Lake Sevan. Past, present, and future state of a unique alpine lake

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Worldwide, many lakes suffer from multiple anthropogenic pressures often resulting in severe negative effects on ecosystem functionality and associated ecosystem services. Among them, nutrient loading and eutrophication still appear to be the dominant one according to Schindler and Vallentyne (2010) and as documented recently by large scale assessments in the European Union (EEA, 2021), United States (EPA, 2022) and China (Le *et al*., 2010). The nutrient-driven increases in productivity often end in harmful algal blooms (HAB) dominated by cyanobacteria (Huisman *et al*., 2018; Wurtsbaugh *et al*., 2019) or anoxia (Jane *et al*., 2021). But also, water abstractions and the resulting water level fluctuations and dry-outs represent typical man-made pressures with negative effects on aquatic ecosystems (Mosley, 2015). *Via* increase of evaporation from the lake surface but even much more via changes of the water balance of the lakes' catchments climate warming is adding on that and resulting in shrinking lakes (Yao *et al*., 2023). And last but not least, climate warming has accelerating effects on lake ecosystems (Woolway *et al*., 2020). Climate warming causes changes in the thermal regime of lakes, *i.e.*, the typical temperature structures (Woolway and Merchant, 2019) and the timing of mixing and stratification (Kraemer *et al*., 2021), the duration of summer stratification and ice cover (Rogora *et al*., 2018; Sharma *et al*., 2019) and, eventually, it is accelerating internal nutrient loading (North *et al*., 2014) and impacting the entire lake ecosystem (Schwefel *et al*., 2019; Woolway *et al*., 2022).

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Recent studies worldwide documented unequivocally that the typical stressors of lakes interact, potentially leading to enforced negative consequences. There is considerable evidence that climate change is exacerbating eutrophication and HABs (Pearl and Huisman, 2008; Woolway *et al*., 2020; Meerhoff *et al*., 2022) and other effects known from eutrophication like hypoxia and anoxia of the hypolimnion of stratified lakes (Fukushima *et al*., 2017; Rogora *et al*., 2018; Jane *et al*., 2021). Although there had been successes in combatting eutrophication in many countries since the 1970s (Schindler *et al*., 2016), HABs have been increasing there again in recent years (Brooks *et al*., 2016; Ho *et al*., 2019) indicating that contribution from climatic effects are increasingly important (Kong *et al*., 2023).

In order to protect lakes as much as possible and to fulfil human needs in parallel, smart knowledge-based management is needed (Fig. 1). This requires a good understanding of the managed system, here the lakes, their catchments and the anthropogenic use, and, in turn, good monitoring and research on all levels from local to global.

Lake Sevan, a large, deep, alpine lake in the Lesser Caucasus (Fig. 2; Tab. 1) is the focus of this Special Issue of the *Journal of Limnology*. It was an outstanding ecosystem 100 years ago characterised by excellent water quality, rich biodiversity with a high level of endemism, wide-ranging beds of macrophytes along the shores and a productive and sustainable fish production (Hovhanissian, 1994; Wilkinson, 2020). Due to its beauty, natural history, and contributions to social and economic welfare it is also a cultural heritage for the Armenian Nation including its large diaspora (Laplante *et al*., 2005). Furthermore, there is only one larger freshwater lake at the same or at higher altitude (1900 m asl), Lake Titicaca. When ranking all lakes worldwide regardless altitude and salinity, Lake Sevan is on rank

135 according to surface area (Herdendorf, 1982; Williams, 1991; Lehner and Döll, 2004).

This special issue is dedicated to the contemporary Lake Sevan because this lake underwent severe degradation from all three stressors introduced above in the past decades (Legovich *et al*., 1973; Parparov, 1990; Aslanyan, 2020; Gevorgyan *et al*., 2020; Gabrielyan *et al*., 2022) and therefore provides a case study of timely relevance. What happened to Lake Sevan is taking place in many other inland waters in semi-arid regions, which usually are understudied and less monitored than lakes in the temperate zone. We therefore encouraged the development and publication of this special issue, so that the limnological status of this lake and the recent effects from anthropogenic stressors become better documented. This may stimulate similar research at other places and help to sensitize for the dramatic changes in lakes of this particularly harried climatic zone.

This Special Issue of the *Journal of Limnology* comprises the following studies:

Gabrielyan *et al*. (2022) give an overview on Lake Sevan and its development in the last almost 90 years. Based on literature and historical and recent data, the changes in water level, nutrient concentrations and the main components of the biocoenosis (plankton, macrophytes, fish) are reported and the reasons and consequences of them are discussed.

Shikhani *et al*. (2021) present the first modelling study on the consequences of climate change on the thermal regime and stratification of Lake Sevan. The 1D model GLM (General Lake Model; Hipsey *et al*., 2019) was used for that study. Although this model cannot fully reflect the morphometry of Lake Sevan (two sub-basins, named Small and Big Sevan, with different depth of 80 m and 30 m, respectively), the results are reliable and indicate that considerable changes have to be expected for Lake Sevan. Also,

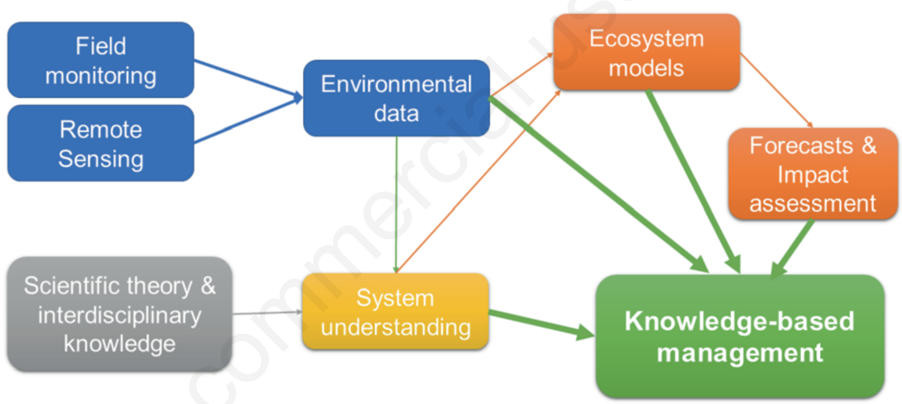

Fig. 1. Contribution of research, monitoring and modelling to knowledge–based lake management.

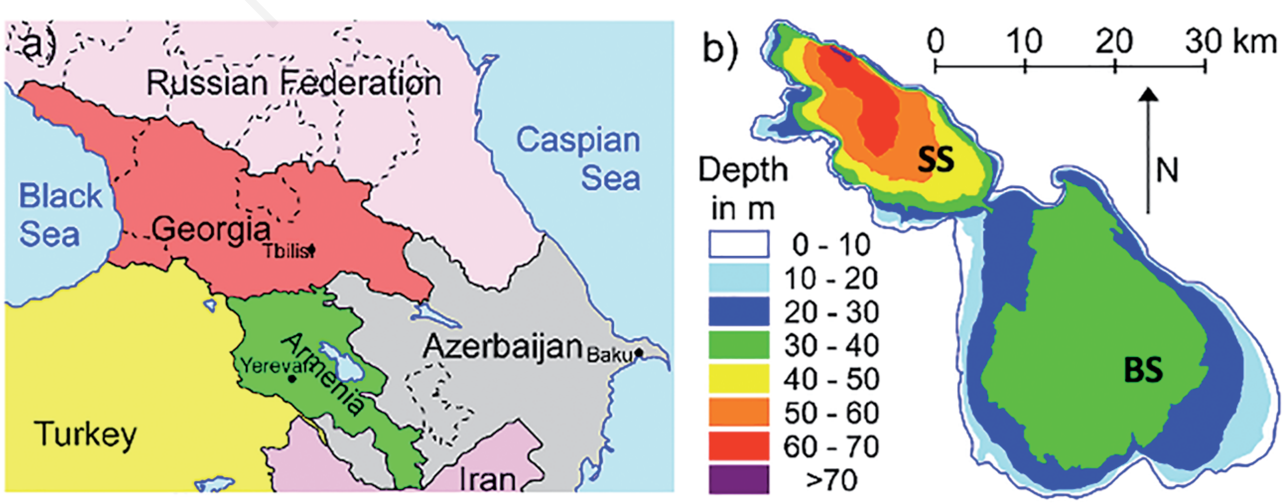

Fig. 2. Location (a) and bathymetric map (b) of Lake Sevan (from Gabrielyan *et al*., 2022).

this model provides an easy-to-use tool for lake management and can serve as a starting point for simulating water quality dynamics.

Hayrapetyan *et al*. (2022) present a four-year study on zooplankton. Since the 1980s, this is the first study presenting data from spring, summer and autumn (three samplings per years) for four consecutive years (2016-2019). The study identified systematic spatial and seasonal patterns of the zooplankton during a particular period: While large crustaceans were dominating in the first two years, smaller zooplankton dominated in the last two years with remarkable consequences on water transparency. However, there were no considerable changes in water level like had been before 2011.

Dadi *et al*. (2022) investigated the phosphorus in the upper lake sediment of Lake Sevan and its potential to be released back into the water. There had been no study on phosphorus in Lake Sevan before, surprisingly. This was combined with a nutrient budget of Lake Sevan. The study demonstrated that there is considerable potential for release of phosphorus back into the water ("internal load") and, at the same time, that the sediment of Lake Sevan is a huge sink for phosphorus. Only a small part of the phosphorus entering Lake Sevan every year is leaving it via the only outflow, Hrazdan River, or remaining in the waterbody.

Gevorgyan *et al*. (2022) looked at the occurrence of trace elements in the water and the sediment of Lake Sevan. There are many small metal ore deposits in the catchment of Lake Sevan (Kaplanyan *et al.*, 1997) and there is also active mining for gold and copper while there had been also mining for chromium in the past. Like for phosphorus, the sediment is a sink for trace elements. Other than for phosphorus, the concentrations in the water body are of no acute concern.

All the papers of this special issue have their limitations and suggest continued future research like *e.g.*, using more sophisticated models (2D or 3D under consideration of water quality and changing water balance of the catchment), using data with higher sampling frequency much better reflecting the dynamics of the ecosystem (*e.g.*, monthly) or investigating the sediment with a more comprehensive spatial resolution and coverage, both horizontally and vertically. Part of that is underway but much is still to be done. We invite the international limnological community to develop new research projects for Lake Sevan and to contribute to the future improved management and protection of Lake Sevan and, doing so, to learn from that example for better understanding and management of other lakes worldwide.

Tab. 1. Morphometric data and water balance of Lake Sevan for 1930 and 2022 (data for 1930 from Pavlov *et al.* (2010) and for 2022 provided by the Hydrometeorology and Monitoring Center SNCO of the Ministry of Environment of the Republic of Armenia).

Year		1930	2022
Morphometry			
Water level	m asl	1915.54	1900.43
Surface area	km^2	1416.0	1277.8
Volume	km^3	58.5	38.1
Maximum depth	m	97.9	82.8
Water balance			
Precipitation on lake surface	$km^3\ a^{-1}$	0.55	0.3379
Total inflow	$km^3\ a^{-1}$	0.77	0.81222
Inflow from rivers	$km^3\ a^{-1}$	–	0.55737
Inflow Arpa–Sevan–Tunnel*	$km^3\ a^{-1}$	0	0.16285
Inflow groundwater	$km^3\ a^{-1}$	–	0.092
Evaporation	$km^3\ a^{-1}$	1.320	1.1047
Outflow Hrazdan River	$km^3\ a^{-1}$	0.05	0.16507
Outflow groundwater	$km^3\ a^{-1}$	0.06	0

**The Arpa–Sevan Tunnel was built (1961–1981 first section, 48.3 km; 1981–2003 second section, 21.6 km) to transfer water from neighbouring catchments into Lakes Sevan.*

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