

Perspective

Catastrophic shifts in large lake levels

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ABSTRACT

Large lakes are important to buffering the potential impacts of global climate change on local water resources that millions of people's livelihoods depend on. However, abrupt changes in water level from one extreme to another (e.g., flood to drought) over short periods of time have been observed recently, threatening aquatic ecosystems and socio-economics in globe. We argue that the seemingly rare dramatic extreme changes are no longer incidental, but are becoming a new norm. The combined forces of ongoing climate change and anthropogenic intensification in many parts of the world are presumably the root causes. More prevalent than the retreating glaciers, lakes are more vulnerable to human modification, an emerging dimension of global changing environment. We call for mechanistic understanding of the interactions of climate-watershed-human across major lakes. Such international collaborative efforts are essential to developing effective solutions to mitigate the impacts of drought and floods in global large-lake regions.

1. Dramatic changes in global lakes

Globally, lakes cover only 2.8% of the Earth's land surface [1]. However, millions of lakes provide invaluable ecosystem services to humans [2]. In particular, lakes harbor many wetlands, which are among the most biologically diverse ecosystems, home to many of the world's endemic species, major carbon pools, and that serve as "nature's kidneys" for assimilating and transforming materials between lands and waters [3]. Drastic changes in lake hydrological processes can yield cascading impacts on geophysical, biological, ecological, economic, and social systems [4].

Lakes are rather dynamic in water level. Satellite altimeters show clear oscillations in large lakes on most continents over the last two decades (Fig. 1). Seasonal oscillations of lake level depend on local climate, and they can be several meters for most lakes, and as much as ten meters for lakes such as Tonle Sap Lake and Poyang Lake. Usually, long-term trends are discernable from inter-annual time series of water levels. Short-time events, such as drastic lake water level changes from lowest/highest to lowest/highest, appear occasionally. However, exceptional water level changes emerge beyond normal frequencies and magnitudes, producing multi-faceted consequences in lake systems, raising global awareness and concern, particularly in recent years [4–6]. For example, the American Great Lakes, including Lake Ontario, have

undergone more shifts from extreme highs to low levels over the past decade than ever before [7,8]. Water levels in the Great Lakes in Africa (Albert, Kivu, Tanganyika and Victoria) rose sharply in 2019/20, breaking historical records (Fig. 1). These sharp changes are also found on the Euro-Asian continent, such as at Lake Ladoga (the largest lake in Europe), the North Aral Sea, Lake Balkhash, Uvs Lake, Tonle Sap Lake (the largest freshwater lake in Southeast Asia), Nam Co, Poyang Lake (China's largest freshwater lake) and Hulun Lake (Fig. 1). Specifically, Lake Kivu in Africa experienced a large inter-annual variability in water level, a quick drop from a flooding level in 2015 to a prolonged drought in 2016. Tonle Sap Lake, after a destructive flooding in September 2019, fell to an extremely low level. In southern China, several large lakes, including Poyang Lake, Dongting Lake, Chao Lake and Hong Lake in the Yangtze River basin, also experienced consecutive extreme fluctuations in 2019 and 2022 as well. Globally, large lakes saw an increasing frequency in extreme events in the 2010s (Fig. 1). The question now is are the observed changes in lake levels around the world signaling global climate change [9], anthropogenic impacts, or a combination of both?

2. Complex processes causing hydrologic extreme change in lakes

Statistically, hydrologic extremes are rare events that may follow a discernable distribution. Hydrologic extremes meanwhile are

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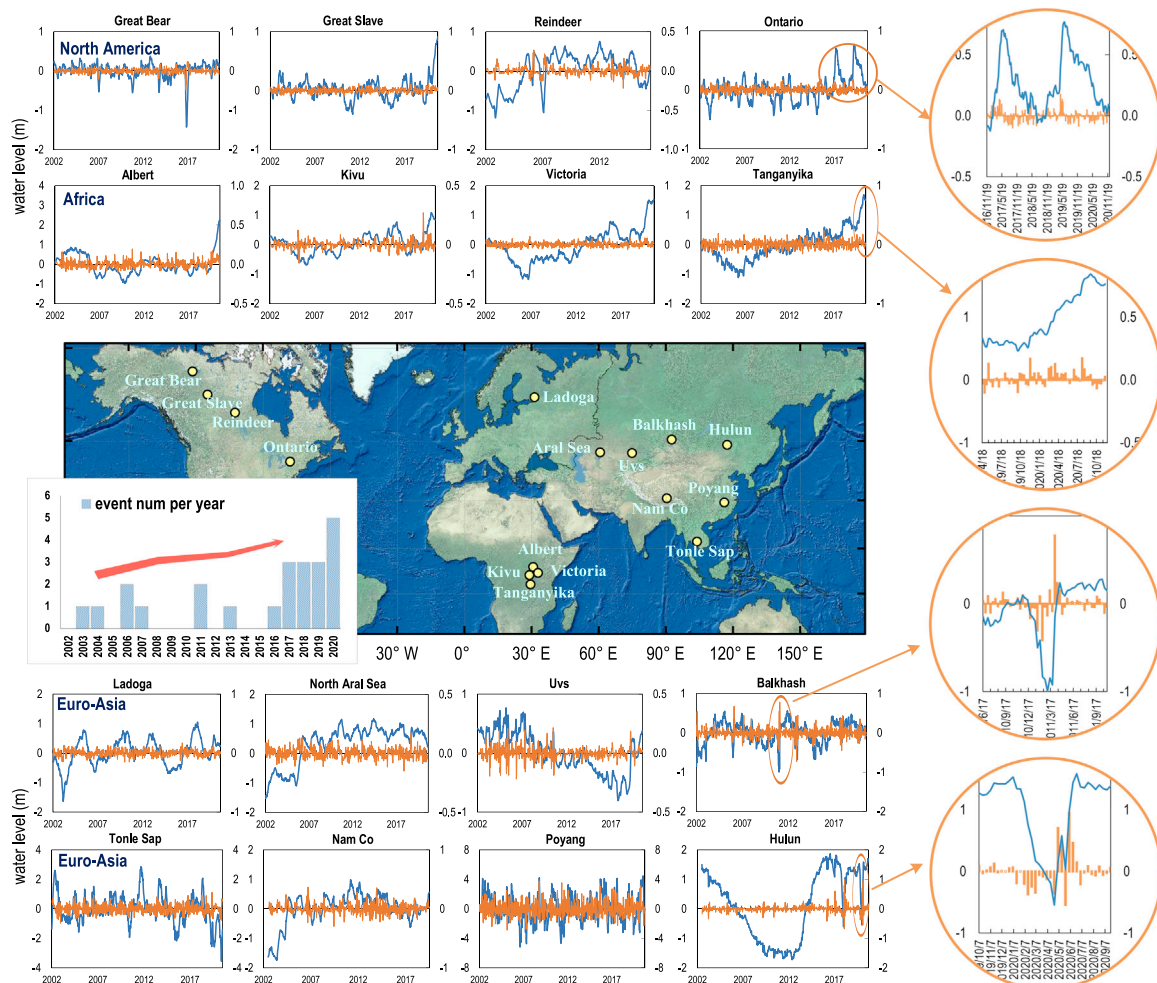


Fig. 1. Water level fluctuations for large lakes on the North American, African, and Euro-Asian continents during the period from 2002 to 2020. Blue lines are 10-day anomalies of water level, normalized from satellite altimeter data, in reference to multi-year seasonal mean. Orange lines are the change rate of the anomalies. Recent sharp change events are zoomed in for Lake Ontario, Lake Tanganyika, Lake Balkhash and Lake Hulun. Satellite altimeter data are available at <https://dahiti.dgfi.tum.de/>.

deterministic rather than stochastic, suggesting that hydrologic events cannot be solely predicted or explained by statistics of the historical events. In the Newtonian paradigm, a change in lake level is the result of the net water balance of lake inflow, over-lake precipitation and evaporation, and outflow (for endorheic lakes). Technically, seasonal and/or decadal oscillations of lake level now can be well described numerically using measured or simulated variables. However, uncertainty about lake evaporation has hindered a full understanding of large water-level change events, especially for those related to drying processes. Recent endeavors have made lake evaporation measurable, which has greatly improved quantifications of water balance components [10,11]. Despite the fallibility, enhanced rainstorm and fastening glacier/snow melting due to climate warming would foster flash floods [12,13], while less rainfall and accompanying high temperatures favor flash droughts [14]. Furthermore, water and energy fluxes from lake surfaces feed back to the diurnal development of the atmospheric boundary layer, and jointly determine local atmospheric circulations that control regional precipitation [15].

In addition to the hydro-climatic forcing, lake water inputs and outputs are subject to anthropogenic influences, particularly in large lakes dominated by humans. Densely populated watersheds are often threatened by flooding or drought. Reservoirs, dykes, and dams are sometimes built along lakeshores to buffer hydrologic extremes. During rainy periods, water might be diverted from surrounding polders into a lake to

increase the lake level. During dry periods, increased water pumping from the lake for irrigation, industrial and other uses could worsen lake water supplies. Moreover, improper water release by upstream reservoirs during rainy seasons and water impoundment during dry seasons could increase the risk of downstream floods and droughts [16]. In the phase switch from rainy to dry or vice versa, the synchronous operation of reservoir for water may amplify or even trigger downstream lake shift between flood and drought. Furthermore, land use changes such as urbanization may aggravate flood peaks [17], and reforestation can enhance droughts due to the large water use by forests, especially young plantations that have high transpiration [18]. Unfortunately, data about anthropogenic influences is often unavailable or discontinuous. Understanding the multi-faceted interactions between anthropogenic catchment, lake dynamics and atmospheric circulation remains a daunting task. Anthropogenic influence deserves a research priority in quantifying lake levels, including long-term lake expansion, shrinkage, and extinction, as well as the magnitudes of floods, droughts and, particularly, their phase shifts. Notably, the long-term trend serves as the baseline, superimposed to the drastic shifts. It may aggravate the shift from flood to drought during the lake shrinkage, and enhance the case from drought to flood during the lake expansion.

In the Darwinian paradigm, the nonstationary theory suggests that anthropogenic climate warming would increase extremes in floods and droughts [19]. Thus, climate change could likely increase the likelihood

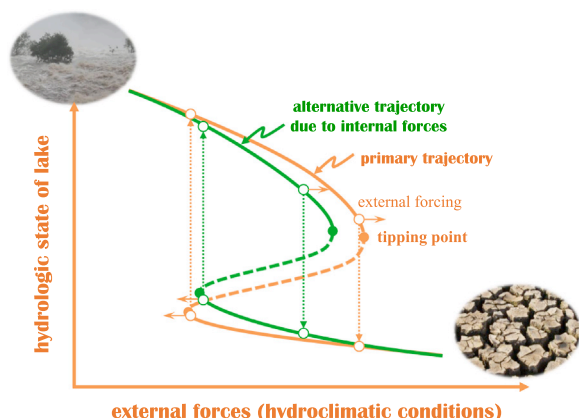


Fig. 2. Illustration of hydro-climatic shifts in lake from one extreme to another. Catastrophic shifts from flood to drought or vice versa may occur due to small forcing in condition passing the tipping point or across the boundary of a basin of attraction. The primary trajectory of the lake dynamics alters, subsequently tipping points, subject to internal and external forces to the catchment. The internal forces may include de-/re-forestation, polder construction, urbanization and other land use, and land cover change, reservoir operation, artificial water drainage and other water uses. The external forces refer to hydro-climatic influences. Anthropogenic influences may enhance or alleviate the shifts through changing trajectory and tipping point (alternative trajectory) upon different water managements.

of consecutive extremes and the shifts between these extremes, not only in rivers [20] but also in lakes. From a regime shift perspective, increased sharp shifts could become a new norm as a result of the hydro-climatic regime passing a tipping point [21], or in combination with altered catchment properties that co-determine the hydro-climatic trajectory [22] (Fig. 2). In spite of the difficulty to detect tipping point, the widely employed intensity-duration-frequency curve offers an option to practically examine whether and when the new norm emerges from the nonstationary time series [23]. Such shifts are generally difficult to predict, posing the challenges for policy makers to manage water in time. Whether these shifts are merely a nonstationary symptom of climate warming or a new normal in the hydro-climatic regime will lead to different planning and decisions in lake management, wetland protection and climatic adaptation.

3. Catastrophic shifts under an uncertain future

More prevalent than the retreating glaciers, lakes are more vulnerable to human modification, an emerging dimension of global changing environment. Even large lakes are supposed to have a higher resilience than smaller lakes, it can be vulnerable under extreme climate conditions in a human-dominated watershed. Other lakes may respond to future climate changes differently. Even in the same hydro-climatic domain, various people have different options to maximize their own benefit, resulting in what is known as “the tragedy of the commons” [24]. Current adaptive use of water promotes positive feedbacks (e.g., draining water into the lake during the rainy seasons and withdrawing during the dry seasons) that will aggravate higher/lower lake levels in rainy/drying periods. Given that human activities are likely to continue to intensify in the future, consecutive and opposite extremes are likely to continue occurring under a changing climate.

In-depth understanding of the emerging extremes deserves high-priority in research in hydrology, limnology, climatology, ecology, anthropology, and other relevant disciplines. In situ observations, satellite monitoring and consistent demographic data are essential to clarification of catastrophic shifts and their background properties for water trajectory, especially including reliable lake evaporation and water use information. The Newtonian and the Darwinian paradigms offer com-

plementary ways to investigate common mechanisms of stationarity and the new normal in global lakes. Worldwide comparison studies are a prerequisite for seeking nature-based solutions to harmonize climate-water-human interactions, especially under large-scale flooding and drought.

In practice, catastrophic lake shifts pose critical threats to sustainable development in lake regions. Consecutive extreme shifts cause more severe damage than single ones, particularly in large-lake regions with a high population density. Notably, the consequences on the human society and economic development may differ between large-shallow lake that has extensive land-lake ecotone (e.g., Poyang Lake) and large-deep lake that hasn't (e.g., Lake Baikal). Current and future risk assessment and management, such as infrastructure construction for both floods and droughts, should take consecutive hazards into account. To live with both extremes, basin-scale cooperative strategies and adaptive measures also should be developed. Early warning systems based on accurate predictions are needed for effective strategies to cope with the catastrophic shifts in over twenty million global lakes and reservoirs on the Earth.

Declaration of competing interest

The authors declare that they have no conflicts of interest in this work.

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