Groundwater Monitoring Concept for Lake Sevan and its Watershed

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Abbreviations

CIS	Common Implementation Strategy
EC	electrical conductivity
GIZ	Gesellschaft für Internationale Zusammenarbeit
IAEA	International Atomic Energy Agency
WMO	World Meteorological Organization
GNIP	Global Network of Isotopes in Precipitation
masl	meter above sea level
meq	milliequivalent
psi	pound per square inch
SNCO	State Non-Commercial Organization
TUDa	Technical University of Darmstadt
WFD	Water Framework Directive
UFZ	Helmholtz-Centre for Environmental Research

1 Introduction

This groundwater monitoring concept for Lake Sevan and its watershed is an outcome of the project “Baseline Study Providing Guidance for a Comprehensive Monitoring Concept Development for Lake Sevan and its Watershed”. The work was funded by Gesellschaft für Internationale Zusammenarbeit (GIZ), Armenia, within the framework of the EU4Sevan project.

The sub-project was carried out by representatives of Technical University of Darmstadt (TUDa) and Helmholtz-Centre for Environmental Research (UFZ). Related deliverables comprise 1) a report summarizing the results of two field campaigns (9-16 October 2022, 3-10 May 2023; see Appendix) and 2) this groundwater monitoring concept, which builds on the former report.

Water monitoring enables informed decisions and forms the basis for an effective water resources management. This holds true generally, but water monitoring and management are particularly important for Lake Sevan and its catchment. First, the lake is of paramount importance for Armenia, for economic, ecologic, and cultural heritage reasons. Second, Lake Sevan’s history has demonstrated a number of detrimental impacts of anthropogenic activities (summarized in Gabrielyan et al. 2022). In the 1930s, intense water abstraction was initiated, for power generation and irrigation purposes. Water use peaked in the late 1940s and early 1950s, and continued until the 1980s. The result was a water level drop of about 19 m, which was partly counteracted by recent restoration efforts. Nevertheless, the outlined water level development impacted the thermal regime and stratification of the lake and its ecology. Algal blooms occurred and the trout stock was reduced. Changes in the lake’s catchment added to the problems. An increased population and intensified fertilizer use caused an increased nutrient input, triggering eutrophication.

Due to these developments, the lake and inflowing streams were studied and closely monitored over the last years and decades. In contrast, the surrounding groundwater received less attention, also due to its apparently relatively small role in the lake’s water balance (Shahnazaryan et al. 2022). Nevertheless, groundwater is an integral part of the local water system and should be considered in a holistic monitoring concept. In this context, it should also be noted that the groundwater is used for a range of purposes, incl. irrigation, animal watering, and human consumption. Moreover, groundwater contributes significantly to stream flow in the area (EUWI+ East 2021).

Importantly, monitoring of the groundwater resources, in terms of quantity and quality, is not only relevant for capturing today’s water cycle and for studying related chemical fluxes, it also provides valuable baseline data for the future. As climate change is likely to have a significant impact on Armenia’s water resources (Arakelyan and Margaryan 2023), the hitherto gathered and future monitoring data will help to study how prone local groundwater resources are to corresponding impacts.

The following Section 2 provides a brief *status quo* description, i.e., the current monitoring activities are summarized. Section 3 outlines suggestions for an adaption and improvement of monitoring concept. In Section 4, additional measures and studies are proposed.

2 Current monitoring activities

The current monitoring activities of the Armenian Hydrometeorology and Monitoring Center (ArmHydromet, SNCO of the Ministry of Environment, Republic of Armenia) comprise two components: 1) parameters that are related to available water quantities (e.g., discharge, water levels) and 2) hydrochemical parameters for monitoring water quality.

2.1 Discharge, temperature, and water levels

Discharge and water temperature are regularly measured at a number of springs and (mostly artesian) wells (Fig. 1). At these wells, water levels (piezometric levels) are measured additionally. Currently, 15 sites are under observation.

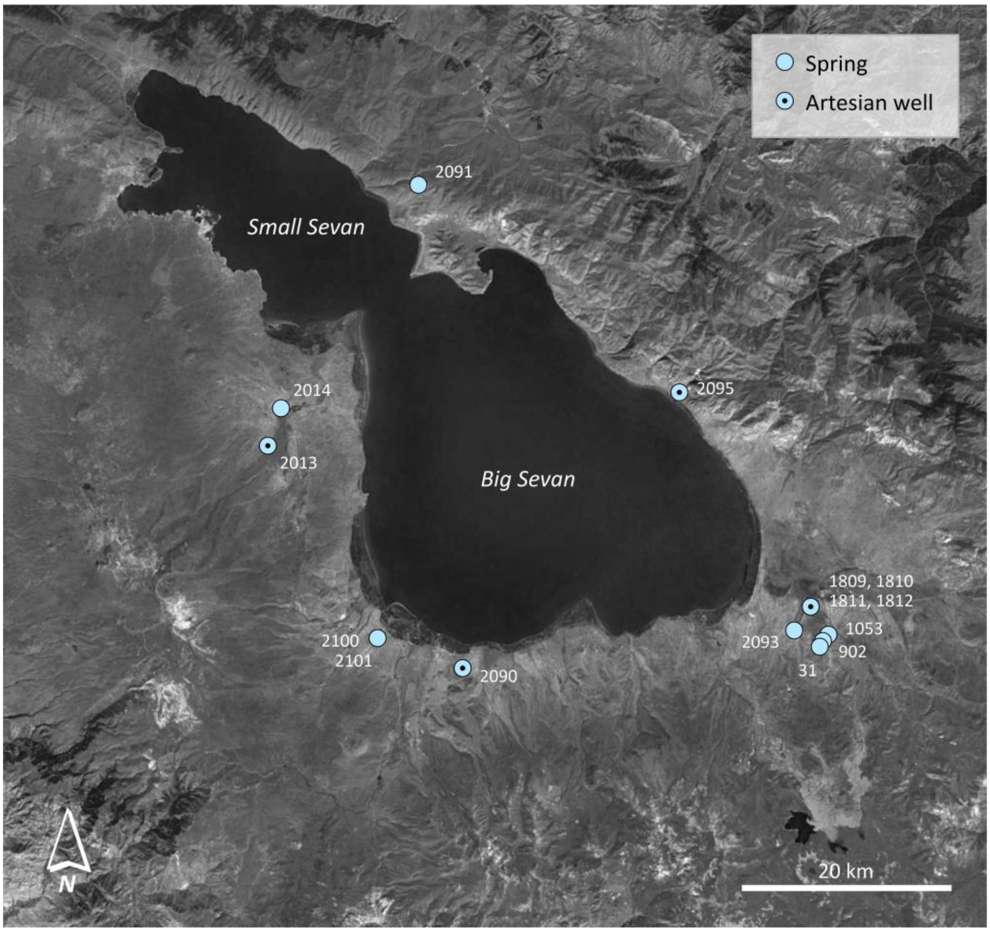

Figure 1: Map showing the monitoring points at which discharge and water temperature are measured as part of the current monitoring scheme. At artesian wells, piezometric water levels are measured additionally. Note that the sites are not evenly distributed around the lake.

The sites are not evenly distributed, but concentrated in the south. Particularly noteworthy is a cluster of monitoring sites located south-east of Lake Sevan. The wells 1809, 1810, 1811, and 1812 are situated in direct vicinity to each other (max. distance 200 m), but exhibit different depths. The reason for the clustering in this area is the general consensus that the largest groundwater inflow into the lake happens here.

The monitoring is coordinated by ArmHydromet representatives, but the practical work is usually carried out by local residents. They visit the field sites approximately every five days and measure discharge [L/s], mostly at weirs, and water temperature [°C]. The water level of artesian wells is determined with a manometer after closing a valve. The obtained pressure is then converted into a piezometric level [m above ground/well head].

The gathered values are compiled in Excel tables and the individual readings are used to calculate monthly means. Such monthly averages are exemplarily shown for three selected sites for the time period 2012-2023 in Fig. 2.

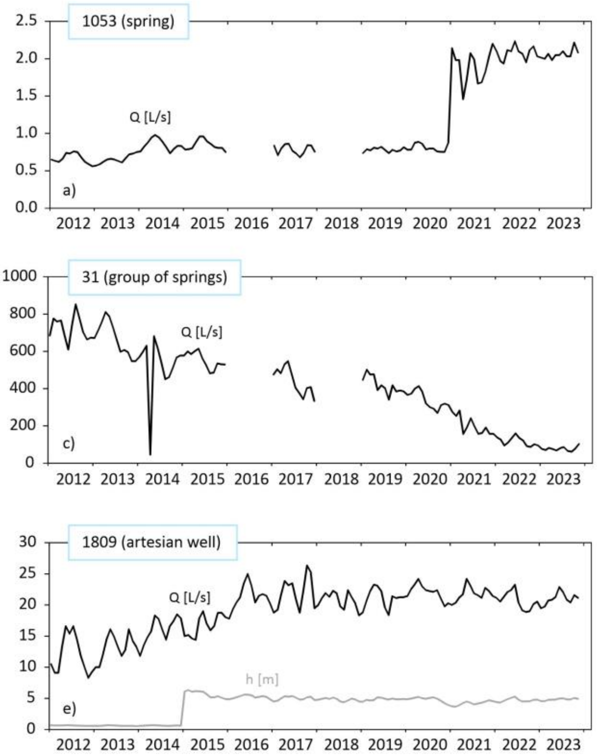

Figure 2: Time series for discharge (Q) and temperature (T) for the monitoring sites 1053 (a, b), 31 (c, d), and 1809 (e, f). Fig. 2e additionally includes piezometric levels (h). Note that T axes do not start at zero.

Although the three sites are located close to each other (south-east of Lake Sevan; Fig. 1), these exemplary data show variable patterns. Discharge exhibits a sudden increase at site 1053 (Fig. 2a), a gradual decrease at site 31 (Fig. 2c), and an initial increase followed by a stabilization at site 1809 (Fig. 2e). Temperatures increase slightly or remain relatively stable, but show differences in temporal variability (often seasonal effects), partly within the dataset for a single site (1809; Fig. 2f). Interestingly, the latter is an artesian well, i.e., one would expect limited variability. It is also noteworthy that the recorded temperatures at site 1809 (9.5 to 11°C) are higher than the mean annual air temperature along the shores of Lake Sevan (about 4 to 6°C; Gevorgyan 2014). The piezometric level at this site apparently increased by several meters in January 2015 (Fig. 2e).

An interpretation of the outlined patterns is beyond the scope of this document, but the encountered differences between adjacent sites and sudden changes in individual time-series are noteworthy and indeed warrant the monitoring of several sites in this area.

For sake of completeness, it is also noted that the dataset provided by ArmHydromet includes several sites at which monitoring was stopped at different points in time (not shown in Fig. 1). Apparently, local residents had started to use the concerned springs/wells, preventing a meaningful monitoring (personal communication, Harutyun Yeremyan, ArmHydromet).

2.2 Water chemistry

The water chemistry component of the current monitoring scheme relies on springs and artesian wells too (Fig. 3). The sites partly match those at which discharge and water temperature (and partly water level) are measured (see Section 2.1).

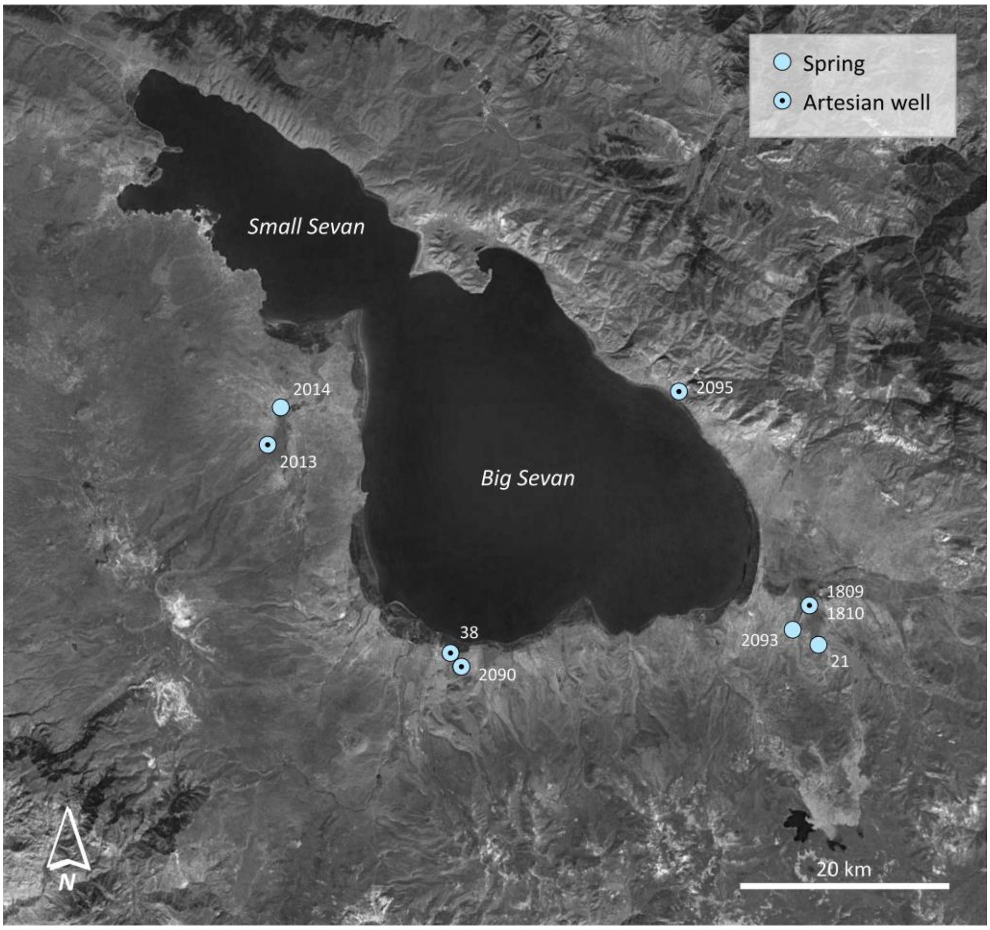

Figure 3: Map showing the monitoring points at which water samples are taken for chemical analyses. Note that the sites are not evenly distributed around the lake.

The sampling is carried out by ArmHydromet staff, mostly in a half-year interval, and the analyses are performed in the ArmHydromet laboratories. Here, collected samples are screened for major ions and selected trace elements.

Exemplary data of this monitoring are shown in Fig. 4. For two selected sites, namely 31 and 1809, major ion concentrations are shown on a mass and on a milliequivalent (meq) basis.

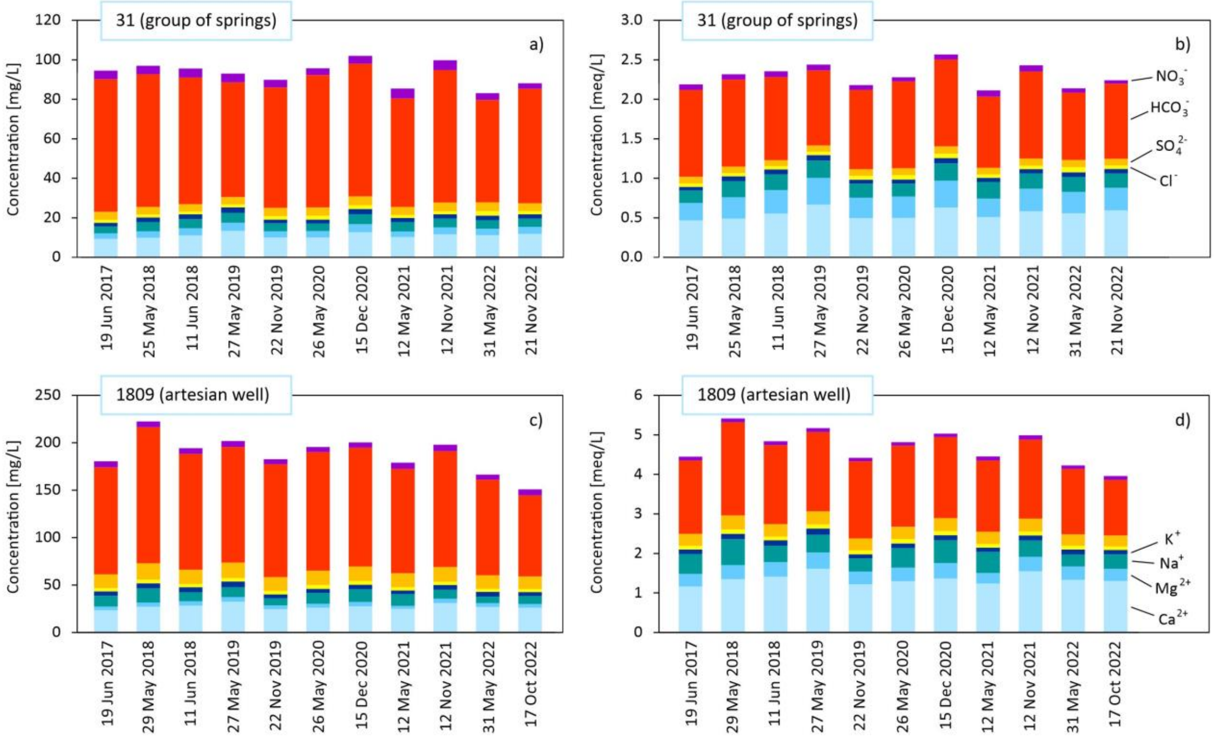

Figure 4: Major ion concentrations for the monitoring sites 31 (a, b) and 1809 (c, d), expressed as mass concentrations (a, c) and on a meq-basis (c, d).

As in case of Fig. 2, a detailed interpretation is beyond the scope of this document, but it can be summarized that groundwater at both sites is dominated by calcium and bicarbonate, which is typical for the area (see Appendix). Apparently, this does not change over time, i.e., the general hydrochemical character remains the same. However, absolute concentrations of individual ions and hence overall mineralizations seem to fluctuate to some extent. Interestingly, this also applies to well 1809. As this is an artesian well, one would actually anticipate a limited variability (see also Section 2.1). In such aquifers, spatio-temporal chemical variability is often levelled out due to efficient mixing in the subsurface.

3 Monitoring concept

3.1 Groundwater

Number of monitoring sites

The current groundwater monitoring (Section 2) yields valuable data and as continuous datasets gain increasing significance over time, monitoring of the currently covered sites should be continued as part of future monitoring activities. This also applies to sites located south-east of Lake Sevan, where a clustering of monitoring locations is observed (Fig. 1 and

3). The often differing patterns, partly observed even for neighboring wells (Fig. 2), apparently justify this site clustering.

On the other hand, the previous sections, particularly Fig. 1 and 3, reveal that large parts of the watershed are devoid of monitoring sites. It is hence suggested to expand the monitoring network by increasing the overall number of sites by 10 to 15.

Additional sites should be strategically located in relevant areas. Corresponding criteria should include the following aspects:

- Potential for groundwater inflow into the Lake Sevan: Particular emphasis should be placed on areas for which a pronounced inflow is suspected, e.g., on the basis of hydraulic data (hydraulic gradients, hydraulic conductivities), based on chemical data, or based on the results of the radon mapping executed as part of the above-mentioned October 2022 field campaigns (see Appendix).
- Representation of geology/groundwater bodies: As the geology is rather diverse in some parts of the study area, adequate representation of different lithologies and groundwater bodies is an important factor.
- Groundwater utilization: Emphasis should also be placed on areas where groundwater is used for public water supply or directly by the local population.
- Critical contaminant concentrations: If elevated concentrations of geogenic or anthropogenic contaminants were encountered in the past, either during the regular monitoring or as part of other surveys, such information should be considered too. Elevated nitrate concentrations, for instance, are of high relevance in this context (see Appendix).
- Availability of suitable sites: A rather practical aspect is the availability of suitable sites in different parts of the watershed. Drilling of dedicated observation wells is an option too, but obviously one that is more expensive.

How the above-mentioned individual criteria are weighted largely depends on the overall monitoring goals. If a lake-centric approach is taken (i.e., focus is on Lake Sevan), groundwater input into the lake and nutrient concentrations in groundwater are most relevant for evaluating the development of lake water quality and the potential of eutrophication. On the other hand, if decision-makers rather place emphasis on general monitoring, to create baseline data, for example in a climate change context or to monitor the quality of a drinking-water resource, the weighting of the different aspects would be quite different. Moreover, a combined approach, aiming at synergy effects, is a viable option too.

Due to the above-mentioned aspects, it is out of scope for this study to suggest exact locations for monitoring sites. Such sites should rather be identified considering the local conditions and the defined criteria.

Type of monitoring sites

The current groundwater monitoring scheme relies on springs and artesian wells. Monitoring of such site types is convenient, because no pumping is required. This implies that sampling staff does not have to bring a sampling pump (incl. power supply) to the field. Moreover, time-consuming well purging, which would be necessary at non-artesian wells, does not apply – at least if the given artesian well flows permanently. Hence, this approach is reasonable and could also be applied when selecting additional sites – assuming that such sites are available in the newly targeted areas (see above).

Furthermore, it should be mentioned that artesian wells seem to be the better option, compared to springs. The latter can dry up, at least temporarily. During own fieldwork, such cases have been observed in the study area. Moreover, dropping discharge values (see Fig. 2c) and eventually complete cease of flow are not unheard of. Artesian wells can also show discharge reductions (even to an extent that they become non-artesian), but unlike springs they can then still be monitored. Water levels can still be measured and samples can be collected (with a sampling pump) too.

Monitored parameters

Discharge, water temperature, and water level are obvious parameters to be monitored, also in an expanded network. A useful complementary parameter would be electrical conductivity (EC). EC is a meaningful parameter, in terms of general water quality and to study apparent fluctuations in total mineralization (Fig. 4). Moreover, measurement of EC is straightforward and fast, and it can also be done in the field.

For all these parameters automatically logging devices are available on the market from a range of manufacturers. Such loggers could be a viable alternative to the current reliance on local residents. As usual, both approaches have advantages and disadvantages.

Loggers offer a much higher temporal resolution and even the option of telemetric data transfer, but they are relatively costly. While they work autonomously after initial programming over long time periods, regular maintenance and calibration are necessary. Finally, they may be subject to vandalism or even theft, although this largely depends on the setting. There is indeed a significant risk, if the site is publicly accessible, while installation on private, fenced property is much safer. It is also noteworthy that discharge and piezometric levels of artesian wells cannot be logged simultaneously.

Manual measurements by local residents, rewarded with a financial compensation, are a cost-efficient option with no risk of vandalism and theft. Further, generated data can be of high quality, if the observers are properly trained by professionals. The downside of this approach is obviously a reduced temporal resolution.

If the current monitoring scheme is complemented to some extent by automatic loggers, various options are available on the market. When selecting a supplier and model, it is recommended to not solely decide for an option based on price, but to also consider robustness, ease of use, availability of spare parts, and previous experience.

With respect to hydrochemical monitoring, focus should be on major ions (incl. alkalinity and nutrients) and trace elements. These can be analyzed in the ArmHydromet laboratories, although measurement of alkalinity should be preferably done in the field. Complementary to the mentioned parameters, the stable isotopes of water (δ^2H, $\delta^{18}O$) should be included as a simple but powerful fingerprinting tool (see Appendix) that is frequently used in hydro(geo)logical studies. Corresponding sampling is straightforward, because required sample amounts are small (<50 mL) and no special treatment is necessary. The only important aspect in this regard is that partial evaporation from the sampling bottle (leaking caps, diffusion through bottle wall) is to be prevented (Böttcher and Schmiedinger 2020, Spangenberg 2012). Analyses of the stable isotopes need to be organized, e.g., through the IAEA laboratory network. The closest laboratory is located in Georgia.

Site ID:	**Location:**
Date:	**Time:**
Latitude [°N]:	Longitude [°E]:
Type of site: ◯ Spring ◯ Artesian well ◯ Non-artesian well ◯ Other:	
Water pressure: ◯ bar ◯ psi ◯ Other:	
Water level [m]:	Reference point:
Discharge [L/s]:	Discharge method:
Discharge comment:	
Field parameters and related information:	
Air temperature [°C]:	Weather conditions:
Odor:	Color:
Turbidity:	Suspended particles:
Temperature [°C]:	Electrical conductivity @ 25°C [µS/cm]:
pH value [-]:	Dissolved O_2 [mg/L]:
Nitrate (test strip) [mg/L]:	
Alkalinity (HANNA Checker) [mg/L $CaCO_3$]:	
Alkalinity (HACH titration kit*) [mg/L $CaCO_3$]:	
* Used acid: Water volume [mL]: Units:	
Photos:	**Collected samples (Sample IDs):**
Overview photo:	
Close-up view:	
Sampling photo:	
Remarks	
Name:	Signature:

Figure 5: Example of a field observation/sampling protocol.

Field work (observations, sampling) should be documented on a standardized protocol. A corresponding example is shown in the following Fig. 5.

In case of all parameters, it is recommended to quickly screen incoming data for plausibility and to double-check non-plausible values. For most parameters, this means that values are compared to previous measurements to identify outliers and artifacts. In some situations, it may also make sense to take auxiliary data into account (e.g., precipitation). Often, general experience or *a priori* knowledge will play a role, but partly established approaches and indices may apply. In case of major ion analyses, charge balance error calculations and correlations between total dissolved solids and EC values should be considered.

Temporal resolution

Measurements of discharge, water temperature, and piezometric level are currently performed every five days. Given the fact that the work is carried out by local residents, this temporal resolution is reasonable and would be so for future monitoring – if relying on locals. Deployment of automatic loggers would obviously allow a much higher resolution (e.g., hourly resolution).

Regarding the collection of samples for hydrochemical monitoring, the current half-year rhythm is suitable to only a limited extent as it does not allow detection of seasonal patterns. Yet, it would be important to know if such seasonal fluctuations occur. In this context, it is noteworthy that detectable tritium (^3H) in several samples taken during the two field campaigns (see Appendix) indicates the presence of a young water component in the groundwater. Furthermore, groundwater recharge seems to be biased towards the snowmelt season, as revealed by the encountered stable isotope signatures (δ^2H, $\delta^{18}O$; see Appendix). Moreover, temperature and partly also discharge seem to show a seasonal pattern, at least at some sites (Fig. 2). Accordingly, a sampling interval of three months is suggested for future monitoring activities. This resolution would help to identify sub-yearly patterns and would enable correlations with other datasets, including discharge, temperature, water level, but also stream flow and meteorological parameters.

Increasing 1) the number of monitored sites and 2) the temporal resolution obviously implies a higher workload for ArmHydromet. It is hence clear that the suggested monitoring intensification would require an increase of the allocated budget. In this context, also additional investments like the purchase of loggers and related equipment as well as equipment for measuring field parameters during sampling should be considered.

3.2 Other water cycle components

While this document largely focusses on the monitoring of groundwater resources, one should not see this water cycle component in isolation. The overall goal should be an integrated, coordinated monitoring with corresponding synergy effects.

A particular example is the monitoring of the stable isotopes of water (δ^2H, $\delta^{18}O$). Corresponding groundwater datasets have to be put in context, by considering the isotopic signature of local precipitation. The primary and most popular source for such data is the Global Network of Isotopes in Precipitation (GNIP), which is coordinated by the International Atomic Energy Agency (IAEA) in cooperation with the World Meteorological Organization

(WMO). As part of this endeavor, monthly integral precipitation samples are collected with cumulative samplers across the globe. Unfortunately, the GNIP network does currently not cover Armenia. To circumvent this problem, data by Brittingham et al. (2019) have been considered for the present study (see Appendix). The authors report isotopic fingerprints of precipitation in Armenia occurring between July 2014 and June 2015 at eight stations. One of these stations was located in the city of Sevan (i.e., at lake level). Here, 38 precipitation events were sampled within the mentioned time period.

While this approach helped to interpret the generated groundwater, stream, and lake data in this project, a more comprehensive and current precipitation dataset would be preferable. Ideally, corresponding monitoring stations would be located at different elevations in the Lake Sevan watershed, i.e., not only at lake level. This would help to constrain the isotopic elevation effect and hence the mean elevation of the regional groundwater recharge. Therefore, four cumulative precipitation collectors were installed in the field along an elevation gradient, namely between the south-western shore of Lake Sevan near Martuni and the Sellim Pass (August 2023). The sites have elevations between 1910 and 2282 masl and are easily reachable by car for sample collection (see Appendix).

The deployed equipment comprises air temperature loggers and the actual cumulative precipitation samplers. The latter are commercial models produced by Palmex (Croatia; http://www.rainsampler.com/) and fulfill the key criterion for such collectors, i.e., the efficient reduction of post-sampling evaporation from the collection bottle. The underlying principle has been outlined by Gröning et al. (2012) and rigorously tested by Michelsen et al. (2018). Over the last years, these devices became the most popular precipitation collectors in the isotope community and are also recommended by the IAEA (2014).

The installed collectors are to be regularly emptied on a monthly basis (synchronized sampling). The gained samples should be analyzed for δ^2H and $\delta^{18}O$. Further, it is recommended to record the gathered precipitation amounts, to enable the calculation of precipitation-weighted means. It has to be kept in mind that this type of monitoring is a long-term endeavor and ideally years or even decades of data will be generated.

For sake of completeness, it is noted that parts of the study area with high elevations (Gegham and Vardenis mountains; partly >3500 masl) are logistically challenging to cover with this approach. This is somewhat unfortunate as precipitation at such elevations obviously leads to groundwater recharge too. While an installation in the summer season would be feasible, the precipitation samplers would not be accessible in most winter months, and could hence not be emptied on a regular basis. Covering these parts of the study area by sampling crater lakes (possibly acting as a "natural collectors" at different elevations) is not possible either. Corresponding analyses have indicated that the water in such lakes is clearly influenced by evaporation effects altering the original isotopic signature (see Appendix).

This evaporation effect is also visible in case of Lake Sevan. Here, however, it may represent an advantage for integrated data interpretation. If the lake shows a pronounced evaporation effect over the summer months and receives an isotopically depleted inflow pulse over the snowmelt season (by streams and contributing groundwater), this probably causes isotopic fluctuation of the lake. If observable in consecutive years, such seasonal isotopic shifts could be used to quantify this type of inflow. This method would hence not depend on measured water quantities (stream gauging, etc.), but would represent an independent isotope-based technique.

The outlined approach requires a regular monitoring of the isotopic composition of Lake Sevan (depth profiles; at least two locations) and all major contributing streams. Because necessary sample amounts are small (see above) this type of monitoring could be integrated into the regular lake and stream sampling campaigns that are conducted anyway.

3.3 Evaluation of monitoring data

If monitoring data are generated for different compartments of the water cycle (precipitation, streams, lakes, groundwater), it may be tempting to analyze them separately, and to some extent and for some applications, this can make sense. However, data sharing is encouraged as for many practical and research questions joint analyses are more appropriate and enable the full exploitation of the generated datasets. Additionally, it is often crucial to consider data from a connected water compartment when making an attempt to verify an unusual reading and answering the question if the value is a valid outlier or represents an artifact (see Section 3.1).

4 Additional measures and aspects to be studied

While the recommended steps aim at an improved monitoring and ultimately at a better understanding of the (ground)water system of Lake Sevan, additional measures should be taken to protect this important resource.

Perhaps the most obvious measure is the reduction of contaminations of Lake Sevan and its associated streams and groundwater. Beside industrial contaminants, nutrients (i.e., nitrogen species, phosphate) are particularly important in this regard. These nutrients mainly originate from agricultural activities (livestock, fertilizer application) and human wastewater. Hence, we repeat previous calls for corresponding reductions and more and better wastewater treatment plants.

In terms of additional investigations, several aspects come to one’s mind, because various contaminant groups require attention in the mid- and long-term. While some contaminant groups have been tackled in the past decades (pesticides, industrial chemicals), studies targeting “emerging contaminants” are still in their infancy in Armenia. Examples comprise pharmaceuticals, personal care products, or microplastics. Given that such contaminations are a ubiquitous phenomenon around the world, their occurrence in Armenia is likely and a global study on pharmaceutical pollution, which included the Hrazdan river, has highlighted the need to tackle such issues in Armenia too (Wilkinson et al. 2022).

Ultimatively, monitoring and management of groundwater and surface water resources in Armenia, and therefore also in the Lake Sevan region, could be developed in a way to be in line with existing regulations of the European Union. The basis for this is the Water Framework Directive (WFD) implemented in the year 2000 (2000/60/EC), and its daughter directives dealing specifically with groundwater and surface water. The related Common Implementation Strategy (CIS) offers several Guidance Documents on various technical issues of the Directive, targeted to those experts who directly or indirectly implement the Water Framework Directive in river basins.

5 Summary

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 (δ^2H, $\delta^{18}O$). The fingerprinting potential of these tracers can give valuable, complementary insights into relevant processes and fluxes. Yet, such an endeavor would also imply a need for δ^2H and $\delta^{18}O$ 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.

6 Acknowledgements

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