Overview of the lakes and their issues, with related reading

Information, reference to the data and images, and related scientific paper.
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The Conference of the Lakes

Abiyata, shrinking lake, habitat loss

Drought is contributing to the shrinking of Lake Abiyata, Ethiopia. Even though this lake is in a protected area, extraction of river water upstream for irrigation means that less water flows into the lake. The declining water levels have consequences for waterbirds and wildlife, including flamingos.

Data source: Water level. Seyoum, WM et al. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. *Hydrological Processes* 29, 4312-4324. doi: 10.1002/hyp.10490. Photo: internet.

Tanganyika, warming, fish loss

Located in the East African Rift Valley, Lake Tanganyika is a critical source of fish for millions of people. Warmer water temperatures make it harder for deep water to mix with the surface water, leading to less nutrients and declines in fish yields.

Data and source: Water temperature at different depths. WL Perry, Illinois State University, CLEAT project, unpublished data. (For more information: O'Reilly CM et al. (2003). Climate change decreases aquatic ecosystem productivity in Lake Tanganyika, Africa. *Nature* 424, 766-768. doi: 10.1038/nature01833.)

Baikal, warming

Lake Baikal is the deepest and oldest lake in the world. It is home to thousands of unique plants and animals that evolved in the lake and are not found elsewhere. As water temperatures have warmed there have been changes in the amount and types of algae in the lake, as well as in the small invertebrate zooplankton that feed off the algae.

Data and source: The abundance of three different invertebrate zooplankton groups. Hampton, SE et al. (2008). Sixty years of environmental change in the world's largest freshwater lake – Lake Baikal, Siberia. Global Change Biology 14, 1947-1958. doi: 10.1111/j.1365-2486.2008.01616.x. (For more information: Moore MV et al. (2009). Climate change and the worlds' 'Sacred Sea' - Lake Baikal, Siberia. *BioScience* 59, 405-417.doi:_10.1525/bio.2009.59.5.8.) Photo: S. Hampton.

Hillier, genome of S. ruber, pink lake

The distinctive water color of the pink lakes of southwestern coastal Australia are sensitive to salinity. The salinity levels of Lake Hillier are about 10 times greater than sea water, creating a unique environment that allows the halophilic (salt-loving) pink bacterium *Salinibacter ruber* to dominate. Lake Hillier is located in a protected area, undisturbed, and thus retains its unique color. Many of the coastal lakes in southwestern Australia are sensitive to salinity, which can be affected by changes in groundwater and sea level rise. The construction of the South Coast Highway and a rail line altered the flow of water into some lakes, reducing the salinity which so that they no longer appear pink.

Data and source: genome of S ruber. Image from González-Torres, P et al. (2018). Genome variation in the model halophilic bacterium *Salinibacter ruber*. *Frontiers in Microbiology* 19, 9, 1499. doi: 10.3389/fmicb.2018.01499. This genome was sequenced as part of the Extreme Microbiome Project (XMP), a project to explore organisms that live in unique environments. The color of the lake had previously been attributed to the red algae *Dunaliella salina*, but the results of the XMP showed that the pink color of the lake was due to the incredible abundance of this bacteria.

Lake Vanda, Antarctica, growing lake, ice melt

Lake Vanda is a permanently ice-covered lake located in the McMurdo Dry Valleys of Antarctica. Lake levels rose 15 m over the past 68 years in response to climate-driven variability, with melting ice increasing the freshwater inflows from the Onyx River, the main source of water to the lake. As lake levels continue to rise from the freshwater input, it will lead to the changes in internal mixing of the water causing drastically different conditions than those observed today.

Data and source: Lake level and satellite imagery. McMurdo Dry Valleys Long Term Ecological Research Station. (For more information: Castendyk DM et al. (2016). Lake Vanda: A sentinel for climate change in the McMurdo Sound Region of Antarctica. *Global and Planetary Change* 144, 213-227. doi: 10.1016/j.gloplacha.2016.06.007.)

Zigadenus Lake, Canada, decreasing turbidity, "Losing blue"

Zigadenus Lake is ice covered for most of the year (October through July), but reveals its beauty during mid-summer. As a high alpine lake fed by glacial meltwater, Zigadenus Lake has historically been a brilliant turquoise color, because of glacial flour. Glacial flour is a powder of silt and clay created by the glacier moving against rocks—that is picked up by meltwater streams. These particles are so fine, they do not sink and remain suspended in the water column, and the reflection of light off these particles gives the lake it's unique color. However, as the glacier has retreated further up the valley, less of the flour gets transported all the way to the lake. Water transparency has been increasing over the last seven years as this glacial input has decreased. Consequently, the brilliant turquoise colour of the lake has been fading to a richer and deeper sapphire blue.

Data and source: Turbidity. J Fischer, Franklin and Marshall College, unpublished data. Also included are an image from water, adapted from a photo of Janet Fischer, and the flower after which the lake is named, *Zigadenus venenosus*, commonly known as the death flower. (for more information: Olson MH et al. (2017). Landscape-scale regulators of water transparency in mountain lakes: implications of projected glacial loss. *Canadian Journal of Fisheries and Aquatic Sciences* 75, 7, doi.org/10.1139/cjfas-2017-0215.

The Loch and Sky Pond, atmospheric nitrogen deposition

Even remote watersheds are subject to human impacts. Expansion of industrial fertilizer use, intensive livestock production, and fossil fuel combustion have increased atmospheric nitrogen deposition to these high elevation lakes in the Rocky Mountains. Together with warmer water temperatures, this nitrogen addition has led to changes in the types of algae that now grow in these lakes. As this nitrogen acts to fertilize the lake, algae also become more abundant, decreasing the clarity of these mountain lakes.

Data and source: Nitrogen deposition, colonial cyanobacteria, and cyanobacteria abundance in both lakes. Olesky IA et al. (2020). Nutrients and warming interact to force mountain lakes into unprecedented ecological states. *Proceedings of the Royal Society B: Biological Sciences* 287, 20200304. doi: 10.1098/rspb.2020.0304. Photo: Alice Hargrave.

Otsego Lake, warming, invasive species

Otsego Lake has changed substantially since new species were introduced to the lake. Among those new species are fish, mussels and pondweed. These introductions have affected the populations of species originally living in the lake, altering the abundance of certain fish to algae and even parasites. The lake has also had declines in winter ice cover, which contribute to warmer water temperatures.

Data and source: Lake water temperature at different depths. K Yokota, State University of New York College at Oneonta, Oneonta, NY, unpublished data. For more information: Harman WN et al. (2002). Trophic Changes in Otsego Lake, NY Following the Introduction of the Alewife (*Alosa psuedoharengus*). *Lake and Reservoir Management* 18, 215–226. doi:10.1080/07438140209354150.

Lake Tovel, Italy, magenta algal bloom loss

Surrounded by the snow-capped Dolomite Mountains, Lake Tovel was historically renowned for its red waters each summer. The magenta color was due to a red algae, *Tovellia sanguinea*. However, there have been no algae blooms since 1964. Improvements in how dairy cow farms are managed in the watershed reduced nutrient inputs and led to a clearer lake.

Data and source. Light at different depths. G. Flaim, Fondazione Edmund Mach, Italy, unpublished data. (For more information: Flaim G et al. (2020). Ice cover and extreme events determine dissolved oxygen in a placid mountain lake. *Water Resources Research* 56, e2020WR027321. doi: 10.1029/2020WR027321.)

Lake Tovel, Italy, warming

Alpine regions are among the fastest warming areas. This high elevation lake in the Dolomite Mountains of Italy has been experiencing less ice cover and warmer waters, making its winters shorter and its summers longer. These changes affect oxygen concentrations in the lake and how well the water mixes. In its cool protected valley high in the mountains, the lake rarely mixed, now the lake is in the process of a metamorphosis from meromixis to dimixis (from not mixing to mixing fully twice a year). As these changes occur, there have been shifts the algae, leading

Data and source. Water temperature at different depths, including during winter. G. Flaim, unpublished data. (For more information: Flaim G et al. (2020). Ice cover and extreme events determine dissolved oxygen in a placid mountain lake. *Water Resources Research* 56, e2020WR027321. doi: 10.1029/2020WR027321.)

Lake Tahoe, USA, decreasing clarity

Lake Tahoe is known around the world for its incredible water clarity. From the late 1960's through the turn of the century, there was a decline in clarity due to increased algae growth and the presence of very fine particles. This was driven by a combination of warmer waters and inputs of sediment and nutrients from the surrounding landscape due to development. Recent conservation efforts have slowed the impact of land use, but the threat of climate change, as well as invasive species, remains.

Data and source: Secchi disk depth. Lake Tahoe Environmental Research Center (also at laketahoeinfo.org). Background is detail of an old poster. (For more information: Domagalski, JL et al. (2021). Trends in nitrogen, phosphorus, and sediment concentrations and loads in streams draining to Lake Tahoe, California, Nevada, USA. *Science of the Total Environment*. Volume: 752, 141815. doi: 10.1016/j.scitotenv.2020.141815.

Northern WI lakes, mercury

The legacy of our past environmental destruction still follows us today. The United States' Clean Air Act improved air quality and led to declines in mercury emissions. However, in northern Wisconsin, mercury in fish can still be so high they are not safe to eat. This is because during wetter years when lake level rises, more mercury is released from the waterlogged soils. Increases in rainfall from climate change could lead to rising lake levels and cause mercury contamination of fish and loons to remain an environmental problem.

Data and source: Water level and mercury concentrations in walleye for 178 lakes. Watras CJ et al. (2020). Near-decadal oscillation of water levels and mercury bioaccumulation in the Laurentian Great Lakes Region. *Environmental Science and Technology Letters* 7, 89-94. doi: 10.1021/acs.estlett.9b00772.

Northern WI lakes, USA, phenological whiplash

In addition to warming, climate change is leading to increasing variability across many ecosystems. In northern lakes, extremely early or late lake ice melt affects fish spawning. In the last decade, walleye have spawned both much earlier and much later than expected due to these dramatic shifts in when lake ice melt occurred. This is referred to as 'phenological whiplash' in reference to the extreme changes in the timing of seasonal events. Phenologies are changing in other lakes from earlier ice-out and warmer waters, and the effects can cascade through the entire food web.

Data and source: Dates of ice melt and of the walleye spawning. Sparking Lake. G. Gerrish, University of Wisconsin, Madison, unpublished data. (For more information: Tanentzap AJ et al. (2020). Climate warming restructures an aquatic food web over 28 years. *Global Change Biology* 26, 6852-6866, doi: 10.1111/gcb.15347.) Photo: Alice Hargrave.

Lake Superior, ice loss

Lake Superior is one of the fastest warming lakes on the planet. Whether or not it has winter ice cover is highly dependent on average winter air temperatures. A difference of just 2 degrees determines whether the lack of ice will allow shipping to remain open or if there will be ice fishing, ice cave tourism and other winter activities that drive a multi-billion-dollar economy. Reductions in ice cover subsequently affect summer water temperature and lead to algal blooms. Lake Superior recently had its first ever known cyanobacteria bloom, pointing toward degraded conditions in summer as well.

Data and sources: Bathymetry and echosound data. J Austin, University of Minnesota, Duluth, unpublished data. The echosound data show many internal dynamics of the lake: breaking waves near the surface, undulating internal waves, regions of phytoplankton concentrations, and little yellow "scratches" that are probably individual zooplankton. (For more information: Sterner, RW et al. (2020). A first assessment of cyanobacterial blooms in oligotrophic Lake Superior. *Limnology and Oceanography* 65: 2984–2998, doi: 10.1002/lno.11569.)

The echosound data are probably July-Sept, the zooplankton change their migration behavior when there is ice vs no ice. With ice over, they all have to migrate up to the surface because there is not much water mixing and the algae (food) are all at the top. But with open water, there is deeper convection and mixing, so algae will get mixed down to where the zooplankton are hanging out in deeper water (to avoid being seen and eaten by fish). So with ice cover, it is like you have to go pick up your take out, but when it is open water, it's like Door Dash, the mixing brings the food to you.

Lakes Mendota, Menona and Wingra, WI, USA, rising salinity
Northern lakes around the world are experiencing increases in salinity due to the use of road salts. We now apply 23 million metric tons of salt to roads in the USA each year, which ultimately ends up being washed into streams and lakes. The fish and other organisms are adapted to fresh water, and biodiversity could decline in response to saltier waters. Some lakes are on track to actually taste salty by 2050!

Data and source: Chloride concentrations. Dugan HA et al. (2017). Salting our freshwater lakes. *Proceedings of the Academy of Sciences* 114, 4453-4458. doi: 10.1073/pnas.1620211114. Photo: vintage

Lake Milford, KS, USA, toxic algal blooms
Harmful algal blooms, also known as "blue-green" algae blooms, have occurred in more than 50 reservoirs in Kansas since 2010, due to warmer, calmer waters and phosphorus inputs in land use. These blooms produce toxins that can affect mammals; in 2011 there were 5 dog deaths from exposure to the water in Lake Milford.

Data and source: Abundance of blue-green algae. United States Geological Survey (For more information: Trevino-Garrison et al. (2015). Human illnesses and animal deaths associated with freshwater harmful algal blooms - Kansas. *Toxins* 7, 353-366. doi: 10.3390/toxins7020353.)

Lake Blávatn, new lake, glacier extinction

Warmer temperatures caused the glacier Okjökull to melt and disappear completely, in the process creating a new lake, Lake Blávatn (meaning: Blue Lake).

Data and source: Satellite images. Malmquist HJ et al (2013). Blávatn: Nýjasta stöðuvatn landsins. *Náttúrufræðingurinn* 83, 13-23. Photo of poster: Alice Hargrave. (For more information: Huss M et al. (2017). Toward mountains without permanent snow and ice. *Earths Future*, 5, 418-435. doi: 10.1002/2016EF000514.

Flathead Lake, MT, USA, invasive species and mercury in the food chain

Introductions of nonnative organisms can cause major changes in aquatic ecosystems. Non-native mysis shrimp were introduced into Flathead Lake by fisheries managers who thought this would increase food sources for salmon. Instead, the shrimp ate the food that otherwise would have gone to the salmon, and then hid from the salmon in deeper darker waters. The salmon populations collapsed, and eagles stopped appearing near the lake to feed on them.

Data and source: Kokanee salmon, eagle, Mysis shrimp, lake trout, and bull trout abundance history in Flathead Lake. Ellis BK et al. (2011). Long-term effects of a trophic cascade in a large lake ecosystem. *Proceedings of the Academy of Sciences* 108, 1070-1075. doi: 10.1073/pnas.1013006108. Photo: Alice Hargrave. Credit: Diane Whited for the bathymetry.

Lake Thingvallavatn, Iceland, ice loss, finger rafting

Winter ice cover on this lake has declined substantially. The lake used to have ice cover for over 4 months, but in the last few decades there have even been winters without any ice cover. In 2017, the lake ice formed a unique pattern that never been seen on this lake before, known as finger rafting. Finger rafting is a rare phenomenon, and forms only when there are substantial differences in water or ice that are freezing towards each other. The ice on Lake Thingvallavatn has been becoming thinner over the past 15 years due to rising air temperatures, which could explain why these patterns are appearing on the lake for the first time.

Data and source: Water temperature data from different depths in the lake. Malmquist HJ et al. (2020). Hlýnun þingvallavatns og hitaferlar í vatninu. *Náttúrufrædingurinn* 90, 80-99. Photo: Finger rafting, Einar Á. E. Sæmundsen. Ice skaters: The National Museum of Iceland.

El Morado proglacial lake, Chile, new lake, before green

This lake is located in the high elevations of the Andes Mountain Range near Santiago, Chile. As a result of the El Morado glacier melting due to climate warming, what used to be a small lake at the end of the glacier expanded substantially between 1955 and 2019. The color of the water is brown, because so many sediments wash into the lake - the landscape is so fresh that there is no soil developed yet for plants to grow and stabilize the sediment.

Data and source: Lake water levels. Farías-Barahona D et al. (2020). A near 90-year record of the evolution of El Morado Glacier and its proglacial lake, Central Chilean Andes. *Journal of Glaciology* 66, 846–860. doi:10.1017/jog.2020.52.

<u>Beyond the Blue</u>

There are only a few lakes in Beyond the Blue that are not already described above.

Crater Lake, OR, USA, then and now

Although it is in a protected national park area, Crater Lake is not immune to the effects of lake climate. The lake has been warming, in part because winds that would typically cool the lake have been declining. This decline in wind speeds is a global phenomenon known as ‘atmospheric stilling’, and it is driven by the fact that the atmosphere is generally warmer everywhere now. Recent wildfires in this region also highlight the effect of warmer air temperatures.

Data and source: vintage photo juxtaposed with the crisis of the wildfires. (For more information: Stetler JT et al. (2021). Atmospheric stilling and warming air temperatures drive long-term changes in lake stratification in a large oligotrophic lake. *Limnology and Oceanography* 9999, 1–11. doi: 10.1002/lno.11654.)

Lake Sunapee, NH, USA, algal blooms

Lake Sunapee is somewhat unique in that the lake is not "supposed" to have algal blooms because it is considered a clear water, pristine lake. Thus it has been surprising to see blooms of *Gloeotrichia*, a type of cyanobacteria. Swimming in these blooms can irritate the skin. The abundance of Gloeotrichia is likely due to changes in how the lake is warming and mixing, related to regional climate patterns.

Data and source: algal blooms of *Gloeotrichia* seen on the lake (photo courtesy of K. Weathers) with vintage photograph of boats. (For more information: Carey CC et al. (2014). Spatial and temporal variability in recruitment of the cyanobacterium Gloeotrichia echinulata in an oligotrophic lake. *Freshwater Science* 33, 577–592. doi: 10.1086/675734.)

Pallette Lake, WI, USA, water rising and loon loss

As water level of this lake has changed, the beaches, once used for picnicking and swimming, have disappeared. Changes in precipitation patterns are part of climate change.

Data and source: bathymetry, Photo: Alice Hargrave.

General readings

O'Reilly CM et al. (2015). Rapid and highly variable warming of lake surface waters around the globe. *Geophysical Research Letters* 42, 10773-10781. doi: 10.1002/2015GL066235 (open access)

Ho JC et al. (2019). Widespread global increase in intense lake phytoplankton blooms since the 1980s. *Nature* 574, 667 doi: 10.1038/s41586-019-1648-7.

Williamson C et al. (2009). Sentinels of Change. *Science* 323:887-888. doi: 10.1126/science.1169443 (open access)

Consolidated list of the readings specific to the pieces

Carey CC et al. (2014). Spatial and temporal variability in recruitment of the cyanobacterium Gloeotrichia echinulata in an oligotrophic lake. *Freshwater Science* 33, 577–592. doi: 10.1086/675734.

Castendyk DM et al. (2016). Lake Vanda: A sentinel for climate change in the McMurdo Sound Region of Antarctica. *Global and Planetary Change* 144, 213-227. doi: 10.1016/j.gloplacha.2016.06.007.

Domagalski, JL et al. (2021). Trends in nitrogen, phosphorus, and sediment concentrations and loads in streams draining to Lake Tahoe, California, Nevada, USA. *Science of the Total Environment*. Volume: 752, 141815. doi: 10.1016/j.scitotenv.2020.141815.

Dugan HA et al. (2017). Salting our freshwater lakes. *Proceedings of the Academy of Sciences* 114, 4453-4458. doi: 10.1073/pnas.1620211114.

Ellis BK et al. (2011). Long-term effects of a trophic cascade in a large lake ecosystem. *Proceedings of the Academy of Sciences* 108, 1070-1075. doi: 10.1073/pnas.1013006108.

Hampton, SE et al. (2008). Sixty years of environmental change in the world's largest freshwater lake – Lake Baikal, Siberia. Global Change Biology 14, 1947-1958. doi: 10.1111/j.1365-2486.2008.01616.x.

Harman WN et al. (2002). Trophic Changes in Otsego Lake, NY Following the Introduction of the Alewife (*Alosa psuedoharengus*). *Lake and Reservoir Management* 18, 215–226. doi:10.1080/07438140209354150.

Huss M et al. (2017). Toward mountains without permanent snow and ice. *Earths Future*, 5, 418-435. doi: 10.1002/2016EF000514.

Farías-Barahona D et al. (2020). A near 90-year record of the evolution of El Morado Glacier and its proglacial lake, Central Chilean Andes. *Journal of Glaciology* 66, 846–860. doi:10.1017/jog.2020.52.

Flaim G et al. (2020). Ice cover and extreme events determine dissolved oxygen in a placid mountain lake. *Water Resources Research* 56, e2020WR027321. doi: 10.1029/2020WR027321.

Malmquist HJ et al. (2020). Hlýnun þingvallavatns og hitaferlar í vatninu. *Náttúrufrædingurinn* 90, 80-99. (Summary and figure captions in English).

Malmquist HJ et al (2013). Blávatn: Nýjasta stöðuvatn landsins *Náttúrufrædingurinn* 83, 13-23. (Summary and figure captions in English).Sterner, RW et al. (2020). A first assessment of cyanobacterial blooms in oligotrophic Lake Superior. *Limnology and Oceanography* 65: 2984–2998, doi: 10.1002/lno.11569.

Moore MV et al. (2009). Climate change and the worlds' 'Sacred Sea' - Lake Baikal, Siberia. *BioScience* 59, 405-417.doi:_10.1525/bio.2009.59.5.8.

Olesky IA et al. (2020). Nutrients and warming interact to force mountain lakes into unprecedented ecological states. *Proceedings of the Royal Society B: Biological Sciences* 287, 20200304. doi: 10.1098/rspb.2020.0304.

Olson MH et al. (2017). Landscape-scale regulators of water transparency in mountain lakes: implications of projected glacial loss. *Canadian Journal of Fisheries and Aquatic Sciences* 75, 7, doi.org/10.1139/cjfas-2017-0215.

O'Reilly CM et al. (2003). Climate change decreases aquatic ecosystem productivity in Lake Tanganyika, Africa. *Nature* 424, 766-768. doi: 10.1038/nature01833.

Seyoum, WM et al. (2015). Understanding the relative impacts of natural processes and human activities on the hydrology of the Central Rift Valley lakes, East Africa. *Hydrological Processes* 29, 4312-4324. doi: 10.1002/hyp.10490.

Stetler JT et al. (2021). Atmospheric stilling and warming air temperatures drive long-term changes in lake stratification in a large oligotrophic lake. *Limnology and Oceanography* 9999, 1–11. doi: 10.1002/lno.11654.

Tanentzap AJ et al. (2020). Climate warming restructures an aquatic food web over 28 years. *Global Change Biology* 26, 6852-6866, doi: 10.1111/gcb.15347.

Trevino-Garrison et al. (2015). Human illnesses and animal deaths associated with freshwater harmful algal blooms - Kansas. *Toxins* 7, 353-366. doi: 10.3390/toxins7020353.

Watras CJ et al. (2020). Near-decadal oscillation of water levels and mercury bioaccumulation in the Laurentian Great Lakes Region. *Environmental Science and Technology Letters* 7, 89-94. doi: 10.1021/acs.estlett.9b00772.