The evolving dynamics of a deep North American lake over a half-century

By S. Geoffrey Schladow and Shohei Watanabe

Lake Tahoe, in the Sierra Nevada Mountains, USA, is widely known for its ultra-oligotrophic status and outstanding clarity[3]. The lake has a surface area of 495 km^2, a maximum depth of 501 m, and is located within a relatively small, forested watershed of 800 km^2. The small ratio of watershed area to lake volume results in a large mean retention time of lake water of approximately 650 years.

Lake Tahoe, United States

Since the late 1950s lake clarity has declined, along with a shift in the blueness of the water[6]. This has been attributed to a range of causes, many associated with altered input loads due to land use changes and visitorship[5]. For example, while the lake Tahoe basin has a permanent population of only 50,000, the annual number of visitors has grown to 15 million over this period. Concomitantly there have also been changes in the lake's physical dynamics and hydrology, many of them linked to global climate change. Here we will describe some of the more pronounced changes that have been observed in the physical dynamics of the Lake Tahoe system. These data are largely derived from the ongoing monitoring program of the UC Davis Tahoe Environmental Research Center. Since 1968, monitoring has taken place at varying intervals from weekly to monthly throughout the year[1]. Many of the variables are also discussed in the Annual Tahoe: State of the Lake Report[4]. As will be made evident in the data presented, the lake physical dynamics have changed to a far greater degree than the external loads, pointing to their importance in better guiding lake management.

Lake Clarity

Addressing the declining clarity of Lake Tahoe is what motivated the investment in load reduction since the late 1990s. Figure 1 shows the annual average Secchi depth (measured with an all-white, 25 cm disk) from approximately 25 measurements per year, taken in all months of each year. In the last 20 years, there has been a cessation of the decline in clarity, but there is no statistical trend of long term clarity improvement.

Meteorological forcing

Many of the meteorological variables measured indicate the impact of climate change. These include the fraction of snow to total precipitation and the number of days each year with below freezing average daily temperature. Shown in Figure 2 is the annual average maximum (upper panel) and minimum (lower panel) air temperature. As has been observed in many locations around the world, there is a long term increase especially in nighttime minima, where the temperature has increased approximately 4°C since 1910.

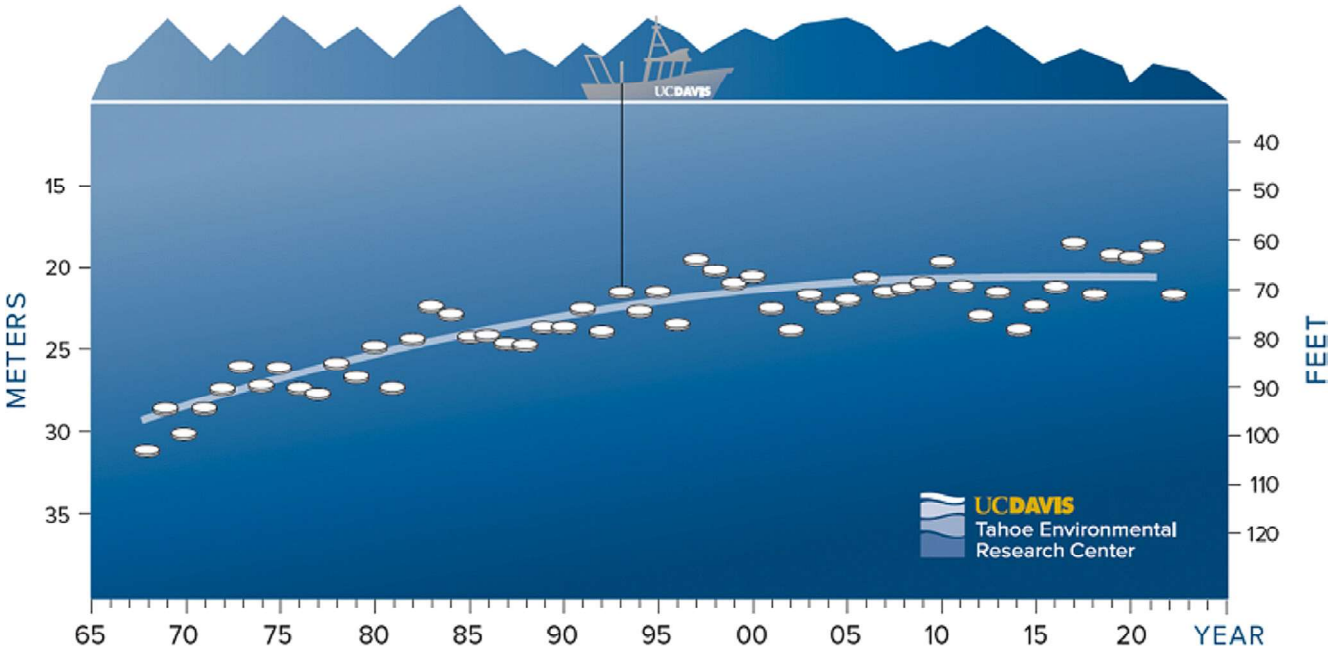

Figure 1 | Lake Tahoe annual average Secchi depth record.

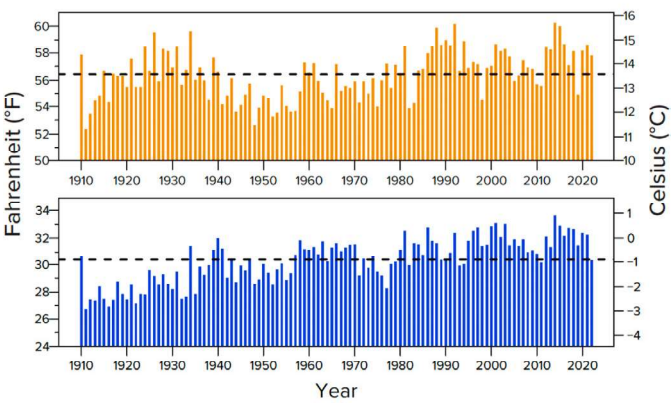

Figure 2 | Annual average maximum (upper panel) and minimum (lower panel) air temperatures. Dashed lines represent the long term mean value.

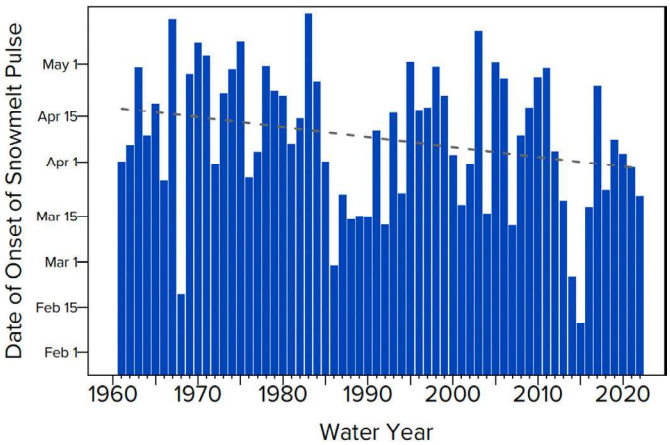

Figure 3 | Date of onset of the peak in the average hydrograph.

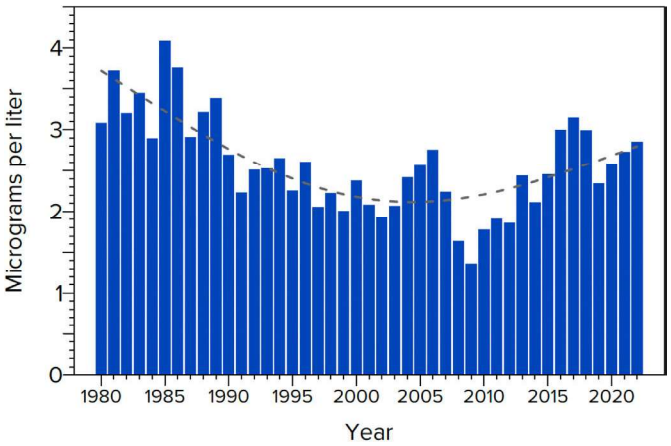

Figure 4 | Depth averages (13 depths) lake THP concentration since 1980.

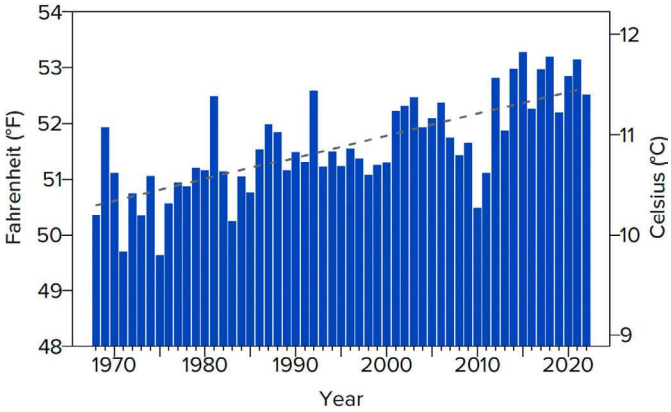

Figure 5 | Annual average surface water temperature Measured at a depth of 1.5 m at Lake Tahoe.

Hydrology

Lake Tahoe is predominantly a snowmelt fed system, with the peak in stream hydrographs occurring in April or May each year. Since 1961 the peak of the stream hydrograph has advanced 19 days, as shown in Figure 3. This has important hydrologic impacts as the stream water (and its associated loads) is inserted into the stratified lake waters at a different time of year, and potentially a different depth. It also carries potentially important ecological consequences, as many aquatic organisms take life cycle cues from variables such as peak streamflow timing. The data in Fig. 3 were derived from the average of the five largest streams flowing into Lake Tahoe. With the expected increased rate of climate warming, this trend could be expected to increase in the future.

Nutrient Concentrations

The actual average lake nutrient concentrations do not appear to have changed very much. From 1980 through 2000, total hydrolysable phosphorus or THP (the part of the phosphorus that is readily accessible by phytoplankton), decreased, as shown in Figure 4. Around 2005 a slight increase in THP was observed, although over the entire 43-year period of data there is a weak downward trend. This load trend, though weak, is counter-intuitive in relation to the changes in lake clarity.

Lake Temperature and thermal stratification

Lake temperature and related changes such as the thermal stratification are where the largest changes have been observed, suggesting the importance of these physical variables. The annual average surface temperature (measured at a depth of 1.5 m) has risen at an average rate of 0.22 °C/decade since 1968 (Figure 5). Over the same period, the hypolimnetic temperature (typically measured at a depth of 450 m) has also risen, albeit in a more complex fashion (Figure 6). The temperature record indicates that during years when complete vertical mixing takes place (shown by dashed vertical lines) there is a drop in bottom temperature. When the lake does not mix to the bottom (stays thermally stratified) the bottom temperature is seen to rise at rate of 0.4 °C/decade. This suggests that lake warming, lake stratification and climate change are very directly connected.

The period when the upper waters (upper 150 m)[2] of Lake Tahoe stay stratified has been lengthening over the last 50 years. Since 1968, the length of the stratification season has increased by 29 days, albeit with considerable year-to-year variation, as seen in Figure 7.

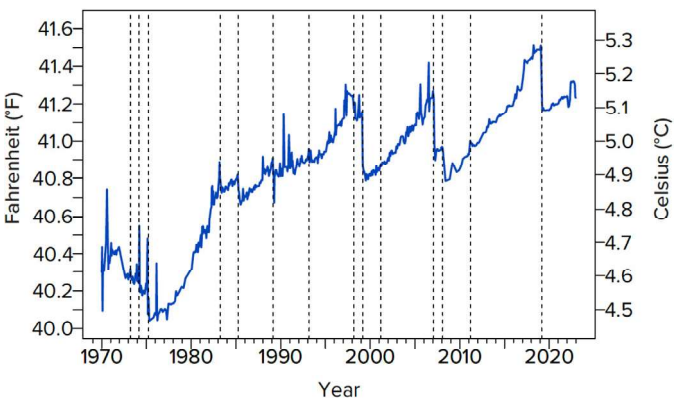

Figure 6 | Hypolimnetic water temperature measured at a depth of 450 m. The dashed vertical lines indicate the times when the lake mixed vertically to the bottom.

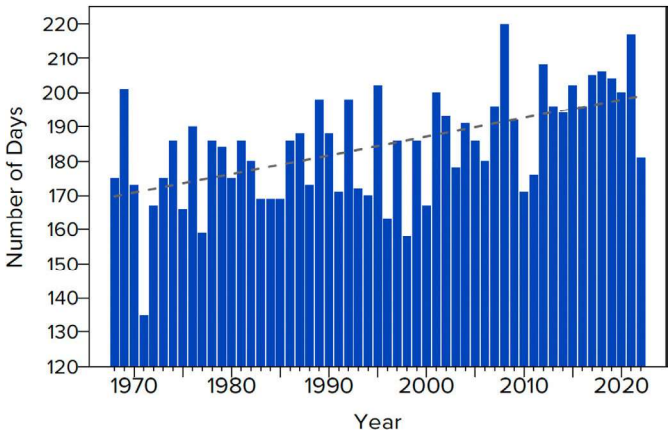

Figure 7 | Number of days each year when the upper 150 m of Lake Tahoe remains stratified.

Conclusions

Efforts to manage the decline in clarity at Lake Tahoe and other lakes around the world have typically focused on efforts to reduce external pollutant loads. Despite the investments over the long term, the results have not to date matched the expectations. At the same time, physical data suggest that atmospheric warming due to climate change is strongly altering variables such as the timing of the peak inflow hydrograph, the lake temperature, and the length of the stratification period. The extent that these variables may be making the attainment of clarity goals more difficult is a current area of research.

References

1 | Cortés, A., Schladow, S.G., Tanaka, L., Trommer, S.C., Valbuena, S.A., Watanabe, S., Melack, J. M., Chandra, S., Suenaga, E.K. and De Souza Cardoso, L. 2022. Lake Tahoe Clarity Analysis and Modeling Phase I: Biogeochemical and Ecological Modeling. A Report to the Tahoe Science Advisory Council (https://www.tahoesciencecouncil.org)

2 | Sahoo, G.B., Schladow, S.G. and Reuter J.E. 2010. Effect of sediment and nutrient loading on Lake Tahoe (CA-NV) optical conditions and restoration opportunities using a newly developed lake clarity model. Water Resources Research, 46(10).

3 | Sahoo, G.B., Forrest, A.L., Schladow, S.G., Reuter, J.E., Coats, R. and Dettinger, M. 2016. Climate Change Impacts on Lake Thermal Dynamics and Ecosystem Vulnerabilities. Limnology and Oceanography, 16(2): 496–507.

4 | Schladow, S.G., Watanabe, S. and Toy, A. 2023. Tahoe: The State of the Lake Report 2023. https://tahoe.ucdavis.edu/stateofthelake.

5 | Swift, T.J., J. Perez-Losada, S.G. Schladow, J.E. Reuter, A.D. Jassby, C.G. Goldman. 2006. Water clarity modeling in Lake Tahoe: Linking suspended matter characteristics to Secchi Depth. Journal, Aquatic Sciences 68, 1-15.

6 | Watanabe, S., Vincent, W., Reuter, J., Hook, S. and Schladow, S.G. 2016. A quantitative blueness index for oligotrophic waters: Application to Lake Tahoe, California-Nevada. Limnology and Oceanography: Methods, 14: 100-109.

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Dr Geoffrey Schladow has been a professor of water resources and environmental engineering at the University of California, Davis, since 1993 and in 2004 became the founding director of the UC Davis Tahoe Environmental Research Center (TERC), the only research and education center based in the Tahoe basin. His research has focused on understanding the complex fluid motions found in lakes and their impacts on water quality and ecosystem health using a combination of field, laboratory and numerical approaches. He has developed three-dimensional water quality models for use in lakes around the world.

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