WWQA
World Water Quality Alliance

FOG
Friends of Groundwater

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GUIDELINES FOR THE ASSESSMENT OF GROUNDWATER QUALITY

Guidelines for the assessment of

GROUNDWATER QUALITY

A Friends of Groundwater product

Friends of Groundwater

World Water Quality Alliance

Contents

1. INTRODUCTION

The sustainable management of water resources and the provision of safe water and sanitation are essential drivers of economic development and offer substantial support for health and education sectors. The United Nations Sustainable Development Goal 6 (SDG6) stresses the need for clean water and sanitation for all. Groundwater holds significant importance among the various natural resources that people depend upon for drinking water and sanitation and should therefore be regularly monitored and assessed to ensure its availability and cleanness. The SDG indicator 6.3.2 reports on the proportion of water bodies (groundwater, rivers, and lakes) with good ambient water quality. However, in 2017 and 2020, groundwaters were the water body type least reported by the United Nations Environment Programme (UNEP) (GEMS/Water, 2020), highlighting the need for increased focus and efforts in ensuring the monitoring and reporting of this vital resource (Misstear et al., 2023).

The assessment of groundwater quality is a complex task, even more than the same endeavour for surface water, due to groundwater's hidden nature, three-dimensional distribution, and long residence times, among others. Additionally, data and information necessary to produce a groundwater quality assessment are often lacking or highly dispersed (Misstear et al., 2023). On a global scale, the overall quality of groundwater is evaluated using different tools and approaches. The absence of standard guidelines for groundwater quality assessment has hindered large-scale assessments and cross-geographic comparisons.

To address the above challenges, the Friends of Groundwater (FoG) workstream of the World Water Quality Alliance (WWQA) took the initiative of proposing standardized guidelines for regional and national groundwater quality assessment. An initial draft of the guidelines was delivered by the FoG workstream in 2022. In 2023, the developed guidelines were further improved and updated, and tested using groundwater data from four case studies, including Uganda, Chile, Sweden and South Korea. The document presented here is a reviewed and improved version of the guidelines, incorporating the outcomes of the case studies.

The primary objective of the guidelines is to advocate and facilitate global-scale groundwater quality assessment, aligning with one of the key goals of the WWQA. The guidelines provide a structured methodology to make effective use of the available groundwater quality data towards global assessments. They have been developed to align with the SDG indicator 6.3.2, which emphasizes three fundamental core parameters - pH, electrical conductivity and nitrate. Furthermore, these guidelines complement the SDG indicator 6.3.2 by introducing a methodology that incorporates additional general and site-specific water quality parameters relevant for the level-2 assessment. The main audiences of the guidelines include a wide range of international and national stakeholders and policy makers (e.g., United Nations, national water authorities), by providing invaluable information for decision making, policy development, and collaborative efforts to protect and improve global and regional groundwater quality. It's important to emphasize that **these guidelines represent an initial step towards large-scale evaluations of groundwater quality**. They are intended to encourage and promote the monitoring and assessment of groundwater quality and support the generation of useful information for decision-making based on monitoring data. **As such, the developed guidelines complement, rather than replace, the comprehensive hydrogeochemical analysis conducted by local specialists**.

2. GUIDELINES FOR THE ASSESSMENT OF GROUNDWATER QUALITY

The guidelines on groundwater quality assessment aim to align with the scope of SDG indicator 6.3.2, which reports the percentage of water bodies with good ambient quality. Indicator 6.3.2 defines "good ambient quality" as water quality that does not damage human health or ecosystem functioning. Although this definition may appear straightforward, practical implementation is challenging due to 1) the diverse and complex water quality criteria related to both human health and ecosystem well-being, 2) the wide array of substances present in natural waters and their effects on humans and ecosystems, many of which are not yet fully understood, and 3) the absence of water quality standards covering a wide range of parameters with regard to ecosystem protection.

Nevertheless, drinking-water quality standards based on potential risk on human health have been well established, such as those defined by World Health Organization (WHO, 2022) or by national legislations. In this context, the guidelines make use of the existing target values from drinking-water guidelines, aiming to assist general groundwater quality assessment at regional and national scales **with an emphasis on the aspect of human health**. The assessment involves the calculation of a groundwater quality index (GQI), followed by classifying the quality of the resource based on its potential risk on human health. It is worth noting that while the core focus of the guidelines is on human health, **the underlying concept can also be further applied to assess groundwater quality for ecosystem protection, by adopting the parameters and target values relevant for ecosystem functioning.**

SDG indicator 6.3.2 proposes parameters for groundwater quality monitoring based on a dual-level approach. The Level 1 monitoring focus solely on core parameters, while Level 2 goes further and provides the flexibility to include information that may be of regional or national relevance. Notably, SDG indicator 6.3.2 does not prescribe specific constraints or guidelines for Level 2 assessment. Considering this, the guidelines outlined in this document aims to provide a structured approach for assessing groundwater quality in terms of Level 2 parameters. Additional approaches such as biological and ecological methods will not be hindered by the hereby presented guidelines; rather, they can be incorporated to enhance the assessment process.

As shown in Figure 1, the guidelines include four major steps: 1) evaluation of existing groundwater monitoring networks according to their representativity, 2) data collection and processing, 3) selection of parameters to use for evaluation, and 4) calculation of a Groundwater Quality Index (GQI) and classification of the groundwater quality. A detailed explanation of the mentioned steps is provided in the sections below.

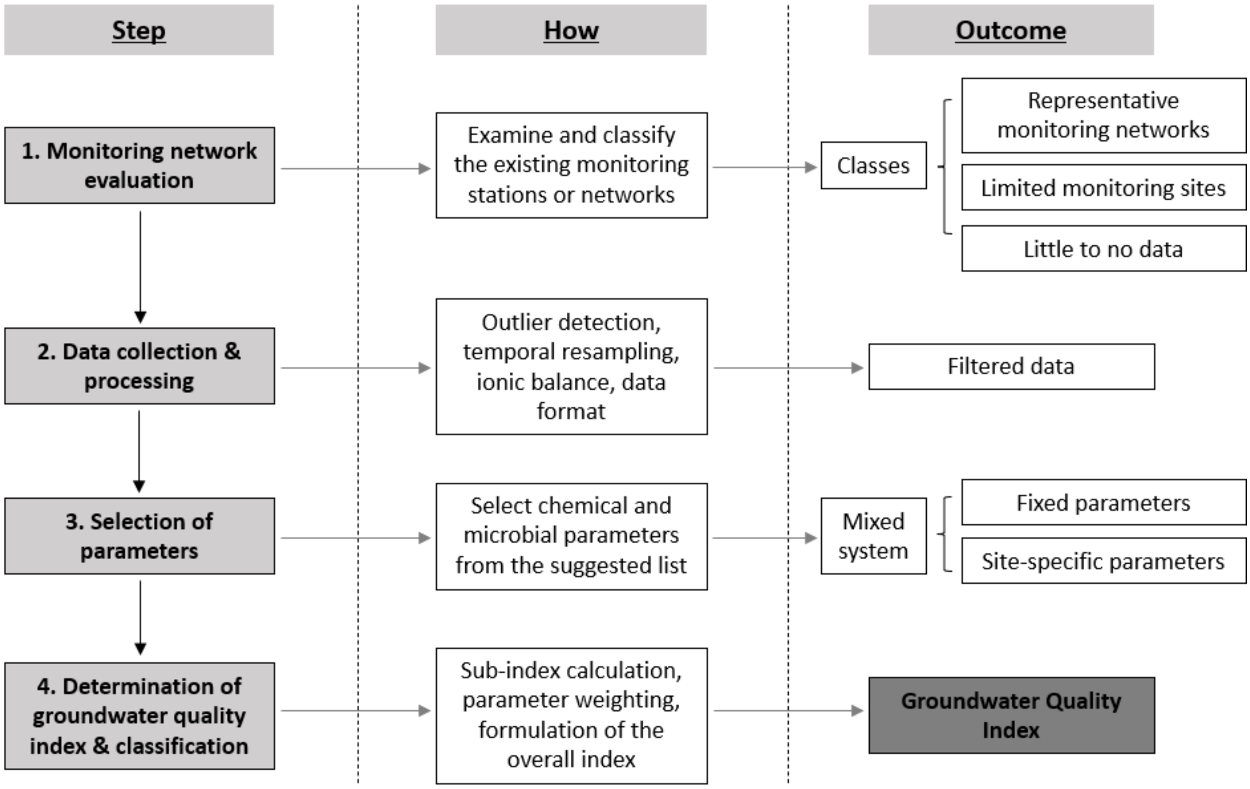

Figure 1: Main steps and outcomes of the guidelines for the assessment of groundwater quality

2.1. Groundwater monitoring network

Groundwater quality monitoring presents distinct challenges compared to surface water monitoring, due to the inherent complexity of aquifers and their limited accessibility for sampling (Misstear et al., 2023). A solid foundation of hydrogeological knowledge is essential for both designing an effective monitoring network and interpreting the ensuring results. **Detailed guidelines for the implementation or enhancement of groundwater monitoring networks are beyond the scope of this document.** For relevant detailed technical guidance, reference can be made to other existing guiding documents, such as Technical Document No.3[1] within the framework of SDG indicator 6.3.2, the Technical Guidance Document for Water Quality Monitoring and Assessment of Groundwater[2] developed by UNEP in 2022, and the Practical Manual on Groundwater Quality Monitoring[3] developed by the World Bank Group in 2022.

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[1] SDG Indicator 6.3.2 Technical Guidance Document No.3: Monitoring and Reporting for groundwater. https://communities.unep.org/display/sdg632/Documents+and+Materials?preview=/32407814/38306235/CDC_GEMI2_TechDoc3_Groundwaters_20200402.pdf

[2] United Nations Environment Programme (2022). Water Quality Monitoring and Assessment of Groundwater - Technical Guidance Document. Nairobi. https://wedocs.unep.org/20.500.11822/40414

[3] Ravenscroft, Peter; Lytton, Lucy. Practical Manual on Groundwater Quality Monitoring (English). Washington, D.C. : World Bank Group. http://documents.worldbank.org/curated/en/099630003212220807/P156924003bd770120a5af0f04c185a3b98

The first steps of the implementation process involve the identification of aquifers and/or groundwater bodies and their delineation based on conceptual hydrogeologic models. These delineations should be used as units for groundwater quality evaluation and reporting. Some countries, especially EU member states and those aligning with EU environmental legislations, have already invested considerable efforts in meeting their obligations to identify aquifers and groundwater bodies. These countries are also likely to possess well-developed groundwater monitoring programmes. However, the state of existing monitoring networks can vary significantly among countries in terms of coverage, parameters measured, and sampling frequency. While some countries have extensive data, others have limited or even no monitoring data available.

To facilitate groundwater quality assessment, the state of groundwater monitoring network can be assigned to one of the following classes:

1) **Class 1: Well-developed monitoring network – Representative GQI.** There is a robust groundwater quality monitoring network (since a specific year), ensuring that GQI can represent the quality status of aquifers within a region or country. Data collection has been conducted over a substantial and representative time frame (e.g., seasonally or annually), covering the entire aquifer in a region or country. To properly represent the aquifers within a region or country, different quantitative criteria (i.e., minimum coverage density of monitoring points) have been established from a few previous studies. For instance, guidelines from the European Environment Agency have set the threshold value as 1 borehole per 25 km^2 (impacted sites) and 100 km^2 (non-impacted sites) (Nixon et al., 1998). In Denmark, studies have employed 25 wells to cover areas of up to 50 km2 (Hansen et al., 2012), whereas Italy has assessed a 580 km^2 area with 90 boreholes (Passarella and Caputo, 2006). In Japan, 50 boreholes were used to monitor a 400 km^2 region (Babiker et al., 2007). Therefore, it is recommended that the minimum density of boreholes required for a representative monitoring network should be determined with consideration of the site-specific hydrogeological characteristics. A literature review of previous work within the region or country and/or experts' opinions are needed to evaluate the complexity of the groundwater settings.
2) **Class 2: Limited monitoring sites – GQI is likely unrepresentative.** A monitoring network is not available, though there are sampling sites in place in a specific area(s). However, spatial and/or temporal resolution of groundwater quality data are insufficient to properly represent the region or country. It is suggested to improve/renew the monitoring network and programme to achieve the level of a well-established monitoring network (Class 1).
3) **Class 3: Little to no data – GQI cannot be assessed.** There are no available groundwater monitoring networks and there are little to no groundwater quality data from any source within a region or a country. It is encouraged to begin implementing a groundwater monitoring network.

It's worth noting that this is a first attempt for classifying groundwater quality monitoring networks, a challenge for which established standards currently do not exist. This step is important for the assessment of groundwater quality, as it helps illustrate the representativity and reliability of the data collected. The guidance proposed above is preliminary, based on qualitative considerations. Further research and efforts are needed to define comprehensive guidelines, including quantitative criteria tailored to various hydrogeological, economical and societal conditions.

2.2. Data processing and quality assurance

The collection and harmonization of groundwater quality data can present several challenges. Groundwater quality data often come from various sources, including government agencies, research institutions as well as private organizations. These sources may use different sampling protocols, analytical methods and data formats, making harmonizing data from these disparate sources a complex task. In addition, groundwater quality data may be incomplete, with missing parameters or measurements at irregular time intervals, making it challenging to conduct comprehensive assessments. To address these challenges, efforts can be made to standardize data collection methods and to promote data sharing and collaboration among stakeholders. Furthermore, maintaining a strong focus on quality assurance and quality control procedures is crucial to ensure the reliability of groundwater quality data. The following process can be followed to ensure a robust assessment of groundwater quality:

a) Utilization of standard methods.

Obtaining credible data can be done by using recognised or standard analytical and sampling methods such as those from the International Organisation for Standardisation (ISO) (www.iso.org) and by following good laboratory practice as prescribed in ISO 17025 (ISO 2017) and ISO 5667-11:2009 for groundwater sampling. The utilization of standard methods also ensures the use of analytical methods that have detection limits appropriate for the specific substances of interest. The detection limits should be clearly reported along with the analytical results and examined prior to data analysis. In cases where the detection limits are either marginally lower or even higher than established drinking water standards, the data should be interpreted with cautious by acknowledging the potential for false negatives when concentrations are close to the detection limit.

a) Identification of outliers

Outliers are exceptionally high or low data points that can emerge due to various factors, including errors during sampling or analysis, human activities (point source of pollution), or even natural variations. It is imperative to detect and assess these outlier values and decide whether to include them in the analysis, a determination that should align with the specific objectives of the study.

b) Temporal resampling

When collecting multiple groundwater samples across different timeframes (e.g., monthly, seasonal, or annual), standardizing data frequency and potentially computing averages (e.g., from monthly to seasonal) or from seasonal to annual) can aid in achieving data uniformity and coherence. However, for parameters that exhibit substantial seasonal fluctuations, like microbial parameters, it's prudent to use a more frequent data collection schedule to capture and represent the nuanced seasonal variations.

c) Ion balance examination

Ion balance is a critical assessment that verifies the electrical neutrality of a water sample, providing assurance that the analytical processes have been accurately executed. While the calculation of the quality index involves a subset of parameters, it is essential to consider the following major cations and anions when performing the ion balance: Cations: Ca, Mg, Na, K, and Anions: HCO_3, SO_4, Cl, NO_3. In addition, CO_3 and NH_4 should also be included in the calculation when measurements are available. The ionic balance error (%) needs to be less than 10% to be acceptable. Nevertheless, it's worth noting that the ionic imbalance doesn't necessarily represent measurement errors; it could be influenced by missing measurements of one or several specific parameters, e.g., NH_4 , organic acids (e.g., Cao et al., 2022; Ladouche et al., 2009). Therefore, the imbalance should be evaluated based on other measured parameters, e.g., redox-potential and pH, and cross comparisons with measurements at adjacent monitoring stations within the same aquifer/groundwater body. This evaluation helps determine whether the data should be retained or excluded from further analysis.

Once the dataset is checked for quality and temporal resolution is standardized, the next step involves organizing the data into tables. These tables should include essential information such as the sampling location coordinates, borehole name, date of sample collection, and the concentration of each chemical parameter per borehole. This structured data organization is fundamental for facilitating subsequent analyses and interpretations.

2.3. Selection of parameters

The selection of groundwater quality parameters for assessing groundwater quality was based on two primary criteria:

1) **SDG Indicator 6.3.2 Technical Guidance Document No.3**[4]: The groundwater quality parameters proposed in the methodology are considered.
2) **Comprehensive Literature Review**: An extensive literature review of published studies was conducted and the main outcomes were presented in Eneogwe and Yeasmin (2023). Through this review, the most relevant parameters for assessing groundwater quality are identified, ensuring that the selected parameters are widely recognized and have been extensively studied.

2.3.1. Proposed parameters for SDG indicator 6.3.2

The proposed groundwater quality parameters for indicator 6.3.2 are categorized into two levels (Table 1). The Level 1 parameters (core parameters) - pH, electrical conductivity (EC), and nitrate (NO_3), provides essential information on acidification, salinization, and nutrient enrichment, respectively. For countries struggling in implementing monitoring programs, Level 1 presents fewer challenges when compared with more exhaustive assessment of groundwater quality.

However, Level 1 parameters cannot fully represent all pressures to groundwater quality. The Level 2 parameters are additional parameters that can serve as useful indicators of other pressures on groundwater quality, specific to regional or national concerns (Table 1). Due to variations in local pressures and hydrogeological settings, there isn't a universally "correct" set of groundwater quality parameters. However, Table 1 provides a suitable framework to guide the selection process.

[4] SDG Indicator 6.3.2 Technical Guidance Document No.3: Monitoring and Reporting for groundwater. https://communities.unep.org/display/sdg632/Documents+and+Materials?preview=/32407814/38306235/CDC_GEMI2_TechDoc3_Groundwaters_20200402.pdf

Table 1: Parameters groups for monitoring groundwater quality (adapted from SDG indicator 6.3.2 guidance document No.3)

Parameters		**Comments and Reason for Inclusion**
Core parameters (Level 1) for periodic measurement in all situations		
EC	Electrical conductivity	Measure of salinization, which helps characterize the water body; TDS (total dissolved solids) or salinity can be used instead.
pH	Acidity	Measure of acidification and helps characterize the groundwater body; pH is also linked to the solubility of certain metals/metalloids, hence determines the corrosivity of water and how this may impact on well casing or metal pipes in distribution systems.
NO_3	Nitrate	Ubiquitous contaminant, good indicator of pollution by human activities, including agriculture and waste disposal, health concern for human consumption.
Additional parameters (Level 2) measured at lower frequency following marked changes in core parameters		
Ca, Mg, Na, K	Major cations	Help evaluate hydrogeological processes and detect significant temporal changes. Cl can be a sensitive indicator of agricultural, urban and industrial impacts and saline intrusion due to over-pumping of groundwater from coastal aquifers.
HCO_3, Cl, SO_4	Major anions	
Microbiological parameters (Level 2)		
E. coli	*Escherichia coli*	WHO recommends the use of E. coli (or thermotolerant coliforms) as indicator of the potential presence of enteric pathogens in water. Highly recommended where groundwater is used directly for drinking water without treatment. When *E. coli* data is not available, faecal coliforms (FC) can be used as surrogate.
Additional parameters (Level 2) required in specific hydrogeologic settings		
As	Arsenic	Essential under some hydrological conditions, as high concentrations of these constituents can have severe effects on human health.
F	Fluoride	
U	Uranium	
NH_4	Ammonium	Only in strongly anoxic/reducing conditions
Fe	Iron	Ubiquitous elements in water, can impact the taste, odour, and colour of water. While Fe is considered not of health concern at levels found in drinking water, Mn has higher health risk due to its neurological effects, especially for bottle-fed infants.
Mn	Manganese	
P	Orthophosphate	Only in karstic aquifers with intensive agricultural pressures
Supplementary Parameters indicative of pollution where specific agricultural, urban, or industrial pressures have been identified		
Selected pesticides, heavy metals, selected volatile organics and other emerging contaminants		Each parameter will require specific sampling protocols used by skilled personnel, and analysis to very low detection limits at laboratories with expensive equipment and specialist staff.

2.3.2. Literature review

A comprehensive literature review of 108 studies on groundwater quality around the world (primarily from 2010 to 2023) was performed (see details in Eneogwe and Yeasmin, 2023). In reviewed studies, the number of parameters utilized for groundwater quality evaluation (mostly for the purpose of suitability for human consumption) varies, ranging from 3 to 22, with an average of 11 parameters. The most frequently used parameters are pH, EC (or TDS) and NO_3. Additionally, major ions are commonly analysed, with Cl being the most frequently used among them and K the least. Other frequently used parameters include F, Fe, Mn, As, Cr and *E. coli*.

2.3.3. Parameter selection

Both chemical and microbial parameters can be included in the groundwater quality evaluation. However, only chemical parameters are involved in the calculation of GQI, while the microbial quality of groundwater is evaluated separately using microbial indicators.

Based on the parameters proposed for SDG indicator 6.3.2 and the literature review, the **chemical parameters** selected to calculate a groundwater quality index were split into two categories:

1) **General (fixed) parameters (6)**:
    - Field measured **pH and EC** (salinity or TDS can be used as surrogate) as well as **NO_3** , which are also core parameters for SDG 6.3.2, were selected to provide essential information on salinization, acidification, and nutrient enrichment, respectively.
    - **Cl, SO_4 and Na** were selected among the major ions for the quality evaluation. However, **it is essential to monitor and report all major ions to enable data quality check through examination of the ionic balance.** According to the WHO drinking water standards, all major ions are not of health concern at levels found in groundwater, and specific guideline values have not been established. Nevertheless, some major ions (Cl, SO_4, Na, Ca and Mg) may affect the acceptability of water due to noticeable taste issues. For the quality evaluation, Ca and Mg, which represent water hardness, have not been included as selected parameters. The reason is that 1) the public acceptability of water hardness may vary considerably from one community to another (WHO, 2022), and 2) severe hardness problems of the water can also be detected from the measurement of EC or TDS. Alkalinity (HCO_3) has a major impact on water corrosivity, which can also be assessed by the measurement of pH. To avoid redundancy in parameters, HCO_3 is not selected for the quality index calculation.

2) **Specific parameters (3)**:
    After data processing and comparing concentrations to relevant target values, the 3 substances with **the highest risk to human health** and **the highest concentrations** relative to the target values are selected. In practice, the parameter selection process is performed within the predefined assessment unit, i.e., watershed, aquifer or groundwater body. Within each unit, the groundwater data is analysed to first identify the parameters that frequently exceed the standards. In cases where the majority, or even all, of the measured values fall below these standards, the frequency of detection is checked to pinpoint substances that exhibit widespread occurrence. The above procedure aims to identify the three "worst" parameters to ensure that the GQI calculated can represent the worst-case scenario of groundwater quality. In addition, experts' opinions can be sought to define the site-specific parameters, based on existing monitoring

programs, preliminary surveys and information regarding local human activities. In the literature, the most addressed specific parameters include F, As, NH_4, Fe, Mn and P, in addition to the general parameters mentioned above.

In regions and/or countries where groundwater is used directly for drinking water without treatment, it is highly recommended to evaluate the **microbial quality** of groundwater. ***E. coli*** or thermotolerant coliforms (faecal coliforms can be used as surrogate) are selected as indicators for the evaluation of microbial quality of groundwater.

2.4. Groundwater Quality Index (GQI)

Water quality indices serve as valuable tools that simplify complex groundwater quality information into a single, unitless numerical value, facilitating effective communication of water quality information to various stakeholders (e.g., Brown et al., 1972; Lukhabi et al., 2023; Lumb et al., 2011). According to the literature review (see more details in Eneogwe and Yeasmin, 2023), the Weighted Arithmetic Water Quality Index (WAWQI) stands out as the most popular approach used for groundwater quality assessment around the world. The National Sanitation Foundation Water Quality Index (NSFWQI) and the Canadian Council of Ministers of the Environment Water Quality Index (CCMEWQI) are also widely used, but to a less extent compared to WAWQI.

Based on the literature review, the proposed methodology adopts the concept of WAWQI to establish the groundwater quality index (GQI). This methodology is chosen for the following key reasons:

1) **Global applicability**: The WAWQI methodology is widely used worldwide for groundwater quality assessment, with a number of examples from both developed and developing countries (e.g., Lukhabi et al., 2023; Patel et al., 2023). The extensive global usage ensures broad acceptance and straightforward dissemination of the methodology.
2) **Simplicity of implementation**: The method is straightforward and easy to implement, making it accessible to a wide range of users.
3) **Parameter flexibility**: It offers flexibility in the selection of parameters, making it possible to include both general and site-specific parameters.
4) **Ability to deal with limited data**: There are no constraints on the number of monitoring sites or sampling frequency, making it particularly suitable for situations with limited data availability.
5) **Objective sub-index assignment**: The methodology employs national or World Health Organization (WHO) standards for sub-index assignment, reducing subjectivity and reliance on expert opinions compared to alternative methods, such as NSFWQI.

It is important to highlight that the proposed GQI is suitable for application within a monitoring network of Class 1 or Class 2, whereas the GQI for Class 2 may not be accurately representative for the entire region or country. In regions or countries where there is a scarcity of groundwater quality data, falling into Class 3, GQI cannot be calculated.

2.4.1. Chemical quality

The GQI is calculated using the selected chemical parameters to assess the_chemical quality of groundwater, with the following steps:

- **Step 1: Sub-index Specification**

The Sub-indexing process helps to transform the concentration of parameters into a unitless value. The sub-index, or quality rating (***Q****i*) is calculated using the equation below:

$$Q_i = \frac{C_i}{S_i} \times 100 \quad (1)$$

Where C_i is the concentration of the i^th^ parameter, S_i is the drinking water standards for the i^th^ parameter.

Whenever possible, it is advisable to prioritize the use of national standards, as they typically incorporate considerations for local geochemical conditions and background values. However, in the case of high-risk contaminants such as arsenic (As), it is crucial to exercise caution when national limit values exceed those recommended by the WHO. When national standards are unavailable, the WHO standards for drinking water can be applied (WHO, 2022).

The sub-index of pH is calculated using the equation (e.g., Franz et al., 2022; Hagage et al., 2022):

$$Q_{pH} = \frac{V_{pH} - 7.0}{S_{pH} - 7.0} \times 100 \quad (2)$$

Where V_{pH} is the observed pH value, S_{pH} is the threshold value in the relevant drinking water standards. If $V_{pH} > 7$, S_{pH} takes the upper limit value of pH, and if $V_{pH} < 7$, S_{pH} adopts the lower limit value of pH.

- **Step 2: Parameter Weighting**

A weight value (w_i) from 1 (lowest impact) to 5 (highest impact) is assigned for each parameter based on their relative impact on human health. Experts' opinions should be sought for assigning these weight values. A review of literature values provides a good summary of opinions from groundwater experts in different countries on parameter weighting (Eneogwe and Yeasmin, 2023). The suggested weights for general parameters and some commonly used site-specific parameters were taken as averages from those in the literature (Table 2).

A relative weight (W_i) for each parameter is then calculated with the equation below:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad (3)$$

Where n is the number of parameters and w_i is the weight of the i^th^ parameter.

Table 2: Suggested parameter weights (w_i) according to literature value based on their relative impact on human health.

Core parameters and major ions	Weight	Selected site-specific parameters	Weight
pH	4	As	5
EC	4	F	5
NO_3	5	NH_4	4
Ca	2	P	2
Mg	2	Fe	4
Na	3	Mn	5
K	2	Cr	5
Cl	4		
HCO_3	2		
SO_4	4		

- **Step 3: Aggregating Function**

The simple additive aggregation function is used in this guideline, which is the most widely used and straightforward function to assess water quality:

$$GQI = \sum_{i=1}^{n} Q_i\, W_i \tag{4}$$

Where $\boldsymbol{Q_i}$ is the sub-index for the i[th] parameter and $\boldsymbol{W_i}$ is the relative weight of the i[th] parameter.

- **Step 4: Classification and interpretation**

The final stage of GQI involves classifying the GQI values to assess groundwater quality. The guidelines outlined in this document primarily emphasize the aspect of human health. The groundwater quality class scales based on the potential risk on human health are shown in Table 3. This classification scheme is adapted from Brown et al. (1972) and has been used in many groundwater quality assessment studies (e.g., Hagage et al., 2022; Muzenda et al., 2019; Yadav et al., 2010). **In addition to classifying groundwater quality using the calculated GQI, the interpretation of evaluation results should give special attention to parameters that pose significant risks to human health and consistently exceed established standards,** which helps to pinpoint site-specific groundwater quality concerns.

It is important to emphasize that **the classification of groundwater quality is exclusively based on the parameters utilized in the GQI calculation and the available data.** It's possible that there may be additional quality concerns related to pollutants that are not accounted for due to the limited number of parameters considered in the GQI calculation.

Table 3: Groundwater quality classification according to GQI

GWQI	Groundwater quality class
0-25	I: Very low risk
26-50	II: Low risk
51-75	III: Medium risk
76-100	IV: High risk

>100	V: Very high risk

2.4.2. Microbial quality

In regions where groundwater is used directly for drinking water without any treatment, it is highly recommended to assess the microbial quality of groundwater. This is performed separately from the assessment of chemical quality. Table 4 presents the classification of microbial quality class using the *E. coli* count as indicator. This is in accordance with the guidelines for water safety management provided by the World Health Organization (WHO, 2016).

Table 4: Risk classification of water supply safety based on E. coli count.

***E. coli* count**	**Risk classification**
0	Low risk
1 - 10	Medium risk
11 - 100	High risk
> 100	Very high risk

3. CASE STUDIES

The established guidelines for groundwater quality assessment are tested through the development of three national-scale case studies. The primary objectives of the case studies are to provide an opportunity to apply the guidelines in real-world settings and to understand how the guidelines perform in diverse environmental and hydrogeological contexts, as well as varying levels of data availability. In addition, testing the guidelines through case studies will help to reveal the limitations and shortcoming of the methodology, therefore providing insights to refine and enhance the methodology.

Uganda, Chile, Sweden and South Korea have been selected as case study locations, because they exhibit varying degrees of data availability, covering situations with limited, moderate, and abundant amount of data. Also, groundwater quality varies significantly in these countries due to different hydrogeological contexts and anthropogenic factors. By developing these case studies, we aim to assess the feasibility and performance of GQI in diverse contexts.

It is important to underscore that the overarching aim of these case studies is not to deliver a conclusive assessment of groundwater quality in the four respective countries. Rather, they serve as a rigorous exercise in testing and validating the guidelines, contributing to the ongoing improvement of groundwater quality assessment practices.

At the current stage, the outcomes of these assessments would only offer groundwater quality classifications in terms of potential risks to human health. No specific management or actionable recommendations are provided, given that the assessment relies solely on available data, and a comprehensive understanding of the individual circumstances within each country is lacking.

3.1. Case study I – Uganda

3.1.1. Background

Located on the equator in East Africa, Uganda occupies a total area of about 236 000 km² in the heart of the African plateau (Figure 2). Much of the land of Uganda is rural, with agriculture, forest, grassland and woodland being the major land use or land cover types (Kilama Luwa et al., 2021). The geology of Uganda is dominated by ancient (Precambrian) crystalline basement complex rocks that underlie over 90% of the country. The remaining rock types are dominantly younger volcanic and sedimentary rocks. The volcanic rocks are either associated with the major East African Rift Valley along the western border or along the border with Kenya in the east (BGS, 2001).

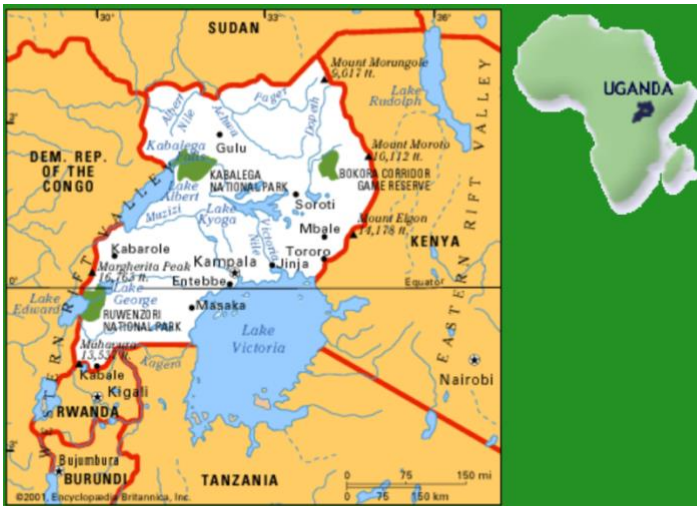


Figure 2: Location and Physical Features of Uganda (source: UN-WATER, 2006)

Groundwater is the most important source of potable water in Uganda, especially in the rural areas, providing over 80% of the water supply (BGS, 2001). The productive aquifers are mainly found in the fractured bedrocks and from the overlying weathered regolith. From previous investigations, groundwater chemistry in Uganda is shown to be highly variable (e.g., BGS, 2001; Owor et al., 2021). The dominant groundwater quality problems are likely to be related to poor sanitation with coliform contamination. The main inorganic groundwater quality problems are associated with excess levels of fluoride, iron, manganese, aluminium and zinc (e.g., BGS, 2001; Owor et al., 2021; UN-WATER, 2006).

3.1.2. Groundwater monitoring network and data processing

The groundwater quality data in Uganda was collected from the *Hidden Crisis project*, which was a 5-year (2015-2020) international research project aimed at examining functionality and performance of groundwater supplies in East Africa (Lapworth et al., 2020; UPGro, 2022). Data can be accessed online from the Hidden Crisis Project, Survey 1 dataset: detailed functionality assessments of hand pump boreholes in Ethiopia, Uganda and Malawi, at https://webapps.bgs.ac.uk/services/ngdc/accessions/index.html#item133685. A total of 124 monitoring sites were surveyed, which were selected randomly from handpump-boreholes within 9 districts across the 4 regions in Uganda (Northern, Eastern, Western and Middle). The location of monitoring sites is shown in Figure 3. All sites were sampled once within the dry season (June to September) in 2016.

The available data in Uganda falls under the classification of a Class 2 monitoring network. This only allowed an assessment of groundwater quality in localized areas, but not representative of the whole country.

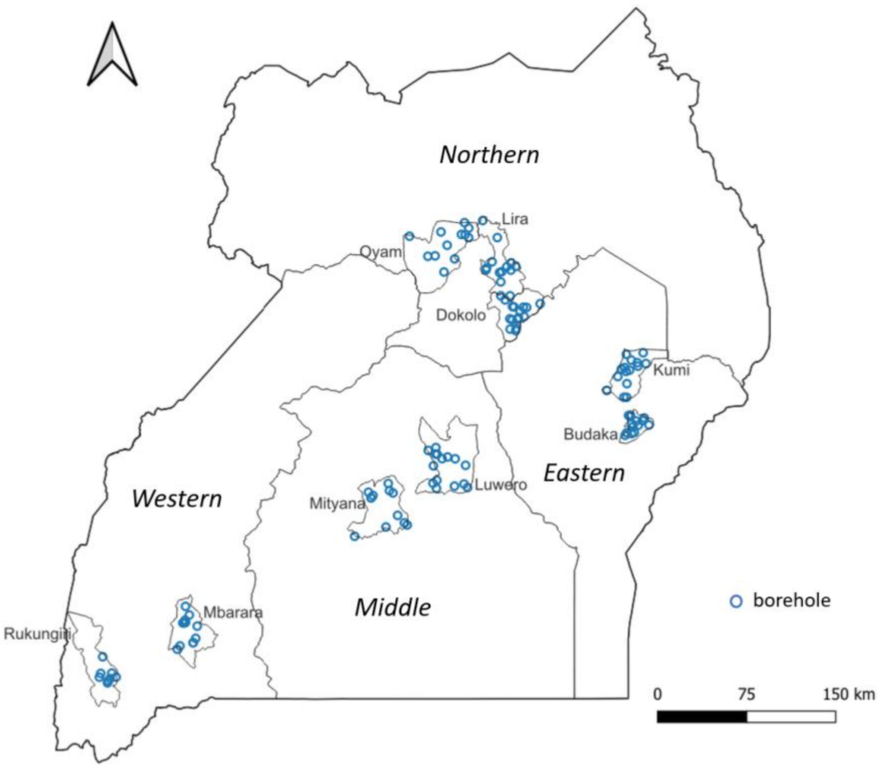


Figure 3: Locations of groundwater quality monitoring sites in Uganda (Source: Own elaboration based on data from the Hidden Crisis project dataset and the UN base map)

Data quality was checked through outlier detection and examination of ion balance. A 10% threshold for the ionic balance error was adopted, and data with errors exceeding 10% were excluded (12 sites). A statistical summary of selected groundwater quality data is shown in Table 5.

Table 5: Average values and ranges for selected parameters in the 9 surveyed districts. Values that are higher than the Uganda drinking water standards are marked in red bold; ND: not detected.

Parameter (Uganda standard)		Budaka	Dokolo	Kumi	Lira	Luwero	Mbarara	Mityana	Oyam	Rukungir
pH	*Mean*	6.6	6.7	6.7	6.5	6.5	6.7	6.6	6.7	6.6
(5.5-9.5)	*Range*	6.4 – 7.1	6.3 – 7.1	6.3 – 7.1	5.9 – 6.8	6.2 – 7.0	6.2 – 7.3	**5.2** – 7.4	6.4 – 7.2	6.3 – 6.9
EC	*Mean*	305	205	448	208	381	604	272	244	437
(2500 µS/cm)	*Range*	145 – 603	120 – 345	107 - 1262	73 -370	136 - 1499	297 - 997	56 - 471	160 - 454	202 - 787
NO_3	*Mean*	11.9	3.3	6.9	8.9	16.1	4.0	6.4	4.1	34.9
(45 mg/l)	*Range*	1.4 – 38.2	ND – 13.6	0.1 – 26.7	0.1 – 30.0	0.2 – **86**	0.1 – 17.3	0.1 – 26.9	0.1 – 23.6	0.2 – **100**
Na	*Mean*	31.1	17.6	31.8	18.8	26.5	36.1	12.9	15.2	25.2
(200 mg/l)	*Range*	13.6 – 64.3	12.1 – 27.9	12.8 – 81.3	6.7 – 44.5	9.4 – 145.0	17.2 – 54.9	1.8 – 25.1	8.6 – 31.3	4.7 – 57.6
Cl	*Mean*	23.9	1.5	23.3	34	27.2	102.0	12.1	3.5	19.9
(250 mg/l)	*Range*	2.4 – 74.5	0.2 – 8.9	0.7 – 192.9	0.6 – 12.8	3.4 – 178.8	11.2 – 195.7	1.2 – 47.4	0.2 – 17.6	5.4 – 56.9
SO_4	*Mean*	4.1	0.4	2.8	2.0	50.0	68.0	12.0	3.8	40.4
(400 mg/l)	*Range*	0.1 – 14.3	0.1 – 1.2	ND – 16.2	0.1 – 9.7	3.5 – **487**	0.5 – 132.9	0.1 – 48.8	0.2 – 12.2	7.0 – 80.8
As	*Mean*	ND	0.5	1.3	0.4	0.4	0.6	1	0.6	0.6
(10 µg/l)	*Range*		ND - 2	ND - 7	ND – 2.3	ND - 4	ND - 5	ND – 1.4	ND - 6	ND - 5
F	*Mean*	0.15	0.17	0.33	0.08	0.17	0.17	0.10	0.10	0.09
(1.5 mg/l)	*Range*	ND – 1.4	ND – 0.5	0.1 – 0.5	ND – 0.4	0.1 – 0.5	ND – 0.5	ND – 0.3	ND – 0.3	ND – 0.2
Fe	*Mean*	ND	0.1	0.1	0.1	ND	0.1	ND	0.2	0.1
(0.3 mg/l)	*Range*		ND – **0.3**	ND – **1.1**	ND – **0.5**		ND – **0.5**		ND – **0.7**	ND – **0.3**
Mn	*Mean*	49.6	30.6	57.1	30.3	11.5	432	88.3	48.8	269
(100 µg/l)	*Range*	1.6 - **504**	4.7 - **133**	5.4 - **212**	9.4 - **104**	0.2 - 77	0.2 - **1551**	0.6 - **272**	10 - **141**	2.3 - **716**
E.coli	*Mean*	7	0	7.4	4.4	0.9	1.8	2.3	0	0.4
(0 in 100ml)	*Range*	0 - **45**	0 - **1**	0 - **101**	0 - **45**	0 - **11**	0 - **7**	0 - **10**		0 - **2**

According to the measured results, pH values of groundwater in the surveyed regions ranged from 5.2 to 7.4, with average values of 6.5 to 6.7 in different districts, showing a neutral-weakly acidic environment of the aquifers. The EC values were highly variable, ranging from 56 to 1477 µs/cm. High NO_3 concentrations mainly occurred in the district of Luwero and Rukungir, in the Western and Middle region of Uganda, respectively.

Apart from the SDG core parameters (pH, EC and NO_3) and the major ions, elevated levels of Fe and Mn were frequently found in the groundwater, exceeding Uganda's drinking water standards. Fluoride was also detected in groundwater, but its values were below the standard limit. Arsenic, although present, occurred at a much lower frequency, and all values remained below the Uganda standard threshold (10 µg/l). As the concentrations of other trace elements were well below the standard values, they were not included in Table 5.

3.1.3. Parameter selection and weighting

Following the guidelines, a mixed system was used for the parameter selection, including a set of general (fixed) parameters and a set of site-specific parameters:

1) General parameters: **pH, EC, NO_3, Cl, SO_4, and Na.**

2) Site specific parameters: **Fe and Mn** were selected due to the frequently detected high concentrations above desirable limits. **Fluoride (F)** was also selected due to its wide occurrence in groundwater (although below standard value) and high risk to human health.

The weighted value for each parameter as well as the calculated relative weights are shown in Table 6.

Table 6: Weight and relative weight of each selected parameter used for GQI determination.

Parameter	WHO drinking water standard	Uganda drinking water standard	Weight	Relative weight
pH	6.5 – 8.5	5.5 – 9.5	4	0.11
EC	NA	2500 µs/cm	4	0.11
NO_3	50 mg/l	45 mg/l	5	0.13
Cl	250 mg/l	250 mg/l	4	0.11
SO_4	250 mg/l	400 mg/l	4	0.11
Na	200 mg/l	200 mg/l	3	0.08
F	1.5 mg/l	1.5 mg/l	5	0.13
Fe	0.3 mg/l	0.3 mg/l	4	0.11
Mn	0.08 mg/l	0.1 mg/l	5	0.13
Sum			38	1

3.1.4. Groundwater Quality Index (GQI)

The Groundwater Quality Index (GQI) was utilized to evaluate the chemical quality of groundwater in terms of suitability for drinking. Based on the GQI results (Table 7), the chemical quality of the surveyed wells was categorized into five categories according to the potential health risk: very low, low, medium, high, very high. Overall, 72% and 16% of the tested groundwater were of very low and low risk for human consumption. Also, 7% of the tested water was classified of medium risk. There are only 4% of the monitoring sites where groundwater is categorized as of very high risk for human health.

The spatial distribution of chemical quality of groundwater is illustrated in Figure 4. Notably, the groundwater classified as of high or very high risk for human consumption occurred mainly in the Mbarara and Rukungir districts, situated in the Western region of Uganda. These two districts displayed the poorest water quality, with only 25% of the tested water demonstrating very low risk. 33% and 13% of the sites in these districts were categorized as of very high risk for human health, respectively (Table 7). Addressing the water quality issues related to inorganic chemical parameters in these regions is of paramount importance to safeguard the health of the communities relying on groundwater sources.

Table 7: Results of GQI based on chemical parameters and its percentage

District	Number of sites	GQI Mean	GQI Range	I Very low risk (0-25)	II Low risk (25-50)	III Medium risk (50-75)	IV High risk (75-100)	V Very high risk (>100)
Budaka	13	18	10 – 71	92%	0%	8%	0%	0%
Dokolo	16	13	6 - 25	94%	6%	0%	0%	0%
Kumi	15	24	11 - 57	67%	27%	7%	0%	0%
Lira	13	16	8 -29	85%	15%	0%	0%	0%
Luwero	15	18	10 - 52	87%	7%	7%	0%	0%

Mbarara	12	72	15 - 214	25%	25%	17%	0%	33%
Mityana	12	21	9 -39	75%	25%	0%	0%	0%
Oyam	12	18	7 -41	75%	25%	0%	0%	0%
Rukungiri	8	53	13 - 28	25%	25%	38%	0%	13%
Overall	124	26	6 - 214	72%	16%	7%	0%	4%

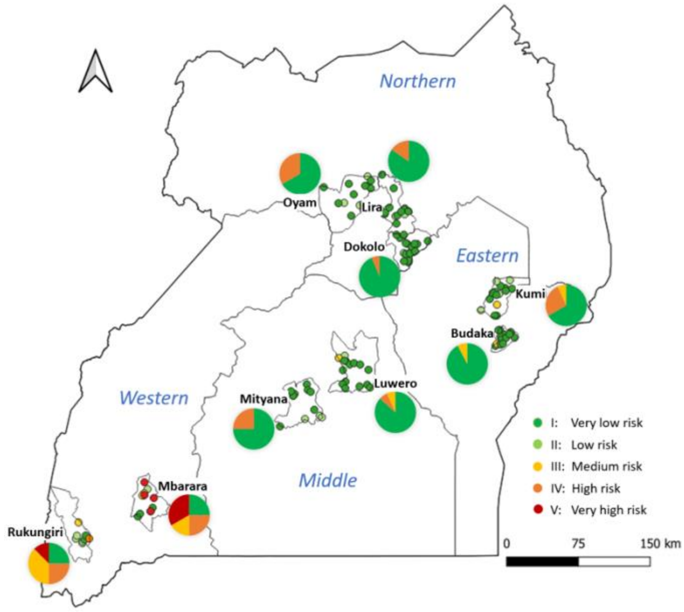


Figure 4: Chemical quality of groundwater in Uganda (Source: Own elaboration based on data from the Hidden Crisis project dataset and the UN base map)

The microbial quality of groundwater was evaluated based on measurements of *E. coli*. Coliforms were detected in 8 out of the 9 surveyed districts (Table 8), indicating potential sources of contamination. Remarkably, the district of Oyam in the Northern region stood out as the sole exception, with no coliforms detected. Among the surveyed districts, Kumi in the Eastern region exhibited the most concerning groundwater microbial quality (Figure 5). Approximately 7% of the tested water samples displayed a very high-risk level, while 27% showed an medium-risk level. These results indicate significant contamination and emphasize the urgent need for remedial actions to safeguard public health. Overall, 78% of the tested groundwater samples demonstrated a low-risk microbial quality, with 17% of the wells exhibiting an medium-risk level. A concerning 4% of the wells presented a high to very high-risk level, indicating a severe threat to water safety and necessitating attention and mitigation efforts.

Table 8: Microbial quality of groundwater in Uganda and the percentages of categories

District	Number of sites	Low risk (0)	Medium risk (1-10)	High risk (11-100)	Very high risk (>100)
Budaka	13	62%	23%	15%	0%
Dokolo	16	94%	6%	0%	0%
Kumi	15	67%	27%	0%	7%
Lira	13	77%	15%	8%	0%
Luwero	15	87%	7%	7%	0%
Mbarara	12	75%	25%	0%	0%
Mityana	12	67%	33%	0%	0%
Oyam	12	100%	0%	0%	0%
Rukungiri	8	75%	25%	0%	0%
Overall	124	78%	17%	3%	1%

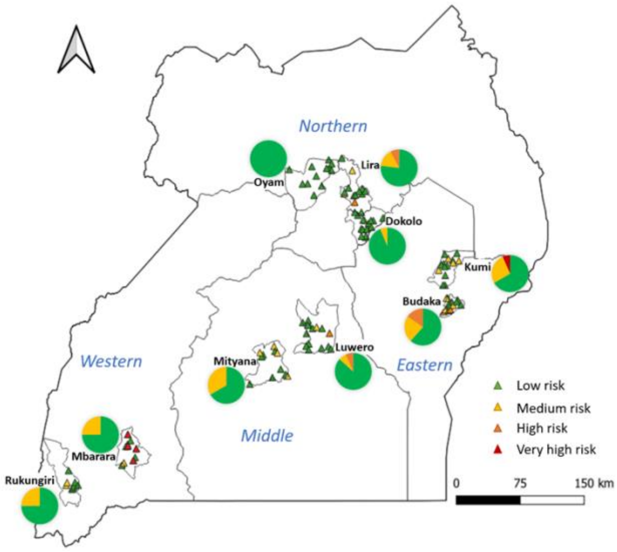


Figure 5: Microbial quality of groundwater in Uganda (Source: Own elaboration based on data from the Hidden Crisis project dataset and the UN base map)

3.1.5. Summary and recommendations

The groundwater quality assessment conducted in the surveyed regions integrated both chemical and microbial parameters to provide an understanding of water safety and suitability for drinking. Generally, the quality of groundwater with respect to inorganic parameters was of acceptable quality in most parts of the surveyed districts. The main inorganic chemical quality problems were related to Fe and Mn as well as NO_3 and SO_4 occasionally. Spatially, the Western region of Uganda exhibited the worst chemical quality, with a significantly higher proportion of water with high risk. Microbial assessment based on E. coli presence indicated potential contamination in most districts. Kumi district had the worst microbial quality with a high-risk level observed.

The case study of Uganda has revealed several issues and challenges in the process of groundwater quality assessment. The key takeaways and recommendations are as follows:

- It's crucial to highlight that the evaluation of groundwater quality in Uganda relies on a significantly limited dataset (Class 2). This dataset may not accurately reflect the true state of the country's groundwater quality, nor does it provide an accurate representation of conditions within each of the respective districts. Groundwater quality data from a well-established monitoring network is essential to ensure a more comprehensive and representative assessment of groundwater quality in Uganda.
- Microbial contamination can be very local, indicating that it may vary significantly even within a relatively small geographic area.
- It should be noted that microbial contamination often displays pronounced temporal variability. Several previous studies have highlighted that microbial contamination levels tend to be considerably higher during the wet season compared to the dry season, mainly attributed to the rising of groundwater table and the increased leaching following precipitation (e.g., Elisante and Muzuka, 2016; Makwe and Chup, 2013; Shrestha et al., 2013). This underscores the need for more frequent monitoring, especially relevant in cases like this one, which involved data from a one-off survey during the dry season.
- Microbial measurements can be highly contingent on the sample source. Borehole headworks are sometimes the source of bacteriological contamination while the groundwater itself is clean (e.g., Ravenscroft and Lytton, 2022), highlighting the need for a comprehensive assessment of the water supply system.

3.2. Case study II – Chile

3.2.1. Background

Continental Chile extends from approximately 17°30'S to 56°30', spanning a vast distance of 4200 km along the west side of the Andes Mountains. The geography of the country is mainly dominated by mountainous terrains, with four major geographical zones discernible from east to west: the Andes Mountains, Intermediate Depression, Coastal Mountains and Coastal plains (INE, 2011). According to Koppen-Geiger climate classification, a diverse range of climates exist through the country, including arid and semi-arid climates in the Northern regions, temperate climates in Central-Chile, humid climates in the Southern regions and tundra and polar climates in the Andes Mountains. From north to South, five natural regions with similar climates can be distinguished (Figure 6): Far North (17°30'S-25°40'S), Near North (25°40'S-32°15'S), Central (32°15'S-36°33'S), South (36°33'S-44°06'S) and Far South (44°06'S -56°00'S) (Valdés-Pineda et al., 2014). The Water Resources Directorate (Dirección General de Aguas, DGA) is the federal authority responsible for managing the water resources of the country. According to DGA (2016, 2017), the Chilean territory comprises 101 main hydrological basins and 212 recognized aquifers.

Figure 6: Five natural regions of continental Chile

Hydrogeological conditions are highly variable in the country. In the northernmost reaches of the country, aquifers are characterized by very low natural recharge rates due to high evaporation and low precipitation, and most groundwater storage can be found as fossil water (Renner and Aguirre, 2015). Moving to the Near North region, most aquifers are situated within fluvial valleys, with aquifer recharge mainly coming from precipitation and surface runoff infiltration, particularly during the snow melting season (Arumí and Oyarzún, 2006). In Central-Chile, aquifers are mainly located in alluvial sedimentary formations, deposited by Andean rivers. However, when it comes to Chilean aquifers in the Southern regions, the available data and information are notably limited.

3.2.2. Groundwater monitoring network and data processing

The National Groundwater Monitoring Network, managed and operated by the DGA, has its origins in the 1990s when the organization embarked on an extensive modernization initiative. The DGA has well identified basins, sub-basins as well as aquifers, which largely facilitates the groundwater monitoring and evaluation. The groundwater quality data in Chile was provided directly by the DGA (data available online at https://snia.mop.gob.cl/BNAConsultas/reportes), which contains data from a total of 914 groundwater monitoring stations across 50 hydrological basins, spanning from 1971 to 2022.

In this case study, the assessment of groundwater quality draws from the 2021 dataset, which encompasses a total of 433 wells distributed in 38 hydrological basins. The distribution of actively monitored groundwater wells in 2021 is shown in Figure 7. Despite that there is a significant lack of wells in the Far South region of the country, the monitoring wells represent relatively well the aquifers in the other regions of country. Therefore, **the groundwater water monitoring**

network (in regions where it is available) is classified as Class 1, meaning that GQI can represent the quality status of aquifers within these regions of continental Chile.

The monitoring includes several basic parameters (pH, electrical conductivity, temperature), major ions (e.g., Ca, Mg, Na, K, HCO_3, Cl, SO_4), total metals (e.g., As, Al, Cu, Fe, Mn), and nutrients (nitrogen and phosphorus). Monitoring frequency varies between regions and stations. In 2021, groundwater resources were monitored once per year at the majority of the monitoring stations. At some stations (mainly in the northern regions), two measurements were performed per year (during spring and autumn). Considering that groundwater quality in the northern regions was rather stable with very low seasonal variability due to the low natural recharge and long residence time (Renner and Aguirre, 2015), a single measurement was taken at each monitoring station (during the autumn) for the groundwater quality assessment.

Data quality was checked through outlier detection and examination of ion balance. During the data processing phase, all measured parameters were examined. The major cations and anions including Ca, Mg, Na, K, HCO_3, SO_4, Cl, NO_3 were used to calculate the ion balance. A 10% threshold for acceptable ionic balance error was adopted. The vast majority of data (95%) complied with this threshold value, indicating an overall high quality of the dataset. Any data points exceeding the 10% error threshold were systematically excluded from the assessment.

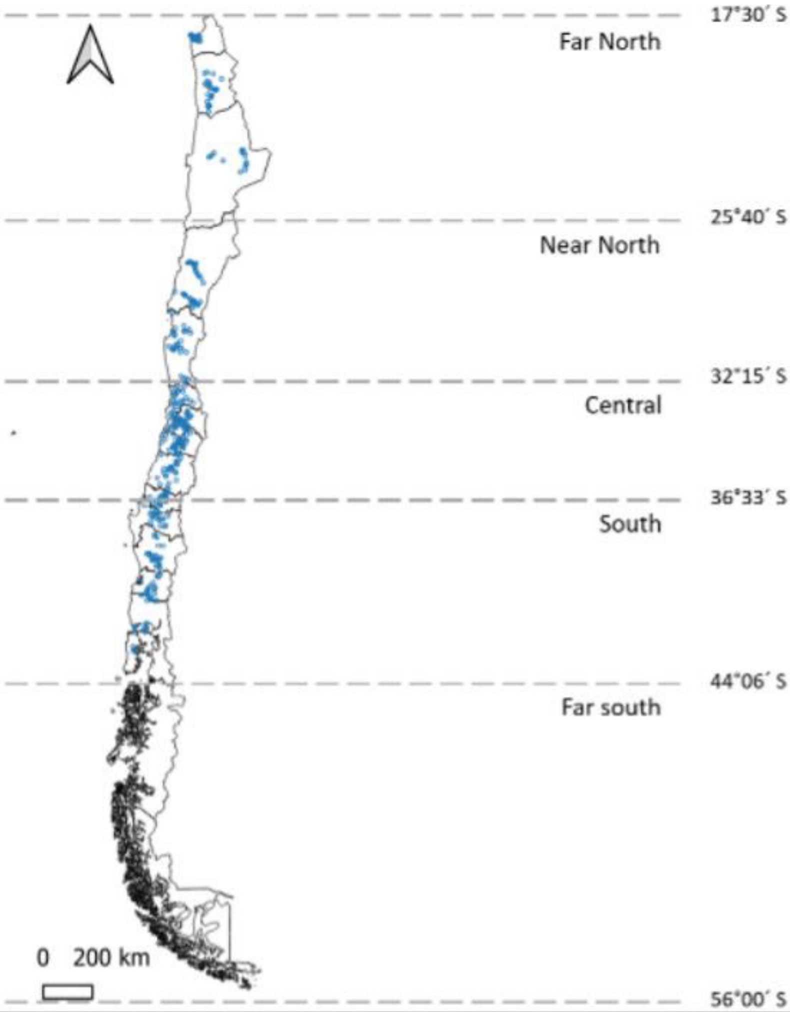


Figure 7: Distribution of groundwater monitoring stations in different administrative regions in Chile (Source: Own elaboration based on data from DGA; the delineation of macrozones from Valdés-Pineda et al., 2014)

The groundwater quality assessment was performed using aquifers as the analysis unit. The results were thereafter summarised and interpreted based on the five macro regions (as illustrated in Figure 7). After quality control and data processing, concentrations of all parameters were compared against the Chilean drinking water standards, allowing to identify the predominant groundwater quality issues in each region (Table 6). The results showed that the Far North region exhibited the highest number of parameters exceeding the threshold values, mainly due to the natural enrichment of dissolved salts and metals in groundwater. Notably, elevated levels of Fe and Mn were frequently detected throughout the country, with As appearing to a lesser extent. In addition, problems associated with high NO_3 contents mainly occurred in the Near North and Central regions of Chile.

Table 9: Groundwater quality considering parameters exceeding Chilean drinking water standards.

Region	Parameters exceeding Chilean drinking water standard
Far north	Cl, SO_4, Na, As, Fe, Mn
Near North	NO_3, Fe, Mn, punctually As and Hg
Central	Mainly Fe, Mn, punctually As, SO_4 and NO_3
South	Mainly Fe, Mn, punctually As
Far South	No available data

3.2.3. Parameter selection and weighting

Following the guidelines, a mixed system was used for the parameter selection, including 6 general fixed parameters and 3 site-specific parameters:

1) General parameters: **pH, EC, NO_3, Cl, SO_4, and Na.**
2) Site-specific parameters: the selection of these parameters was based on measured concentrations and their related risk to human health. Measured concentrations of all parameters were compared with the Chilean drinking water standard (NCh 409/1) to identify the parameters that were frequently detected with high concentrations exceeding desirable limits. The three most contaminated parameters with the highest potential risk to human health were prioritized to calculate the GQI. **As, Mn and Fe** were selected as site-specific parameters in most hydrological basins. One exception was the aquifer of Costeras entre Elqui y Limari, where the **As, Hg and Fe** were used.

The microbial parameters (e.g., *E.coli*) was not included due to the absence of data.

The weighted value for each parameter as well as the calculated relative weights are shown in Table 10.

Table 10: Weight and relative weight of each selected parameter used for GWQI determination.

Parameter	WHO drinking water standard	Chilean drinking water standard	Weight	Relative weight
pH	6.5 – 8.5	6.5 – 8.5	4	0.11
EC	NA	2500 µs/cm	4	0.11
NO_3	50 mg/l	50 mg/l	5	0.13
Cl	250 mg/l	400 mg/l	3	0.11
SO_4	250 mg/l	500 mg/l	4	0.11
Na	200 mg/l	200 mg/l	3	0.08
As	0.01 mg/l	0.01 mg/l	5	0.13
Fe	0.3 mg/l	0.3 mg/l	4	0.11
Mn	0.08 mg/l	0.1 mg/l	5	0.13
(Hg)*	0.006 mg/l	0.001 mg/l	(5)	0.13
Sum			38	1

** In the aquifer of Costeras entre Elqui y Limari, Hg was used for GWQI calculation instead of Mn in other aquifers*

3.2.4. Groundwater quality index (GQI)

For the Chile case study, the GQI was utilized to evaluate the chemical quality of groundwater in terms of suitability for drinking. The microbial quality of groundwater was not evaluated due to a lack of data. Based on the GQI results (Table 11), the groundwater quality of the surveyed wells was categorized into five categories according to the potential risk to human health: I (very low risk), II (low risk), III (medium risk), IV (high risk) and V (very high risk).

The spatial distribution of GQI is illustrated in Figure 8. Notably, the groundwater classified as of high risk to human health occurred mainly in the Far North region of Chile. The groundwater resources in this region displayed the poorest water quality, with only 5% of the tested water demonstrating very low or low risk. 11% and 69% of the sites in this region were categorized as of high or very high risk for human consumption, respectively (Table 11 and Figure 9). Groundwater in the Near North region displayed a better water quality compared to the Far North region (Figure 8), with 34% and 36% of the tested water demonstrating very low or low risk to human health. 20% of the sites in this region were categorized as of high or very high risk for human consumption. The groundwater resources in Central Chile displayed the best water quality among the investigated four natural regions (Figure 8), with a total of 85% of the tested sites categorized as of very low or low risk to human health. Only 7% of the tested water demonstrated very high risk for human consumption. In the South region of Chile, about 72% of the tested water displayed very low or low risk, while 22% of the sites were categorized as of very high risk for human consumption. Due to data limitations, groundwater quality in the Far South region was not able to be evaluated.

Table 11: GWQI results in different hydrological basins and natural regions in continental Chile

REGION	BASIN	nb_well	mean	max	min	I	II	III	IV	V
Far north	Quebrada de la Concordia	4	80	132	36	0%	25%	25%	25%	25%
	R. Lluta	7	237	535	115	0%	0%	0%	0%	100%
	R. San Jose	7	59	66	51	0%	0%	100%	0%	0%
	Pampa del Tamarugal	25	1505	16004	21	4%	4%	8%	24%	60%
	R. Loa	6	2320	6859	272	0%	0%	0%	0%	100%
	Quebrada Caracoles	4	1414	2086	768	0%	0%	0%	0%	100%
	Salar de Atacama	11	2027	6859	272	0%	0%	0%	0%	100%
	Total	***64***	***1161***	***16004***	***21***	***2%***	***3%***	***16%***	***11%***	***69%***
Near north	R. Copiapo	19	78	176	26	0%	32%	21%	21%	26%
	R. Huasco	20	33	120	13	45%	40%	5%	5%	5%
	R. los Choros	2	33	37	29	0%	100%	0%	0%	0%
	R. Elqui	7	30	50	18	43%	43%	14%	0%	0%
	R. Limari	13	31	87	14	54%	31%	8%	8%	0%
	Costeras entre Elqui y Limari	4	79	150	37	0%	25%	25%	25%	25%
	R. Choapa	4	16	35	9	75%	25%	0%	0%	0%
	R. Petorca	4	19	27	13	75%	25%	0%	0%	0%
	Total	***73***	***45***	***176***	***9***	***34%***	***36%***	***11%***	***10%***	***10%***
Central	R. Ligua	4	31	53	19	50%	25%	25%	0%	0%
	Costeras Ligua-Aconcagua	2	22	26	18	50%	50%	0%	0%	0%
	R. Aconcagua	10	32	144	13	70%	20%	0%	0%	10%
	Costeras entre Aconcagua y Maipo	6	20	54	11	83%	0%	17%	0%	0%
	R. Maipo	46	31	83	9	35%	59%	4%	2%	0%
	Costeras entre Maipo y Rapel	2	13	15	11	100%	0%	0%	0%	0%
	R. Rapel	34	53	854	5	65%	18%	3%	9%	6%

	Costeras Rapel-E. Nilahue	4	230	855	8	50%	25%	0%	0%	25%
	Costeras entre limite Region y R. Mataquito	1	576	576	576	0%	0%	0%	0%	100%
	R. Mataquito	7	17	37	10	86%	14%	0%	0%	0%
	R. Maule	21	76	1082	7	76%	5%	10%	5%	5%
	Costeras Maule y Limite Region	1	491	491	491	0%	0%	0%	0%	100%
	R. Itata	20	18	105	5	90%	5%	0%	0%	5%
	Costeras e Islas entre Rio Itata y Rio Bio-Bio	1	11	11	11	100%	0%	0%	0%	0%
	R. Bio-Bio	22	58	389	5	68%	5%	9%	0%	18%
	Total	***181***	***51***	***1082***	***5***	***62%***	***23%***	***5%***	***3%***	***7%***
South	R. Imperial	11	133	787	4	45%	27%	0%	0%	27%
	R. Tolten	14	24	197	4	86%	7%	0%	0%	7%
	R. Valdivia	7	38	168	7	71%	14%	0%	0%	14%
	R. Bueno	17	96	701	6	47%	12%	6%	6%	29%
	Cuencas e Islas entre R. Bueno y R. Puelo	7	59	125	10	29%	29%	14%	0%	29%
	Islas Chiloe y Circundantes	4	88	249	7	50%	0%	0%	25%	25%
	Total	***60***	***74***	***787***	***4***	***57%***	***15%***	***3%***	***3%***	***22%***
	Chilean National Total	***378***	***280***	***16004***	***4***	***46%***	***21%***	***8%***	***6%***	***20%***

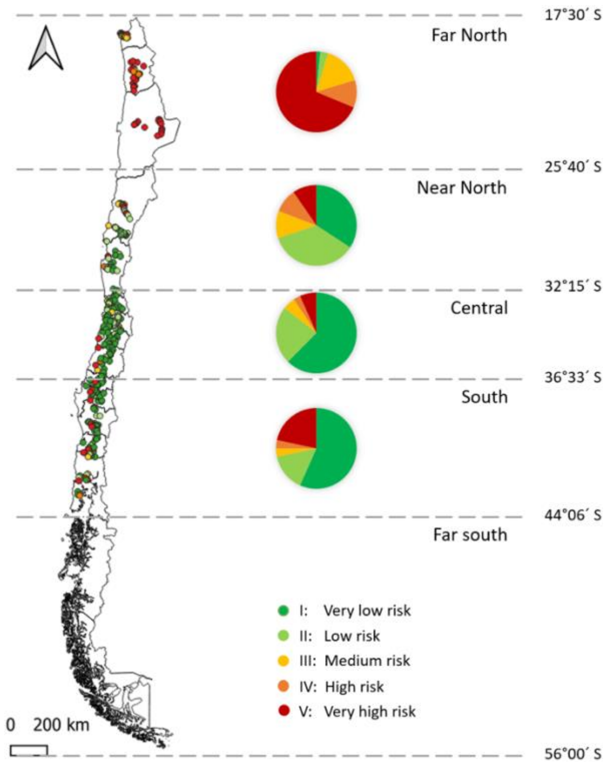


Figure 8: Spatial distribution of groundwater quality categories in Chile (each point representing a monitoring well (Source: Own elaboration based on data from DGA; the delineation of macrozones from Valdés-Pineda et al., 2014)

Overall, the GQI showed that 67% of the tested groundwater in Chile were of very low or low risk for human consumption (Table 11). Also, 8% of the tested water was classified as of medium risk, while 6% and 20% of the monitored sites are water of high and very high risk, stressing the water quality issues related to inorganic chemical substances, especially in the Far North regions of the country (Figure 8). The treatment of groundwater used for drinking purposes is of paramount importance. This is an important issue for rural communities relying on groundwater without any treatment.

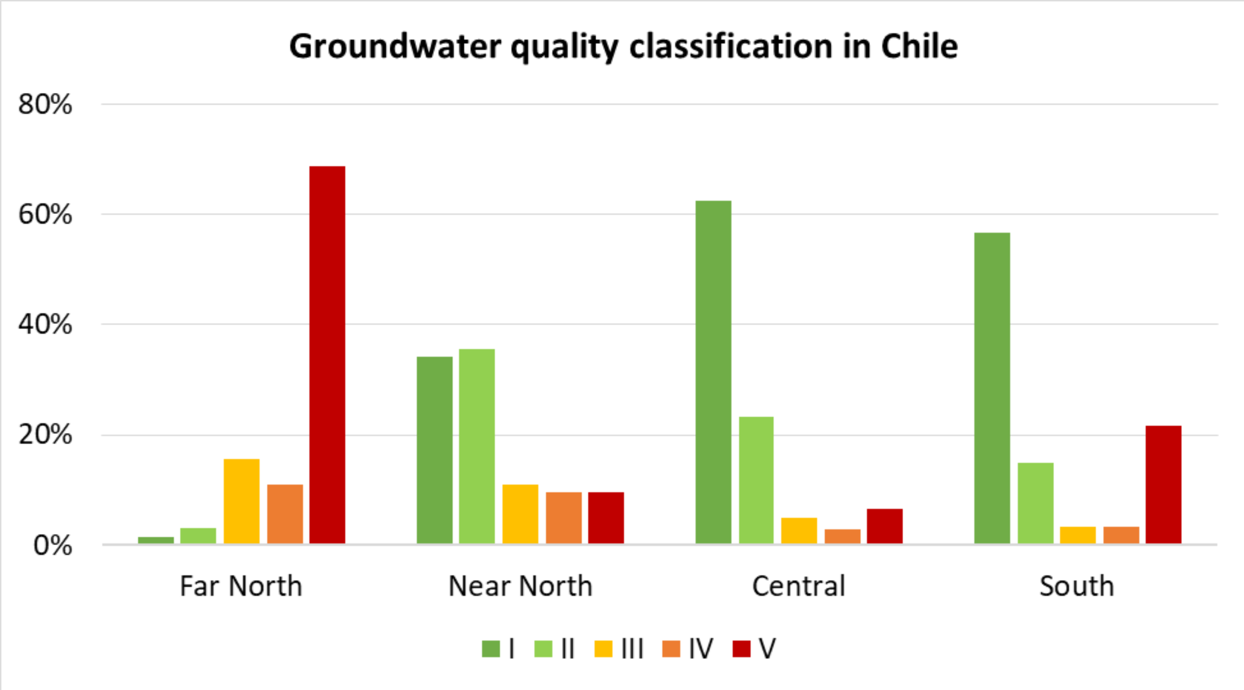


Figure 9: Groundwater quality and categories in different regions evaluated based on chemical parameters.

3.2.5. Summary and recommendations

The groundwater quality assessment in Chile has provided valuable insights into the state of groundwater resources in several regions. However, several challenges and limitations have been identified, which impacted the representativeness and accuracy of the results on a national scale:

a) The significant lack of groundwater data in the southern regions of the country has limited the comprehensiveness of the assessment at a national level. To address this limitation, it is recommended that efforts be directed towards enhancing and renovating the monitoring stations, thereby bridging the gaps in groundwater data for this part of the Chilean territory.

b) In many regions, especially the central and southern regions of the country where groundwater recharge as well as surface-groundwater interactions have significant seasonal variations, groundwater was monitored only once per year. This hinders the possibility to account for seasonal variations in groundwater quality. More frequent monitoring is recommended for a more accurate assessment of groundwater quality.

c) The groundwater quality dataset provided by the DGA lacks sufficient information regarding the purpose or type of monitoring stations. This raises challenges in accurately assessing groundwater quality for specific purposes. The groundwater monitoring network can be improved by enhancing the documentation of detailed information of the monitoring stations.

3.3. Case study III – Sweden

3.3.1. Background

The largest country in Northern Europe, Sweden lies west of the Baltic Sea and Gulf of Bothnia and forms the eastern part of the Scandinavian Peninsula. About 15% of Sweden lies north of the Artic circle. Southern Sweden is predominantly agricultural, with increasing forest coverage northward. Overall, Sweden is abundant in water resources with a relatively low population. About 80% of municipalities in Sweden use groundwater as a source of drinking water (Barthel et al., 2021). In Sweden, the main aquifers are found in unconsolidated sedimentary formations of glacifluvial sand and gravel deposits, which are generally no deeper than 10 m (Kleman et al., 2008). Additionally, aquifers in porous sedimentary rock are found in southwestern of Sweden, covering only a small percentage of the Swedish territory (Asch, 2003).

Sweden is divided into five different water districts, based on the borders of the major sea basins and catchment areas: the Gulf of Bothnia, the Bothnian Sea, the North Baltic Sea, the South Baltic Sea and Skagerrak and Kattegat (Figure 10). In each water district, one of the county administrative boards is appointed by the government to act as water district authority. The five water districts of Sweden are of varying size and characteristics. The groundwater quality can be affected by the hydrogeological conditions, population, prevalence of industries and land use within the district. For instance, pollution load leaching from agricultural is of greater importance in the southern water districts while contamination originating from mining activities is more relevant in the north.

Figure 10: Water districts in Sweden (Source: https://www.vattenmyndigheterna.se/vattendistrikt/vattendistrikt-i-sverige.html)

3.3.2. Groundwater monitoring network and data processing

Sweden has invested considerable efforts to fulfil its obligations in alignment with EU environmental legislations to establish a robust groundwater monitoring network. The groundwater monitoring network in Sweden operates partly at national level by the SGU (Swedish Geological Survey) and partly at regional level by the water districts authorities. SGU supports the water authorities with tasks related to groundwater monitoring, reporting and quality assessment at the regional level.

Groundwater quality data in Sweden was collected from the open database of SGU (data available at: https://www.sgu.se/produkter-och-tjanster/geologiska-data/oppna-data/grundvatten-oppna-data/miljoovervakning-av-grundvatten/), who collects and compiles groundwater quality data from both national and regional monitoring programs as well as analysis results from one-off surveys. The groundwater quality dataset of SGU contains data from about 1700 sites distributed all over the country since 1960s. In this case study, the assessment of groundwater quality draws from the 2021 dataset, which encompasses about 300 stations, distributed in all the five water districts. The distribution of actively monitored groundwater wells in 2021 is shown in Figure 11. The groundwater water monitoring network in Sweden is classified as Class 1. The groundwater monitoring included basic parameters (pH, electrical conductivity, temperature), major ions (e.g., Ca, Mg, Na, K, HCO_3, Cl, SO_4), total metals (e.g., As, Al, Cu, Fe, Mn), nutrients (nitrogen and phosphorus) as well as organic contaminants (e.g., pesticides, pharmaceuticals). Measurements of basic parameters and major ions are available for most stations, whereas total metals and nutrients are measured less frequently. Other trace elements and organic contaminants are measured to a lesser extent. Monitoring frequency varied between stations, ranging from one to four times per year. In cases where multiple measurements were taken at a station within a year, typically only one measurement contained a comprehensive set of parameters, while the others focused solely on core parameters. Consequently, only the measurement covering the larger range of parameters was used to represent the site for the assessment of groundwater quality.

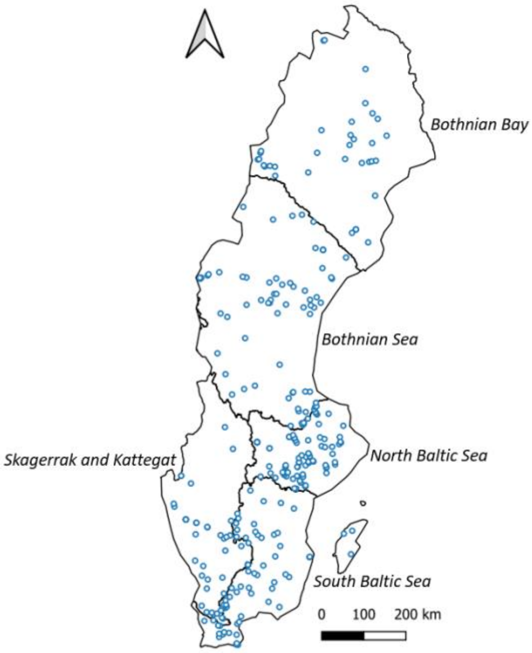


Figure 11: Distribution of groundwater monitoring stations of 2021 in Sweden (Source: Own elaboration based on groundwater data from SGU and the UN base map; the delineation of the water districts from VISS – Water Information System in Sweden at https://viss.lansstyrelsen.se/Maps.aspx)

Data quality was checked through outlier detection and examination of ion balance. During the data processing stage, all measured parameters were examined. The major cations and anions including Ca, Mg, Na, K, HCO_3, SO_4, Cl, NO_3 were used to calculate the ion balance. A 10% threshold for acceptable ionic balance error was adopted, data with errors exceeding 10% were excluded.

The groundwater quality assessment was performed and interpreted on a water district basis (Figure 12). After quality control and data processing, concentrations of all parameters were compared against the Swedish drinking water standards to highlight the prevailing groundwater quality issues. The results showed that in the two northern water districts (Bothnian Bay and Bothnian Sea), concentrations of monitored parameters barely exceeded the threshold values, with only Fe occasionally detected with concentrations beyond the drinking water standard. In the other water districts, elevated levels of Fe and Mn were occasionally detected, with Al appearing to a lesser extent. Furthermore, problems associated with high NO_3 levels mainly occurred in the South Baltic Sea water district.

3.3.3. Parameter selection and weighting

Following the guidelines, a mixed system was used for the parameter selection, including 6 general (fixed) parameters and 3 site-specific parameters:

1) General parameters: **pH, EC, NO_3, Cl, SO_4, and Na.**
2) Site specific parameters were selected according to the measured concentrations and the related risk to human health. Among the measured parameters, **Al, F, Fe and Mn** emerged as the primary substances of concern nationwide.

Three among the four parameters were selected in different regions for GQI calculation according to the measured concentrations.

Microbial parameter (e.g., *E. coli*) was not included due to the lack of data.

The threshold value and assigned weight for each parameter are shown in Table 12.

Table 12: Weight and relative weight of each selected parameter used for GQI determination.

Parameter	WHO drinking water standard	Swedish drinking water standard	Weight
pH	6.5 – 8.5	5.5 – 8.5	4
EC	NA	1500 µs/cm	4
NO_3	50 mg/l	50 mg/l	5
Cl	250 mg/l	300 mg/l	3
SO_4	250 mg/l	100 mg/l	4
Na	200 mg/l	100 mg/l	3
Al	0.9 mg/l	0.5 mg/l	3
Fe	0.3 mg/l	1.0 mg/l	4
Mn	0.08 mg/l	0.4 mg/l	5
F	1.5 mg/l	4 mg/l	5

3.3.4. Groundwater quality index (GQI)

For the Swedish case study, the GQI was utilized to evaluate the chemical quality of groundwater in terms of suitability for drinking. Based on the GQI results, the groundwater quality of the surveyed wells was categorized into five categories according to the risk to human health: I (very low risk), II (low risk), III (medium risk), IV (high risk) and V (very high risk).

In summary, the GWQI results showed that 92% of the tested groundwater in Sweden were of very low or low risk to human health (Table 13), indicating the overall good groundwater quality in Sweden. Additionally, a minor 4% of the assessed water sources fell into the medium risk category, whereas only 1% and 3% of the monitored sites were classified as high and very high-risk water sources, respectively.

Table 13: GWI classification in Sweden

Water district	Nb of wells	mean	max	min	I	II	III	IV	V
Bothnian Bay	36	10	34	3	94%	6%	0%	0%	0%
Bothnian Sea	62	12	58	1	97%	2%	2%	0%	0%
North Baltic Sea	90	23	178	4	72%	20%	6%	0%	2%
South Baltic Sea	71	34	240	5	70%	15%	3%	4%	7%
Skagerrak and Kattegat	37	30	241	4	68%	19%	8%	0%	5%
Sweden National Total	***296***	***22***	***241***	***1***	***79%***	***13%***	***4%***	***1%***	***3%***

The spatial distribution of GQI is illustrated in Figure 12. Groundwater in the northern water districts (Bothnian Bay and Bothnian Sea) displayed a better water quality compared to the water districts in the south, with more than 95% of the tested water demonstrating very low or low risk to human health (Table 13). The groundwater resources in the South Baltic Sea water district displayed the poorest water quality among the 5 districts, with 11% of the tested water demonstrating high or very high risk to human health.

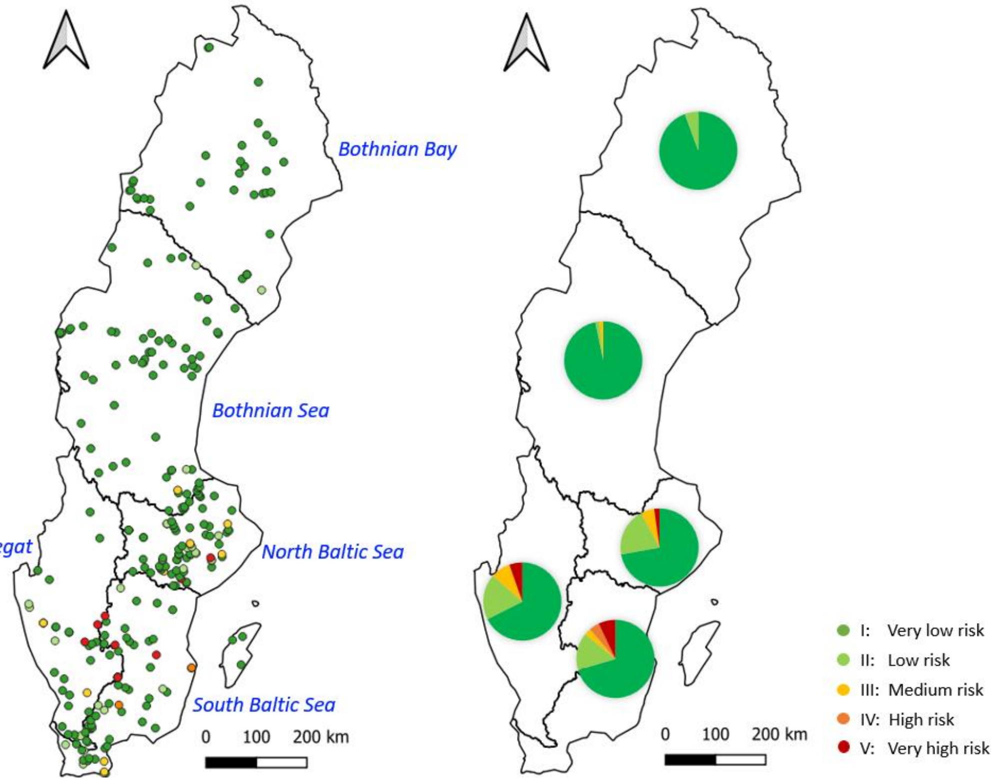


Figure 12: Spatial distribution of GQI in Sweden with each point representing a monitoring well (Source: Own elaboration based on groundwater data from SGU and the UN base map; the delineation of the water districts from VISS – Water Information System in Sweden at https://viss.lansstyrelsen.se/Maps.aspx)

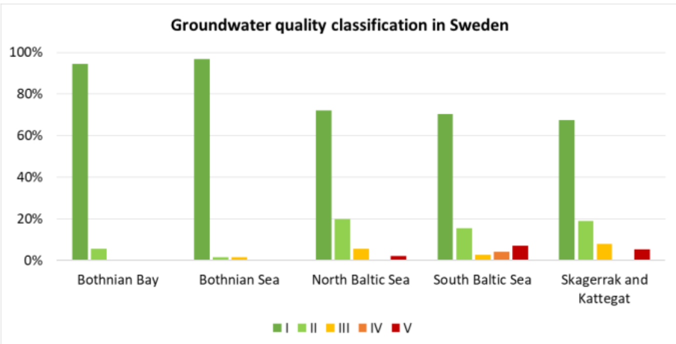


Figure 13: Groundwater quality classification in five water districts in Sweden

3.3.5. Summary and recommendations

The well-established groundwater monitoring network and clearly defined water districts in Sweden enabled a representative assessment of groundwater quality on a national level. Nevertheless, there is room for enhancement in terms of data documentation.

The SGU database currently lacks comprehensive information regarding the purpose or specific type of monitoring stations, which could provide valuable context for analysis. Additionally, there is room for enhancement in the frequency of groundwater monitoring, particularly in regions where the groundwater level is shallow, and/or significant groundwater-surface water interactions are observed. Expanding the scope of parameters considered and the number of monitoring stations can further bolster the effectiveness of monitoring efforts in these areas.

3.4. Case study IV – South Korea

3.4.1. Background

South Korea is located on a peninsula in the North-east part of the Asian continent, which extends to the southeast and covers about 45% of the Korea Peninsula. About 75% of the total area is mountainous, with higher elevations in the north and east, and lowlands developed in the southwest (Lee et al., 2007). Consequently, most of the rivers and streams flow from the east to the west. There are five large rivers: Nakdong, Han, Geum, Seomjin, and Yeongsan, and the total area is divided into five major watersheds accordingly (Figure 14). The climate is intermediate between continental and oceanic climate which features four distinct seasons. Rainfall is concentrated in the summer months from June to early September (wet season), which is a typical characteristic of monsoon climate in east Asia.

In South Korea, there are two types of main aquifers: shallow alluvial aquifers and deep bedrock aquifers. The alluvial aquifers are primarily distributed along the main rivers, with a thickness ranging from 2 to 30 m. The bedrock aquifers are usually accompanied by faults, fractures and joints formed by tectonic activities and are often overlain by shallow aquifers (Lee et al., 2007). With the population increase and the economic development, groundwater use in South Korea has been gradually increasing. Wells have been drilled deeper and deeper and most drinking water is now likely to depend on deep bedrock aquifers.

Figure 14: The five watersheds in South Korea

3.4.2. Groundwater monitoring network and data processing

The Ministry of Environment is a key administrative authority to control and manage groundwater resources in South Korea. A National Groundwater Monitoring Network (NGMN) has been established and operated since 1995, with the main purpose of monitoring long-term trends in groundwater level fluctuations and in groundwater quality throughout the country.

To test the guidelines for the assessment of groundwater quality in South Korea, groundwater data was collected from the database of National Groundwater Information and Management Service Centre (GIMS: https://www.gims.go.kr/). GIMS is responsible for collecting and managing groundwater quality data and information throughout the country since 2019. Korea National Institute of Environmental Research (NIER) examine the data quality through verification process. In this case study, the assessment draws from the 2021 dataset, which encompasses 669 stations, well distributed in all the five watersheds. The distribution of actively monitored groundwater wells in 2021 is shown in Figure 15. **The groundwater water monitoring network in South Korea is classified as Class 1**.

The groundwater monitoring includes basic parameters (pH, electrical conductivity, temperature), major ions (e.g., Ca, Mg, Na, K, HCO_3, Cl, SO_4), heavy metals (e.g., As, Hg, Pb, Cr), nutrients (nitrogen) as well as organic contaminants. Analysis of groundwater quality is performed twice per year for all the monitoring stations. The first scenario is performed in March to June (before the wet season) and the second one is in September to December (after the wet season). In addition, based on the screening depth of the groundwater wells, monitoring is performed at one to three different depths, including alluvial (5 – 30 m), bedrock deep 1 (15 – 70 m), and bedrock deep 2 (70 – 200 m).

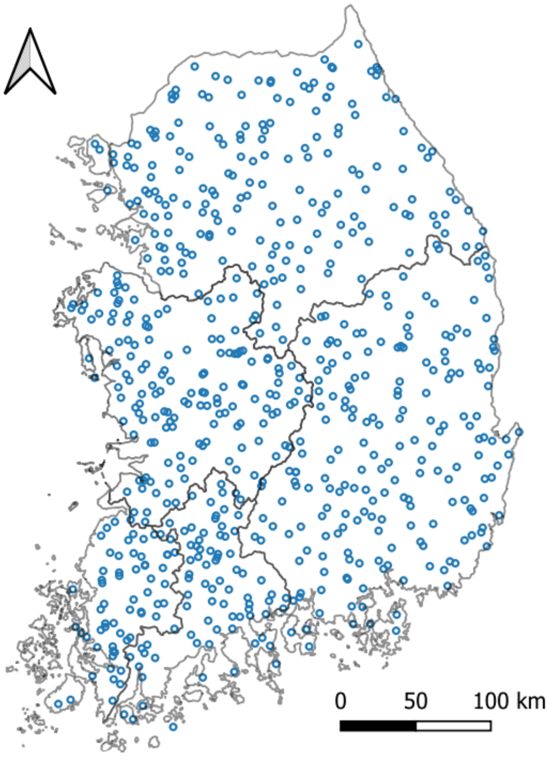


Figure 15: Distribution of groundwater monitoring stations of 2021 in South Korea Note that the Jeju island as well as other small islands are not shown on the map due to the unavailability of groundwater quality data. (Source: Own elaboration based on data from GIMS and the UN base map; the delineation of major basins from K-water, the water authority in South Korea)

Data quality was checked through outlier detection and examination of ion balance. During the data processing stage, all measured parameters were examined. The major cations and anions including Ca, Mg, Na, K, HCO_3, SO_4, Cl, NO_3 were used to calculate the ion balance. A 10% threshold for acceptable ionic balance error was adopted, data with errors exceeding 10% were excluded. The vast majority of data (98%) complied with this threshold value, indicating an overall high quality of the dataset.

The groundwater quality assessment was performed and interpreted on a watershed basis (Figure 14). After quality control and data processing, concentrations of all parameters were compared against the Korean drinking water standards to highlight the prevailing groundwater quality issues. The results showed that the contaminants frequently occurred in groundwater included NO_3, As, and petroleum contaminants such as toluene and xylene. This was consistent with previous studies on groundwater quality in South Korea (e.g., Lee, Cha, and Raza 2021; Kim et al. 2016). In addition, elevated levels of Hg, Pb and benzene were occasionally detected.

3.4.3. Parameter selection and weighting

Following the guidelines, a mixed system was used for the parameter selection, including 6 general (fixed) parameters and 3 site-specific parameters:

3) General parameters: **pH, EC, NO_3, Cl, SO_4, and Na.**
4) Site specific parameters were selected according to the measured concentrations and the related risk to human health. Among the measured parameters, **As, Hg, toluene, xylene, benzene** emerged as the primary substances of concern nationwide. Three among the five parameters were selected in different watersheds or monitoring depths for GQI calculation according to the measured concentrations.

The threshold value and assigned weight for each parameter are shown in Table 14.

Table 14: Weight and relative weight of each selected parameter used for GQI determination.

Parameter	WHO drinking water standard	Korean drinking water standard	Weight
pH	6.5 – 8.5	5.5 – 8.5	4
EC	NA	1000 µs/cm	4
NO_3	50 mg/l	45 mg/l	5
Cl	250 mg/l	250 mg/l	3
SO_4	250 mg/l	200 mg/l	4
Na	200 mg/l	200 mg/l	3
As	0.01 mg/l	0.01 mg/l	5
Hg	0.001 mg/l	0.001 mg/l	5
Toluene	0.7 mg/l	0.7 mg/l	5
Xylene	0.5 mg/l	0.5 mg/l	5
Benzene	0.01 mg/l	0.01 mg/l	5

3.3.4. Groundwater quality index

For the South Korean case study, the GQI was utilized to evaluate the chemical quality of groundwater in terms of suitability for drinking. Based on the GQI results, the chemical quality of the surveyed wells was categorized into five categories according to the risk to human health: I (very low risk), II (low risk), III (medium risk), IV (high risk) and V (very high risk).

In summary, the GQI results showed that, for all the monitoring scenarios (all depths and sampling periods), more than 93% of the tested groundwater in South Korea were of very low or low risk to human health with **a mean GQI ranging from 16 to 34** (Table 15), **indicating the overall good chemical quality of groundwater in South Kora**. Additionally, a minor 1%-4% of the assessed water fell into the medium risk category, whereas 0 - 3% of the sites were classified as high or very high-risk water sources in terms of chemical quality (Table 15).

Chemical quality of groundwater at different depths were very similar to each other. However, a seasonal effect was observed: the chemical quality monitored after the wet season from September to December was slightly better than that monitored before the wet season (from March to June) (Table 15 and Figure 16).

Table 15: Groundwater quality classification in South Korea

		Chemical quality classification						
		Nb of wells	mean GQI	Very low risk	Low risk	Medium risk	High risk	Very high risk
Mar. - Jun.	Alluvial	385	20	80%	15%	3%	1%	1%
	Bedrock deep1	279	34	83%	11%	3%	1%	0%
	Bedrock deep2	591	27	72%	21%	4%	1%	2%
Sep. – Dec.	Alluvial	379	16	88%	11%	2%	0%	0%
	Bedrock deep1	277	19	88%	10%	1%	1%	0%
	Bedrock deep2	586	19	84%	12%	3%	1%	1%

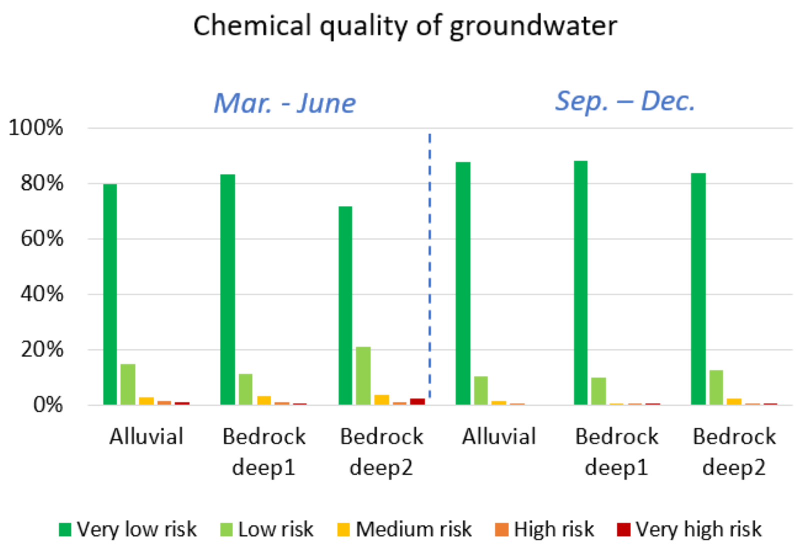
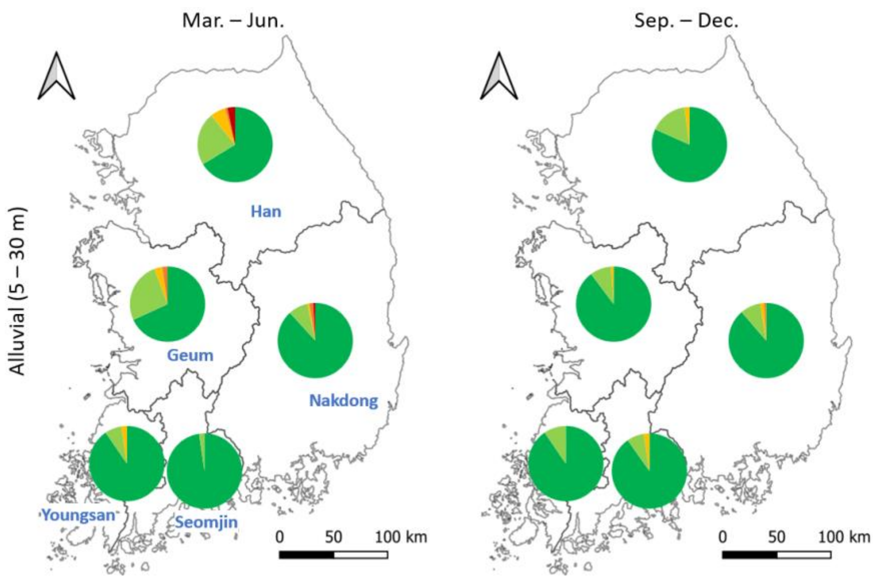


Figure 16: Groundwater quality classification in South Korea

The spatial distribution of chemical quality of groundwater are illustrated in Figure 17. Groundwater in the Han River, Nakdong River and Geum river watersheds displayed a poorer chemical quality of groundwater compared to the other two watersheds in the south the country, with more tested water demonstrating very high or high risk to human health. Similar spatial distribution was observed for both the two sampling scenarios (before and after the wet season), as shown in Figure 17.



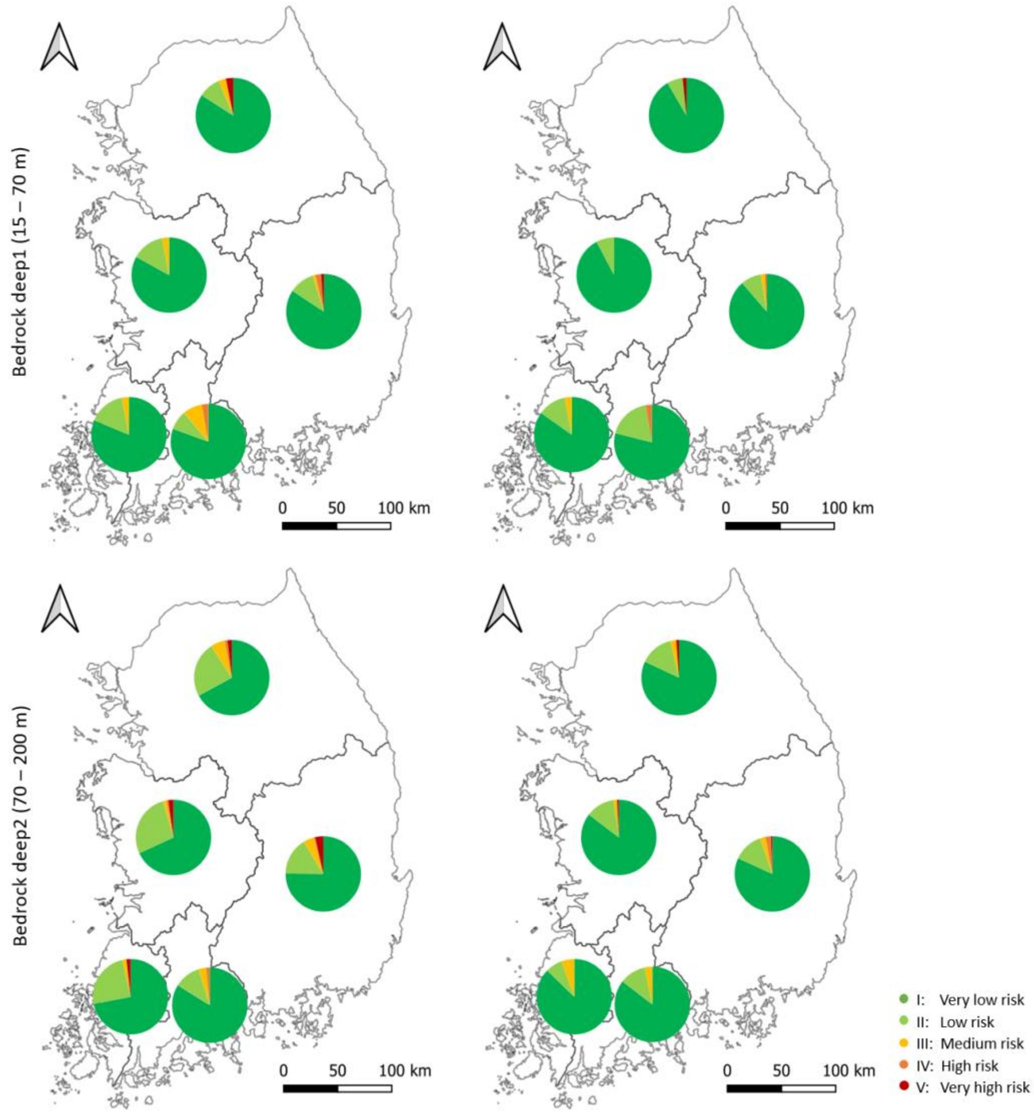


Figure 17: Chemical quality of groundwater in South Korea. Note that the Jeju island as well as other small islands are not shown on the map due to the unavailability of groundwater quality data. (Source: Own elaboration based on data from GIMS and the UN base map; the delineation of major basins from K-water, the water authority in South Korea)

3.4.5. Summary and recommendations

The well-established groundwater monitoring network and clearly defined watersheds in South Korea enabled a representative assessment of groundwater quality at a national level. A seasonal comparison has been performed thanks to two scenarios of measurements (before and after the wet season) at each monitoring station.

The case study of South Korea shows that the developed guidelines based on the concept of water quality index provide an efficient tool for the assessment of general quality of groundwater on regional and/or national scales. The calculated unitless index value facilitates the comparison of assessment results among different scenarios (sampling depths and periods). By condensing the extensive information gathered through the monitoring network into a single index value, stakeholders can readily discern shifts in groundwater quality and assess the impact of different factors, such as seasonal fluctuations and geographic variations.

3.5. Conclusion and perspectives

In conclusion, the evaluation of groundwater quality guidelines through a series of case studies has brought to light several pivotal insights:

- The Groundwater Quality Index (GQI) proves to be a valuable tool to facilitate groundwater quality assessment on regional and/or national scales. However, our case studies, particularly the one in Uganda, underscore the critical significance of data availability. Globally, groundwater data and information are often lacking or highly dispersed, which hiders the accurate evaluation of groundwater quality. We encourage countries to put more efforts on enhancing their monitoring networks to ensure a more comprehensive and representative assessment of groundwater quality.
- Besides the quantity of data, it's also curial to maintain a strong focus on the quality of data to ensure the reliability of evaluation. This depends on several factors, including the quality of the monitoring network and the sources and objectives of data collection. Groundwater quality data often come from various sources applying different sampling protocols and analytical methods, making quality assurance and data harmonization a complex task. Efforts should be made to standardize data collection and quality assurance procedures.
- These guidelines serve as an initial step towards large-scale evaluations of groundwater quality. The purpose is to encourage and promote the monitoring and assessment of groundwater quality and facilitate the generation of useful information for decision-making. It's essential to note that these guidelines are designed to complement, rather than replace the comprehensive hydrogeological analysis conducted by local specialists. In this way the GQI also offers a way for national policymakers to assess the state of groundwater resources within and across their country (depending on data availability and quality of groundwater monitoring network) in order to prioritize actions where they are most needed.
- While the core focus of the guidelines is on human health, the underlying concept can also be further applied to assess groundwater quality for ecosystem protection, by adjusting parameters, weights and target values relevant for ecosystem functioning.

The methodology outlined in the proposed guidelines still has certain limitations that require further refinement.

- **Limited parameters:** The GQI calculation employs a limited number of parameters, potentially leading to the loss of information. It's important to emphasize that the evaluation results exclusively rely on the parameters included in the GQI calculation and the available data, and additional quality concerns might exist due to pollutants that are not accounted for due to the limitation in parameters.
- **Selection of site-specific parameters:** The site-specific parameters are selected as the three "worst" parameters based on the predefined assessment units, such as river basins or aquifers. Future refinement may involve developing algorithms to select the site-specific parameters of interest at the monitoring well scale, to ensure that the calculated GQI represent the worst-case scenario at each sampling station.

- **Cross-country comparisons:** Different parameters were selected as site-specific parameters for the four case studies, since the list of parameters measured in each country differs from one to another. As a result, at the current stage, the case studies are not performed to enable cross-country comparisons, but rather to evaluate the guidelines within each case study independently. More studies are needed to determine the most effective approach for comparing each country's status in a clear and equitable manner. One possible approach could involve categorizing parameters into groups, such as inorganic chemicals, pesticides, and petroleum contaminants, with site-specific parameters encompassing at least one parameter from each category.
- **Weighting and aggregation:** The weighting and aggregation process may introduce biases in results, potentially weaking the impact of specific quality issues. Therefore, the interpretation of evaluation results must give special attention to the presence of substances that pose significant risks to human health, which helps to pinpoint site-specific groundwater quality concerns and their potential implications.

In summary, our development of case studies highlights the potential of the GQI as a useful and effective tool for advancing global water quality assessment, while acknowledging the complementary role it plays alongside comprehensive site-specific hydrogeological studies. It is imperative to recognize the urgent need for increased efforts in developing comprehensive groundwater monitoring networks and ensuring the availability of high-quality groundwater data, to facilitate large-scale evaluations of groundwater quality in terms of sustainable management of groundwater resources. While the proposed groundwater quality guidelines provide valuable insights, they still have limitations that need refinement, especially the need for improved site-specific parameter selection, strategies for cross-country comparisons, and careful interpretation of results to address potential biases.

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