can be chronic or episodic, causing a large variety of chemical changes in lake waters, including the release of metals, with pronounced effects on the growth and reproduction of pH sensitive microorganisms, plants and animals (Muniz, 1990; Vrba et al., 2016). In severe cases, fish kills can occur. In general, acidification shifts the balance between acid-sensitive and acid-tolerant species (Muniz, 1990), thereby altering the structure of aquatic food webs. Acidification affects human well-being not only by reducing food resources but often results in substantial economic losses due to reduced or extirpated fish stocks of commercial or recreational value (Caputo et al., 2017; Tammi et al., 2003). Despite efforts to raise the pH in lakes by controlling emissions of sulfate and nitrogen oxides at national (e.g., U.S.A.'s Clean Air Act) and international levels (e.g., United Nations regulations) and by treating lakes and surrounding watersheds with calcium carbonate (e.g., Nordic countries) acidification remains a current issue because biological recovery has often not shown the desired response to a pH increase (Evans et al., 2001). In addition, acidification is expected to increase again in the future due to projected population and consumption increases that lead to an increase in mining, smelting, fossil-fuel combustion, food production, use of nitrogen fertilizers, deforestation and other processes (Rice & Herman, 2012). Another factor behind increasing acidification with effects on biota is an increase in carbon dioxide concentrations in lakes (Hasler et al., 2016), although trends of carbon dioxide concentrations in freshwaters are highly variable, sometimes even decreasing over time (Nydahl et al., 2017).

2.4.2. Salinization

Salinization can be severe when lakes dry out. Salinization of lakes is of particular concern due to its strong effects on the structure of biological communities and ecosystem health (Williams, 1998). The process of salinization by rapid evaporative water loss can be amplified by salts that enter lakes due to agricultural activities in the watershed (Wakeel, 2013), by pressures associated with dryland and wetland salinity (De Sousa et al., 2023), and/or by hydrological changes that cause incursion of coastal waters (Tibby et al., 2020). Apart from the rapid increase in salinity in lakes of the semi-arid and arid regions of the world, with no signs of improvement, salinization has also become a concern for lakes located in cold geographical regions, mainly due to an increased use of road salts (Dugan et al., 2017). In those regions, current water quality guidelines are inadequate to protect lake biota from harm (Hintz et al., 2022). For the salinization process in cold geographical regions mitigation measures such as using less road salt in winter or the application of salt alternatives, such as the utilization of sand and heating of roads, are presently under consideration by policy makers.

2.4.3. Browning of Lakes

Many lakes across boreal, temperate and arctic regions have become browner due to increased human-induced (i.e., climate change, acidification, forestry) inputs of dissolved organic matter and iron (Kritzberg et al., 2020; Weyhenmeyer et al., 2014). When lake waters become browner, increased light limitation can reduce primary and fish production (Karlsson et al., 2009; van Dorst et al., 2019). In contrast, the growth and reproduction rates of microorganisms are usually increased in browner lakes, with an increased risk of oxygen depletion (Brothers et al., 2014) and increased internal nutrient loading (Kazanjian et al., 2021). These changes can favor the production of methane in lakes with effects on global warming (Dean et al., 2018). The increased growth and reproduction of (pathogenic) microorganisms is also a major challenge for the generation of safe drinking water (Edge et al., 2013). There are treatment options to prevent bacterial presence in drinking water such as chlorine additions but the disinfection by-products are often carcinogenic (Eikebrokk et al., 2004). Exposure to UV-light or membrane filtration are other treatment options, but are costly (Eikebrokk et al., 2004). Although browning is often regarded as a lake health issue, mainly due to its effect on drinking water quality, reference conditions remain undefined, and the extent of its effect on lake health is therefore uncertain. Browning is common for lakes that are surrounded by soils that contain a high amount of organic carbon in the top layer (Weyhenmeyer et al., 2012). According to LakeATLAS, ~837,500 lakes are surrounded by a watershed in which soils contain more than 100 tonnes of organic carbon per hectare in the top 5 cm soil layer. These lakes are mainly located in regions with a low population density. Browning might continue into the future, driven by climate change and forestry, but there are also indications that the process of browning has slowed down in geographical regions that have recovered from acidification (Riise et al., 2018; Worrall et al., 2018).

2.5. Infections

Infections can occur when there is a massive input or a rapid growth of disease-causing microorganisms in a lake. The infections might spread among lake organisms, but also among humans when they consume or are in contact with non-purified lake water. Disease-causing microorganisms are primarily found in untreated wastewater which enters lakes (Ford, 2016), but they can sometimes enter lakes also through discharge of ballast water (Ruiz et al., 2000) and defecation by animals such as water fowl, cattle and dogs (Graczyk et al., 2009). Globally, only about 56% of the world's household domestic wastewater is presently adequately treated to be at safe levels for consumption (UN Habitat and WHO, 2021). This kind of lake health issue poses a major challenge for countries that still do not have an adequate infrastructure for the treatment of wastewater. Improvement of water sanitation and hygiene has been shown to be a very efficient method to reduce waterborne infections (Ford, 2016). Each dollar invested in water sanitation and hygiene interventions gives approximately 4.3 dollars in return from preventative healthcare costs (World Health & Water, 2015). People who live in countries that have a low human development index, a summary measure of the average achievement in key dimensions of human development, including standard of living, access to education and having a long and healthy life (Kummu et al., 2018) are unlikely to have adequate infrastructure for the treatment of sewage water with the occurrence of many waterborne diseases (Ford, 2016). Using a very low human development index as a rough estimate for a high likelihood of untreated sewage water to enter lakes with infections as a consequence, we found approximately 0.5% of the 1.4 million lakes ≥10 ha where the human development index was ≤0.5 (Figure 4c), potentially affecting more than 44 million people in their close vicinity (3 km radius). Of these 44 million people, 5% live in Asia and 46% in Africa. Raising the human development index with adequate treatment of wastewater should be of highest priority, given that the growth and reproduction of microorganisms are expected to further increase in a warmer world, as metabolic rates of microorganisms are highly sensitive to temperature increases (Brown et al., 2004; Yvon-Durocher et al., 2012). Together with eutrophication and an increased cycling of organic matter, often linked to diffuse pollution from intensive agricultural practices, the growth and reproduction rates of microorganisms are likely to further accelerate, with an increased risk for a higher abundance of disease-causing microorganisms.

2.6. Poisoning and Other Harmful Disturbances

Many lake health issues are related to inputs of human-made chemicals and materials, overexploitation, introductions of non-native species and/or hydromorpholocial modifications. We classify these issues as poisoning and other harmful disturbances. This classification has similarities to the category "Injury, poisoning or certain other consequences of external causes" in the human health classification system (https://icd.who.int/en).

10.1029/2023EF004387

2.6.1. Accumulation of Hazardous Substances

The list of hazardous substances that can poison lakes is long and rapidly increasing. Hazadous substances commonly spread via air and water and are consequently found in lakes all around the world (Wang et al., 2019), and even in drinking water (Bao et al., 2012; Fick et al., 2009; Yadav et al., 2015). A well-known hazardous substance where the spread, fate and consequences have been intensively studied, is mercury (Ma et al., 2021; Meili et al., 2003). Mercury is of primary concern as it occurs in a highly toxic form (i.e., methylmercury) and can easily be taken up by organisms, thus finding its way into the food chain. When humans consume fish with high mercury levels, it may occasionally cause irreversible and fatal neurological diseases, in particular in vulnerable subpopulations, such as pregnant women, infants and young children. An example of a catastrophic outcome of mercury pollution is the poisoning event in the Japanese city Minamata, which was caused by methylmercury in the industrial wastewater released from a chemical factory from 1932 to 1968 (Harada, 1995). In general, mercury exposure to freshwater organisms has a strong potential for deleterious effects and ecological risks to sensitive fauna, and it alters biochemical, physiological, hematological and behavioral conditions (Chan et al., 2003). Although mercury emissions have successfully been reduced in some countries following international legislation such as the Minamata Convention, the presence of mercury in everyday products and processing operations constitutes an ongoing challenge (Selin & Selin, 2022). This mercury primarily comes from mining, as well as fossil fuel combustion, forestry including deforestation and open burning of waste and industrial processes such as chlor-alkali manufacturing (Obrist et al., 2018).

Numerous other hazardous substances besides mercury are found in lake water, ranging from pharmaceutical residues, endocrine disrupters, personal care products to industrial chemicals and pesticides. Of particular concern are persistent organic pollutants (POPs) and per- and polyfluoroalkyl substances (PFAS) because of their persistence and potential to cause toxic reactions (Daughton & Ternes, 1999; Ibor et al., 2019; Vandenberg et al., 2012). Apart from direct toxic reactions, hazardous substances can also cause additional problems; there is, for example, a high risk that antibiotic resistance increases when antibiotics are released into the environment (Ben et al., 2019). Many regional and global regulations have been implemented to decrease the spread but despite legislation, more and more hazardous substances become detectable in lakes all around the world and in drinking water (Morin-Crini et al., 2022), in particular in low-income countries (Wee & Aris, 2023).

2.6.2. Accumulation of Microplastic and Nanomaterials

Micromaterials such as microplastics occur in lakes all around the world (Nava et al., 2023) and have become a major concern because of their persistence with complex effects on aquatic ecosystems (Sarijan et al., 2021). Plastic production reached 359 million tonnes worldwide in 2018 and is projected to increase (Plastics Europe, 2019). Microplastics are defined as synthetic polymers with an upper size limit of 5 mm and without a specified lower limit (Eerkes-Medrano et al., 2015), although the smallest fractions might be classified as nanoplastics that pose additional health risks due to their very small size (Lai et al., 2021), see below. Well established sources for microplastics are commercial and sport fishing, boats, textile industries, personal care products, air-blasting processes, improperly disposed plastics, car tires and leachates from landfills (Yang et al., 2021). Microplastics can act as substrate for microorganisms and pollutants, including antibiotic resistant bacteria (Di Cesare et al., 2021) and are suggested to negatively impact the health of fish communities as well as human health through the consumption of fish and water from lakes containing microplastics (Angnunavuri et al., 2023; Azizi et al., 2021). Although many microplastics, together with their associated bacteria and pollutants, will end up in marine systems, they can also accumulate in lakes, in particular in those with an endorheic watershed (Cai et al., 2022). Since the lake health issue of microplastics has only recently been recognized, there are not yet commonly used treatment strategies in place.

In addition to microplastics, an increasing global release of engineered nanomaterials into aquatic environments poses another growing concern (Reidy et al., 2013). Broadly defined, the term "nano" refers to any material with at least one dimension that measures 100 nm or less (American Society for Testing and Materials, 2006), implying that they show large variations in size, toxicity and coating materials. The main sources of nanomaterials found in lakes are products used by humans that enter waterways via wastewater treatment plants, industrial effluent, atmospheric deposition, and surface water runoff (Malakar et al., 2021). The risks of nanomaterials to lake health are numerous with observed effects on the growth and reproduction of, for example, fish (Martin et al., 2018). Human health implications include those from nanoparticle ingestion through drinking water.The effects of nanomaterials found in purified drinking water, however, are still not well understood, ranging from being judged as posing a low risk to human health (Westerhoff et al., 2018) to a relatively high risk (Sousa & Teixeira, 2020; Zhang et al., 2021). As with microplastics, the lake health issue of nanomaterials has only recently gained broader attention, a reason why common treatment strategies are still at the very beginning.

2.6.3. Macropollutants

Macropollutants are visible pollutants in particulate form, such as litter and macroplastics. Most macropollutants found in lakes come from waste dumped at the shore or dumped from ships. Macropollutants can also enter lakes when wastewater is not adequately treated (Aragaw, 2021; Merga et al., 2021). Macropollutants cause a substantial loss in recreational, spiritual, esthetic and cultural values of lakes (Wood et al., 2021) and they can reduce the quality of drinking water resources (Cera et al., 2023). Macropollutants can also affect lake organisms when they digest the smaller sized fractions (Cera et al., 2023). To treat the lake health issue of macropollutants, which is particularly common in low-income countries, it may be most efficient to educate people on the consequences of spreading macropollutants into nature (Irfan et al., 2020). In addition, adequate infrastructure to manage waste and sewage water can substantially decrease the lake health issue of macropollutants (Baron et al., 2002).

2.6.4. Overexploitation

Overexploitation of lakes in the form of overfishing and excessive water removal for domestic, industrial and agricultural use commonly results in obvious lake health issues which have been intensively reviewed in other studies (Beeton, 2002; Coble et al., 1990; Ogutu-Ohwayo et al., 1997; Winfield, 2016). Overexploitation is frequently occurring in densely populated low- income countries where food shortage is common and legislations might not be followed if they at all exist (Odada et al., 2020).

2.6.5. Hydromorphological Modifications

Hydromorphological modifications such as dams, weirs, sluices, locks, channelization, decoupling of floodplains from active river channels, shoreline destruction and many more human alterations are widespread globally, occurring in both low- and high- income countries (Zarfl et al., 2015). Such modifications, in particular hydropower plants for the provision of electricity, have tradeoffs that can be beneficial for human health (Avtar et al., 2019), but at the same time, they have been linked to a severe reduction in habitat diversity, connectivity and complexity within the global river system, as well as the loss of specific habitats such as boulders and rocks, coarse woody debris, submerged tree roots, and macrophyte stands, with pronounced effects on invertebrate and fish communities (Cebalho et al., 2017; Poikane et al., 2020; Ziv et al., 2012). Apart from habitat degradation, several other ecosystem services are negatively affected by hydromorphological modifications, that is, the loss of recreational, spiritual, esthetic and cultural values (Lin & Qi, 2017), reduction in navigation and transport capacity (von Sperling, 2012) and enhanced greenhouse gas emissions (Borges et al., 2015; Deemer et al., 2016). Hydromorphological modifications can lead to conflicts over water at regional and national scales, demonstrating the need to undertake modifications without impacting social values or compromising environmental resilience, defined here as the capacity to retain a functional ecosystem while under stress (Scheffer & Carpenter, 2003). Hydromorphological modifications are manifold, with the establishment of large dams turning lakes and rivers into reservoirs. Human-made reservoirs can be found all around the world (Figure 1). The majority of large dams has been built since 1950 (Lehner et al., 2011), and there are no signs that the establishment of new dams is slowing down, particularly not in low-income countries, due to the worldwide rapid expansion of human activities, land use change, urbanization and, in particular, the demand for hydropower (Zarfl et al., 2015).

2.6.6. Invasive Species

Intensified trade, tourism, and recreational activities, as well as climate change have been linked to an increasing invasion of non-native species that can harm native species and entire ecosystems (Rahel & Olden, 2008). The direct effects of invasive species on human health range from physical effects (e.g., allergies, poisoning, and bites) to psychological effects (e.g., phobias, discomfort, loss of recreation; Mazza et al., 2014). One well studied example known to directly affect human health is the invasion of the red swamp crayfish, which now can be found on all continents except Oceania and Antarctica (Oficialdegui et al., 2020). This crayfish forms poisonous spines that can cause respiratory issues, arterial hypotension and an irregular heartbeat in anglers when they come into contact with the spines (Lodge et al., 2012). Another globally widespread invader is the *Dreissena* mussels, both zebra and quagga. Dreissenids spread quickly and, as a filter feeder, can change the functioning of lakes, with resources being funneled from pelagic to benthic communities (Karatayev & Burlakova, 2022). It has been suggested that *Dreissena* can facilitate harmful cyanobacteria blooms by removing competitors (Vanderploeg et al., 2001) and by concentrating bioavailable nutrients previously bound in phytoplankton during excretion (Raikow et al., 2004), but no support for this was found by Pires et al. (2005). *Dreissena* settlement often leads to enormous costs to human infrastructure, like blocking cooling systems of power plants and industry (Karatayev & Burlakova, 2022). In some lakes, these mussels may, however, also help to enhance water clarity, control algal blooms, promote macrophyte growth and in some shallow lakes they have become a staple food for large numbers of diving ducks (Ibelings et al., 2005). The lake health issue of invasive species is rapidly increasing along with the general trend of globalization (Sentis et al., 2021).

3. Co-Existence and Interactions of Lake Health Issues

Lake health issues may occur in isolation but most health issues co-exist and interact due to close connections between physical, chemical and biological processes in lakes (Shimoda et al., 2011). In medical sciences, the presence of two or more long-term health conditions is defined as multimorbidity which has gained increasing attention across nations over the past years (Chua et al., 2021). It has been estimated that almost a third of the world's population (2–3 billion individuals) suffers from multimorbidity with the co-occurrence of more than five ailments (Vos et al., 2015). Such estimates are not available for lakes but it is highly likely that multimorbidity is the norm. A classic example of multimorbidity in lakes is the occurrence of thermal and circulatory issues that co-exist with, for example, oxygen depletion and nutritional imbalances (see sections above). Although many co-existing and interacting lake health issues are known the health risks of mixtures of thousands of interacting chemical compounds in lakes is poorly understood. Some of the harmful substances might be flushed out or deposited on sediments at the bottom of lakes. Lake sediments are, however, not a safe final repository because harmful substances can be remobilized when redox conditions change, for example, when lakes suffer from oxygen depletion or acidification or when the sediments are resuspended (Weyhenmeyer, 1998). In addition, nutrients and warming can enhance negative effects of chemical mixtures (Vijayaraj et al., 2022). The increasing accumulation of interacting harmful substances constitutes a global lake health issue that has gained far too little attention, probably because it is a major challenge to implement prevention and treatment strategies for a threat that is not yet fully understood and invisible.

4. Treatment Strategies

To treat lake health issues is complex, particularly when several health issues co-exist and interact and where the causes for the health issues can range from global, for example, climate change (Adrian et al., 2009; Woolway et al., 2020) and/or atmospheric deposition (Baron et al., 2011; Elser et al., 2009; Meili, 1992; Weyhenmeyer, 2008) to regional and local causes, for example, intensive land-use, in particular agriculture (Carpenter et al., 1998), forestry (Kritzberg et al., 2020) and urbanization (Hall et al., 1999), water regulations (Zarfl et al., 2015), wildfires (Scordo et al., 2021), wars (Shumilova et al., 2023), contamination by disease-causing microorganisms (Ford, 2016) and local exploitation such as water removal for domestic, industrial and agricultural use, chemical pollution and overfishing (Micklin, 1988). Additional challenging aspects of treating lake health issues are potential conflicts with human demands such as maximizing food productivity, energy generation, economic prosperities etc. To find sustainable solutions, lake health issues need to be diagnosed and related to tradeoffs among energy, food and water. We suggest applying strategies that are similar to those used in human healthcare: (a) intervention and preventative actions before health problems occur by, for example, nature conservation efforts, (b) regular screening and early identification of lake health issues and (c) remediation and mitigation efforts at an appropriate scale, spanning from local to global (Figure 5). Ultimately, we need to act locally to treat most lake health issues where local community involvement and participation in both prevention and treatment of lake health issues is critical to ensuring appropriate and sustainable solutions (Cianci-Gaskill et al., 2024).

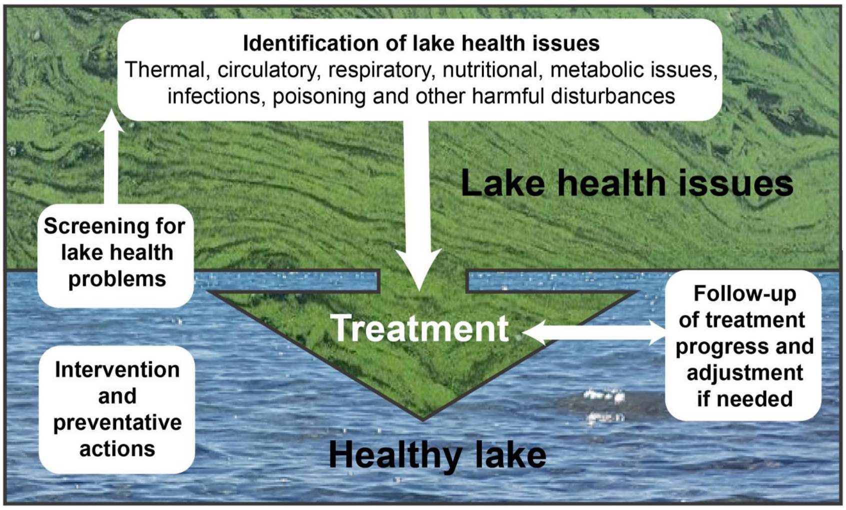

Figure 5. Treatment strategies of lake health issues. In the best case, lake health issues can be prevented by, for example, nature conservation efforts. Independent of such efforts, lakes need to be screened for health issues on a regular basis, which might be done by interpreting satellite images, using high-frequency sensor technology, taking water and/or sediment samples etc. From those screening data, lake health issues need to be identified at an early stage so that cost-efficient treatments can be started. Whenever treatments are started, there is an urgent need to follow-up the progress of the treatments and to adjust the treatments if necessary.

4.1. Intervention and Preventative Actions

Many efforts have been made to protect lakes around the world which is an efficient primary prevention measure, provided that regulations are in place and followed. Data from LakeATLAS (Lehner et al., 2022), indicate that approximately 14% of the 1.4 million lakes ≥10 ha are to some extent protected, with almost 12% being fully protected, that is, where the protection is 100% of the lake surface area. Other efficient prevention strategies comprise the management and treatment of waste and sewage water as well as education of society, which goes along with a rise of the general socioeconomic status of a country (United Nations, 2018). Another example of a preventative action is the Water Safety Plan (WSP) which has been advocated by the World Health Organisation (Gunnarsdottir et al., 2012). The overall goal of WSPs is to protect consumers against pollutants in their drinking water, be it persistent organic pollutants, mercury, cyanotoxins or other contaminants. The WSPs provide a comprehensive framework for risk assessment and management, where barriers to exposure are implemented at multiple levels encompassing all steps in the drinking water supply chain, captured in the popular catchphrase "from catchment to consumer." The protection measures taken at catchment scales immunizes lakes from a variety of health issues. The World Health Organization and the International Water Association have developed a manual to guide authorities in the implementation of WSPs.

4.2. Regular Screening and Early Identification of Lake Health Issues

Regular screening and early identification of lake health issues using consistent indicators, metrics and classification systems, is poorly developed globally. Many more harmonized diagnostic measurements and reliable reference conditions for lakes around the world are needed to provide evidence of lake health problems. One effective way to increase the reliability of reference conditions is to assess them by applying different methods, for example, through paleolimnology and coupled catchment-lake modeling (Abell et al., 2019). Recently, some improvements have been made in harmonizing diagnostics on a global scale by analyzing satellite images. Many lake health issues are, however, invisible and thus cannot be diagnosed by the interpretation of satellite images. Those invisible lake health issues require additional screening methods, mainly by taking water samples that can be screened for contaminants of emerging concern, such as pharmaceutical residues, endocrine disruptors, POPs, PFAS etc. Another option to screen for critical health conditions is the use of inexpensive sensors that can provide reliable measurements of multiple vital signs of a lake, such as temperature, oxygen saturation, water clarity and pH. In the future, lake health might be assessed digitally in similar ways as the digital assessment of human health.

4.3. Remediation and Mitigation Efforts

Worldwide, many lake health issues have already been diagnosed, but only some are adequately treated, and even then only in a few lakes. When treatments are chosen, it is of utmost importance to identify the causes of the health issues, which is challenging because they are usually manifold, ranging from global to regional and local causes. The easiest to treat are local causes, in particular when a lake health issue can be related to a local point source. Many countries have come far in identifying and successfully treating local point sources, the implementation of waste water treatment plants that cured many lakes from infections and eutrophication being an example (Krantzberg, 2012; Yu et al., 2023). Sometimes the causes of a lake health issue might not be known, and for this reason only the symptoms can be treated. Symptoms might also be treated if the causes of health issues are too expensive and complex to treat, for example, cyanobacteria are removed from lakes by using hydrogen peroxide (H_2O_2) instead of addressing the causes of the nutrient excess in the lake (Matthijs et al., 2012). Likewise, aerators or fountains are installed in lakes to successfully cure lakes from oxygen desaturation (Mackay et al., 2014), but the actual causes of the oxgen depletion are not treated.

Despite well-known cost-effective local treatment options such as the investment in adequate domestic and industrial sewage and stormwater infrastructure, including runoff from agricultural landscapes, there are still many vulnerable or degraded lakes that are untreated, in particular in densely populated low-income countries where resources are low and many other problems supersede lake health (Jamu et al., 2011). A concept which has been used to overcome some of the socioeconomic hindrances is active participation of society in managing their water resources (United Nations, 2018). Engagement to improve the health of a lake can be maximized by compensating lakeside communities for any efforts they make to improve the health of lakes that sustain them. The mobilization of multiple sectors, disciplines and communities in society to work together corresponds to the One Health approach, which has the overall goal to balance and optimize the health of people, animals and the environment (Adisasmito et al., 2022).

Apart from the large variety of local and regional efforts, many lake health issues, in particular those that spread via the air, may be helped by national and international legislation. The list of national and international environmental laws and agreements is very long, with new laws and agreements constantly being added. The success rate of these laws and agreements to improve lake health is mixed. A good example for successful legislation has been the international regulation of atmospheric sulfur dioxide emissions, which cured many lakes in the Northern Hemisphere from acidification (Baldigo et al., 2021). Other agreements are less successful, for example, the legally binding international treaty on climate change. Without additional multilateral and international efforts to combat climate change, lake water volume in many parts of the world will further decline, causing multiple cascading effects such as salinization, oxygen depletion with fish kills and accumulation of harmful substances. The global problem of water scarcity has been outlined many times before (Masson-Delmotte et al., 2021; Rodell et al., 2018) but to date there are no signs of improvement. To better treat the rapid spread of water scarcity, there is also an urgent need to reduce the human water consumption, in particular by persons who have a high living standard, as this group consumes disproportionally large amounts of water (Savelli et al., 2023). The reduction can thus be done either directly or, more effectively, indirectly by reducing the demand for products that require large amounts of water for their production (i.e., decreasing the water footprint of food).

Although legislation might be an efficient treatment strategy for many lake health issues, additional actions are required. Presently, there is, for example, too much focus on the decline in lake health caused by individual harmful substances, often not taking account of legacy effects. Lake health is usually not a matter of single substances posing a threat and it is no longer solely a local or national issue. Instead, it is a cocktail of chemical substances from various sources worldwide that determines the health status of a lake. According to Rockström et al. (2009) and Wang-Erlandsson et al. (2022) chemical pollution and green water have been identified as planetary boundaries that should not be crossed in order to safeguard humanity. Far too little is known on the complex transformations that chemical substances undergo in the atmosphere and in water. Since climate and the spread of harmful substances via the atmosphere are not independent, a coupling of mitigation strategies for anthropogenic influences on physical, chemical and biological processes in the atmosphere and freshwaters is needed to achieve substantial improvement in global lake health.

An additional issue with legislation is the large variability of environmental laws and enforcement across countries where low-income countries often lack appropriate laws. Such inequalities are problematic because countries with strict environmental laws increasingly rely on the production of- and trade in- harmful substances, with countries that do not yet have regulations, a practice that is globally not sustainable (Goulson, 2020). Since there are no signs that global production and human consumption are decreasing (Wang et al., 2022), we have to find strategies to change human behavior toward a more sustainable pattern. No degree of legislation or technical clean up measures can replace the long-term effectiveness of changing our ways of living.

The list of treatment options for lake health issues is long, ranging from nature-based solutions, physical, chemical and biological treatments to legislation. It is often a combination of treatments which is needed to cure lakes from health problems. Whenever treatments are chosen, there is an urgent need to move to watershed-oriented treatment strategies as practiced by, for example, the European Union. Such strategies can imply big challenges, in particular when watersheds cross jurisdictional or national boundaries. It is important to tackle these challenges, because globally only relatively few nations presently have laws that acknowledge the role of watershed hydrology and riparian buffers in the movement of pollutants from anthropogenic hotspots across watersheds into the adjacent water bodies (Owokotomo et al., 2020). Once treatments have been chosen and started, the progress of the treatments needs to be followed-up, a step which is commonly not yet done. Here, lake managers can learn from the human healthcare system—a medical doctor usually closely follows the outcome and effectiveness of a treatment and makes adjustments whenever needed. Thus, in the human healthcare system, strong efforts are made to find the optimal dose and duration of a treatment, efforts which are also urgently needed for treating lake health issues.

5. Conclusions

Lakes need to be recognized as living systems that can suffer from a large variety of health issues with similarities to human health issues. Despite increasing preventation and treatment efforts in many countries, we were not able to find evidence for a substantial improvement in the overall global lake health status. Thus, there is a high risk that more and more lake health issues will become chronic. Chronic health issues caused by climate change, human consumption, intensive agriculture, deforestation, mining, dams, industrial emissions, urbanization, wars etc. are complex and interconnected and consequently very challenging to treat. A balance between trade-offs from those activities and water ecosystem services must be presented to governments to find a viable way to sustain lake health and the consequential ecosystem services. There is an urgent need for international treaties, a coalition of economy and society and an engagement of local citizens and non-governmental organizations. For example, the World Water Quality Alliance of the University National Environment Program (https://www.unep.org/explore-topics/water/what-we-do/improving-and-assessing-world-water-quality-partnership-effort) seeks to improve access to safe, clean water using a coalition of local communities, non-governmental organizations, national administrations, water authorities, farmers and fishers. Such a model could be applied to lakes, particularly those shared across borders, and lead to improved coordination of national legislation and a common understanding of lake health and management strategies.

In this study, we took a human-centric approach, where we outlined that hundreds of millions of people are living around lakes that most likely suffer from one or more health issues. This human-centric approach may give a biased view (Schroter et al., 2014), where it remains unknown how many other living organisms are affected by the various lake health issues. Instead, our focus on humans acknowledges us as both the agents of harm and the potential agents of remediation, in a classification framework that will hopefully resonate to stimulate prompt action. While we acknowledge that many additional human threat databases exist they are not always compatible, which makes the task of mapping the spread of health issues challenging and highlights the need for improved global data alignment and co-ordination.

At present, many lake health issues are well-known but not yet treated. Thus, there is an urgent need to start treatments, particularly in densely populated low-income countries. When lakes and their watersheds are treated the outcome and effectiveness of the treatments need to be well-documented, with adjustments being made whenever needed, so that treatment strategies can be refined and promoted.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

All data used in this study are published data from Lehner et al. (2022).

Acknowledgments

This work is the result of an international team science effort facilitated by the Global Lake Ecological Observatory Network (GLEON). GAW acknowledges financial support for this study from the Swedish Research Council (Grant 2020-03222) and Swedish Research Council for Environment, Agricultural Sciences and Spatial Planning (FORMAS; Grant 2020-01091), BL and HPG from the German Science Foundation (DFG; project Pycnocline GR1540/37-1), MAX from the Canada's Research Chairs program, KK from the Estonian Research Council (Grant PRG 1266), RM from Alter-C (PID2020-114024GB-C32/AEI/10.13039/501100011033), RLN from the IGB Senior Research Fellows Program, FS from IAI-CONICET, PICT-2020-Serie A-00548, and PGI Piccolo UNS, SAW from the New Zealand Ministry of Business, Innovation and Employment research programme—Our lakes, Our future (CAWX2305), JH and MCPM Ma. Cristina Paule-Mercado from TAČR/Norway Grant (No. TO01000202) and from Czech Science Foundation (No. 22-33245S), DPH from the Australian Research Council (DP210102575), and YZ from the National Natural Science Foundation of China (42322104). We are thankful to the reviewers who provided very constructive comments.

References

Abell, J. M., Özkundakci, D., Hamilton, D. P., van Dam-Bates, P., & McDowell, R. W. (2019). Quantifying the extent of anthropogenic eutrophication of lakes at a national scale in New Zealand. *Environmental Science & Technology*, *53*(16), 9439–9452. https://doi.org/10.1021/acs.est.9b03120

Adisasmito, W. B., Almuhairi, S., Behravesh, C. B., Bilivogui, P., Bukachi, S. A., Casas, N., et al. (2022). One health: A new definition for a sustainable and healthy future. *PLoS Pathogens*, *18*(6), e1010537. https://doi.org/10.1371/journal.ppat.1010537

Adrian, R., O'Reilly, C. M., Zagarese, H., Baines, S. B., Hessen, D. O., Keller, W., et al. (2009). Lakes as sentinels of climate change. *Limnology & Oceanography*, *54*(6), 2283–2297. https://doi.org/10.4319/lo.2009.54.6_part_2.2283

Alsdorf, D. E., Rodriguez, E., & Lettenmaier, D. P. (2007). Measuring surface water from space. *Reviews of Geophysics*, *45*(2), RG2002. https://doi.org/10.1029/2006rg000197

American Society for Testing and Materials. (2006). Standard terminology relating to nanotechnology.

Angnunavuri, P. N., Attiogbe, F., & Mensah, B. (2023). Particulate plastics in drinking water and potential human health effects: Current knowledge for management of freshwater plastic materials in Africa. *Environmental Pollution*, *316*, 120714. https://doi.org/10.1016/j.envpol.2022.120714

Aragaw, T. A. (2021). The macro-debris pollution in the shorelines of Lake Tana: First report on abundance, assessment, constituents, and potential sources. *Science of the Total Environment*, *797*, 149235. https://doi.org/10.1016/j.scitotenv.2021.149235

Arbuckle, K. E., & Downing, J. A. (2001). The influence of watershed land use on lake N:P in a predominantly agricultural landscape. *Limnology & Oceanography*, *46*(4), 970–975. https://doi.org/10.4319/lo.2001.46.4.0970

Avtar, R., Tripathi, S., Aggarwal, A. K., & Kumar, P. (2019). Population-urbanization-energy nexus: A review. *Resources-Basel*, *8*(3), 136. https://doi.org/10.3390/resources8030136

Azizi, N., Khoshnamvand, N., & Nasseri, S. (2021). The quantity and quality assessment of microplastics in the freshwater fishes: A systematic review and meta-analysis. *Regional Studies in Marine Science*, *47*, 101955. https://doi.org/10.1016/j.rsma.2021.101955

Baldigo, B. P., George, S. D., Winterhalter, D. R., & McHale, M. R. (2021). Biological and chemical recovery of acidified Catskill mountain streams in response to the clean air act amendments of 1990. *Atmospheric Environment*, *249*, 118235. https://doi.org/10.1016/j.atmosenv.2021.118235

Bao, L. J., Maruya, K. A., Snyder, S. A., & Zeng, E. Y. (2012). China's water pollution by persistent organic pollutants. *Environmental Pollution*, *163*, 100–108. https://doi.org/10.1016/j.envpol.2011.12.022

Baron, J. S., Driscoll, C. T., Stoddard, J. L., & Richer, E. E. (2011). Empirical critical loads of atmospheric nitrogen deposition for nutrient enrichment and acidification of sensitive US lakes. *BioScience*, *61*(8), 602–613. https://doi.org/10.1525/bio.2011.61.8.6

Baron, J. S., Poff, N. L., Angermeier, P. L., Dahm, C. N., Gleick, P. H., Hairston, N. G., et al. (2002). Meeting ecological and societal needs for freshwater. *Ecological Applications*, *12*(5), 1247–1260. https://doi.org/10.1890/1051-0761(2002)012[1247:measnf]2.0.co;2

Bartosiewicz, M., Maranger, R., Przytulska, A., & Laurion, I. (2021). Effects of phytoplankton blooms on fluxes and emissions of greenhouse gases in a eutrophic lake. *Water Research*, *196*, 116985. https://doi.org/10.1016/j.watres.2021.116985

Beeton, A. M. (2002). Large freshwater lakes: Present state, trends, and future. *Environmental Conservation*, *29*(1), 21–38. https://doi.org/10.1017/s0376892902000036

Bégin, P. N., Tanabe, Y., Kumagai, M., Culley, A. I., Paquette, M., Sarrazin, D., et al. (2021). Extreme warming and regime shift toward amplified variability in a far northern lake. *Limnology & Oceanography*, *66*(S1), S17–S29. https://doi.org/10.1002/lno.11546

Ben, Y. J., Fu, C. X., Hu, M., Liu, L., Wong, M. H., & Zheng, C. M. (2019). Human health risk assessment of antibiotic resistance associated with antibiotic residues in the environment: A review. *Environmental Research*, *169*, 483–493. https://doi.org/10.1016/j.envres.2018.11.040

Benayache, N. Y., Afri-Mehennaoui, F. Z., Kherief-Nacereddine, S., Bao, V. Q., Hushchyna, K., Tri, N. Q., & Bouaicha, N. (2022). Massive fish death associated with the toxic cyanobacterial Planktothrix sp. bloom in the Beni-Haroun Reservoir (Algeria). *Environmental Science and Pollution Research*, *29*(53), 80849–80859. https://doi.org/10.1007/s11356-022-21538-7

Boehrer, B., & Schultze, M. (2008). Stratification of lakes. *Reviews of Geophysics*, *46*(2), RG2005. https://doi.org/10.1029/2006rg000210

Borges, A. V., Darchambeau, F., Teodoru, C. R., Marwick, T. R., Tamooh, F., Geeraert, N., et al. (2015). Globally significant greenhouse-gas emissions from African inland waters. *Nature Geoscience*, *8*(8), 637–642. https://doi.org/10.1038/ngeo2486

Bouleau, G., & Pont, D. (2015). Did you say reference conditions? Ecological and socio-economic perspectives on the European water framework directive. *Environmental Science & Policy*, *47*, 32–41. https://doi.org/10.1016/j.envsci.2014.10.012

Brothers, S., Kohler, J., Attermeyer, K., Grossart, H. P., Mehner, T., Meyer, N., et al. (2014). A feedback loop links brownification and anoxia in a temperate, shallow lake. *Limnology & Oceanography*, *59*(4), 1388–1398. https://doi.org/10.4319/lo.2014.59.4.1388

Brown, J. H., Gillooly, J. F., Allen, A. P., Savage, V. M., & West, G. B. (2004). Toward a metabolic theory of ecology. *Ecology*, *85*(7), 1771–1789. https://doi.org/10.1890/03-9000

Cai, Y. M., Li, C., & Zhao, Y. Q. (2022). A review of the migration and transformation of microplastics in Inland Water Systems. *International Journal of Environmental Research and Public Health*, *19*(1), 148. https://doi.org/10.3390/ijerph19010148

Caputo, J., Beier, C. M., Fakhrae, H., & Driscoll, C. T. (2017). Impacts of acidification and potential recovery on the expected value of recreational fisheries in Adirondack lakes (USA). *Environmental Science & Technology*, *51*(1), 742–750. https://doi.org/10.1021/acs.est.6b05274

Carmichael, W. W., & Boyer, G. L. (2016). Health impacts from cyanobacteria harmful algae blooms: Implications for the North American Great Lakes. *Harmful Algae*, *54*, 194–212. https://doi.org/10.1016/j.hal.2016.02.002

Carpenter, S. R., Caraco, N. F., Correll, D. L., Howarth, R. W., Sharpley, A. N., & Smith, V. H. (1998). Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications*, *8*(3), 559–568. https://doi.org/10.1890/1051-0761(1998)008[0559:nposww]2.0.co;2

Cebalho, E. C., Diez, S., Filho, M. D., Muniz, C. C., Lazaro, W., Malm, O., & Ignacio, A. R. A. (2017). Effects of small hydropower plants on mercury concentrations in fish. *Environmental Science and Pollution Research*, *24*(28), 22709–22716. https://doi.org/10.1007/s11356-017-9747-1

Cera, A., Gallitelli, L., & Scalici, M. (2023). Macroplastics in lakes: An underrepresented ecological problem? *Water*, *15*(1), 60. https://doi.org/10.3390/w15010060

Chan, E. Y. (2021). Saving Mr. Water: Anthropomorphizing water promotes water conservation. *Resources, Conservation and Recycling*, *174*, 105814. https://doi.org/10.1016/j.resconrec.2021.105814

Chan, H. M., Scheuhammer, A. M., Ferran, A., Loupelle, C., Holloway, J., & Weech, S. (2003). Impacts of mercury on freshwater fish-eating wildlife and humans. *Human and Ecological Risk Assessment*, *9*(4), 867–883. https://doi.org/10.1080/713610013

Chen, J., Zhang, D. W., Xie, P., Wang, Q., & Ma, Z. M. (2009). Simultaneous determination of microcystin contaminations in various vertebrates (fish, turtle, duck and water bird) from a large eutrophic Chinese Lake, Lake Taihu, with toxic microcystis blooms. *Science of the Total Environment*, *407*(10), 3317–3322. https://doi.org/10.1016/j.scitotenv.2009.02.005

Chua, Y. P., Xie, Y., Lee, P. S. S., & Lee, E. S. (2021). Definitions and prevalence of multimorbidity in large database studies: A scoping review. *International Journal of Environmental Research and Public Health*, *18*(4), 1673. https://doi.org/10.3390/ijerph18041673

Cianci-Gaskill, J. A., Klug, J. L., Merrell, K. C., Millar, E. E., Wain, D. J., Kramer, L., et al. (2024). A lake management framework for global application: Monitoring, restoring, and protecting lakes through community engagement. *Lake and Reservoir Management*, *40*(1), 66–92. (published online). https://doi.org/10.1080/10402381.2023.2299868

Coble, D. W., Bruesewitz, R. E., Fratt, T. W., & Scheirer, J. W. (1990). Lake trout, sea lampreys, and overfishing in the Upper Great Lakes—A review and reanalysis. *Transactions of the American Fisheries Society*, *119*(6), 985–995. https://doi.org/10.1577/1548-8659(1990)119<0985:ltslao>2.3.co;2

Codd, G. A., Plinski, M., Surosz, W., Hutson, J., & Fallowfield, H. J. (2015). Publication in 1672 of animal deaths at the Tuchomskie Lake, northern Poland and a likely role of cyanobacterial blooms. *Toxicon*, *108*, 285–286. https://doi.org/10.1016/j.toxicon.2015.10.005

Daughton, C. G., & Ternes, T. A. (1999). Pharmaceuticals and personal care products in the environment: Agents of subtle change? *Environmental Health Perspectives*, *107*(suppl 6), 907–938. https://doi.org/10.1289/ehp.99107s6907

Dean, J. F., Middelburg, J. J., Rockmann, T., Aerts, R., Blauw, L. G., Egger, M., et al. (2018). Methane feedbacks to the global climate system in a warmer world. *Reviews of Geophysics*, *56*(1), 207–250. https://doi.org/10.1002/2017rg000559

Deemer, B. R., Harrison, J. A., Li, S. Y., Beaulieu, J. J., Delsontro, T., Barros, N., et al. (2016). Greenhouse gas emissions from reservoir water surfaces: A new global synthesis. *BioScience*, *66*(11), 949–964. https://doi.org/10.1093/biosci/biw117

De Sousa, E. R., Hipsey, M. R., & Vogwill, R. I. J. (2023). Data assimilation, sensitivity analysis and uncertainty quantification in semi-arid terminal catchments subject to long-term rainfall decline. *Frontiers in Earth Science*, *10*. https://doi.org/10.3389/feart.2022.886304

Di Cesare, A., Pinnell, L. J., Brambilla, D., Elli, G., Sabatino, R., Sathicq, M. B., et al. (2021). Bioplastic accumulates antibiotic and metal resistance genes in coastal marine sediments. *Environmental Pollution*, *291*, 118161. https://doi.org/10.1016/j.envpol.2021.118161

Dornhofer, K., & Oppelt, N. (2016). Remote sensing for lake research and monitoring—Recent advances. *Ecological Indicators*, *64*, 105–122. https://doi.org/10.1016/j.ecolind.2015.12.009

Downing, J. A., Prairie, Y. T., Cole, J. J., Duarte, C. M., Tranvik, L. J., Striegl, R. G., et al. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology & Oceanography*, *51*(5), 2388–2397. https://doi.org/10.4319/lo.2006.51.5.2388

Dugan, H. A., Bartlett, S. L., Burke, S. M., Doubek, J. P., Krivak-Tetley, F. E., Skaff, N. K., et al. (2017). Salting our freshwater lakes. *Proceedings of the National Academy of Sciences of the United States of America*, *114*(17), 4453–4458. Article. https://doi.org/10.1073/pnas.1620211114

Edge, T. A., Khan, I. U. H., Bouchard, R., Guo, J., Hill, S., Locas, A., et al. (2013). Occurrence of waterborne pathogens and escherichia coli at offshore drinking water intakes in Lake Ontario. *Applied and Environmental Microbiology*, *79*(19), 5799–5813. https://doi.org/10.1128/aem.00870-13

Eerkes-Medrano, D., Thompson, R. C., & Aldridge, D. C. (2015). Microplastics in freshwater systems: A review of the emerging threats, identification of knowledge gaps and prioritisation of research needs. *Water Research*, *75*, 63–82. https://doi.org/10.1016/j.watres.2015.02.012

Eikebrokk, B., Vogt, R. D., & Liltved, H. (2004). NOM increase in Northern European source waters: Discussion of possible causes and impacts on coagulation/contact filtration processes. In G. Newcombe & L. Ho (Eds.), *Natural organic material research: Innovations and applications for drinking water* (Vol. 4, pp. 47–54).

Elser, J. J., Andersen, T., Baron, J. S., Bergstrom, A. K., Jansson, M., Kyle, M., et al. (2009). Shifts in Lake N:P Stoichiometry and nutrient limitation driven by atmospheric nitrogen deposition. *Science*, *326*(5954), 835–837. https://doi.org/10.1126/science.1176199

Environmental Protection Agency. (1998). *Lake and reservoir bioassessment and biocriteria. Report EPA 84 IB-98-007*. U.S. Environmental Protection Agency.

Evans, C. D., Cullen, J. M., Alewell, C., Kopacek, J., Marchetto, A., Moldan, F., et al. (2001). Recovery from acidification in European surface waters. *Hydrology and Earth System Sciences*, *5*(3), 283–297. https://doi.org/10.5194/hess-5-283-2001

Fick, J., Soderstrom, H., Lindberg, R. H., Phan, C., Tysklind, M., & Larsson, D. G. J. (2009). Contamination of surface, ground, and drinking water from pharmaceutical production. *Environmental Toxicology and Chemistry*, *28*(12), 2522–2527. https://doi.org/10.1897/09-073.1

Fischer, M., Korup, O., Veh, G., & Walz, A. (2021). Controls of outbursts of moraine-dammed lakes in the greater Himalayan region. *The Cryosphere*, *15*(8), 4145–4163. https://doi.org/10.5194/tc-15-4145-2021

Ford, T. (2016). Water and health. In H. Frumkin (Ed.), *Environmental health: From global to local*. John Wiley and Sons.

Fukushima, T., Matsushita, B., Subehi, L., Setiawan, F., & Wibowo, H. (2017). Will hypolimnetic waters become anoxic in all deep tropical lakes? *Scientific Reports*, *7*(1), 45320. https://doi.org/10.1038/srep45320

Funari, E., & Testai, E. (2008). Human health risk assessment related to cyanotoxins exposure. *Critical Reviews in Toxicology*, *38*(2), 97–125. https://doi.org/10.1080/10408440701749454

Goulson, D. (2020). Pesticides, corporate irresponsibility, and the fate of our planet. *One Earth*, *2*(4), 302–305. https://doi.org/10.1016/j.oneear.2020.03.004

Graczyk, T. K., Lucy, F. E., Mashinsky, Y., Thompson, R. C. A., Koru, O., & da Silva, A. J. (2009). Human zoonotic enteropathogens in a constructed free-surface flow wetland. *Parasitology Research*, *105*(2), 423–428. https://doi.org/10.1007/s00436-009-1400-6

Gunnarsdottir, M. J., Gardarsson, S. M., Elliott, M., Sigmundsdottir, G., & Bartram, J. (2012). Benefits of water safety plans: Microbiology, compliance, and public health. *Environmental Science & Technology*, *46*(14), 7782–7789. https://doi.org/10.1021/es300372h

Hall, R. I., Leavitt, P. R., Quinlan, R., Dixit, A. S., & Smol, J. P. (1999). Effects of agriculture, urbanization, and climate on water quality in the northern Great Plains. *Limnology & Oceanography*, *44*(3), 739–756. https://doi.org/10.4319/lo.1999.44.3_part_2.0739

Hampton, S. E., Galloway, A. W. E., Powers, S. M., Ozersky, T., Woo, K. H., Batt, R. D., et al. (2017). Ecology under lake ice. *Ecology Letters*, *20*(1), 98–111. https://doi.org/10.1111/ele.12699

Harada, M. (1995). Minamata disease—Methylmercury poisoning in Japan caused by environmental-pollution. *Critical Reviews in Toxicology*, *25*(1), 1–24. https://doi.org/10.3109/10408449509089885

Hasler, C. T., Butman, D., Jeffrey, J. D., & Suski, C. D. (2016). Freshwater biota and rising pCO(2)? *Ecology Letters*, *19*(1), 98–108. https://doi.org/10.1111/ele.12549

Hernandez, N., & Bessone, F. (2022). Hepatotoxicity induced by biological agents: Clinical features and current controversies. *Journal of Clinical and Translational Hepatology*.
Hinojosa, M. G., Gutierrez-Praena, D., Prieto, A. I., Guzman-Guillen, R., Jos, A., & Camean, A. M. (2019). Neurotoxicity induced by microcystins and cylindrospermopsin: A review. *Science of the Total Environment*, *668*, 547–565. https://doi.org/10.1016/j.scitotenv.2019.02.426
Hintz, W. D., Arnott, S. E., Symons, C. C., Greco, D. A., McClymont, A., Brentrup, J. A., et al. (2022). Current water quality guidelines across North America and Europe do not protect lakes from salinization. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(9). https://doi.org/10.1073/pnas.2115033119
Ho, L. T., & Goethals, P. L. M. (2019). Opportunities and challenges for the sustainability of lakes and reservoirs in relation to the sustainable development goals (SDGs). *Water*, *11*(7), 19. https://doi.org/10.3390/w11071462
Hori, Y., Gough, W. A., Butler, K., & Tsuji, L. J. S. (2017). Trends in the seasonal length and opening dates of a winter road in the western James Bay region, Ontario, Canada. *Theoretical and Applied Climatology*, *129*(3–4), 1309–1320. https://doi.org/10.1007/s00704-016-1855-1
Hoyer, M. V., Watson, D. L., Wills, D. J., & Canfield, D. E. (2009). Fish kills in Florida's canals, creeks/rivers, and ponds/lakes. *Journal of Aquatic Plant Management*, *47*, 53–56.
Huot, Y., Brown, C. A., Potvin, G., Antoniades, D., Baulch, H. M., Beisner, B. E., et al. (2019). The NSERC Canadian lake pulse network: A national assessment of lake health providing science for water management in a changing climate. *Science of the Total Environment*, *695*, 133668. https://doi.org/10.1016/j.scitotenv.2019.133668
Ibelings, B. W., Bruning, K., de Jonge, J., Wolfstein, K., Pires, L. M. D., Postma, J., & Burger, T. (2005). Distribution of microcystins in a lake foodweb: No evidence for biomagnification. *Microbial Ecology*, *49*(4), 487–500. https://doi.org/10.1007/s00248-004-0014-x
Ibor, O. R., Adeogun, A. O., Regoli, F., & Arukwe, A. (2019). Xenobiotic biotransformation, oxidative stress and obesogenic molecular biomarker responses in Tilapia guineensis from Eleyele Lake, Nigeria. *Ecotoxicology and Environmental Safety*, *169*, 255–265. https://doi.org/10.1016/j.ecoenv.2018.11.021
Irfan, T., Khalid, S., Taneez, M., & Hashmi, M. Z. (2020). Plastic driven pollution in Pakistan: The first evidence of environmental exposure to microplastic in sediments and water of Rawal lake. *Environmental Science and Pollution Research*, *27*(13), 15083–15092. https://doi.org/10.1007/s11356-020-07833-1
Jamu, D., Banda, M., Njaya, F., & Hecky, R. E. (2011). Challenges to sustainable management of the lakes of Malawi. *Journal of Great Lakes Research*, *37*, 3–14. https://doi.org/10.1016/j.jglr.2010.11.017
Jane, S. F., Hansen, G. J. A., Kraemer, B. M., Leavitt, P. R., Mincer, J. L., North, R. L., et al. (2021). Widespread deoxygenation of temperate lakes. *Nature*, *594*(7861), 66–70. https://doi.org/10.1038/s41586-021-03550-y
Jane, S. F., Mincer, J. L., Lau, M. P., Lewis, A. S. L., Stetler, J. T., & Rose, K. C. (2023). Longer duration of seasonal stratification contributes to widespread increases in Lake Hypoxia and anoxia. *Global Change Biology*, *29*(4), 1009–1023. https://doi.org/10.1111/gcb.16525
Jenny, J. P., Anneville, O., Arnaud, F., Baulaz, Y., Bouffard, D., Domaizon, I., et al. (2020). Scientists' warning to Humanity: Rapid degradation of the world's large lakes. *Journal of Great Lakes Research*, *46*(4), 686–702. https://doi.org/10.1016/j.jglr.2020.05.006
Kafumbata, D., Jamu, D., & Chiotha, S. (2014). Riparian ecosystem resilience and livelihood strategies under test: Lessons from Lake Chilwa in Malawi and other lakes in Africa. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1639), 20130052. https://doi.org/10.1098/rstb.2013.0052
Kangur, K., Ginter, K., Kangur, P., Kangur, A., Noges, P., & Laas, A. (2016). Changes in water temperature and chemistry preceding a massive kill of bottom-dwelling fish: An analysis of high-frequency buoy data of shallow Lake Vortsjarv (Estonia). *Inland Waters*, *6*(4), 535–542. https://doi.org/10.1080/iw-6.4.869
Kangur, K., Kangur, P., Ginter, K., Orru, K., Haldna, M., Mols, T., & Kangur, A. (2013). Long-term effects of extreme weather events and eutrophication on the fish community of shallow Lake Peipsi (Estonia/Russia). *Journal of Limnology*, *72*(2), 376–387. https://doi.org/10.4081/jlimnol.2013.e30
Karatayev, A. Y., & Burlakova, L. E. (2022). What we know and don't know about the invasive zebra (*Dreissena polymorpha*) and quagga (*Dreissena rostriformis bugensis*) mussels. *Hydrobiologia*. https://doi.org/10.1007/s10750-022-04950-5
Karlsson, J., Bystrom, P., Ask, J., Ask, P., Persson, L., & Jansson, M. (2009). Light limitation of nutrient-poor lake ecosystems. *Nature*, *460*(7254), 506–580. https://doi.org/10.1038/nature08179
Kazanjian, G., Brothers, S., Kohler, J., & Hilt, S. (2021). Incomplete recovery of a shallow lake from a natural browning event. *Freshwater Biology*, *66*(6), 1089–1100. https://doi.org/10.1111/fwb.13701
Keatley, B. E., Bennett, E. M., MacDonald, G. K., Taranu, Z. E., & Gregory-Eaves, I. (2011). Land-use legacies are important determinants of lake eutrophication in the Anthropocene. *PLoS One*, *6*(1), e15913. https://doi.org/10.1371/journal.pone.0015913
Knoll, L. B., Sharma, S., Denfeld, B. A., Flaim, G., Hori, Y., Magnuson, J. I., et al. (2019). Consequences of lake and river ice loss on cultural ecosystem services. *Limnology and Oceanography Letters*, *4*(5), 119–131. https://doi.org/10.1002/lol2.10116
Kraemer, B. M., Pilla, R. M., Woolway, R. I., Anneville, O., Ban, S. H., Colom-Montero, W., et al. (2021). Climate change drives widespread shifts in lake thermal habitat. *Nature Climate Change*, *11*(6), 521–529. https://doi.org/10.1038/s41558-021-01060-3
Kragh, T., Martinsen, K. T., Kristensen, E., & Sand-Jensen, K. (2020). From drought to flood: Sudden carbon inflow causes whole-lake anoxia and massive fish kill in a large shallow lake. *Science of the Total Environment*, *739*, 140072. https://doi.org/10.1016/j.scitotenv.2020.140072
Krantzberg, G. (2012). Renegotiation of the 1987 Great Lakes water quality agreement: From confusion to promise. *Sustainability*, *4*(6), 1239–1255. https://doi.org/10.3390/su4061239
Kritzberg, E. S., Hasselquist, E. M., Skerlep, M., Lofgren, S., Olsson, O., Stadmark, J., et al. (2020). Browning of freshwaters: Consequences to ecosystem services, underlying drivers, and potential mitigation measures. *Ambio*, *49*(2), 375–390. https://doi.org/10.1007/s13280-019-01227-5
Kummu, M., Taka, M., & Guillaume, J. H. A. (2018). Data descriptor: Gridded global datasets for gross domestic product and human development index over 1990-2015. *Scientific Data*, *5*(1), 180004. https://doi.org/10.1038/sdata.2018.4
Ladwig, R., Rock, L. A., & Dugan, H. A. (2023). Impact of salinization on lake stratification and spring mixing. *Limnology and Oceanography Letters*, *8*(1), 93–102. https://doi.org/10.1002/lol2.10215
Lai, Y. J., Dong, L. J., Li, Q. C., Li, P., & Liu, J. F. (2021). Sampling of micro- and nano-plastics in environmental matrixes. *TrAC Trends in Analytical Chemistry*, *145*, 116461. https://doi.org/10.1016/j.trac.2021.116461
Lehner, B., Liermann, C. R., Revenga, C., Vorosmarty, C., Fekete, B., Crouzet, P., et al. (2011). High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Frontiers in Ecology and the Environment*, *9*(9), 494–502. https://doi.org/10.1890/100125
Lehner, B., Messager, M. L., Korver, M. C., & Linke, S. (2022). Global hydro-environmental lake characteristics at high spatial resolution [Dataset]. *Scientific Data*, *9*(1), 351. https://doi.org/10.1038/s41597-022-01425-z
Le Moal, M., Gascuel-Odoux, C., Ménesguen, A., Souchon, Y., Étrillard, C., Levain, A., et al. (2019). Eutrophication: A new wine in an old bottle? *Science of the Total Environment*, *651*, 1–11. https://doi.org/10.1016/j.scitotenv.2018.09.139

Lemoalle, J., Bader, J. C., Leblanc, M., & Sedick, A. (2012). Recent changes in Lake Chad: Observations, simulations and management options (1973-2011). *Global and Planetary Change*, *80–81*, 247–254. https://doi.org/10.1016/j.gloplacha.2011.07.004
Leonardi, F. (2018). The definition of health: Towards new perspectives. *International Journal of Health Services*, *48*(4), 735–748. https://doi.org/10.1177/0020731418782653
Lin, Z. H., & Qi, J. G. (2017). Hydro-dam—A nature-based solution or an ecological problem: The fate of the Tonle Sap Lake. *Environmental Research*, *158*, 24–32. https://doi.org/10.1016/j.envres.2017.05.016
Liu, J. G., Yang, H., Gosling, S. N., Kummu, M., Flörke, M., Pfister, S., et al. (2017). Water scarcity assessments in the past, present, and future. *Earth's Future*, *5*(6), 545–559. https://doi.org/10.1002/2016ef000518
Lodge, D. M., Deines, A., Gherardi, F., Yeo, D. C. J., Arcella, T., Baldridge, A. K., et al. (2012). Global introductions of crayfishes: Evaluating the impact of species invasions on ecosystem services. In D. J. Futuyma (Ed.), *Annual review of ecology, evolution, and systematics* (Vol. 43, pp. 449–+).
Lugomela, C., Pratap, H. B., & Mgaya, Y. D. (2006). Cyanobacteria blooms—A possible cause of mass mortality of lesser flamingos in Lake Manyara and Lake Big Momela, Tanzania. *Harmful Algae*, *5*(5), 534–541. https://doi.org/10.1016/j.hal.2005.10.001
Ma, H. H., Wei, L. L., Zhu, H. Y., & Liao, L. (2021). Advances in mercury biogeochemical cycles in lakes and reservoirs. *Fresenius Environmental Bulletin*, *30*(6), 6064–6074.
Mackay, E. B., Maberly, S. C., Pan, G., Reitzel, K., Bruere, A., Corker, N., et al. (2014). Geoengineering in lakes: Welcome attraction or fatal distraction? *Inland Waters*, *4*(4), 349–356. https://doi.org/10.5268/iw-4.4.769
Malakar, A., Kanel, S. R., Ray, C., Snow, D. D., & Nadagouda, M. N. (2021). Nanomaterials in the environment, human exposure pathway, and health effects: A review. *Science of the Total Environment*, *759*, 143470. https://doi.org/10.1016/j.scitotenv.2020.143470
Martin, J. D., Frost, P. C., Hintelmann, H., Newman, K., Paterson, M. J., Hayhurst, L., et al. (2018). Accumulation of silver in yellow Perch (Perca flavescens) and northern Pike (Esox lucius) from a lake dosed with Nanosilver. *Environmental Science & Technology*, *52*(19), 11114–11122. https://doi.org/10.1021/acs.est.8b03146
Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S. L., Péan, C., Berger, S., et al. (2021). In *IPCC, 2021: Climate change 2021: The physical science basis. Contribution of working group I to the sixth assessment report of the Intergovernmental Panel on Climate Change. Cambridge, United Kingdom and New York, NY, USA*. Cambridge University Press.
Matthijs, H. C. P., Visser, P. M., Reeze, B., Meeuse, J., Slot, P. C., Wijn, G., et al. (2012). Selective suppression of harmful cyanobacteria in an entire lake with hydrogen peroxide. *Water Research*, *46*(5), 1460–1472. https://doi.org/10.1016/j.watres.2011.11.016
Mazza, G., Tricarico, E., Genovesi, P., & Gherardi, F. (2014). Biological invaders are threats to human health: An overview. *Ethology Ecology & Evolution*, *26*(2–3), 112–129. https://doi.org/10.1080/03949370.2013.863225
Meili, M. (1992). Sources, concentrations and characteristics of orgnaic matter in softwater lakes and streams of the Swedish forest region. *Hydrobiologia*, *229*(1), 23–41. https://doi.org/10.1007/bf00006988
Meili, M., Bishop, K., Bringmark, L., Johansson, K., Munthe, J., Sverdrup, H., & de Vries, W. (2003). Critical levels of atmospheric pollution: Criteria and concepts for operational modelling of mercury in forest and lake ecosystems. *Science of the Total Environment*, *304*(1–3), 83–106. https://doi.org/10.1016/s0048-9697(02)00559-4
Mendoza, J. N., Pruse, B., Mattalia, G., Kochalski, S., Ciriaco, A., & Soukand, R. (2022). Fishers' perspectives: The drivers behind the decline in fish catch in Laguna Lake, Philippines. *Maritime Studies*, *21*(4), 569–585. https://doi.org/10.1007/s40152-022-00287-w
Merga, L. B., Mengistie, A. A., Alemu, M. T., & Van den Brink, P. J. (2021). Biological and chemical monitoring of the ecological risks of pesticides in Lake Ziway, Ethiopia. *Chemosphere*, *266*, 129214. https://doi.org/10.1016/j.chemosphere.2020.129214
Mesman, J. P., Stelzer, J. A. A., Dakos, V., Goyette, S., Jones, I. D., Kasparian, J. M., et al. (2021). The role of internal feedbacks in shifting deep lake mixing regimes under a warming climate. *Freshwater Biology*, *66*(6), 1021–1035. https://doi.org/10.1111/fwb.13704
Messager, M. L., Lehner, B., Grill, G., Nedeva, I., & Schmitt, O. (2016). Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nature Communications*, *7*(1), 13603. https://doi.org/10.1038/ncomms13603
Micklin, P. P. (1988). Desiccation of the Aral Sea—A water management disaster in the Soviet-Union. *Science*, *241*(4870), 1170–1175. https://doi.org/10.1126/science.241.4870.1170
Morin-Crini, N., Lichtfouse, E., Liu, G. R., Balaram, V., Ribeiro, A. R. L., Lu, Z. J., et al. (2022). Worldwide cases of water pollution by emerging contaminants: A review. *Environmental Chemistry Letters*, *20*(4), 2311–2338. https://doi.org/10.1007/s10311-022-01447-4
Muniz, I. P. (1990). Fresh-water acidification—Its effects on species and communities of fresh-water microbes, plants and animals. *Proceedings of the Royal Society of Edinburgh - Section B: Biological Sciences*, *97*, 227–254. https://doi.org/10.1017/s0269727000005364
Nava, V., Chandra, S., Aherne, J., Alfonso, M. B., Antao-Geraldes, A. M., Attermeyer, K., et al. (2023). Plastic debris in lakes and reservoirs. *Nature*, *619*(7969), 317–322. https://doi.org/10.1038/s41586-023-06168-4
New, T., & Xie, Z. Q. (2008). Impacts of large dams on riparian vegetation: Applying global experience to the case of China's three Gorges dam. *Biodiversity & Conservation*, *17*(13), 3149–3163. https://doi.org/10.1007/s10531-008-9416-2
Njaya, F., Snyder, K. A., Jamu, D., Wilson, J., Howard-Williams, C., Allison, E. H., & Andrew, N. L. (2011). The natural history and fisheries ecology of Lake Chilwa, southern Malawi. *Journal of Great Lakes Research*, *37*, 15–25. https://doi.org/10.1016/j.jglr.2010.09.008
Noges, P., van de Bund, W., Cardoso, A. C., Solimini, A. G., & Heiskanen, A. S. (2009). Assessment of the ecological status of European surface waters: A work in progress. *Hydrobiologia*, *633*(1), 197–211. https://doi.org/10.1007/s10750-009-9883-9
Nydahl, A. C., Wallin, M. B., & Weyhenmeyer, G. A. (2017). No long-term trends in pCO(2) despite increasing organic carbon concentrations in boreal lakes, streams, and rivers. *Global Biogeochemical Cycles*, *31*(6), 985–995. https://doi.org/10.1002/2016gb005539
Obrist, D., Kirk, J. L., Zhang, L., Sunderland, E. M., Jiskra, M., & Selin, N. E. (2018). A review of global environmental mercury processes in response to human and natural perturbations: Changes of emissions, climate, and land use. *Ambio*, *47*(2), 116–140. https://doi.org/10.1007/s13280-017-1004-9
Ochumba, P. B. O. (1990). Massive fish kills within the Nyanza Gulf of Lake Victoria, Kenya. *Hydrobiologia*, *208*(1–2), 93–99. https://doi.org/10.1007/bf00008448
Odada, E. O., Olago, D. O., & Olaka, L. A. (2020). An East African perspective of the Anthropocene. *Scientific African*, *10*, e00553. https://doi.org/10.1016/j.sciaf.2020.e00553
Oficialdegui, F. J., Sanchez, M. I., & Clavero, M. (2020). One century away from home: How the red swamp crayfish took over the world. *Reviews in Fish Biology and Fisheries*, *30*(1), 121–135. https://doi.org/10.1007/s11160-020-09594-z
Ogutu-Ohwayo, R., Hecky, R. E., Cohen, A. S., & Kaufman, L. (1997). Human impacts on the African Great Lakes. *Environmental Biology of Fishes*, *50*(2), 117–131. https://doi.org/10.1023/a:1007320932349
Owokotomo, A. I., Ajayi, O. O., Alabi, O. O., & Chukwuka, A. V. (2020). Watershed land use, surface water vulnerability and public health risks of two urban rivers, Ado-Ekiti, South-West Nigeria. *SN Applied Sciences*, *2*(11), 1788. https://doi.org/10.1007/s42452-020-03572-7

Paprotny, D., Sebastian, A., Morales-Napoles, O., & Jonkman, S. N. (2018). Trends in flood losses in Europe over the past 150 years. *Nature Communications*, *9*(1), 1985. https://doi.org/10.1038/s41467-018-04253-1
Pedler, R. D., Ribot, R. F. H., & Bennett, A. T. D. (2014). Extreme nomadism in desert waterbirds: Flights of the banded stilt. *Biology Letters*, *10*(10), 20140547. https://doi.org/10.1098/rsbl.2014.0547
Pi, X. H., Luo, Q. Q., Feng, L., Xu, Y., Tang, J., Liang, X. Y., et al. (2022). Mapping global lake dynamics reveals the emerging roles of small lakes. *Nature Communications*, *13*(1), 5777. https://doi.org/10.1038/s41467-022-33239-3
Pires, L. M. D., Ibelings, B. W., Brehm, M., & Van Donk, E. (2005). Comparing grazing on lake seston by Dreissena and Daphnia:: Lessons for biomanipulation. *Microbial Ecology*, *50*(2), 242–252. https://doi.org/10.1007/s00248-004-0147-6
Plastics Europe. (2019). Plastics—The facts 2019.
Poikane, S., Zohary, T., & Cantonati, M. (2020). Assessing the ecological effects of hydromorphological pressures on European lakes. *Inland Waters*, *10*(2), 241–255. https://doi.org/10.1080/20442041.2019.1654800
Rahel, F. J., & Olden, J. D. (2008). Assessing the effects of climate change on aquatic invasive species. *Conservation Biology*, *22*(3), 521–533. https://doi.org/10.1111/j.1523-1739.2008.00950.x
Rahimi, A., & Breuste, J. (2021). Why is Lake Urmia drying up? Prognostic modeling with land-use data and artificial neural network. *Frontiers in Environmental Science*, *9*. https://doi.org/10.3389/fenvs.2021.603916
Raikow, D. F., Sarnelle, O., Wilson, A. E., & Hamilton, S. K. (2004). Dominance of the noxious cyanobacterium Microcystis aeruginosa in low-nutrient lakes is associated with exotic zebra mussels. *Limnology & Oceanography*, *49*(2), 482–487. https://doi.org/10.4319/lo.2004.49.2.0482
Rao, Y. R., Howell, T., Watson, S. B., & Abernethy, S. (2014). On hypoxia and fish kills along the north shore of Lake Erie. *Journal of Great Lakes Research*, *40*(1), 187–191. https://doi.org/10.1016/j.jglr.2013.11.007
Reidy, B., Haase, A., Luch, A., Dawson, K. A., & Lynch, I. (2013). Mechanisms of silver nanoparticle release, transformation and toxicity: A critical review of current knowledge and recommendations for future studies and applications. *Materials*, *6*(6), 2295–2350. https://doi.org/10.3390/ma6062295
Reyer, C. P. O., Adams, S., Albrecht, T., Baarsch, F., Boit, A., Trujillo, N. C., et al. (2017). Climate change impacts in Latin America and the Caribbean and their implications for development. *Regional Environmental Change*, *17*(6), 1601–1621. https://doi.org/10.1007/s10113-015-0854-6
Rice, K. C., & Herman, J. S. (2012). Acidification of Earth: An assessment across mechanisms and scales. *Applied Geochemistry*, *27*(1), 1–14. https://doi.org/10.1016/j.apgeochem.2011.09.001
Riise, G., Muller, R. A., Haaland, S., & Weyhenmeyer, G. A. (2018). Acid rain—A strong external driver that has suppressed water colour variability between lakes. *Boreal Environment Research*, *23*, 69–81.
Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E., et al. (2009). Planetary boundaries: Exploring the safe operating space for humanity. *Ecology and Society*, *14*(2), art32. https://doi.org/10.5751/es-03180-140232
Rodell, M., Famiglietti, J. S., Wiese, D. N., Reager, J. T., Beaudoing, H. K., Landerer, F. W., & Lo, M. H. (2018). Emerging trends in global freshwater availability. *Nature*, *557*(7707), 650–659. https://doi.org/10.1038/s41586-018-0123-1
Roebuck, B. D., & Virginia, E. J. (2010). Mercury in fish as a result of the James Bay hydroelectric development: Perceptions and realities. *International Journal of Circumpolar Health*, *69*, 317–318.
Roelke, D. L., Grover, J. P., Brooks, B. W., Glass, J., Buzan, D., Southard, G. M., et al. (2011). A decade of fish-killing Prymnesium parvum blooms in Texas: Roles of inflow and salinity. *Journal of Plankton Research*, *33*(2), 243–253. https://doi.org/10.1093/plankt/fbq079
Rosseland, B. O. (1986). Ecological effects of acidification on tertiary consumers—Fish population responses. *Water, Air, & Soil Pollution*, *30*(1–2), 451–460. https://doi.org/10.1007/bf00305214
Ruiz, G. M., Rawlings, T. K., Dobbs, F. C., Drake, L. A., Mullady, T., Huq, A., & Colwell, R. R. (2000). Global spread of microorganisms by ships—Ballast water discharged from vessels harbours a cocktail of potential pathogens. *Nature*, *408*(6808), 49–50. https://doi.org/10.1038/35040695
Sahoo, G. B., Forrest, A. L., Schladow, S. G., Reuter, J. E., Coats, R., & Dettinger, M. (2016). Climate change impacts on lake thermal dynamics and ecosystem vulnerabilities. *Limnology & Oceanography*, *61*(2), 496–507. https://doi.org/10.1002/lno.10228
Sarijan, S., Azman, S., Said, M. I. M., & Jamal, M. H. (2021). Microplastics in freshwater ecosystems: A recent review of occurrence, analysis, potential impacts, and research needs. *Environmental Science and Pollution Research*, *28*(2), 1341–1356. https://doi.org/10.1007/s11356-020-11171-7
Savelli, E., Mazzoleni, M., Di Baldassarre, G., Cloke, H., & Rusca, M. (2023). Urban water crises driven by elites' unsustainable consumption. *Nature Sustainability*, *6*(8), 929–940. https://doi.org/10.1038/s41893-023-01100-0
Sayer, C. D., Davidson, T. A., Rawcliffe, R., Langdon, P. G., Leavitt, P. R., Cockerton, G., et al. (2016). Consequences of fish kills for long-term trophic structure in shallow lakes: Implications for theory and restoration. *Ecosystems*, *19*(7), 1289–1309. https://doi.org/10.1007/s10021-016-0005-z
Scheffer, M., & Carpenter, S. R. (2003). Catastrophic regime shifts in ecosystems: Linking theory to observation. *Trends in Ecology & Evolution*, *18*(12), 648–656. https://doi.org/10.1016/j.tree.2003.09.002
Schindler, D. W. (1988). Effects of acid-rain on fresh-water ecosystems. *Science*, *239*(4836), 149–157. https://doi.org/10.1126/science.239.4836.149
Schroter, M., van der Zanden, E. H., van Oudenhoven, A. P. E., Remme, R. P., Serna-Chavez, H. M., de Groot, R. S., & Opdam, P. (2014). Ecosystem services as a contested concept: A synthesis of critique and counter-arguments. *Conservation Letters*, *7*(6), 514–523. https://doi.org/10.1111/conl.12091
Scordo, F., Chandra, S., Suenaga, E., Kelson, S. J., Culpepper, J., Scaff, L., et al. (2021). Smoke from regional wildfires alters lake ecology. *Scientific Reports*, *11*(1), 10922. https://doi.org/10.1038/s41598-021-89926-6
Scott, S. J., & Bollinger, T. K. (2014). Flavobacterium columnare: An important contributing factor to fish die-offs in southern lakes of Saskatchewan, Canada. *Journal of Veterinary Diagnostic Investigation*, *26*(6), 832–836. https://doi.org/10.1177/1040638714553591
Selin, H., & Selin, N. E. (2022). From Stockholm to Minamata and beyond: Governing mercury pollution for a more sustainable future. *One Earth*, *5*(10), 1109–1125. https://doi.org/10.1016/j.oneear.2022.09.001
Sentis, A., Montoya, J. M., & Lurgi, M. (2021). Warming indirectly increases invasion success in food webs. *Proceedings of the Royal Society B-Biological Sciences*, 288(1947)
Sharma, S., Blagrave, K., Magnuson, J. J., O'Reilly, C. M., Oliver, S., Batt, R. D., et al. (2019). Widespread loss of lake ice around the Northern Hemisphere in a warming world. *Nature Climate Change*, *9*(3), 227–231. https://doi.org/10.1038/s41558-018-0393-5
Sharma, S., Blagrave, K., Watson, S. R., O'Reilly, C. M., Batt, R., Magnuson, J. J., et al. (2020). Increased winter drownings in ice-covered regions with warmer winters. *PLoS One*, *15*(11), e0241222. https://doi.org/10.1371/journal.pone.0241222

Shatwell, T., Adrian, R., & Kirillin, G. (2016). Planktonic events may cause polymictic-dimictic regime shifts in temperate lakes. *Scientific Reports*, *6*(1), 24361. https://doi.org/10.1038/srep24361

Shimoda, Y., Azim, M. E., Perhar, G., Ramin, M., Kenney, M. A., Sadraddini, S., et al. (2011). Our current understanding of lake ecosystem response to climate change: What have we really learned from the north temperate deep lakes? *Journal of Great Lakes Research*, *37*(1), 173–193. https://doi.org/10.1016/j.jglr.2010.10.004

Shugar, D. H., Burr, A., Haritashya, U. K., Kargel, J. S., Watson, C. S., Kennedy, M. C., et al. (2020). Rapid worldwide growth of glacial lakes since 1990. *Nature Climate Change*, *10*(10), 939–945. https://doi.org/10.1038/s41558-020-0855-4

Shumilova, O., Tockner, K., Sukhodolov, A., Khilchevskyi, V., De Meester, L., Stepanenko, S., et al. (2023). Impact of the Russia–Ukraine armed conflict on water resources and water infrastructure. *Nature Sustainability*, *6*(5), 578–586. https://doi.org/10.1038/s41893-023-01068-x

Small, G. E., Cotner, J. B., Finlay, J. C., Stark, R. A., & Sterner, R. W. (2014). Nitrogen transformations at the sediment-water interface across redox gradients in the Laurentian Great Lakes. *Hydrobiologia*, *731*(1), 95–108. https://doi.org/10.1007/s10750-013-1569-7

Smith, P. T., Imbun, B. Y., & Duarte, F. P. (2016). Impacts of a fish kill at lake Kutubu, Papua New Guinea. *Pacific Science*, *70*(1), 21–33. https://doi.org/10.2984/70.1.2

Sondergaard, M., Jensen, J. P., & Jeppesen, E. (2003). Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia*, *506*(1–3), 135–145. https://doi.org/10.1023/b:hydr.0000008611.12704.dd

Sousa, V. S., & Teixeira, M. R. (2020). Metal-based engineered nanoparticles in the drinking water treatment systems: A critical review. *Science of the Total Environment*, *707*, 136077. https://doi.org/10.1016/j.scitotenv.2019.136077

Talbot, C. J., Bennett, E. M., Cassell, K., Hanes, D. M., Minor, E. C., Paerl, H., et al. (2018). The impact of flooding on aquatic ecosystem services. *Biogeochemistry*, *141*(3), 439–461. https://doi.org/10.1007/s10533-018-0449-7

Tam, K. P., Lee, S. L., & Chao, M. M. (2013). Saving Mr. Nature: Anthropomorphism enhances connectedness to and protectiveness toward nature. *Journal of Experimental Social Psychology*, *49*(3), 514–521. https://doi.org/10.1016/j.jesp.2013.02.001

Tammi, J., Appelberg, M., Beier, U., Hesthagen, T., Lappalainen, A., & Rask, M. (2003). Fish status survey of Nordic lakes: Effects of acidification, eutrophication and stocking activity on present fish species composition. *Ambio*, *32*(2), 98–105. https://doi.org/10.1639/0044-7447(2003)032[0098:fssonl]2.0.co;2

Tellman, B., Sullivan, J. A., Kuhn, C., Kettner, A. J., Doyle, C. S., Brakenridge, G. R., et al. (2021). Satellite imaging reveals increased proportion of population exposed to floods. *Nature*, *596*(7870), 80–86. https://doi.org/10.1038/s41586-021-03695-w

Tibby, J., Haynes, D., & Muller, K. (2020). The predominantly fresh history of Lake Alexandrina, South Australia, and its implications for the Murray-Darling Basin Plan: A comment on Gell (2020). *Pacific Conservation Biology*, *26*(2), 142–149. https://doi.org/10.1071/pc19039

Trevino-Garrison, I., DeMent, J., Ahmed, F. S., Haines-Lieber, P., Langer, T., Menager, H., et al. (2015). Human illnesses and animal deaths associated with freshwater harmful algal blooms-Kansas. *Toxins*, *7*(2), 353–366. https://doi.org/10.3390/toxins7020353

UN Habitat and WHO. (2021). *Progress on wastewater treatment—Global status and acceleration needs for SDG indicator 6.3.1*. United Nations Human Settlements Programme (UN-Habitat) and World Health Organization (WHO).

United Nations. (2018). The sustainable development goals report 2018 - Goal 6: Clean water and sanitation. Department of Economic and Social Affairs.

United Nations. (2022). World population prospects 2022: Summary of results. Department of Economic and Social Affairs. UN DESA/POP/2022/TR/NO. 3.

Vadeboncoeur, Y., Moore, M. V., Stewart, S. D., Chandra, S., Atkins, K. S., Baron, J. S., et al. (2021). Blue waters, green bottoms: Benthic filamentous algal blooms are an emerging threat to clear lakes worldwide. *BioScience*, *71*(10), 1011–1027. https://doi.org/10.1093/biosci/biab049

Vandenberg, L. N., Colborn, T., Hayes, T. B., Heindel, J. J., Jacobs, D. R., Lee, D. H., et al. (2012). Hormones and endocrine-disrupting chemicals: Low-dose effects and nonmonotonic dose responses. *Endocrine Reviews*, *33*(3), 378–455. https://doi.org/10.1210/er.2011-1050

Vanderploeg, H. A., Liebig, J. R., Carmichael, W. W., Agy, M. A., Johengen, T. H., Fahnenstiel, G. L., & Nalepa, T. F. (2001). Zebra mussel (Dreissena polymorpha) selective filtration promoted toxic microcystis blooms in Saginaw Bay (Lake Huron) and Lake Erie. *Canadian Journal of Fisheries and Aquatic Sciences*, *58*(6), 1208–1221. https://doi.org/10.1139/f01-066

van Dorst, R. M., Gardmark, A., Svanback, R., Beier, U., Weyhenmeyer, G. A., & Huss, M. (2019). Warmer and browner waters decrease fish biomass production. *Global Change Biology*, *25*(4), 1395–1408. https://doi.org/10.1111/gcb.14551

Verpoorter, C., Kutser, T., Seekell, D. A., & Tranvik, L. J. (2014). A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters*, *41*(18), 6396–6402. https://doi.org/10.1002/2014gl060641

Vijayaraj, V., Laviale, M., Allen, J., Amoussou, N., Hilt, S., Holker, F., et al. (2022). Multiple-stressor exposure of aquatic food webs: Nitrate and warming modulate the effect of pesticides. *Water Research*, *216*, 118325. https://doi.org/10.1016/j.watres.2022.118325

von Bertrab, E. (2003). Guadalajara's water crisis and the fate of Lake Chapala: A reflection of poor water management in Mexico. *Environment and Urbanization*, *15*(2), 127–140. https://doi.org/10.1177/095624780301500204

von Sperling, E. (2012). Hydropower in Brazil: Overview of positive and negative environmental aspects. In *International conference on clean energy solutions for sustainable environment (TerraGreen), Beirut, Lebanon*.

Vörösmarty, C. J., Green, P., Salisbury, J., & Lammers, R. B. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284

Vos, T., Barber, R. M., Bell, B., Bertozzi-Villa, A., Biryukov, S., Bolliger, I., et al. (2015). Global, regional, and national incidence, prevalence, and years lived with disability for 301 acute and chronic diseases and injuries in 188 countries, 1990-2013: A systematic analysis for the global burden of disease study 2013. *Lancet*, *386*(9995), 743–800. https://doi.org/10.1016/s0140-6736(15)60692-4

Vrba, J., Bojkova, J., Chvojka, P., Fott, J., Kopacek, J., Macek, M., et al. (2016). Constraints on the biological recovery of the Bohemian Forest lakes from acid stress. *Freshwater Biology*, *61*(4), 376–395. https://doi.org/10.1111/fwb.12714

Wakeel, A. (2013). Potassium-sodium interactions in soil and plant under saline-sodic conditions. *Journal of Plant Nutrition and Soil Science*, *176*(3), 344–354. https://doi.org/10.1002/jpln.201200417

Wang, J. Y., Wang, S. J., Zhou, C. S., & Feng, K. S. (2022). Consumption-based carbon intensity of human well-being and its socioeconomic drivers in countries globally. *Journal of Cleaner Production*, *366*, 132886. https://doi.org/10.1016/j.jclepro.2022.132886

Wang, X. P., Wang, C. F., Zhu, T. T., Gong, P., Fu, J. J., & Cong, Z. Y. (2019). Persistent organic pollutants in the polar regions and the Tibetan plateau: A review of current knowledge and future prospects. *Environmental Pollution*, *248*, 191–208. https://doi.org/10.1016/j.envpol.2019.01.093

Wang-Erlandsson, L., Tobian, A., van der Ent, R. J., Fetzer, I., te Wierik, S., Porkka, M., et al. (2022). A planetary boundary for green water. *Nature Reviews Earth & Environment*, *3*(6), 380–392. https://doi.org/10.1038/s43017-022-00287-8

Wee, S. Y., & Aris, A. Z. (2023). Revisiting the "forever chemicals," PFOA and PFOS exposure in drinking water. *Npj Clean Water*, *6*(1), 57. https://doi.org/10.1038/s41545-023-00274-6

Westerhoff, P., Atkinson, A., Fortner, J., Wong, M. S., Zimmerman, J., Gardea-Torresdey, J., et al. (2018). Low risk posed by engineered and incidental nanoparticles in drinking water. *Nature Nanotechnology*, *13*(8), 661–669. https://doi.org/10.1038/s41565-018-0217-9

Weyhenmeyer, G. A. (1998). Resuspension in lakes and its ecological impact—A review. In C. Forsberg & K. Pettersson (Eds.), *Advances in limnology 51: Lake Erken—50 years of limnological research* (Vol. 51, pp. 185–200).

Weyhenmeyer, G. A. (2008). Water chemical changes along a latitudinal gradient in relation to climate and atmospheric deposition. *Climatic Change*, *88*(2), 199–208. https://doi.org/10.1007/s10584-007-9331-7

Weyhenmeyer, G. A., Froberg, M., Karltun, E., Khalili, M., Kothawala, D., Temnerud, J., & Tranvik, L. J. (2012). Selective decay of terrestrial organic carbon during transport from land to sea. *Global Change Biology*, *18*(1), 349–355. https://doi.org/10.1111/j.1365-2486.2011.02544.x

Weyhenmeyer, G. A., Obertegger, U., Rudebeck, H., Jakobsson, E., Jansen, J., Zdorovennova, G., et al. (2022). Towards critical white ice conditions in lakes under global warming. *Nature Communications*, *13*(1), 4974. https://doi.org/10.1038/s41467-022-32633-1

Weyhenmeyer, G. A., Peter, H., & Willen, E. (2013). Shifts in phytoplankton species richness and biomass along a latitudinal gradient consequences for relationships between biodiversity and ecosystem functioning. *Freshwater Biology*, *58*(3), 612–623. https://doi.org/10.1111/j.1365-2427.2012.02779.x

Weyhenmeyer, G. A., Prairie, Y. T., & Tranvik, L. J. (2014). Browning of Boreal Freshwaters Coupled to Carbon-Iron Interactions along the Aquatic Continuum (vol 9, e88104, 2014). *PLoS One*, *9*(8), e88104. https://doi.org/10.1371/journal.pone.0088104

Wilk-Wozniak, E. (2020). An introduction to the 'micronet' of cyanobacterial harmful algal blooms (CyanoHABs): Cyanobacteria, zooplankton and microorganisms: A review. *Marine and Freshwater Research*, *71*(5), 636–643. https://doi.org/10.1071/mf18378

Williams, W. D. (1998). Salinity as a determinant of the structure of biological communities in salt lakes. *Hydrobiologia*, *381*(1/3), 191–201. https://doi.org/10.1023/a:1003287826503

Winfield, I. J. (2016). Recreational fisheries in the UK: Natural capital, ecosystem services, threats, and management. *Fisheries Science*, *82*(2), 203–212. https://doi.org/10.1007/s12562-016-0967-y

Wood, L. E., Andriamahefazafy, M. Z., Guilder, J., Kull, C. A., & Shackleton, R. T. (2021). Lake users' perceptions of environmental change: Ecosystem services and disservices associated with aquatic plants. *Water*, *13*(11), 1459. https://doi.org/10.3390/w13111459

Woolway, R. I., Huang, L., Sharma, S., Lee, S. S., Rodgers, K. B., & Timmermann, A. (2022). Lake ice will be less safe for recreation and transportation under future warming. *Earth's Future*, *10*(10). https://doi.org/10.1029/2022ef002907

Woolway, R. I., Jennings, E., Shatwell, T., Golub, M., Pierson, D. C., & Maberly, S. C. (2021). Lake heatwaves under climate change. *Nature*, *589*(7842), 402–407. https://doi.org/10.1038/s41586-020-03119-1

Woolway, R. I., Kraemer, B. M., Lenters, J. D., Merchant, C. J., O'Reilly, C. M., & Sharma, S. (2020). Global lake responses to climate change. *Nature Reviews Earth & Environment*, *1*(8), 388–403. https://doi.org/10.1038/s43017-020-0067-5

Woolway, R. I., Sharma, S., Weyhenmeyer, G. A., Debolskiy, A., Golub, M., Mercado-Bettin, D., et al. (2021). Phenological shifts in lake stratification under climate change. *Nature Communications*, *12*(1), 2318. https://doi.org/10.1038/s41467-021-22657-4

World Health Organisation Water, U. N. (2015). Investing in water and sanitation: Increasing access, reducing inequalities, GLAAS 2014 findings —Special report for Africa. Retrieved from https://apps.who.int/iris/handle/10665/204276

Worrall, F., Howden, N. J. K., Burt, T. P., & Bartlett, R. (2018). Declines in the dissolved organic carbon (DOC) concentration and flux from the UK. *Journal of Hydrology*, *556*, 775–789. https://doi.org/10.1016/j.jhydrol.2017.12.001

Wurtsbaugh, W. A., & Sima, S. (2022). Contrasting management and fates of two sister lakes: Great Salt Lake (USA) and Lake Urmia (Iran). *Water*, *14*(19), 3005. https://doi.org/10.3390/w14193005

Yadav, I. C., Devi, N. L., Syed, J. H., Cheng, Z. N., Li, J., Zhang, G., & Jones, K. C. (2015). Current status of persistent organic pesticides residues in air, water, and soil, and their possible effect on neighboring countries: A comprehensive review of India. *Science of the Total Environment*, *511*, 123–137. https://doi.org/10.1016/j.scitotenv.2014.12.041

Yang, L., Zhang, Y. L., Kang, S. C., Wang, Z. Q., & Wu, C. X. (2021). Microplastics in freshwater sediment: A review on methods, occurrence, and sources. *Science of the Total Environment*, *754*, 141948. https://doi.org/10.1016/j.scitotenv.2020.141948

Yao, F., Livneh, B., Rajagopalan, B., Wang, J., Crétaux, J.-F., Wada, Y., & Berge-Nguyen, M. (2023). Satellites reveal widespread decline in global lake water storage. *Science*, *380*(6646), 743–749. https://doi.org/10.1126/science.abo2812

Yao, M. Y., Henny, C., & Maresca, J. A. (2016). Freshwater bacteria release methane as a by-product of phosphorus acquisition. *Applied and Environmental Microbiology*, *82*(23), 6994–7003. https://doi.org/10.1128/aem.02399-16

Yin, Q., Gong, C. L., Kuang, D. B., Zhou, N., Hu, Y., Zhang, F. L., et al. (2005). Method of satellite remote sensing of lake water quality and its applications. *Journal of Infrared and Millimeter Waves*, *24*(3), 198–202.

Yu, S. Y., Du, X. Z., Lei, Q. L., Wang, X., Wu, S. C., & Liu, H. B. (2023). Long-term variations of water quality and nutrient load inputs in a large shallow lake of Yellow River Basin: Implications for lake water quality improvements. *Science of the Total Environment*, *900*, 165776. https://doi.org/10.1016/j.scitotenv.2023.165776

Yvon-Durocher, G., Caffrey, J. M., Cescatti, A., Dossena, M., del Giorgio, P., Gasol, J. M., et al. (2012). Reconciling the temperature dependence of respiratory across timescales and ecosystem types. *Nature*, *487*(7408), 472–476. https://doi.org/10.1038/nature11205

Zaher, S. S., & Aly, W. (2021). Impact of flood regime on phytoplankton communities in the large African reservoir, Lake Nasser, Egypt. *African Journal of Aquatic Science*, *46*(3), 340–352. https://doi.org/10.2989/16085914.2021.1888688

Zarfl, C., Lumsdon, A. E., Berlekamp, J., Tydecks, L., & Tockner, K. (2015). A global boom in hydropower dam construction. *Aquatic Sciences*, *77*(1), 161–170. https://doi.org/10.1007/s00027-014-0377-0

Zhang, T. T., Zhu, X., Guo, J. H., Gu, A. Z., Li, D., & Chen, J. M. (2021). Toxicity Assessment of Nano-ZnO exposure on the human intestinal microbiome, metabolic functions, and resistome using an in vitro colon simulator. *Environmental Science & Technology*, *55*(10), 6884–6896. https://doi.org/10.1021/acs.est.1c00573

Zhao, G., Li, Y., Zhou, L. M., & Gao, H. L. (2022). Evaporative water loss of 1.42 million global lakes. *Nature Communications*, *13*(1), 3686. https://doi.org/10.1038/s41467-022-31125-6

Zhou, Y. Q., Jeppesen, E., Zhang, Y. L., Niu, C., Shi, K., Liu, X. H., et al. (2015). Chromophoric dissolved organic matter of black waters in a highly eutrophic Chinese lake: Freshly produced from algal scums? *Journal of Hazardous Materials*, *299*, 222–230. https://doi.org/10.1016/j.jhazmat.2015.06.024

Ziv, G., Baran, E., Nam, S., Rodriguez-Iturbe, I., & Levin, S. A. (2012). Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences of the United States of America*, *109*(15), 5609–5614. https://doi.org/10.1073/pnas.1201423109

Zomer, R. J., Xu, J. C., & Trabucco, A. (2022). Version 3 of the global aridity index and potential evapotranspiration database. *Scientific Data*, *9*(1), 409. https://doi.org/10.1038/s41597-022-01493-1