Monitoring concept for Lake Sevan and its catchment

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Contents

Background

Lakes provide essential ecosystem services to the society like providing raw water for water supply, space for fishery, for recreation, and for sustaining biodiversity. Since human activities can lead to degradation of lake ecosystems, integrated lake management and conservation of lakes is needed for future sustainable use of lakes. This requires a good understanding of the lake ecosystems, up-to-date knowledge of the state of the lake ecosystem, and control of success of implemented management strategies and measures and, thus, continues monitoring of the lakes (Marcé et al. 2016; UNEP WWQA Ecosystems 2023; Cianci-Gaskill et al. 2024).

Therefore, developing a monitoring concept for Lake Sevan was one of the project goals of the German-Armenian research project SEVAMOD2 (https://www.ufz.de/index.php?en=44302). SEVAMOD2 was funded by the Federal Ministry for Education and Research of Germany (Project ID 01DK20038; 91.5% of planned costs) and the Ministry of Environment of the Republic of Armenia (8.5% of planned costs). Developing a monitoring concept for the catchment of Lake Sevan was also a task in the EU-UNDP-project EU4Sevan. In order to reach high efficiency and to avoid redundancies, the work on both concepts was widely combined and done in close cooperation between the mentioned projects and their project partners. This concept is the result of this joint work and integrates different components including the lake, its catchment, its tributaries, and the corresponding hydrological and meteorological variables. The final writing was done by the Department Lake Research of the Helmholtz Centre for Environmental Research – UFZ. All other involved partners are listed in Appendix 1.

This document focusses on the monitoring of Lake Sevan. While the following text includes explanations for the recommended monitoring, Annex 2 provides a table, which summarize the recommended monitoring strategy and the set priorities. The reports on the improvement of the groundwater monitoring, the monitoring of priority substances and the biological monitoring of the rivers entering Lake Sevan are attached to this document as Annex 3, 4, and 5.

Lake Sevan and its catchment

Lake Sevan is one of the largest Eurasian high-mountain fresh water lakes. In the overall list of lakes on Earth, it is at position 136 (based on surface area; Lehner & Döll 2004). This is a very prominent place given that there are >250,000 lakes on Earth (Lehner & Döll 2004). Many of the larger lakes located at a comparable altitude (1900 m asl) are saline lakes making Lake Sevan an even more valuable unique lake. Furthermore, Lake Sevan is the largest freshwater lake in the Caucasus region and has a high relevance as natural water resource for irrigation, hydropower, fishery and recreation and as habitat, even for endemic species (e.g. Gabrielyan et al. 2022). Lake Sevan also has a high cultural value for the Armenian Nation (Laplante et al. 2005).

Such lake requires sustainable management in order to be maintained in good conditions for nature and for future generations. Lake management requires a good understanding of the entire system, here Lake Sevan and its catchment. A sufficient monitoring is key for sustainable management.

Due to the climatic and hydrological conditions, Lake Sevan has a very long flushing time of more than 100 years (volume divided by annual outflow; according to Vincent (2018) the time needed to flush a substance out of a lake). This means that insufficient management will have a long-lasting legacy and that the management of Lake Sevan and its catchment always has to keep in mind long-term consequences of existing or planned practices or measures. Mistakes in the management today, e.g. caused by missing data for predictive modelling and doing well informed decisions will affect Lake Sevan and its ecosystem for many generations. Detrimental management in the past has caused many problems for Lake Sevan like lake level lowering and algal blooms (Hovhanissian 1994;

Arakelyan et al. 2020; Gevorgyan et al. 2020; Gabrielyan et al. 2022). Climate change is expected to worsen the conditions further (Aslanyan 2020; Shikhani et al. 2021). All this is underlining that an adequate monitoring is essential for current and future use of Lake Sevan, its catchment and also the Hrazdan River downstream of Lake Sevan.

In order to overcome the consequences of mismanagement in the past and to extend the management options, water transfer from the neighbouring catchments of Arpa River and Vorotan River have been established. Consequently, the catchments of these two rivers upstream the water extraction for transfer from Kechut Reservoir and Spandarian Reservoir, including these two reservoirs, have to be included into the monitoring for Lake Sevan.

Goals of monitoring Lake Sevan and its catchment

The monitoring of Lake Sevan and its catchment has the following goals:

- Documenting the state of the water bodies and its change over time
- Early alerting of undesirable developments in Lake Sevan or in its catchment
- Providing data that enable system analysis and the identification of the relevant processes in the lake and in its catchment
- Providing data needed for predictive modelling and informed decision making
- Checking and proving the outcome and success of implemented management measures
- Documenting the reaction of the lake and its watershed to climate change.

Due to the agreement between Armenia and the EU, the monitoring also has to support the approximation of the Armenian monitoring system to the principles of the EU Water Framework Directive (EU-WFD 2000). Besides the legal framework given (see EU-WFD 2000), a thorough assessment of the national implementation in the member states is given in Arle et al. (2016). While the EU-WFD distinguishes three activities in environmental monitoring: (1) surveillance monitoring, (2) operational monitoring, and (3) investigative monitoring, the most relevant monitoring sector is certainly the operational monitoring, which include far more monitoring stations and form the core of the status assessment.

The operational monitoring is the tool for assessing the status of those water bodies that probably may not meet the environmental objectives. It is also used to control whether measures have been successfully implemented. For lakes, operational monitoring is mandatory for water bodies larger than 50 ha surface area and include regular monitoring (e.g. every third year, at least 6 times a year for biological components (e.g. phytoplankton, fish, macrophytes) and physicochemical variables (e.g. nutrients, oxygen, transparency). The monitoring of Lake Sevan recommended in this concept largely fulfils the requirements for EU-WFD guided operational monitoring and goes far beyond this framework in many aspects.

The principles of monitoring as developed in the EU are strongly based on bioindication and focus on the description of the ecological state of the monitored water body. This means that simply transferring the monitoring practice from EU member states to Armenia is not enough to fulfil the above defined monitoring goals as they lack important components and do not include the required spatial and temporal resolution of monitoring activities. Furthermore, when considering the limited resources of Armenia, it is more efficient in some cases to divert to some extent from the monitoring practice inside the EU for enabling and supporting sustainable management of Lake Sevan and its catchment.

Current situation

The current monitoring can be divided into the following components:

- Meteorological monitoring
- Lake monitoring
- River monitoring
- Groundwater monitoring

Each of the last three components comprised hydrological monitoring, chemical monitoring, and, in case of Lake Sevan and the inflowing rivers, biological monitoring.

Meteorological monitoring

There are 7 meteorological stations in the natural catchment of Lake Sevan and 2 in the catchments of Arpa and Vorotan rivers. Additionally, precipitation is measured also at 7 of the hydrological stations. The number and location of the meteorological stations is satisfying. The meteorological stations within the catchment of Lake Sevan have been updated to automated observation allowing for up-to-date frequency of measurements according to the requirements of WMO (2021).

Armhydromet is monitoring also atmospheric deposition (Perikhanyan et al. 2020). One of the monitoring stations is relatively close to Lake Sevan, near Tsaghkadsor. Because of the large surface area of Lake Sevan, the relatively small catchment and the considerable contribution of precipitation directly on the lake surface to the water budget of Lake Sevan, the import of nutrients via direct precipitation is also relevant. This monitoring should be continued.

Lake monitoring

Hydrological monitoring

The water level of Lake Sevan is measured at four stations. At these stations, the temperature of the surface water is measured as well near the shore and the occurrence of lake ice and its extension is monitored. All this takes place two times per day and is valuable and satisfying the demand.

From 2001 until 2019, a monthly ship excursion was done by the Hydrometeorological Service of the Ministry of Emergency Situations RA on the last day of the month and measurements were done at 16 sites spread over Lake Sevan. Secchi depth and temperature at different depths at each site were measured. These activities ceased due to technical problems with the used ship and because of administrative issues related to the change of the Hydrometeorological Service from the Ministry of Emergency Situations to the Ministry of Environment. The resulting data are not yet fully explored. However, the temperature data were used for calibration and validation of the model used in Shikhani et al. (2021) and the collected data for Secchi depth (as a measure of transparency) are considered to be a valuable long-term data set that e.g. clearly reflect trophic state conditions (including the occasional occurrence of algal blooms) and food-web-based effects from the temporal dominance of the large cladoceran *Daphnia magna* in the zooplankton community of Lake Sevan, which are well documented in the Russian-Armenian studies from the last 15 years (Krylov et al. 2013, 2015, 2016, 2018, 2019, 2021a,b). Astonishingly, the existing phytoplankton investigations, based on cell counts, could not document these developments in that detail. This indicates this monitoring component as particularly valuable and points to the recommendation to proceed with these monthly campaigns on the lake. In future, the integration of measurements of depth profiles using multiparameter probes would be a major enhancement. Such a probe is meanwhile available at the Hydrometeorology and Monitoring Center of the Ministry of Environment RA (further referred to as Armhydromet) and taking the profile during the sampling campaign requires only approximately

10 minutes so that these measurements can be realistically included in the sampling campaign schedules.

Chemical monitoring

In the last about 10 years, Lake Sevan was sampled three times per year (May, July, October) for chemical analyses. 16 sites were sampled, each at a number of different depths. The analyses comprised major ions, nutrients and a set of trace elements. The goal was to cover spatial and seasonal variations in the concentrations of the analysed water constituents. The temporal dynamics caused by the growth dynamics of the phytoplankton community of Lake Sevan, however, could not be covered by this approach due to the too coarse seasonal resolution and, thus, also not the corresponding spatial differences induced by spatially heterogeneous plankton dynamics. The chemical analyses have been done by Armhydromet. Accordingly, the frequency of the sampling is not satisfying.

Since 2018, a monthly sampling of Lake Sevan at the deepest sites of Small and Big Sevan has been operated within the framework of the German-Armenian research projects SEVAMOD and SEVAMOD2. The higher frequency of sampling reflected much better the temporal dynamics.

Besides taking samples for chemical analyses in the laboratory, measuring temperature, electrical conductivity and concentration of oxygen directly in the field (measured at several depths) became a standard part of the monitoring. In recent years, multi-parameter probes have been included as standard instrument allowing for higher vertical resolution and for higher quality of the produced data. Measuring the Secchi depth as a measure of transparency is also a standard component of the existing monitoring.

Biological monitoring

There have been yearly surveys of the fish population and of macrophytes in the past done by the Scientific Center of Zoology and Hydroecology NAS RA (further referred to as SCZHE). Investigations of the plankton were done mainly within the framework of Russian-Armenian research projects and a research project financed by the Foundation for Restoration of Sevan Trout Stocks and Development of Aquaculture. The sampling was done at 16 sites three times per year in order to cover seasonality and spatial variability. While the current frequency (1-3 times per year) is adequate for the monitoring of macrophyte, benthic organisms and fish populations, the frequency of the plankton sampling cannot cover the temporal dynamics of the plankton. However, seasonal differences were covered and spatial heterogeneity as well (Krylov et al. 2013, 2015, 2016, 2018, 2019, 2021a,b).

Since April 2020, a monthly monitoring of phytoplankton and zooplankton at the deepest sites of Small and Big Sevan was operated as part of the research project SEVAMOD2. A third sampling site was added within the Armenian research project “The rising problem of blooming cyanobacteria in Lake Sevan: identifying mechanisms, drivers, and new tools for lake monitoring and management” (funded by the Science Committee of Ministry of Education, Science, Culture and Sport RA and conducted by the SCZHE under the leadership of Dr. Gor Gevorgyan) near the fish farm in Small Sevan (near Lchap). The higher frequency of sampling allowed for a much better representation of the growth dynamics of the phytoplankton. However, the peaks of bloom events have been not covered and sometimes even a whole bloom remained undetected because wax and wane of the blooms sometimes covers only 2-3 weeks. The spatial heterogeneity could not be well covered too.

River monitoring

In the natural catchment of Lake Sevan, there are 12 hydrological stations along rivers and one at the outflow channel of the Arpa-Sevan tunnel. One of the river stations has to be called “upstream-station” since it is located in the up-stream stretches of Tsaghkashen River which is tributary of

Argichi River. A further hydrological station is located at the outflow of Lake Sevan near Geghamavan downstream the tunnel connecting Lake Sevan with the downstream natural river bed of Hrazdan River. Many of the stations are not automated and not in a good state which is limiting the quality of the produced data. Since all larger rivers flowing into Lake Sevan (8 out of 28 + Arpa-Sevan tunnel) are equipped with a hydrological station, the catchment coverage has been seen as satisfying so far. All ungauged rivers are considered contributing about additional 20% to the inflow into Lake Sevan. Accordingly, the situation can be called acceptable but not satisfying.

Groundwater monitoring

There are only 11 monitoring sites for groundwater in the natural catchment of Lake Sevan. This is a much too low number given the size and the geological and, thus, hydrogeological diversity of the catchment of Lake Sevan, even when considering that according to existing estimates, the groundwater contributes only about 10% of the water flowing into Lake Sevan. Consequently, the situation is unsatisfactory and improvement is needed.

Recommendations for the Lake monitoring

A basic assumption of lake limnology is that there are vertical gradients in the physical and chemical conditions and in the distribution of organisms and their metabolic activities but no comparably strong horizontal gradients. Therefore, doing monitoring at the deepest location of a lake provides representative data for the entire lake. The reason for that is the occurrence of seasonal thermal stratification which limits exchange along the vertical axis leading to the formation of layers (epilimnion on top, hypolimnion at the bottom and metalimnion in between) during the stratified season, which lasts in case of lake Sevan for several months. At the same time, the typical horizontal transport velocities in the epilimnion are in the range of 1 to 20 km per day and of 1 to 10 km per day in the hypolimnion (Imboden & Schwarzenbach 1985) leading to intense horizontal exchange.

However, when the size of a given lake is very large, these assumptions become more and more violated as systematic (and random) horizontal gradients gain importance, e.g. due to inflow locations, meteorological influences, etc. Large lakes and lakes consisting of considerably separated and differing sub-basins like Lake Sevan do therefore not fulfil the prerequisites for the above-mentioned basic assumption of lake limnology. In such lakes, considerable differences have to be expected between existing sub-basins and between different sites in the lake in general. Consequently, more than one location for regular monitoring is required in Lake Sevan and at least the two sub-basins need to be accounted for.

Water level Monitoring

As stated above, the monitoring of the water level of Lake Sevan is basically satisfying. It should be continued. The monitoring equipment should be maintained and updated where needed.

Chemical monitoring

Each sampling should contain the measurement of Secchi depth and of the key physico-chemical quantities temperature, electrical conductivity, pH value and concentration of dissolved oxygen in the field. The latter ones should be measured at high vertical resolution from surface to bottom using multi-parameter probes. If the used probes allow for that, additionally turbidity, chlorophyll a and an optical indicator for cyanobacteria (e.g. phycocyanin fluorescence should be measured. Since the measurements with multi-parameter probes does not require much time such measurements could be done at even more locations than the collection of water samples for analysis in the laboratory.

As in all environmental monitoring programmes, a trade-off between spatial resolution and sampling frequency exists and both need to be optimised with respect to balancing effort, costs, and information. Given the existing knowledge of ecosystem dynamics in Lake Sevan we propose the following strategy. The sampling for chemical monitoring should be done monthly. Keeping the sampling frequency on that level is more important than sampling more than two sites in Lake Sevan: the deepest sites of Small and Big Sevan. However, sampling both sub-basins is a needed as a minimum.

Since the main water quality concern for Lake Sevan are eutrophication and harmful algal blooms, the focus of the chemical monitoring should be the concentrations of nutrients, i.e. the chemical species of phosphorus, nitrogen, silica and carbon. However, the program of chemical analyses as used by Armhydrometin the last years (e.g. targeting on trace metals and other major cations/anions) should be continued as far as possible to allow for comprehensive evaluation of the produced monitoring results. Even some extensions have to be recommended: (i) analysis of the chlorophyll a concentration; (ii) analysis of dissolved sulphide/hydrogen sulphide in the samples taken from the deepest layers of Small and Big Sevan at the end of the summer stratification. The analysis of chlorophyll a has been done by SCZHE sing May 2018 and should become a standard method in for Armhydrometas well. Since the occurrence and relevance of sulphate reduction has been demonstrated in Lake Sevan recently (Avetisyan et al. 2021) and sulphate reduction is known to be a key-factor for the potential of lake sediments to store or release phosphorus (i.e. for eutrophication; e.g. Heinrich et al. 2021), the occurrence of dissolved sulphide/hydrogen sulphide should be quantified. Avetisyan et al. (2021) have not investigated the spatial and temporal extension of sulphate reduction in Lake Sevan over an entire stratification period. Therefore, a quantification the spatio-temporal extent and variation of sulphate reduction would be beneficial for a risk assessment. Based on the results from such a campaign, an adaptation of this monitoring component may become relevant.

Biological Monitoring

In addition to the established yearly surveys of macrophytes and fish community, a monthly monitoring of phytoplankton and zooplankton is required. Like for the chemical monitoring, high sampling frequency is more important that high number of sampling sites although the lateral heterogeneity of the phytoplankton, at least during blooms, is obvious from satellite images (see e.g. Aslanyan 2020; Gevorgyan et al. 2020). Covering this heterogeneity by traditional sampling is not possible since the effort for taking enough samples within one day is technically not possible and not efficient, particularly when compared to remote sensing (see below).

Remote sensing

Satellite based remote sensing allows for measurements of the entire lake surface within one moment, the moment of satellite overpass. Therefore, remote sensing is able to overcome the problem of heterogeneity in the horizontal direction occasionally occurring in large lakes. In the last decades, data from remote sensing became increasingly available, partly even freely. Based on that, remote sensing was increasingly used for lake water quality monitoring. However, remote sensing has important limitations: (i) only the surface layer can be monitored via remote sensing; (ii) only a limited number of quantities can be monitored (turbidity, concentration of chlorophyll, water temperature); (iii) clouds and reflection of sunlight from the lake surface (sun glint) can exclude the use of single satellite images partly or even completely. The research work within the project SEVAMOD2 found that satellite images of Lake Sevan are almost never usable in winter and that about 30% of satellite images cannot be used in the rest of the year.

The evaluation of the usable satellite images of Lake Sevan within the project SEVAMOD2 showed that the quantitative detection of the concentration of chlorophyll a in the epilimnion is not yet possible. There are not yet enough data. However, the detection of harmful algal blooms worked, even when not (yet) covering the entire lake. The detection of the blooms was found to be more robust that possible based on monthly sampling at the deepest sites of Small and Big Sevan. Therefore, the use of remote sensing should be used as supporting method for monitoring Lake Sevan.

In addition to satellite based remote sensing, more and more other approaches were used for remote sensing and sampling in the last years (Kwon et al. 2023). So-called unmanned areal vehicles (UAV), unmanned surface vehicles (USV) and unmanned underwater vehicles (UUV) were used for that. The UAVs were not only used for the measurement of optical quantities analogously to satellite based remote sensing but also for measurements by multi-parameter probes and for taking water samples from different depths (Kwon et al. 2023). For Lake Sevan, Medvedev et al. (2020) demonstrated the potential benefit of UAVs for monitoring and investigation along the shore line. The advantage of UAVs over satellites are the much higher spatial resolution and the wide independence from cloud cover while the disadvantage is the time needed for collecting the data. Covering the entire lake within one moment is not possible by using UAVs. A further important limitation is the limited power and carrying capacity which in turn limit the distances that can be flown and the mass (i.e. the number and weight of equipment and water samples) that can be transported. USVs have been used for bathymetric surveys, for measurements by multi-parameter probes and for taking water samples from different depths while UUVs were used for optical inspection of the lake bottom, for measurements by multi-parameter probes and for taking water and sediment samples (Kwon et al. 2023). E.g., UUVs have been used by the Lake Biwa Environmental Research Institute (Japan) for the investigation of benthic animals since more than 10 years (Ishikawa et al. 2014). Although the power and carrying capacity of USVs and UUVs is usually much bigger than that of UAVs, these capacities are still limiting the use of USVs and UUVs.

Theoretically, UAVs, USVs and UUVs can be operated both fully autonomously along a pre-defined pathway or remotely in real-time by operators standing at the shore or being on board of a vessel. In case of Lake Sevan, the gillnets used by the fishermen hardly allow for the autonomous operation of USVs and UUVs. Due to this and the above-mentioned limitations, the use of UAVs, USVs, and UUVs cannot yet be recommended for use in the standard monitoring of Lake Sevan while there might be special investigations that can be very well done by the use UAVs, USVs, or UUVs. E.g. the complete mapping of locations of gas release from the bottom of Lake Sevan as described in Avagyan et al. (2020) could be done by remotely operated UUVs, particularly in the deep parts of Lake Sevan where divers reach their limits. In future, further technical improvement may change the situation may make UAVs, USVs and UUVs standard equipment for standard monitoring.

Recommendations for the Monitoring of the catchment of Lake Sevan

Meteorological monitoring

Although the number and location of the existing meteorological stations is satisfying and the stations have recently been updated, some further improvement is recommended. The accessibility of the two high altitude station in the catchment of Lake Sevan should be improved in winter in order to allow for continuous maintenance also in winter and, thus, avoiding interruption of observations due to snow cover. The stations should be brought technically on an up-to-date level, at best follow the WMO recommendations (WMO 2021). Important aspects for meteorological stations will be:

The monitoring of the atmospheric deposition should be continued as mentioned above. We also recommend further research, if the monitoring needs to be adapted regarding its extent (e.g. more detailed monitoring of the dry deposition) and if a different monitoring site or additional monitoring sites are needed to collect representative data for Lake Sevan and its entire catchment.

Groundwater

The development of the concept for the improvement of the groundwater monitoring was subject of the separate study “Groundwater Monitoring Concept for Lake Sevan and its Watershed”, prepared by the Hydrogeology group of the Institute of Applied Geosciences of the Technical University of Darmstadt (Germany) and the Department Catchment Hydrology of the Helmholtz-Centre for Environmental Research – UFZ (Germany) and completed in February 2024. This study was financed by the EU project EU4Sevan. The following text is the summary of the study, placed here literally.

Due to Lake Sevan’s outstanding role for Armenia and a number of environmental issues, the lake and inflowing streams have been intensively studied and monitored over the last years and decades. Groundwater, however, received far less attention, despite its proved contribution to the lake and the fact that it is also used for various purposes.

As the currently conducted groundwater monitoring yields valuable data, the active sites should also be part of future monitoring activities. It is however recommended to complement them with 10 to 15 additional sites to better cover the Lake Sevan area.

For the selection of artesian wells and springs as new monitoring sites, a range of criteria should be considered, depending on the monitoring purpose (lake-centric vs. “general” monitoring). An area’s potential for groundwater inflow into Lake Sevan may, for instance, play a role, but the prevailing geology is relevant too. Groundwater use in a certain area and critical contaminant concentrations encountered in previous analyses will play a role as well. Practically, it obviously also matters if suitable wells or springs are available in a targeted area at all.

The currently studied parameters (discharge, temperature, water level, major ions, trace elements) represent a reasonable selection, but it is recommended to also include the stable isotopes of water ($\delta^{2}H$, $\delta^{18}O$). The fingerprinting potential of these tracers can give valuable, complementary insights into relevant processes and fluxes. Yet, such an endeavour would also imply a need for δ2H and δ18O monitoring in other compartments of the local water cycle (precipitation, Lake Sevan, contributing streams).

The temporal resolution of discharge, temperature, and piezometric level monitoring is currently five days, which seems appropriate, given the reliance on local residents as observers. For the hydrochemical monitoring component, however, quarterly sampling would be better than the currently used half-year intervals, as the latter do not allow a detection of seasonal changes.

As parameters such as discharge, temperature, pressure/piezometric level, or EC can be measured automatically, the deployment of corresponding automatic loggers, possibly with telemetric data transfer, is an option. The key advantage would be a better temporal resolution, but higher costs and a certain vandalism risk have to be considered.

The recommended intensification of the monitoring efforts (more sites, higher resolution) would obviously be associated with higher costs, making an adequate increase of the ArmHydromet budget necessary.

Rivers

Hydrological monitoring

As stated above, the established hydrological monitoring is acceptable but not satisfying yet. Most stations are not equipped with modern automatic instruments and also need improvement of the flow channel at the monitoring site in order to allow for producing high quality data. A big improvement would be realised if gauges facilitate at least hourly observations of water levels and/or discharge and electronic data storage or transfer.

The estimation of the contribution of ungauged rivers and streams is based on older investigations. Despite the limited contribution of these rivers and streams to the overall inflow, these rivers and streams should be subject of hydrological monitoring for a limited number of years in order to check the currently used estimate and make it more precise if required. The needed observations have not to be made at all the small rivers in parallel. However, this is not a first priority issue and rather a long-term task.

Chemical monitoring

Sampling the rivers flowing into Lake Sevan monthly is an adequate frequency. However, the usually occurring gap in the winter need to be closed.

For some rivers, sampling was done not only at the inflow into Lake Sevan but also at a second location upstream. This strategy should be continued and as far as possible extended and further improved. Such upstream sampling should be located in that way that it allows for characterising the natural background or a particular influence of a certain kind of land use (e.g. urban area, life stock breeding, arable farming) or major pollution sites from point sources. As far as possible, such additional sampling should also be accompanied by hydrological measurements in order to not only measure concentrations but to quantify the transport of substances into Lake Sevan.

The water inflow via Arpa-Sevan tunnel is basically well monitored, like other inflowing rivers. However, for designing the management of the upstream catchment, a good monitoring of the rivers Arpa and Vorotan and the reservoirs Kechut and Spandarian is also needed. This monitoring should follow the same principles like the monitoring of Lake Sevan and the rivers in its natural catchment.

Biological monitoring

The biological monitoring of the rivers and streams in the catchment of Lake Sevan had been the subject of a recent study (Kazanjian & Asatryan 2022). Therefore, it is not discussed here. The main recommendations and findings of the study were:

The biological monitoring of the rivers flowing into Lake Sevan should be based on phytobenthos, macrophytes, macroinvertebrates and fish with a focus on phytobenthos and macroinvertebrates. This is in line with the requirements of the EU-WFD and helps reaching the needed adaptation of the Armenian monitoring to the EU-WFD. The monitoring sites should be located as close as possible to the sampling sites for chemical monitoring and also for the hydrological monitoring. This will allow for an integrative ecological evaluation and for the identification of stressors which may have caused impacts on the aquatic communities found by the biological monitoring.

A not yet fully solved issue is the definition of reference conditions and the identification of indicator species suiting for Armenia. This also applies for the definition of river types. Although research has been done on that in the past (e.g. EUWI+ 2020; Asatryan & Dallakyan 2021), further work is needed. However, this open issue is no reason to wait with the implementation of the monitoring since it is related to the final ecological evaluation of the monitoring results. I.e. collecting data is already possible now. When including river stretches which are (almost) uninfluenced by human activities, this may even help identifying indicator species and defining reference conditions. Due to the limited capacities of Armhydromet for biological monitoring, Kazanjian & Asatryan (2022) recommend inclusion of the Scientific Center of Zoology and Hydroecology NAS RA into the monitoring.

Further aspects

Priority substances

The monitoring according to the requirements of the EU WFD includes the regular analysis of so-called priority substances. The monitoring of these substances has been subject of a separate study

(Minasyan & Shahnazaryan 2022). Therefore, these substances were not considered in this concept in detail. According to the results of Minasyan & Shahnazaryan (2022), there is evidence that the priority substances do not play an important role in Lake Sevan and its catchment. However, the study also addressed considerable limitations and gaps related to the occurrence and handling of priority substances or other chemicals having comparable properties and associated environmental risks. Therefore, the documented knowledge gaps should be closed as soon as possible and an update of the survey conducted in 2015 is also recommended to be done every 5 years under consideration of the results of previous surveys and knowledge about the use of relevant chemicals in the catchment of Lake Sevan.

Development of biological monitoring schemes specific for Armenia

Within the frame of EU4Sevan, tailored biological monitoring schemes for Armenia has been developed, including identification of suitable indicator organisms (Kazanjian & Asatryan 2022). This is an excellent concept to build a future monitoring centred on bioindication in line with current EU regulations. Based on the experiences of application and further research, a regular check and update of the applied monitoring should be done.

Increasing relevance of (micro-) plastic

In recent years, plastic has been identified as an important pollution in rivers and lakes (Koelmans et al. 2019; Dusaucy et al. 2021). Recent research indicates that this is also relevant in Armenia (Khosrovyan et al. 2020, 2023). However, although guidelines for monitoring plastic in rivers and lakes have been published by the United Nations Environmental Program (Wendt-Potthoff et al. 2021), the methodology is not yet ready for routine monitoring (Blettler et al. 2018; Koelmans et al. 2020). Therefore, we recommend starting with a survey study for Lake Sevan and its inflows, e.g. as a research project. According to Wendt-Potthoff et al. (2020), the very first step should be focussed on macroplastic in order to get an estimate of the potential of contamination. Based on the completed survey, more detailed strategies can be developed for a targeted and efficient future monitoring.

Monitoring water use

The River Basin Management Plan for Sevan River Basin District (Arakelyan et al. 2020) identified considerable knowledge gaps regarding water abstraction, water use, wastewater quantity and quality regarding the catchment of Lake Sevan. These gaps need to be closed for a sustainable water management. Since this issue does not directly belong to the monitoring of Lake Sevan and water bodies in its catchment, it is not discussed here. However, the strong need for a comprehensive monitoring of the water use and the water quality of discharged wastewater has to be underlined here one more time as it constitutes not only a major management component but will moreover become a crucial aspect in assessing climate change impacts on Lake Sevan. The future practise in water abstractions for irrigation, aquaculture and water supply as well as the wastewater management will be major determinants in the resilience of Lake Sevan towards climate change and a proper assessment followed by a set of future regulations is required here.

Data management and data evaluation

Monitoring produces many data. Therefore, a systematic handling, quality check and evaluation of the produced data is needed. This requires centralised data infrastructures, technical equipment and qualified personnel, which still needs to be improved in Armenian environmental monitoring and, therefore, is underlined here. Collecting monitoring data without regular data evaluation hardly makes sense. A regular evaluation of the collected monitoring results is not only important for quality control but also provides the information basis for a sustainable and adaptive management of Lake Sevan.

Large technical equipment

For the regular sampling on Lake Sevan, a vessel is needed. The currently used vessel is quite heavy and robust but rather outdated and economically inefficient due to very high costs for fuels and maintenance. The Science Committee of MESCS RA provided this year the money needed for such new vessel, including some equipment. The intended joint use by SCZHE and Armhydrometis a very efficient approach for future monitoring of Lake Sevan.

In recent years, automated stations and buoys have been implemented on many lakes. They allow for a new quality of monitoring due to the high frequency of measurements when using up-to-date equipment. However, buying and operating such facilities is expensive. Considerable regular maintenance is needed and additional efforts for the large amount of produced data, as well. Operation of such facilities makes sense only if there is an option to use the continuous availability of actual data for rapid implementation of management measures. Given that the core water quality problem of Lake Sevan is eutrophication and e.g. wastewater treatment is widely missing, the implementation of automatic monitoring stations on Lake Sevan cannot be recommended for standard monitoring currently. The limited resources should rather be committed to other measures (e.g. reducing nutrient loading from waste water). As part of research projects that aim to get deeper insights into the functioning of the ecosystem of Lake Sevan, the temporal use of such automated facilities can make sense.

Trans-institutional cooperation

Armhydromet has started to build up its own capacities for biological monitoring. However, the recommended monitoring cannot be done by this group today. Therefore, the inclusion of SCZHE into the monitoring based on an agreement between Armhydromet and SCZHE would be a good option from the point of view of the authors. SCZHE has experienced personnel and provides a work environment that allows for keeping the personnel on an up-to-date scientific level. There is the option for a win-win-situation: The monitoring is done on an adequate scientific level and the produced data can support ongoing research on Lake Sevan and its ecology.

Basically, the same has to be stated regarding remote sensing. Armhydromethas started building up own capacities for forest monitoring but is not yet able to take over monitoring Lake Sevan by satellite based remote sensing. The Center for Ecological-Noosphere Studies of the NAS RA (CENS) has the needed competences and could support the monitoring until Armhydromet will be able to fully take over.

Complementary research options

For the characterisation of the state of Lake Sevan and for its management some additional improvements of knowledge is desirable which does not belong to the category “monitoring” but rather to the category “research”. This applies for instance for the preparation of a new bathymetric map. The last comprehensive bathymetric survey was made in the 1920s to our knowledge. Modern equipment allows for much higher precision and would provide a more reliable dataset for predictive modelling Lake Sevan. In order to allow for simulation and assessment of higher water levels and also for managing the coastal zone of Lake Sevan, data for a high-resolution digital elevation model of the direct vicinity of Lake Sevan should be conducted, at least including the water level to be reached in 2030 according to current Armenian legislation. Ideally, the entire area that fell dry due to the water level reduction since 1930 should be included.

There are some investigations on the composition of the sediment of Lake Sevan but no comprehensive one. Since sediments are a key component of lake ecosystems their comprehensive characterisation and a quantitative understanding of the interactions between water body and sediment is very valuable for sustainable lake management. However, this cannot be part of standard monitoring. Well-designed research projects are the suitable way to address this issue.

Final remarks

The authors are aware that the implementation of the proposed monitoring requires considerable resources and that the resources of Armenia are limited, like for every country. However, Lake Sevan is an exceptionally important and valuable water body and its sustainable management will not be possible without an adequate monitoring. We tried to keep our recommendations as small as possible and to differentiate between indispensable minimum requirements and additional options for improvement.

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Appendix 1

Project partners involved into the preparation of the Monitoring Concept for Lake Sevan and its catchment

- Hydrometeorology and Monitoring Center state non-commercial organization of the Ministry of Environment of the Republic of Armenia (Armhydromet), Yerevan, Armenia
- Scientific Centre of Zoology and Hydroecology of the National Academy of Sciences of the Republic of Armenia, Institute of Hydroecology and Ichthyology, Yerevan, Armenia
- Center for Ecological Noosphere Studies of the National Academy of Sciences of the Republic of Armenia (CENS), Yerevan, Armenia
- Team of EU4Sevan of GIZ Armenia, Yerevan, Armenia
- Technical University of Darmstadt, Institute of Applied Geosciences, Hydrogeology group, Darmstadt, Germany
- Helmholtz-Centre for Environmental Research – UFZ, Department Catchment Hydrology, Halle/Saale, Germany
- Acopian Center for the Environment, American University of Armenia, Yerevan, Armenia
- A.B. Nalbandyan Institute of Chemical Physics National Academy of Science of the Republic of Armenia, Yerevan, Armenia

Appendix 2

Summary of recommended monitoring; priority substances, biological monitoring of rivers and groundwater monitoring are not considered

Compartment	**Category**	**Must have**			**Nice to have**		
		Quantities to be measured/analysed	Spatial resolution	Frequency	Quantities to be measured/analysed	Spatial resolution	Frequency
Atmosphere	Meteorology	air temperature, humidity, wind speed, wind direction, cloud cover, global radiation, precipitation	9 stations	hourly		additional floating station on Lake Sevan	10 minutes
Atmosphere	Meteorology	Atmospheric deposition (wet and dry), mainly nutrients, if possible further chemicals	1	daily		more stations	
Lake water	Hydrology	water level, water temperature, air temperature, ice phenomena	4 stations	daily			hourly
Lake water	in-situ water quality parameters	Secchi depth	deepest sites of Small and Big Sevan	monthly		more stations	bi-weekly during growing season
Lake water	in-situ water quality parameters	O_2 concentration, pH, electrical conductivity, chlorophyll concentration	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly	turbidity, phycoerythrin sensor, phycocyanin sensor	more stations; continuous depth profiles	bi-weekly during growing season
Lake water	Chemistry (laboratory)	nutrients: soluble reactive phosphorus, total phosphorus, nitrate, ammonium, silica	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly	nitrite, total nitrogen	more stations	bi-weekly during growing season
Lake water	Chemistry (laboratory)	major ions: Na, K, Mg, Ca, Cl^-, SO_4^{2-}	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly		more stations	
Lake water	Chemistry (laboratory)	alkalinity	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly		more stations	bi-weekly during growing season
Lake water	Chemistry (laboratory)	carbon components: DOC, TOC, DIC, TIC	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly	POC, PIC	more stations	bi-weekly during growing season
Lake water	Chemistry (laboratory)	iron, manganese	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly		more stations	bi-weekly during growing season
Lake water	Chemistry (laboratory)	trace elements	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly	rare earth elements	more stations	
Lake water	Chemistry (laboratory)	chlorophyll a	deepest sites of Small and Big Sevan; 9 depths in Small Sevan, 7 depths in Big Sevan	monthly	phycocyanin	more stations	bi-weekly during growing season
Lake water	Biology	phytoplankton	deepest sites of Small and Big Sevan; 0m, 0-20 integral (taken at 0, 0.5, 5;10,20),bottom	monthly		more stations, higher depth resolution	bi-weekly during growing season
Lake water	Biology	zooplankton	deepest sites of Small and Big Sevan; one vertically integrated sample (net)	monthly		more stations, higher depth resolution	bi-weekly during growing season
Lake water	Biology	fish	whole lake	2 times per year			
Lake water	Biology	macrophytes	5 transects	yearly		more transects	
Lake water	Biology	macrozoobenthos	5 transects, 3 depths	3 times per year		more transects	

Compartment	Category	Must have			Nice to have		
		Quantities to be measured/analysed	Spatial resolution	Frequency	Quantities to be measured/analysed	Spatial resolution	Frequency
Lake sediment	Chemistry (laboratory)	water content, grain size distribution, silica, biogenic silica, TIC, TOC, loss on ignition, nutrients, iron, manganese, trace elements	deepest sites of Small and Big Sevan;	every 5 years	rare earth elements, sequential extractions of phosphorus and metals; dating of the sedments	five or more transects and three or more depth	
Rivers	Hydrology	discharge, water temperature, air temperature	main inflows, outflow	daily		more rivers, more up-stream stations	hourly or higher frequency
Rivers	in-situ water quality parameters	O_2 concentration, pH, electrical conductivity	main inflows, outflow	monthly	turbidity	more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	nutrients: soluble reactive phosphorus, total phosphorus, nitrate, ammonium, silica	main inflows, outflow	monthly		more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	major ions: Na, K, Mg, Ca, Cl^-, SO_4^{2-}	main inflows, outflow	monthly		more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	alkalinity	main inflows, outflow	monthly		more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	carbon components: DOC, TOC, DIC, TIC	main inflows, outflow	monthly	POC, PIC	more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	BOD, COD	main inflows, outflow	monthly		more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	iron, manganese	main inflows, outflow	monthly		more rivers, more up-stream stations	bi-weekly during flood period
Rivers	Chemistry (laboratory)	trace elements	main inflows, outflow	monthly	rare earth elements	more rivers, more up-stream stations	bi-weekly during flood period