GUIDELINES FOR THE ASSESSMENT OF GROUNDWATER QUALITY

Alexandra Urgilez Vinueza, Claudia Ruz Vargas, Bruce Dudley Misstear, Dan Lapworth, Junguo Liu, Karen Villholth, Yan Zheng, and Friends of Groundwater in the World Water Quality Alliance (WWQA)

Guidelines for the assessment of groundwater quality

Executive summary

The World Water Quality Alliance (WWQA) has the goal of producing an assessment of global water quality, including groundwater. The Friends of Groundwater (FoG) workstream of the WWQA, already in 2020, pointed out that a global groundwater quality assessment is a very challenging task (see “Assessing Groundwater Quality: A Global Perspective”) due to the complex nature of groundwater and data availability. There are many examples of groundwater quality assessments at local scale; however, there are not many at larger scales (e.g., national, or regional). The FoG took the initiative of proposing a standard set of guidelines to produce a regional groundwater quality assessment, to assist national authorities, international organisations, policy makers, among others, that need to understand groundwater quality at a large scale. The guidelines are based on the few existing methodologies used by countries and independent researchers, and it considers the creation of a quality index. This approach is considered as a first step towards a large-scale assessment of groundwater quality, and it does not replace a complete hydrogeological analysis made by local specialists. However, it provides an initial indication of the groundwater quality in a region. Ultimately, if the guidelines are implemented in several regions, it could be possible to cover larger regions. A global groundwater quality assessment could be produced, supporting the efforts of the WWQA.

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Table of contents

1. Introduction

WHO and UNICEF (2019) indicate that 1/3 people globally do not have access to safe drinking water and about 2.2 billion people around the world do not have safely managed drinking water services. The United Nations Sustainable Development Goal 6 (SDG6) stresses the need for clean water and sanitation. Groundwater is one of the natural resources that people rely on 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/aquifers and surface water) with good ambient water quality. However, in 2017 and 2020, groundwaters were the water body type least reported by the UNEP (GEMS/Water, 2020).

In the context of groundwater, ambient quality is assessed through in-situ and laboratory-based analysis of physical, chemical, and biological parameters. This task has been performed by many countries, e.g., the member states in the European Union (Todo & Sato, 2002), or the United States through the National Ground-Water Monitoring Network, managed by the USGS (U.S. Geological Survey, 2022). However, a consistent groundwater quality assessment relies on the availability of groundwater monitoring networks with sufficient spatio-temporal resolution. Currently, there are a considerable number of guidelines for the implementation of monitoring networks (e.g., Grath et al. (2007), Jousma et al. (2006), and Ravenscroft & Lytton (2022)), as well as national standards for the assessment of groundwater quality per country based in these networks. Some of these national examples are presented in Table 1 and evaluated further in this document. There are plenty of other national examples that were not covered in this report; however, it is important to be aware of them and learn from them as well.

Table 1: Examples of national standards assessing groundwater quality, evaluated in Section 3 and summarized in Annex 1.

Country	Scope of analysis	Groundwater quality indicator
Chile (Muñoz Pardo, 2009)	Aquifer to regional	Quality index – range of classes
Italy (Passarella & Caputo, 2006)	Regional	Quality index – range of classes
Ireland (Craig & Daly, 2010)	Aquifer	Class: “Good” or “Poor”
Australia/Queensland (Government Department of Environment, 2021)	Site-specific	Compliance guidelines

Globally, the overall quality of groundwater is evaluated using different tools and approaches. In some cases, only one chemical parameter is considered (e.g., nitrates in Denmark (Hansen et al., 2012)), or each groundwater body is studied into detail to determine its baseline chemistry (e.g., in the UK (Shand et al., 2002)). Others include more than one chemical parameter into the evaluation and develop a quality index with the purpose to include as much information as possible into the assessment groundwater quality (e.g., Classification of groundwater quality in Italy (Passarella & Caputo, 2006)). Nevertheless, the lack of internationally accepted standard guidelines for the assessment of groundwater quality hinders the possibility large scale assessments and cross-geographic (especially international) assessments and comparisons.

Hence, this report seeks to fill this gap by providing the necessary tools to standardize groundwater quality assessment procedures with the purpose of defining the potential use of groundwater based on its quality. This will be done through an overview of existing examples of different approaches to assess groundwater quality, and based on this overview, propose a consistent set of steps and considerations as guidelines for the assessment of groundwater quality at the regional/national scale, which can be implemented globally. These guidelines are a first step towards the understanding of groundwater quality at large scales. There are a number of assessments and considerations that were not included but are worth mentioning in case the user wants to complement these guidelines.

In Chapter 2, a review and a critical assessment of existing techniques/steps for the implementation and review of monitoring networks are presented. This review aims to guide the user in the first step of the assessment, presented in chapter 4.

In Chapter 3 of this document, a review of some international examples on the assessment of groundwater quality is provided. All approaches were evaluated and served as inspiration to propose a groundwater quality assessment using a quality index. A quality index indicates the quality of groundwater through a classification system, based on the concentration of available chemical parameters compared to groundwater quality standards. The proposed quality index provides an overview of potential uses of the groundwater, ranging from water for drinking purposes to water for agricultural purposes when water is not treated.

In Chapter 4, global guidelines for the assessment of groundwater quality are proposed. These include the 1) evaluation of the current state of existing monitoring networks, where these are classified according to their representativity, 2) selection of chemical parameters, 3) quality assurance and control of the available data, and 4) calculation of a groundwater quality index at the point scale and regional/country scale.

In Chapter 5, the proposed guidelines are discussed, including limitations of the proposed methodology for upscaling borehole information to aquifer/region/nation scale.

2. Review of existing guidelines for a groundwater monitoring network implementation

Groundwater monitoring encompasses all the activities that collect data on groundwater quality and quantity dynamics, to later interpret those data based on potential influences on that resource (United Nations Environment Programme, 2022).

Ideally, functioning monitoring networks that are able to represent a region or country are available to perform a groundwater quality assessment. However, reliable groundwater monitoring and assessment hinges on the availability of a groundwater monitoring network with sufficient spatio-temporal resolution and established based on acceptable standards and guidelines. In this section a short review on the existing guidelines/steps for establishing consistent groundwater monitoring networks is provided to support its implementation in areas with limited data and with specific focus on how to make groundwater quality assessment spatially and temporarily representative.

The guidelines reflect many similarities among them, even though some are more detailed and elaborated than others. They can be classified into two categories:

- **Guidelines for the implementation of new monitoring networks:** This category can be referred to in regions or countries where there is no operating groundwater monitoring network. This category includes the WFD (Grath et al., 2007), IGRAC (Jousma et al., 2006), UNEP (United Nations Environment Programme, 2022), and USEPA (USEPA, 1992) guidelines. They provide detailed steps to implement a groundwater quality monitoring network. However, those steps differ slightly, and one is free to choose the guideline that best fit current conditions.
- **Guidelines for the renewal or improvement of groundwater monitoring networks:** This category indicates the steps required to review or to improve an existing network and should be referred to in regions with limited number of boreholes or where there is a need to improve the existing network. This category includes the World Bank Guideline (Ravenscroft & Lytton, 2022) and the Department of Regional Development, Manufacturing and Water of the Queensland government (Water Services of the Water Division, 2022).

All guidelines highlight the common considerations for a consistent groundwater quality monitoring network design through: (1) defining the competing objectives of a monitoring program; (2) determination of the spatial and temporal distribution of the sampling points; (3) assessment of the complex nature of geologic, hydrologic, and other environmental factors.

1) **Defining the objectives of a monitoring program:** The objective of a ground-water quality monitoring program is the main factor determining the cost, the level of detail, and the appropriate method for the design and planning of a monitoring network. A groundwater quality monitoring program typically uses a monitoring network and has one, or more, of the following objectives: i) Ambient monitoring (ground-water quality variations over time), ii) Detection monitoring (detect targeted contaminant), iii) Compliance monitoring (verify the progress and success of ground-water protection, clean-up, and remediation works), or (iv) Research monitoring (to meet specific research goals).

2) **Determination of the spatial and temporal distribution of the sampling points:** The spatial scale defines the areal coverage of the monitoring network. An ambient monitoring program is often related to groundwater quality monitoring at regional scale. A compliance monitoring implies more site-specific coverage. A regional-scale monitoring program typically requires annual or semi-annual sampling frequency and may emphasize the geographical distribution and density of sampling wells relative to population or economic centres. A compliance monitoring program most likely dictates monthly or quarterly sampling frequency, and this is determined based in the specific water quality issue or aquifer type.
3) **Hydrogeological characterization:** Hydro-geological characterization provides the fundamental data and input to a conceptual model required to design any groundwater monitoring network. This involves knowledge of the spatial pattern in aquifer configuration and properties that helps in detection of flow and contaminants pathways.

It is important to consider that the guidelines to implement a monitoring network mainly serve as a preliminary input to network designs, and quite often the implementation steps and or the choice of using any guidelines is dictated by institutional, financial, and environmental factors. However, common considerations have been highlighted and should be considered while designing a consistent groundwater monitoring network. A detailed summary of the guidelines revised in this section can be found in Annex 3.

3. Review of existing large-scale groundwater quality assessments around the world

The assessment of groundwater quality is a task performed by a number of countries, and is facilitated when an international agreement (e.g., the Water Framework Directive in Europe (G. Directive, 2006), and the technical guidance on groundwater monitoring and assessment proposed by UNEP (United Nations Environment Programme, 2022)) enabling groundwater monitoring and reporting is in place. Each country is responsible to carry out this assessment, and they report the quality of groundwater in a specific format. However, the assessment itself can be performed in different ways. Due to the lack of standard guidelines, these assessments can apply varied methodologies, chemical parameters considered, ways of interpreting borehole information, among other important aspects and steps. Therefore, a review of the available country-scale assessments of groundwater quality and a review of some international examples where the quality of groundwater is evaluated on a regional scale is given. This step is important in the development of the guidelines proposed in this document, as it is considered as a basis for this purpose.

Eight examples were assessed and a summary of each one of them can be found in Annex 1. These were selected because they represent good examples of how a groundwater quality assessment can be done in a large contiguous area either by national authorities or independent researchers. Some of the country-scale reports (e.g., Hansen et al. (2012) in Denmark and Muñoz Pardo (2009) in Chile) indicate that the groundwater quality assessment is done through the assessment of one or more chemical parameters compared to their water quality standard, and the study of the evolution of the concentration values in time. While in Denmark snapshot-type maps of e.g., nitrate in groundwater over the country is used, in Chile, an aggregate quality index, which takes into consideration multiple chemical parameters and their spatio-temporal distribution, is used to indicate the quality of groundwater over the region to be assessed. Another country-scale example is Ireland (Craig & Daly, 2010), which indicates the kind of tests needed in groundwater bodies to determine whether the quality of groundwater is good or poor. The international examples where groundwater quality is assessed on a regional scale use a quality index as a tool to indicate the quality on a categorical scale (Babiker et al., 2007; Craig & Daly, 2010; Muñoz Pardo, 2009).

From this review, it is proposed to proceed with the groundwater quality index approach due to its capability to capture the effects of more than one chemical parameter in the overall quality of groundwater in space and time. A groundwater quality index can be defined as value that is determined using chemical, physical, and biological parameters, and indicates the suitability of water by comparing it to water quality standards (i.e., potable water and water for agricultural purposes). It represents the groundwater quality level and is presented as categories that range from “Excellent” to “Bad”.

4. Guidelines for the assessment of groundwater quality

The guidelines proposed in this document aim at assisting in the assessment of groundwater quality at a regional or country scale, with the purpose of defining the potential use of groundwater based on its quality. Groundwater quality is assessed via the calculation of a **groundwater quality index** that will give an indication of the status of the resource, e.g., the groundwater quality status is “good”, or “regular”, etc. Specifically, and depending on the availability of chemical parameters, the output of the assessment is an individual or general quality index expressing the quality at a disaggregated scale for a regional/country-scale analysis. Figure 1 shows the steps needed to perform the groundwater quality assessment and determine the quality index.

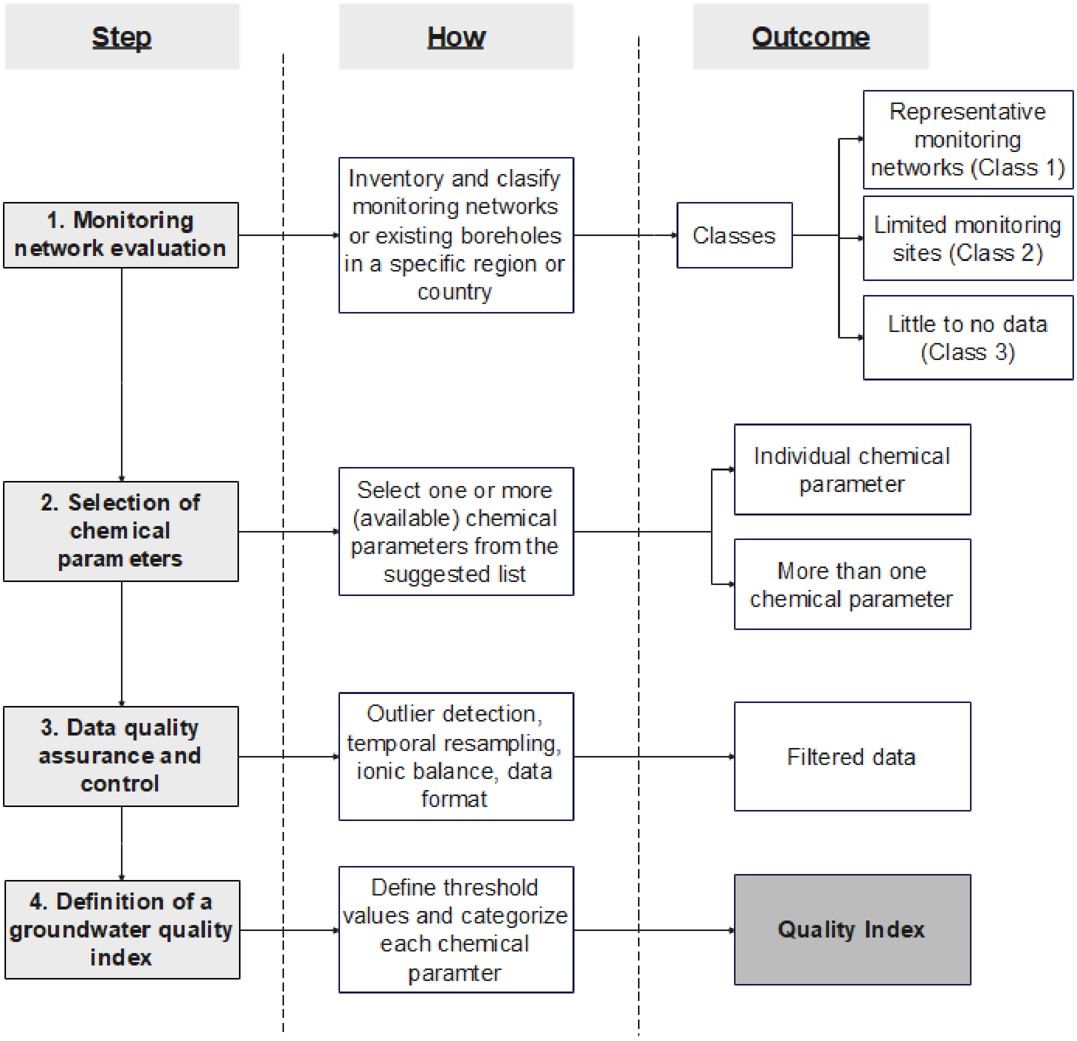


Figure 1. Main steps for the assessment of groundwater quality

The first step is to evaluate the current state of the monitoring network, and based on this evaluation, the monitoring network is classified into either Class 1 or Representative monitoring networks, Class 2 or Limited monitoring sites, or Class 3 or Little to no data. These classes reflect how well the region or country is represented by the available data. A more detailed definition of the three classes is illustrated in Section 4.1.

Once the state of the current monitoring network is defined, a predefined number of chemical parameters that are used for the definition of the quality index are selected based on the literature, local conditions, and expected use or service (e.g., ambient) of the groundwater. An expert opinion is needed in this step and throughout the assessment. Ideally, the expert is a local hydrogeologist with knowledge of the area. In the next step, the data goes through a quality and control process, where the concentration of the selected chemical parameters is cross-checked, and if necessary, adjusted. The data is then presented in a predefined standard format. Finally, the quality index is defined as the result of evaluating the concentration of the chemical parameter(s) to predefined water quality standard values. It can be presented in four types depending on the state of the current monitoring network (if available) and the availability of chemical parameters (one or more than one), as illustrated in Figure 2. The quality index is defined as a unique index/category per borehole or pixel, representing the quality in space and time. It can represent five categories: Excellent, Good, Regular, Insufficient, and Bad.

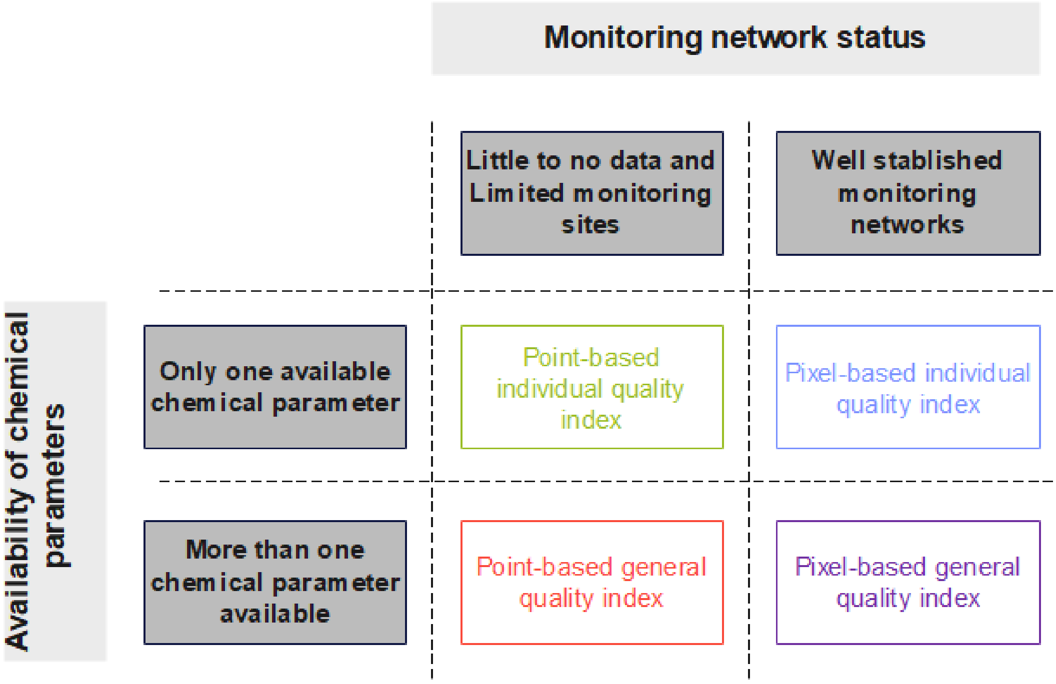


Figure 2: Types of quality index based on the availability of data and chemical parameters

A detailed explanation of the mentioned steps is provided in the sections below.

4.1. Monitoring network evaluation

To perform the proposed assessment of groundwater quality in a country or region, an evaluation of the current monitoring network status (if existent) needs to be carried out. As mentioned above, the outcome of this step is to come up with a category that describes the current situation, and based on that category, there will be specific steps to continue with the assessment. If a monitoring network does not exist, there are two options:

- No data on groundwater quality exists: In this case, the groundwater quality assessment cannot take place and it is urged to implement a monitoring network. More information on this topic can be found in in Section 2.
- A few boreholes are available in the area of interest; however, they do not belong to any monitoring network, nor they are representative: In this case the groundwater quality assessment can take place. The specific situation is analysed and further classified to proceed with the assessment. It is also urged to implement a monitoring network.

In the context of the Water Framework Directive and the Groundwater Directive (GWD) (G. Directive, 2006), a monitoring network and its conceptual model need to be in place for the reporting of the groundwater chemical status of a country or a region. In the WFD Guidance document No. 7 (W. F. Directive, 2003), a conceptual model is defined as "… shorthand for the understanding, or working description, of the real hydrogeological system that is needed to design effective groundwater monitoring programmes…". In this context, it is intended as a conceptual understanding of the system, based on field evidence, hydrogeological characterization, hypothesis, and assumptions of the system. It is written down as a set of characteristics or as a diagram that can be three-dimensional, illustrating the groundwater system with one or more groundwater bodies and the hypothesized features and functionalities with respect to e.g., flow, water storage, and chemical retention properties. A good conceptual model leads to an efficient monitoring network, which in turn, refines the understanding of the groundwater body (European Commission, 2007). Such conceptualization is ideally an ongoing and iterative process, reflected by the outcomes of the monitoring

To get all information available, it is important to identify previous work on the region or country to be assessed through a literature review. This way, a first definition of a conceptual model and the first assessment of a monitoring network (if available) can be found and used. Some of the elements that might exist in previous assessments and are relevant include previous aquifer/groundwater body delineation, location of existing wells and springs, available monitoring points, data availability (types of data and quantity), sources of data (national networks, local/public/private entities), among others.

The state of a monitoring network can vary greatly, ranging generally from a very well-established network to groups of few sampling points with low spatial density and/or irregular sampling frequency. For the purposes of these guidelines, the state of the monitoring network is classified into three classes:

- **Class 1: Representative monitoring networks:** The situation in a region or a country, where there is a well-established groundwater quality monitoring network with data collected for a representative period (e.g., seasonally or quarterly) and extending over the entire region or country. To properly represent the region or country, some studies defined the adequate density of monitoring points to 1 borehole per 25 km^2 (on impacted sites) and 100 km^2 (on non-impacted sites) (Nixon et al., 1998). This density changes in the presence of areas with saline intrusion, being up to 1 borehole per 20 km^2 (Espinoza & Molina, 2005). Studies in Denmark (Hansen et al., 2012) use 25 wells covering up to 50 km^2. In Italy, an area of 580 km^2 was assessed with 90 boreholes (Passarella & Caputo, 2006), while in Japan 50 boreholes were used in an area of 400 km^2 (Babiker et al., 2007). It is therefore suggested that the minimum density of boreholes required for a representative monitoring network should be determined considering the site-specific characteristics of the site. An expert opinion is needed to evaluate the complexity of the groundwater settings and the density can be set considering the presented examples in this section. It also refers to in-place monitoring networks that started collecting data recently.

- **Class 2: Limited monitoring sites:** The situation in a region or a country, where a monitoring network is not available and there are sampling sites in place in a specific region, but insufficient to properly represent the region or country. This also refers to existing boreholes that have been used in previous sampling campaigns where quality has been collected at least once. These can be boreholes, but also information can come from alternative sources such as springs, or domestic production wells. Spatial and/or temporal resolution of groundwater quality data are, however, not enough to represent the quality status of groundwater in the region or country as a whole. If there are sampling sites, but they are limited in terms of availability of spatial and temporal data, it is suggested to improve the situation to a well-established monitoring network (Class 1) following the guidelines illustrated in Section 2.
- **Class 3: Little to no data:** The situation in a region or a country, where there are no groundwater quality data from any source or when a few scattered groundwater quality sampling sites are present. These can be boreholes, but also information can come from alternative sources such as springs, or domestic production wells. There are no available monitoring networks and there are only spatially scattered boreholes from which samples have been gathered at a specific time for a specific purpose.
  - In the case where there are a few scattered boreholes where quality is measured, the assessment can continue, but a monitoring network needs to be implemented referring to the guidelines mentioned in Section 2.
  - In the case where there are no boreholes, groundwater quality assessment does not take place, and it is encouraged to implement a monitoring network according to the guidelines mentioned in Section 2.

  In this class the analysed parameters are not necessarily representative, and the spatio-temporal resolution of the available data is significantly lower than data specified in Class 2.

Although groundwater monitoring should be the responsibility of each country or region, this is limited by the availability of resources (financial, legislative, infrastructure, human resources, among others). Recently, efforts have been made by international organizations such as the World Bank (Ravenscroft & Lytton, 2022), and the United Nations Environment Programme (United Nations Environment Programme, 2022) towards developing specific guidelines for the establishment of monitoring networks.

4.2. Selection of Chemical parameters

This step consists of selecting the chemical parameters that are used to assess groundwater quality. The quality of groundwater is defined by the concentration or measure of the selected chemical parameters compared to the current water quality standard, which can be the national standard, a standard based on WFD guidance, as it is done in Europe (Todo & Sato, 2002), the World Health Organization (WHO) standard (Organization, 2017) globally, or something else.

Based on the evaluation of the international examples, the selection of chemical parameters depends on several factors that include the purpose of the assessment, data availability, or significance of a specific parameter in the given context (Stigter et al., 2006). Additionally, it is suggested to select only one parameter that represents a specific water condition (e.g., TDS, or EC for water salinity). The number of chemical parameters that are used in the definition of the quality index is therefore reduced to avoid bias in the calculation of the quality index.

In general, these chemical parameters are characterized in two sets (e.g., the Chilean example (Muñoz Pardo, 2009) or the Italian example (Passarella & Caputo, 2006)) to differentiate between the mandatory parameters and the locally chosen parameters:

- **Set 1 or general parameters:** aims to provide a representative overview of the groundwater quality and avoids using redundant chemical parameters.
- **Set 2 or specific parameters:** aims to give room for site-specific conditions and are chosen depending on their relative relevance in a specific area, specific land use, natural or anthropogenic origin, among other factors. The number of specific parameters is usually less than the ones selected in Set 1 (Muñoz Pardo, 2009; Todo & Sato, 2002)

Based on the literature review and the analysis in Annex 2, it was defined that the selected general chemical parameters (Set 1) used to define the quality index are eight: Electrical conductivity (EC), Nitrate (NO_3^-), Chloride (Cl^-), Sulphate (SO_4^{2-}), Sodium (Na^+), pH, Temperature, and faecal coliforms; and 3 chemical parameters in Set 2 that are defined on-site, depending on each site's specific characteristics (e.g., Ammonium (NH_4^+), Fluoride (F^-), Arsenic (As_3^+)).

It is advised that all eleven chemical parameters are made available to obtain a representative overview of the groundwater quality. If this cannot be the case, the quality index can still be calculated using the available parameter(s). However, this assessment would be more limited but can provide a first impression of the groundwater quality.

The chemical parameters are then compared to water quality standards in later stages of the assessment. The water quality standards that are considered for the comparison in the international examples are set by national standards, a standard based on WFD guidance, as it is done in Europe, or WHO standards globally. In the absence of national regulations, we suggest following the guidance of the WFD for standard setting or using WHO standards in case the WFD does not apply to a specific region.

4.3. Data quality assurance and control

Data quality assurance and control ensures that the data that are used for a certain analysis are of high quality; and therefore, can yield high quality results. The process can have several approaches, building on the literature and previous experience. An example can be found in the SADC Framework for Groundwater Data Collection and Data Management (SADC-GMI et al., 2019). For this assessment, specific steps will be applied to the quality control of the measurement of the chemical parameters. The data may come from different sources or organizations, which may lead to different units of measurement, data with outliers in either the temporal or spatial domain, or datasets with different temporal resolution.

For the quality index calculation, it is suggested that the concentration values of the chemical parameters are filtered, organized, and statistically analysed to identify outliers that may hinder the interpretation of the behaviour of the parameter (Babiker et al., 2007; Muñoz Pardo, 2009; Passarella & Caputo, 2006; Saeedi et al., 2010; Stigter et al., 2006). Once outliers are identified, they can be either removed if the source of the deviation is identified (e.g., measurement error, human error, scale error) or kept, if they are not explained and may be representing a real anomaly (Passarella & Caputo, 2006).

Another consideration is to observe the temporal resolution of the chemical parameters. There are cases where there are multiple groundwater samples for several periods (e.g., seasonal or yearly sampling takes place or multiple samplings are taken within one season for different purposes). It is suggested to standardize the frequency of the data and average the measurements (e.g., daily to monthly or monthly to seasonal) if necessary.

An additional step is to perform an ion balance once the concentrations of the different parameters in a sample is obtained (Muñoz Pardo, 2009). The ion balance checks for electrical neutrality. This means that the equivalent concentration of positively charged ions is equal to the equivalent concentration of negatively charged ions in the water sample. This procedure ensures that the analyses were correctly performed. Even though only a subset of parameters will be used for the quality index calculation, the following major cations and anions need to be considered to calculate the ion balance: Cations: Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}, and Anions: $HCO3^{-}$, $CO3^{2-}$, $SO4^{2-}$, Cl^{-}, $NO3^{-}$. The ionic balance error (%) needs to be less than 5% to be acceptable. The error is calculated as follows (from Muñoz Pardo (2009)):

$$error\ (\%) = \frac{\sum cations - \sum anions}{\sum cations + \sum anions} \times 100\ \leq 5\% \qquad \text{Eq.1}$$

Finally, and after the concentrations/measures per chemical parameter are determined, dataset adjusted for outliers and temporal resolution, the ion balance checked, the data should be organized into tables, including the following information: location (coordinates), borehole name, date of sample collection, and the concentration per chemical parameter per borehole.

4.4. Definition of groundwater quality index

The groundwater quality of a country or region will be assessed through a quality index, which will indicate whether the quality at a distributed scale is Excellent, Good, Regular, Insufficient, or Bad. International examples of applying this approach were evaluated, and the most important steps were identified, considering the state of the monitoring network (if available) defined in Section 4.1 and the availability of measured chemical parameters, as indicated in Section 4.2. Consequently, four types of quality index can result from the assessment, as shown in Figure 3.

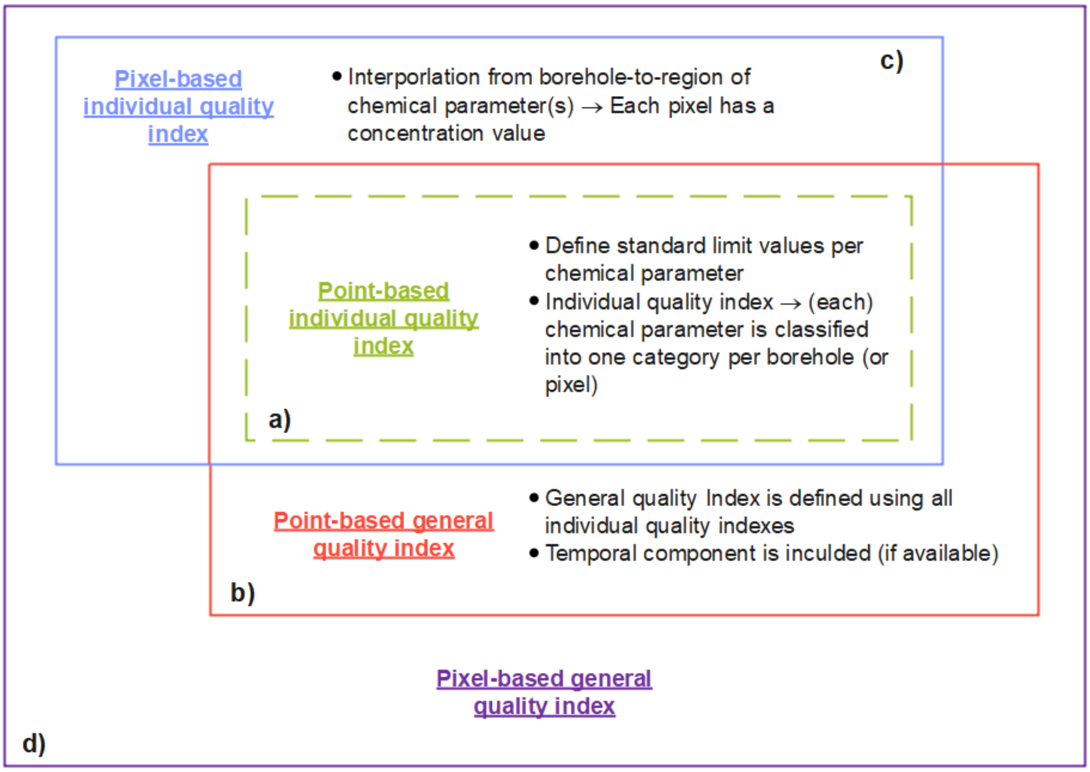


Figure 3: *Diagram of the methodology to determine the groundwater quality index. a) Indicates the steps required to calculate the individual quality index for a point-based assessment in case that there is only one chemical parameter. b) Indicates the additional steps to follow (after following the steps in a)) to calculate the point-based general quality index, in case that there is more than one chemical parameter. c) Indicates the steps required to calculate the individual quality index at the pixel scale for a spatio-temporal assessment in case that there is only one chemical parameter. d) Collects all previous steps and indicates the additional steps to follow to calculate the general quality index at the pixel scale in case that there is more than one chemical parameter.*

The quality index is calculated using the available chemical parameters from the specified list in Section 4.2, and depending on the state of the monitoring network (if available), two approaches are proposed:

- **A point-based quality index which will be used for Classes 2 and 3:** The outcome of the point-based assessment will be an individual or general quality index per borehole depending on the availability of chemical parameters across available boreholes. If the temporal resolution is representative (i.e., all boreholes have more than one sampling campaign, for an overlapping period), the point-based quality index will be complemented by a temporal component.
- **A pixel-based quality index which will be used for Class 1:** The outcome of the pixel-based assessment will be an individual or general quality index (depending on the availability of chemical parameters) per region or country, that indicates the spatio-temporal state of the groundwater quality. Alternatively, when the temporal resolution is not adequate (as specified in Section 2), but the spatial

resolution is adequate, the assessment will be performed without the temporal component.

The proposed methodology takes into consideration the methodologies studied in the literature. Most methodologies come up with a quality index, either calculated through sets of equations, interpolation of classes, or mapping techniques. The proposed approach in this document aims at selecting the most straight forward steps to define a quality index. The Chilean method (Muñoz Pardo, 2009) was the one closest to this objective, since the steps involved in the quality index definition are common with other methodologies and at the same time, they are not too complex to apply to a certain region. The main steps of the proposed methodology are taken from the Chilean method and are applied to the definition of the point-based quality index for Classes 2 and 3, and to the pixel-based quality index for Class 1.

4.4.1. Point-based quality index

The point-based quality index is calculated for Classes 2 and 3 defined in Section 4.1. The assessment is done per available borehole and the outcome specified in this section is at the borehole scale (i.e., each borehole has an individual or general quality index) and can represent an area around the borehole (as reviewed in the literature and defined in Section 4.1.). An expert opinion is needed to decide the area coverage per available borehole. This area is representative when the groundwater body has few discontinuities and can be considered homogeneous in an extended area. This size of the area is reduced when the groundwater body presents complexities like perched aquifers in between, more than one aquifer system, differences in geology and lithology in the area, among other factors.

The quality index is calculated based in the availability of the chemical parameters. When there is one common chemical parameter across the available boreholes, an **individual quality index** is calculated. When there is more than one common chemical parameter across the available boreholes, a **general quality index is calculated**. Ideally, the general quality index is calculated based on the 8 (general) + 3 (specific) chemical parameters proposed and illustrated in Section 4.2. Alternatively, a general quality index can be calculated using less than the suggested 11 chemical parameters, but the representativeness and comparability of the index is reduced. Additionally, a temporal component is considered if the temporal resolution is representative, as stated in Section 4.1. The steps to be used are adapted from the methodology applied in Chile (Muñoz Pardo, 2009) and illustrated below.

1. There are five different categories that are recommended to classify the quality of groundwater per parameter. The categories are derived from the concentration values (CV) of each chemical parameter compared to the four limit values (LV: LV1<LV2<LV3<LV4), defined from national standards, a standard based on WFD guidance, or WHO drinking water standards, as illustrated in Table 2, and explained in step 2.

Table 2: Groundwater quality categories based on concentration values compared to limit values

Concentration	Category	Colour
CV ≤ LV1	Excellent	Dark green
LV1 < CV ≤ LV2	Good	Light green
LV2 < CV ≤ LV3	Regular	Yellow
LV3 < CV ≤ LV4	Insufficient	Orange
CV > LV4	Bad	Red

2. For every parameter, 4 limit values are defined (LV: LV1<LV2<LV3<LV4), which correspond to different groundwater quality levels/categories based on water quality standard values and uses, as described below.
   I. LV1 – Defines maximum concentration for ***Excellent*** category: Corresponds to a maximum concentration/measure of a chemical parameter in groundwater that considers human health and ensures quality for consumption, being potable water. WHO water quality standards for potable water quality are considered.
   II. LV2 - Defines maximum concentration for ***Good*** category: Corresponds to a maximum concentration/measure of a chemical parameter in groundwater for potable water considered by a legal standard. This can be set by national legislation for potable water quality. If such national legislation is not in place, other sources of information can be considered e.g., WHO, European standards, among other international guides. The difference with LV1 is that the standard used to determine if water is potable or not might be less strict than WHO guidelines.
   III. LV3 - Defines maximum concentration for ***Regular*** category: Corresponds to a maximum concentration/measure of a chemical parameter in groundwater for agricultural purposes. The reference values to be used can be found in the "Water quality for agriculture" (Ayers & Westcot, 1985), and if available, national legislation for groundwater quality for agriculture.
   IV. LV4 - Defines maximum concentration for ***Insufficient*** category: Corresponds to a maximum concentration/measure of a chemical parameter in groundwater that allows treatment and could reach potable water chemical conditions according to current legislation (***Good***). This value depends on treatment technologies and the effectiveness of remotion, considering also economical and technical feasibility. LV4 is defined with the following equation:

$$LV4 = \frac{VL}{1-\%\ Removal\ Effectiveness} \qquad \text{Eq. 2}$$

   where VL is LV2 and the percentage of removal effectiveness can be found in HAMANN et al. (1996) and MENA (2007), that illustrate some methods for this purpose.
   V. Chemical parameters with concentration values above LV4 are classified as ***Bad***: This classification refers to waters that could be treated, but the

processes that ensure a ***Good*** water quality are more complex and expensive.

3. **Point-based individual quality index (P-IQI):** Per borehole, if there is only one chemical parameter available for the assessment, the P-IQI is defined by the assigned category, that results from comparing the concentration value to the limit values. The assessment ends here and each borehole is assigned a P-IQI.
4. **Point-based general quality index (P-GQI):** Per borehole, when there is more than one chemical parameter, an aggregated quality index is derived from the individual quality indexes. This quality index defines the overall groundwater quality for a specific borehole. See Table 3.
    - I. P-GQI is **Bad (red)** if there is at least 1 chemical parameter with quality index classified as Bad (any P-IQI is Bad).
    - II. P-GQI is **Good (Light green)**, **Regular (yellow)**, or **Insufficient (orange)** if none of the chemical parameters involved in the analysis is Bad, and at least one is not Excellent. The resulting P-GQI (Good, Regular, or Insufficient) will be the worst ranked P-IQI.
    - III. P-GQI is **Excellent (Green)** if all chemical parameters have an Excellent quality index (all P-IQI are Excellent).

Table 3:Values of PB-GQI for the 5 established categories

Category	Value		Potential use
Excellent	All P-IQI are Excellent → P-GQI is Excellent		Drinking water
Good	No P-IQI is Bad and at least one P-IQI is not Excellent → P-GQI is lowest P-IQI	Good →	Potable water
Regular		Regular →	Agriculture
Insufficient		Insufficient →	Potable when treated
Bad	Any P-IQI is Bad → P-GQI is Bad		Not treated

The general quality index provides a better representation of the groundwater quality than the individual quality index per borehole and could provide a representative overview of the groundwater quality in the surrounding area, within the region or country to be evaluated.

There might be cases on Classes 2 and 3 where the 11 proposed chemical parameters are not available. In this case, a general quality index can still be calculated if the available chemical parameters used for the calculation of the general quality index are the same for all the available boreholes in the analysis. This is to ensure that the resulting index is comparable across boreholes. Then, the quality index is calculated per borehole. An illustration of the procedure is given in Figure 4.

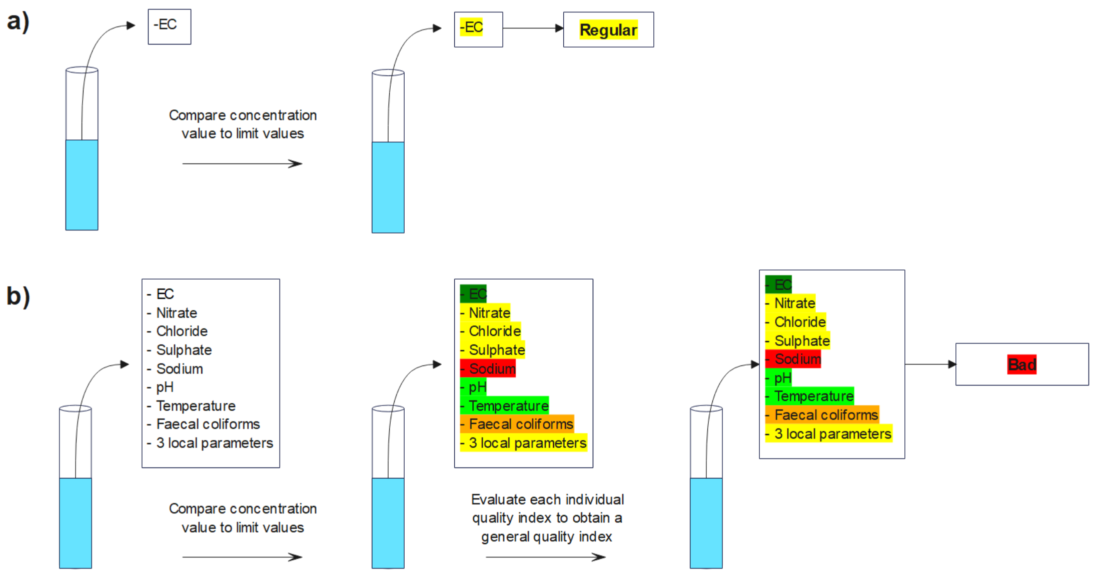


Figure 4: Illustration of the procedure to obtain the point-based quality index. a) For individual quality index and b) for general quality index

A temporal component to the P-GQI can be incorporated to its representation in the case where there is more than one overlapping sampling campaign. We consider two scenarios: only 2 sampling campaigns or more than 2 sampling campaigns.

5. When there are 2 sampling campaigns, we suggest comparing the percentual difference between initial P-GQI and final P-GQI, to a predefined percentage (T1%). When the percentual difference is greater than T1%, the situation is worsening, when it is lower than T1%, the situation is improving, otherwise there is no significant changes in the situation.
6. When there are more than two measurements in time, the P-GQI is calculated for all time stamps (e.g., 1 P-GQI per year) and a time series is obtained per borehole. If the slope of the regression line of the time series is positive, the situation is worsening, if it is negative, the situation is improving, and if the slope is within a range (T2), the situation is not changing.
7. Both T1% and T2 are determined with expert opinion and considering the temporal evolution of the QI.
8. The final representation of the QI per borehole that includes the temporal component is presented in Figure 5:

Figure 5:Representation of the point-based individual or general quality index, including the temporal component

4.4.2. Pixel-based quality index

The pixel-based quality index is calculated for Class 1, defined in section 4.1. In this case, the spatial and the temporal requirements to represent a region or a country are met. The outcome of the assessment will be a distributed/raster map at the regional or country scale, where each pixel is assigned a groundwater quality category. The outcome will be an individual quality index or a general quality index depending on the availability of chemical parameters. The development of the quality index for Class 1 is done compiling some of the steps previously described in Section 4.4.1 and includes a spatial and temporal representation of the quality index over the region or country.

In case there is more than 1 borehole in a 5 km x 5 km area, it is advised to average the concentration values per parameter (Hansen et al., 2012).

1. A concentration map per chemical parameter is developed though interpolation methods. The most common interpolation method is kriging (Babiker et al., 2007; Hansen et al., 2012; Passarella & Caputo, 2006; Stigter et al., 2006). Other interpolation methods could be also used depending on the particularities of the region or the groundwater bodies such as the spline method, linear interpolation, or Thiessen polygons (Muñoz Pardo, 2009). The size of the grid for the interpolation is determined depending on the number of available boreholes, size of the region, computational capabilities, among other factors.
    a. When only one chemical parameter is available for the assessment, there is only one concentration map.
    b. When more than one chemical parameter is available, ideally the proposed 11 chemical parameters, there are 11 concentration maps covering the region or country of interest.
2. For each concentration map, the **pixel-based individual quality index (X-IQI)** is determined per pixel as explained in Section 4.4.1, steps 1 through 3.

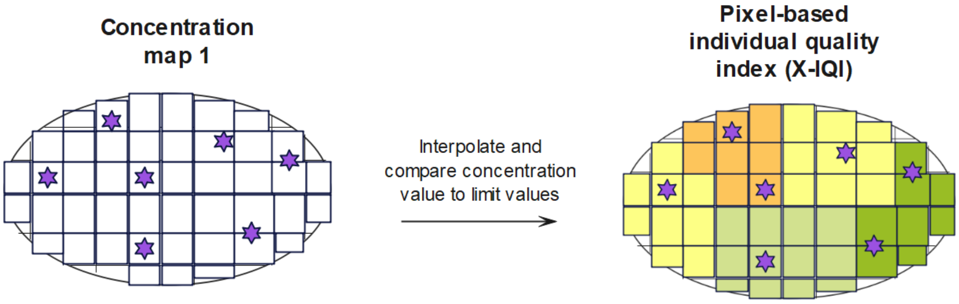


Figure 6: Pixel-based individual quality index definition

3. The **pixel-based general quality index (X-GQI)** is then calculated per pixel, as explained in Section 4.4.1, step 4. Each pixel will have a X-GQI based on the individual concentration maps per parameter. At this point, there is one X-GQI map covering the region or country of interest, where each colour represents the quality of groundwater per pixel, as illustrated in Figure 7.

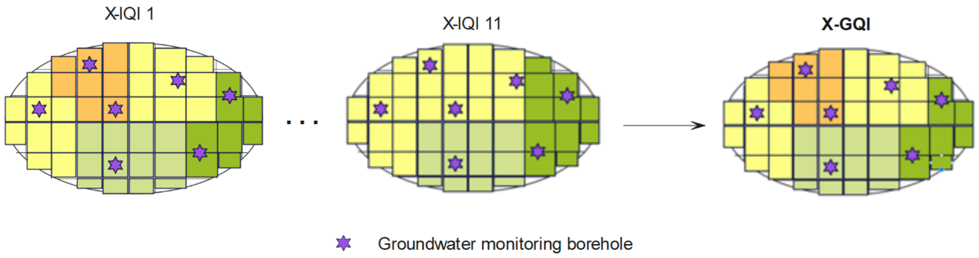


Figure 7: Pixel-based general quality index definition

4. To incorporate the temporal component to the X-GQI representation, the procedure explained in Section 4.4.1, steps 5 through 8 is followed; where every pixel will have an associated time series from which the regression line slope will be analysed. Then, every pixel will be corrected for the temporal evolution of the quality of groundwater.

In the case of recently established monitoring networks the temporal component only takes place after having collected data for representative period of time.

5. Discussion and recommendations

There is high uncertainty when a point-based analysis is upscaled to be representative of a region or a country. A representative network should comply with the minimum criteria discussed in Section 2, and if this is not the case, a spatio-temporal analysis will not yield accurate results. In the case of little to no data, there might be cases where there are scattered boreholes around a small area or region. The representativeness of a single borehole needs to be defined with an expert opinion and can be as varied as, for instance, from 25 boreholes covering an area of 50 km2 (Hansen et al., 2012) in complex areas to 1 borehole covering an area of 100 km2 (Nixon et al., 1998) in a more homogenous environment. The lack of knowledge regarding the type of aquifer that is present (e.g., confined or unconfined) complicates further the interpretation. When the density of boreholes is not enough to cover the area, the results might not be able to reflect real conditions in the whole study area. If this is the case, it is better to display the quality index per single borehole or pixel, rather than use this one value as a representation of the quality of the groundwater body/region/country.

Many countries simply do not have the capacity to establish a national groundwater quality monitoring network, or they have little to no data available. If this is the case, the first step is to encourage the implementation of a monitoring network in a country level. Once monitoring takes place, it is possible to apply the guidelines proposed in this document.

It is expected that many of the chemical parameters in Set 1 do not vary significantly with time (at least in the short-medium term) for many groundwater settings or conditions. Groundwater systems tend to evolve slowly over several years-decades, and when they do evolve within monitoring timescales (seasonally to yearly), these tend to be forced by anthropogenic factors such as pumping, land use change, pollution lead by industrial activities, among other anthropogenic factors. This consideration needs to be taken into account when incorporating the temporal component to the quality index. Rapid changes in concentration in time may occur and need to be double-checked and related to possible sources or hydrogeological conditions.

It has been shown that the representation of the quality index per borehole needs to be determined using an expert opinion. However, the more complex the groundwater body, the smaller should be the pixel size representing groundwater quality, although it can be argued that this complexity can be replicated over a larger area. In any case, it is important to have an updated conceptual model to guide this decision.

Although the area that is represented is limited to the location of the borehole, it can give an idea of the quality of groundwater in specific locations and give context to the region or country to be evaluated (e.g., a region where boreholes indicate poor quality may require more attention than a region where boreholes indicate good quality). A regional representation based on the point-based quality assessment is not possible but can be achieved through the improvement of the groundwater monitoring program. When more spatial data is available, in the case of Limited monitoring sites, a greater area can be covered by the available data, and the uncertainty decreases when assigning groundwater quality to the region where the boreholes are located. This region becomes more represented. More pixels are classified, and the overview of groundwater quality is more representative.

The outcome of the suggested guidelines is a quality index. Depending on the status of the monitoring network and the availability of chemical parameters, the quality index can be of four types. This allows for flexibility in the calculation of the quality index when the area of interest is not properly represented, or only few chemical parameters are measured. However, the index is less comparable. The general quality index, either point-based or pixel-based, calculated with the 11 suggested chemical parameters is the one able to be comparable internationally. Nationally, there might be certain accommodations to calculate the general quality index with fewer chemical parameters. This way, a first interpretation of the quality is achieved.

The groundwater quality assessment can be enhanced by improving the monitoring network, from site-based to regional or national scale. This can be achieved by implementing the available guidelines to monitor groundwater quality and expanding the network to cover the main groundwater bodies in a region or country.

Ultimately, by proposing a standard set of steps for the assessment of groundwater quality, national or regional assessments can be comparable. These guidelines are a first step towards the understanding of the groundwater quality at large scales and is to be complemented when applied to the field. This knowledge can be used in decision making to take responsible actions towards a proper management of groundwater quality.

6. Annexes:

Annex 1: Literature review on groundwater quality assessments around the world and development of a quality index

Chile: "Diagnosis and classification of aquifer zones", (original text in Spanish);
Muñoz Pardo (2009)

Groundwater quality in Chile is assessed at the aquifer/regional scale by the Water General Directory (DGA). The quality is assessed based on a set of contaminants, from which their concentration is mapped and categorized according to the standard values found in national and international directives. There is one map per contaminant or parameter. The maps are merged into a single categorical map indicating different levels of quality, from very good to very poor. The spatial analysis is complemented by a temporal analysis if there are data from different periods of time. A statistical analysis is included to determine the origin of the current state of the groundwater quality in each aquifer and the relationship between aquifers.

The first step is to collect all hydrogeological and aquifer data in a suitable format. In this case, data such as topography, drainage, geology, urban sites, monitoring points is collected in GIS format.

The Chilean case argues the use of different spatial interpolation tools depending on the study area. The factors to consider include the quantity and location of data points, area of the aquifer, interpolation grid size, relationship between measurements and close by points, geometry, and hydrogeology of the aquifer, among others. In general, kriging is the most used method, but spline is also used when hydrogeological barriers are present.

Once data is available and an interpolation method is defined, the following step is to define the chemical parameters to be used in the assessment. These are selected based on international methodologies, national monitored parameters, and/or project objectives. They are divided into 2 groups. Group 1 represent the parameters that are usually monitored in any water sample and widely used internationally. These are: Total dissolved solids (TDS), chlorides, sulphates, calcium, sodium, and magnesium. Group 2 or local parameters accounts for the particularities of each aquifer. These are: nitrates and two other local parameters that reflect the local particularities. These can only amount to three. This selection of parameters avoids having highly correlated parameters and allows a complete chemical analysis of the samples.

The validity of the chemical data is checked using the ionic balance. The error should be less than 5%. The data should be from the same aquifer, also considering the possibility of having lateral flow between two aquifer systems close by. Outliers found in the data should be eliminated, replaced, or validated depending on each special case. If some substances are not detected with the instruments, a numeric value should be given, around 25% or 50% of the limit value.

The local parameters are chosen based on a local evaluation of natural and anthropogenic parameters that may have an elevated concentration due to specific activities in the area. An analysis of the possible sources of contamination is done. As a result of this evaluation, two parameters are chosen depending on the health risk they represent, most concentration, no correlated and representative of anthropogenic activities.

The chemical parameters from groups 1 and 2, and the spatial data that have been collected so far are used to calculate the quality index. The idea is to obtain maps of chemical iso-concentration per each chemical parameter using the interpolation method previously defined (kriging, spline, or others). As a result, 6 maps are generated for Group 1 (fixed parameters) and 3 maps for Group 2 (nitrates plus 2 local parameters). Each pixel in each map has a concentration value, that is then classified based on national and international standards. At this stage, there is a quality index (QI) per pixel, per parameter. A general QI is defined per pixel, which reflects the aquifer quality by the worst quality parameter. The results are displayed using a discrete scale with 5 classes: Excellent, good, mediocre, insufficient, and bad.

Finally, a temporal analysis is performed, where the objective is to identify the evolution of the tendency of groundwater quality in time, classified as better, worse, or equal. A percentual change is calculated between initial and final quality. This change is compared to a pre-defined value and is included in the color-coded map. The colours of the final map will have 5 categories, which include the spatial categorization and temporal categorization. Figure 8 illustrates an example of the final result after applying the methodology and calculating the general quality index.

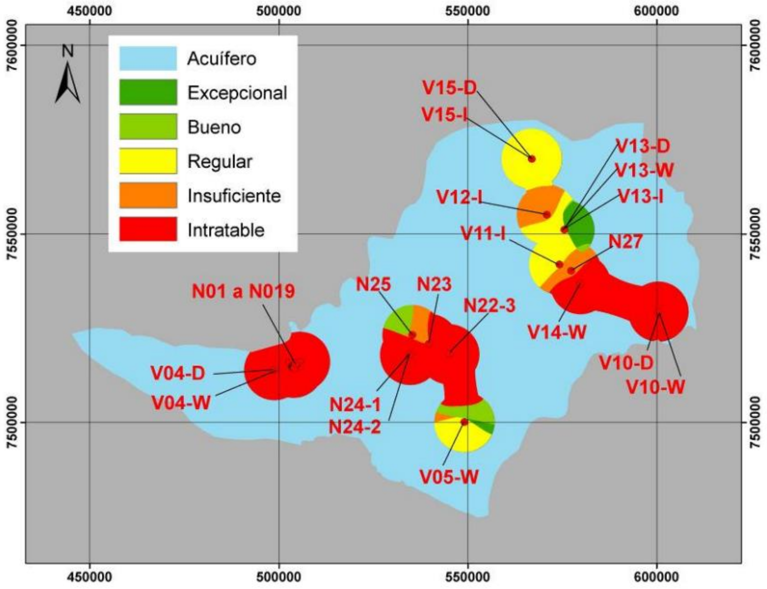


Figure 8: General quality index for the Loa Aquifer, Chile (extracted from Muñoz Pardo (2009)*)*

Japan: “Assessing groundwater quality using GIS”; Babiker et al. (2007)

Researchers in the Hydrospheric Atmospheric Research Center, Nagoya University carried out a regional study in the Nasuno basin, Tochigi, Japan. The alluvial basin is formed by shallow, unconfined aquifers and have a high capacity to hold water. It extends over an area of 400 km^2 approximately. There are around 50 wells spread over the area, where seasonal data is collected every year. Physical and chemical parameters of groundwater such as water temperature, electric conductivity, and pH are collected in-situ and determined in the laboratory. Other determined parameters are major cations (Ca^{2+}, Mg^{2+}, K^+, Na^+) and SiO_2, major anions (Cl^-, NO^{-3}, $SO2^{-4}$), HCO^{-}_{3}. The assessment is performed using only spring data because it was observed that during this season the nitrate concentration increased. It is believed that this happens due to start of the rice cultivation season.

Seven groundwater chemical parameters listed in the World Health Organization (WHO) guidelines were chosen to determine the groundwater quality index. Drinking water standards were selected due to the importance for human health. Six chemical parameters are chemically derived contaminants that affect the appearance of water (Cl^-, Na^+, Ca^{2+}, Mg^{2+}, SO_4^{2-}, and total dissolved solids, TDS), while one chemical parameter (NO_3^-) is listed as a chemical that might produce “potential health risk” (Organization & O, 2004).

The spatial variation of groundwater was captured by spatial analyses performed by GIS, using ILWIS, the GIS software of the International Institute for Geo-Information Science and Earth Observation (ITC). Physical maps with topography and the location of the evaluated boreholes were digitized and converted to a raster format with a pixel size of 50 m. Once the information is digitized, a spatial analysis was performed. Frist, it was verified that the boreholes were randomly distributed. Then, a spatial autocorrelation was performed to show the correlation at different shifts in space to observe the spatial variability of groundwater quality and to evaluate if the different variables are independent.

Finally, the groundwater quality index (GQI) is developed. It is derived from the spatial representation of the scattered measurements of the selected chemical parameters into an index which indicates the quality of groundwater. The first step is to elaborate the primary map I. This is a concentration map, and it is constructed for each parameter using kriging as the interpolation method. Then, every pixel is related to the WHO standards using the following equation:

$$C = \frac{X' - X}{X' + X} \qquad \text{Eq.3}$$

where X’ is the measured concentration on each pixel on each map and X is the WHO standard value for each parameter. The result is the primary map II and shows, per pixel, normalized contamination index values that range from -1 to 1. Thereafter, a rank map was generated. It brings the range of contamination index values to a range from 1 to 10, where 1 indicates minimum impact in groundwater quality and 10 indicates maximum impact. Equation 4 shows the rank value per pixel:

$$r = 0.5 \times C^2 + 4.5 \times C + 5 \qquad \text{Eq. 4}$$

Finally, the general quality index (GQI) is calculated. It represents an averaged linear combination of factors and is calculated using equation 5:

$$GQI = 100 - \left(\frac{r_1 w_1 + r_2 w_2 + \cdots + r_n w_n}{N}\right) \qquad \text{Eq. 5}$$

Where r comes from the rank map, w is the relative weight of the parameter that corresponds to the “mean” rating value (r) of each rank map and to the “mean (r+2)”, r ≤ 8 when the chemical parameters have the potential to harm life. The higher the mean rate from the rank map, the higher the influence in the evaluation of the groundwater quality. N is the number of chemical parameters used in the suitability analyses. The index scores are classified based on a fixed interval of area percentage in the area. The values are sorted from high to low and each 10 percent is taken as one category. Colours blue, green, red indicate Maximum, Medium, and Minimum water quality respectively. An additional step is to further select the best combination of chemical parameters to calculate the potential GQI and avoid bias in the calculation process.

The seasonal variation of groundwater quality is also considered in the analysis. The coefficient of variation is calculated for each borehole that are sampled at least 3 seasons and is expressed as: (standard deviation/mean * 100). This is done for each parameter. Then, the total variation in each borehole is calculated as the summation of the coefficient of variation of all parameters. Lastly, a seasonal variation map is produced and integrated with the GQI. As an example, the methodology is applied in the Nasuno basin, and the results are shown in Figure 9.

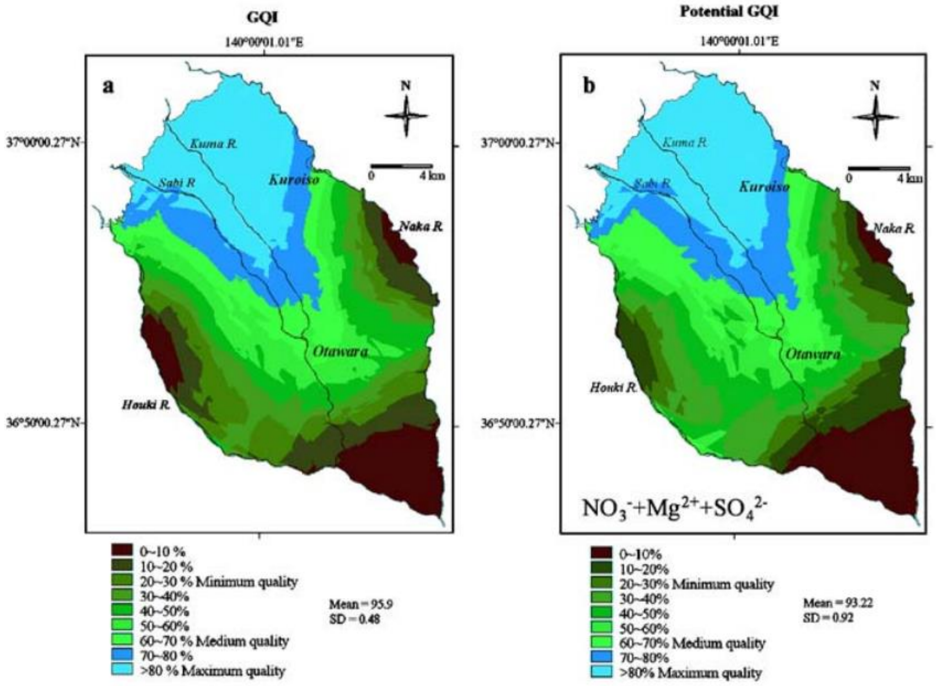


Figure 9: The groundwater quality index, GQI (a) and potential groundwater quality index (b) of the Nasuno basin. The potential GQI was computed using three parameters only (NO_3^- , Mg^{2+} and SO_4^{2-}). Extracted from (Babiker et al., 2007)

Italy: "A methodology for space-time classification of groundwater quality"; Passarella & Caputo (2006)

Researchers from the Water Research Institute, IRSA – CNR, using data from the Regional Environmental Protection Agency (ARPA) of the Emilia Romagna Region represented the base groundwater quality in a large scale based on simple methodology. The methodology assesses the status of groundwater quality and goes beyond a strict implementation of the WFD. The methodology evaluated the concentration of the main chemical parameters typical of natural quality or contamination induced by human activities. The data was obtained from 2 different monitoring networks. It was filtered and statistically analysed to observe their main characteristics. Then, borehole data were interpolated, and quality maps were derived. In addition, a temporal component was included to the graphic representation.

The study was performed in Italy, in an area of 580 km^2 and a total of 180 wells were available, but only 90 wells were used. Eight parameters were used for this analysis, divided into 2 groups:

- Group 1: "chemical and physical parameters", found naturally in groundwater and includes hardness, electric conductivity, sulphates, and chlorides.
- Group 2: "undesirable substances", mainly human-induced and includes nitrates, iron, manganese, and ammonia.
- Groundwater level is also analysed.

The data that was collected was filtered, organized, and statistically analysed to observe the behaviour of each parameter. Then, variographic techniques were used to study spatial correlations.

To evaluate the piezometric levels, contour maps were plotted and evaluated. They showed the differences when observing the confined and unconfined portions of the aquifer. The chemical parameters are evaluated regarding two fixed threshold values: the guideline value (GV) and the maximum allowable concentration (MAC). These threshold values allow to classify the groundwater quality into three classes:

- Class A (optimal): When the parameter value is lower than the GV. Groundwater is suitable for drinking and no treatment is necessary. Acceptable for almost all uses.
- Class B (acceptable): When the parameter value is lower than MAC, but larger than GV. Groundwater is suitable for drinking without treatment. There are some limitations with other uses such as industrial and agricultural.
- Class C (poor): When the parameter value is larger than MAC. Groundwater is not suitable for drinking and other uses are limited. If the parameter is from Group 1, treatment is required, while if it is from Group 2, advanced oxidation treatment is needed.

In each chemical parameter group (Group 1 or Group 2), if one of the chemical parameters exceeds the MAC, the quality of the group is poor. If the GV is not exceeded by any of the parameters, the groundwater quality in the group is optimal. The quality of each group is determined by the worst parameter. Each parameter per group is given a category depending on its value (A1, B1, C1, A2, B2, or C2). Then, a water sample is classified as a combination of the categories obtained from the chemical parameter group (e.g., if the quality is optimal for group 1 and poor for group 2, the water sample class is A1-C2). In this way, there are nine combinations that define the quality of a sample of groundwater. Lastly, these combinations are associated with five categories that account for the undesirable substances by giving them a significant weight. Table 4 shows the final classification.

Table 4:Simplified general classification for groundwater quality

Original*	Simplified
General classification	
A1 A2	Optimal
B1 A2	
C1 A2	Good
A1 B2	Acceptable
B1 B2	
C1 B2	
A1 C2	Poor
B1 C2	Very poor
C1 C2	

The result is a map showing the category to which each pixel belongs. This map is plotted for each time step available, providing an overview of the temporal evolution of groundwater quality. To add a temporal component to the result, two new classification indexes are used: a “position index” and a “trend index”. These would indicate, per pixel, the mean cell value (MCV) per parameter in a scale from 1 to 5, and if the temporal trend of the quality is increasing, decreasing or stable. As a result, there are fifteen classes that express the space-time classification of groundwater quality, as observed in Table 5, and illustrated in Figure 10.

Table 5: Space-time classification

Position Index		Trend index*		
Value	**Label**	**Worsening**	**Constant**	**Improving**
1 ≤ MCV < 1.5	Optimal	B	BB	BB
1.5 ≤ MCV < 2.5	Good	BP	BB	BB
2.5 ≤ MCV < 3.5	Acceptable	P	BP	B
3.5 ≤ MCV < 4.5	Poor	PP	PP	BP
4.5 ≤ MCV ≤ 5	Very poor	PP	PP	P

MCV = Arithmetic mean of the seasonal values of the quality indexes.
*Slope of linear regression line.

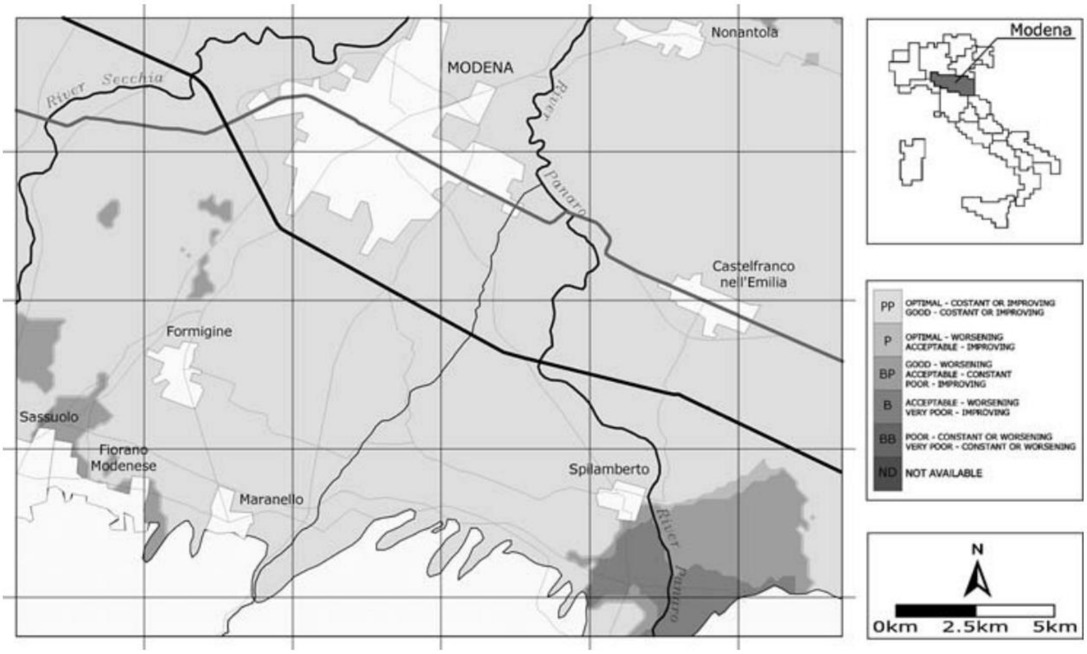


Figure 10: Map of the classification. Extracted from (Passarella & Caputo, 2006).

Ireland: "Methodology for establishing groundwater threshold values and the assessment of chemical and quantitative status of groundwater, including an assessment of pollution trends and trend reversal"; (Craig & Daly, 2010)

As part of the WFD and the GWD, developing and maintaining a list of threshold values for pollutants in groundwater to assess the chemical and quantitative status of groundwater is responsibility of the Environmental Protection Agency (EPA). These values help determine if the conditions for good chemical status imposed by the WFD and the GWD are being met. To achieve this objective, tests have been established for each of the quality elements that define a good chemical and quantitative groundwater status. There are five chemical tests that are independently performed and combined in the end to provide an overall assessment of the groundwater body chemical status. The worst-rated test is used to represent to overall quality of groundwater.

Additionally, pollution trends need to be assessed by the EPA. Significant and sustained upward trends in the concentration of pollutants in groundwater bodies at risk of failing to achieve the WFD objectives need to be identified. Also, the starting point for trend reversal need to be identified and expressed as a percentage of the relevant groundwater standard. The trend assessments need to be done in two of the tests mentioned before: Drinking Water Protected Area and Saline Intrusion tests.

The tests used to assess the chemical status of a groundwater body are: 1) Saline or Other Intrusions test, 2) Impact of Groundwater on Surface Water Ecological/Chemical Status test, 3) Groundwater Dependent Terrestrial Ecosystems – Chemical Assessment test, 4) Drinking Water Protected Area test, and 5) General Chemical Assessment test.

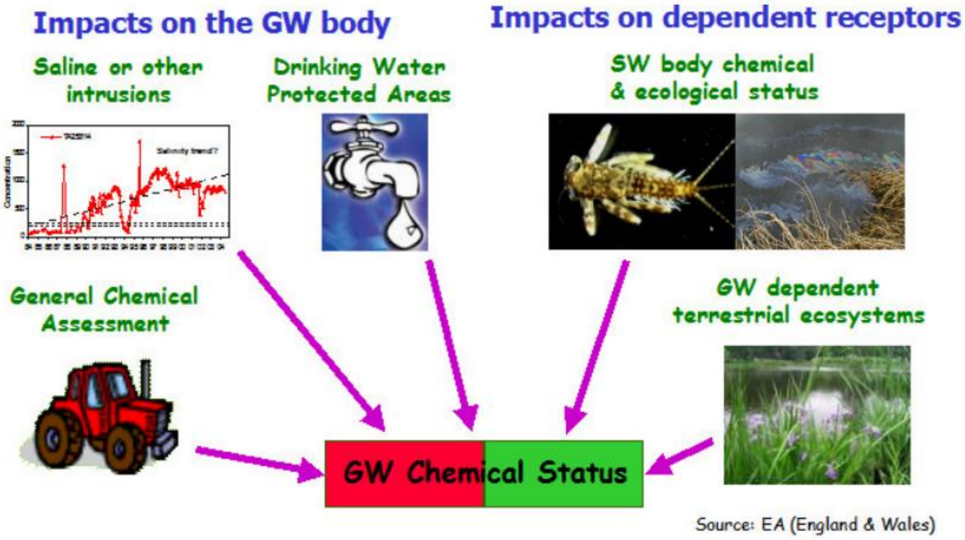
1) **Saline or Other Intrusions test:** The status and the presence of a pollutant in the groundwater body is determined assessing Electrical Conductivity and

Chloride trends. The presence of an intrusion that is induced by groundwater abstraction is detected by the test. The threshold value is set at the upper limit of the natural background range (Electrical Conductivity = 800 µS/cm; Chloride = 24 mg/l.). When Electrical Conductivity and Chloride concentrations are above natural background levels, a significant upward trend in the parameter concentration or an impact in the site is identified. In this case, the chemical status of the groundwater body is classified as poor. If this is not the case, the chemical status is set at good. The tests were performed in groundwater bodies at risk of failing good chemical status according to the WFD.

2) **Impact of Groundwater on Surface Water Ecological/Chemical Status test**: The chemical status is determined when combining surface water classification results and an assessment of chemical intrusion in surface water from groundwater. Through the test, the contribution from groundwater quality to surface water quality is evaluated and it can be seen the impact is sufficient to threaten the WFD objectives. The threshold values are set for surface water standards adjusted by dilution and attenuation factors (Molybdate Reactive Phosphorus (as P) = 35 µg/l (based on River EQS); Ammonium (as N) = 65 µg/l (based on River EQS)). The chemical status is set as poor if the associated surface water body does not meet WFD regulations and threshold values are exceeded, where groundwater contributes at least 50% of the relevant surface water standard. Good status was assigned to the groundwater bodies that contributed less than 50% of the loading.
3) **Groundwater Dependent Terrestrial Ecosystems (GWDTE) – Chemical Assessment test**: Chemical status is defined by combining two assessments. A GWDTE assessment to determine ecological damage and an assessment of chemical inputs from groundwater into GWDTEs. The idea is to determine if the contribution from groundwater quality into the GWDTEs and its impact in GWDTEs puts in risk the compliance of GWDTEs to WFD objectives and regulations. The threshold values that are used are wetland quality standards or action values adjusted by dilution and attenuation factors. Concentrations of nutrients in groundwater bodies are considered for the test, such as phosphates, nitrates, and ammonium. These have the potential to affect groundwater dependant wetlands. When a significant damage coming from chemical pressures is identified, the status of the groundwater body is set to poor.
4) **Drinking Water Protected Area (DWPA) test**: According to the WFD, the objective of the DWPA is to avoid deterioration in water quality by having the necessary protection to reduce purification treatment needs. Therefore, a good chemical status requires the assessment of water for human consumption at the point of abstraction. If anthropogenic activities have caused deterioration in groundwater quality, it could lead to an increase in purification treatments. The threshold values used for this assessment are chosen from the Drinking Water Standards or other standards that ensure water for human consumption (Nitrate (as NO_3) = 37.5 mg/l, Ammonium (as N) = 175 µg/l, Electrical

Conductivity = 1,875 µS/cm, Nitrite (as NO_2) = 375 µg/l, Chloride = 187.5 mg/l, Sulphate = 187.5 mg/l, Sodium = 150 mg/l, Boron = 750 µg/l, Individual Pesticides = 0.075 µg/l, Total Pesticides = 0.375 µg/l). A poor chemical status is met when a significant and sustained rising trend in the concentration of one or more chemical parameters at the point of abstraction and threshold values are exceeded.

5) **General Chemical Assessment test**: The chemical status is determined by assessing the areal extent of a groundwater body that is exceeding a threshold value for a particular pollutant. This assessment is done for chemical parameters that have a standard prescribed by the EU, or for chemical parameters that, after performing a risk characterization process, may cause significant loss of human uses of groundwater. The threshold values that are used are chosen from the EU prescribed standards for nitrates and pesticides. A use-related standard that is relevant for the use of the groundwater body can also be used. A poor chemical status is met when at an individual monitoring point scale, the threshold values are exceeded, and at the groundwater body scale, when a representative aggregation of the monitoring data indicates a significant environmental risk or significant loss of human uses of the groundwater body. See Figure 11.



Source: EA (England & Wales)

Figure 11: Chemical status assessment tests. Extracted from (Craig & Daly, 2010)

Portugal: "Application of a Groundwater Quality Index as an Assessment and Communication Tool in Agro-Environmental Policies - Two Portuguese Case Studies"; Stigter et al. (2006)

Researchers from the University of Algarve and the Superior Technical Institute in Portugal developed a methodology based on multivariate analysis to create a groundwater quality index aiming at monitoring the influence of agriculture on several key parameters of groundwater chemistry and potability. The data consist of several samples collected for three years and the methodology involves 4steps:

- **Step 1. The selection of the parameters:** The selection of the parameters that make up the index depends on the purpose of the index, the importance of the parameter and the availability of data. In this present case, the purpose was to monitor the impact of agriculture on the groundwater quality and potability and therefore, parameters such as pH, NH_4^+, NO_3^-, PO_4^{3-} and TDS were of interest. Others could be EC, Cl^-, NO^{2-}, SO_4^{2-} , Ca^{2+} and K^+.
- **Step 2. Distribution of data in three classes:** In this step, each chemical parameter involved is classified referring to the drinking water guidelines. The first class has concentrations below the guide level (≤GL). The third class has concentrations above the maximum admissible concentration (>MAC) for each parameter. The second class has concentrations between the two guideline values (MAC-GL).
- **Step 3. Standardisation:** The standardisation procedure is performed by applying a simple binary codification: 1 if the sample belongs to a class, 0 if not. Two standard water samples are defined as extremely high and low quality. The first class (≤GL) is signed to all parameters for the high-quality sample, while the low-quality sample is entirely located in the third class (>MAC).
- **Step 4. Correspondence factor analysis (CFA):** The values are aggregated by running the standard and real samples through a statistical routine named correspondence factor analysis (CFA). The diagonalization is performed solely on the similarity matrix of the two standard samples, as this results in the extraction of a single eigenvector explaining 100% of the data variance and diametrically opposing the high and low quality samples. Subsequently, the real water samples are orthogonally projected on the extracted factor, to define the degree of association between these real samples and the two quality standards. The resulting scores correspond to the final index values, which range between -1 (expressing high quality) and 1 (expressing low quality). With CFA, the orthogonal projection or index calculation is mathematically expressed by the following equation:

  $$\mathrm{F_i} = \frac{1}{\mathrm{p}\sqrt{\lambda}} \sum_{\mathrm{j}=1}^{\mathrm{m}} \mathrm{d_j L_j} \qquad \text{Eq. 1}$$

  with Fi equal i’s factor score, p is the number of parameters involved in the index definition, λ is the factor eigenvalue, dj is the Boolean code (1 if sample belongs to parameter class j, or 0 if not), Lj is factor loading of class j, m is the number of classes (i.e., 3). Results of the application of the methodology are observed in Figure 12.

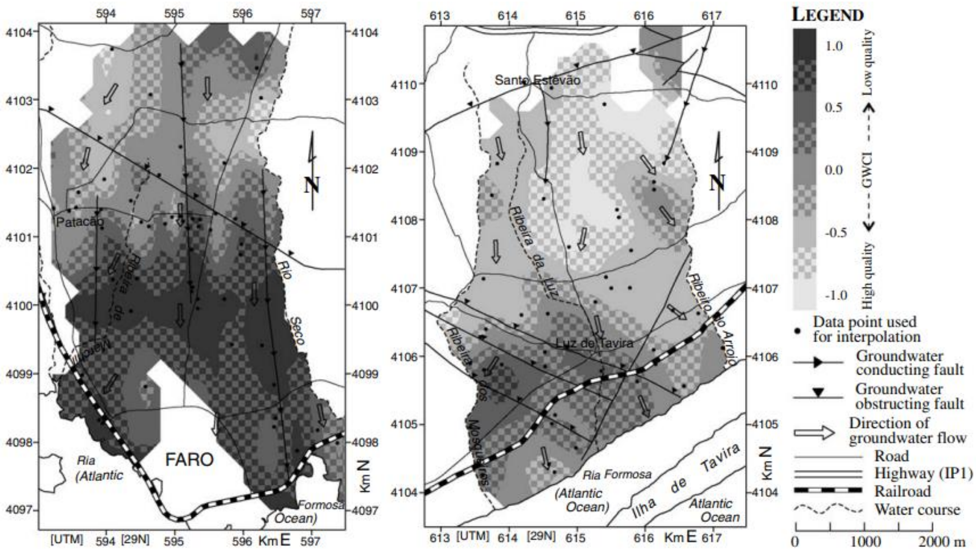


Figure 12: GWCI maps of Campina de Faro (left, depth <55 m) and Campina da Luz (right, depth <85 m), based on the parameters Ca2+, NO3, SO2 4 and Cl. Extracted from (Stigter et al., 2006)

Iran: "Development of Groundwater Quality Index"; (Saeedi et al., 2010)

Researchers from the Department of Hydraulics and Environment from the Iran University of Science and Technology in Iran developed a methodology based on multivariate analysis to create a groundwater quality index (GWQI), aiming at identifying places with best quality for drinking within the Qazvin province of west central of Iran. The methodology involves some steps:

- **Step 1. Selection:** In the phase of selection, eight different parameters, K$^+$, Na$^+$, Ca^{2+}, Mg^{2+}, SO$_2^{-4}$, Cl$^-$, pH, and TDS are selected as important components of healthy water to be involved in the index.
- **Step 2. Calculation of standard value of parameters:** This step evaluates the proportion of observed concentrations of selected parameters to the maximum admissible concentration in water quality standards and the standard values are calculated as fraction between observed and standard values. The obtained fractions are normalized values of concentration of each parameter in each observation well.
- **Step 3. Weighting of parameters and Aggregation:** The relative importance or the weights of parameters in final groundwater quality index are defined. These weight values are identified based on judgment of water quality experts and or referring to some studies indicating the relative importance of each drinking water components. By aggregating the normalized value of parameters according to the weights, the final groundwater quality indices (GWQI) are identified for each well. The derived quality index value of each well indicates the quality characteristic of that specific well to be used as the source of drinking water. The identified indices are used to draw iso-index map of the study area. Finally, based on the GWQI, the mineral content of the wells is

classified as high (GWQI> 0.15), low (GWQI< 0.04), and suitable (0.04 < GWQI < 0.15). An example of the application of this approach is observed in Figure 13.

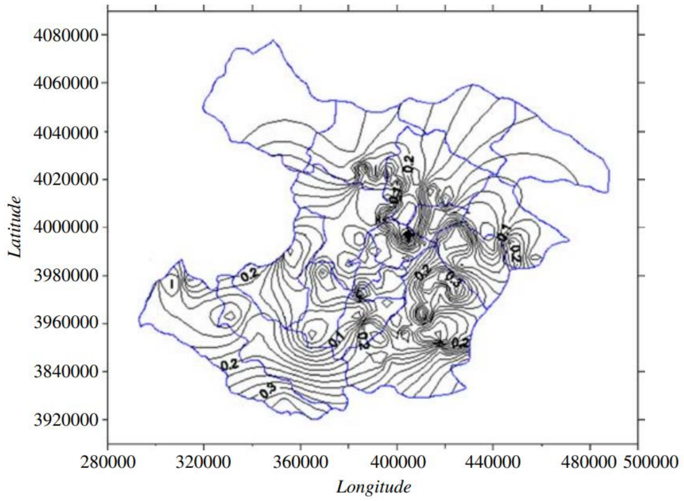


Figure 13: Iso-index map for r Qazvin plateau groundwater, from (Saeedi et al., 2010)

India: "Application of a Water Quality Index for Groundwater Quality Assessment: Thirumanimuttar Sub-Basin, Tamilnadu, India"; (Vasanthavigar et al., 2010)

Researchers in the Department of Earth Sciences, Annamalai University in India, the authors tried to understand the hydrogeochemical parameters to develop water quality index in Thirumanimuttar sub-basin. A total of 148 groundwater samples were collected and analysed for major cations (Na, Mg, Ca, K) and anions (Cl, HCO3, SO4). The water quality index was calculated to quantify overall water quality for human consumption using the following steps:

- **Step1. Determination of the weight of each parameter:** In the first step, each of the 12 parameters (TDS, HCO_3, Cl, SO_4, PO_4, NO_3, F, Ca, Mg, Na, K, and Si) has been assigned a weight (wi) according to its relative importance in the overall quality of water for drinking purposes. The maximum weight of 5 was assigned to the parameters like NO_3, TDS, Cl, Fl, and SO_4. HCO_3 and PO_4 are given the minimum weight of 1 as they play an insignificant role in the water quality assessment. Ca, Mg, Na, and K were assigned weight between 1 and 5 depending on their importance in water quality determination as determined by expert judgement.
- **Step2. Computation of the relative weight:** the relative weight (Wi) is computed with the following equation:

$$W_i = \frac{w_i}{\sum_{i=1}^{n} w_i} \quad \textbf{Eq. 2}$$

Where Wi is the relative weight, wi is the weight of each parameter an n is the number of parameters.

- **Step 3. Quality rating:** In the third step, a quality rating scale (qi) for each parameter is as- signed by dividing its concentration in each water sample by its respective standard according to the standard guidelines using the following equation:

$$q_i = \frac{c_i}{s_i} \qquad \text{Eq. 3}$$

Where q_i (%) is the quality rating, c_i (mg/l) is the concentration of each chemical parameter in each water sample, and s_i (mg/l) is the Indian drinking water standard for each chemical parameter according to the guidelines of the BIS 10500 (Bureau of Indian Standards).

- **Step 4. Computation of sub-index:** The sub-index SI is determined for each chemical parameter as per the following equation:

$$SI_i = W_i \qquad \text{Eq. 4}$$

- **Step 5. Computation of water quality index:** The water quality index WQI is computed as the sum of all SI with the following equation:

$$WQI = \sum_{i=1}^{n} SI_i \qquad \text{Eq. 5}$$

- **Step 6. Definition of water quality types:** The water quality types are determined based on: WQI with <50 Excellent water; 50-100.1 Good water; 100-200.1 Poor water; 200-300.1 Very poor water; >300 Unsuitable for drinking purposes.
- **Step 7. Creation of groundwater quality map:** This methodology was adopted in many studies in Kenya (e.g., (Ashun & Bansah, 2017; Ochungo et al., 2019)). An example can be found in Figure 14.

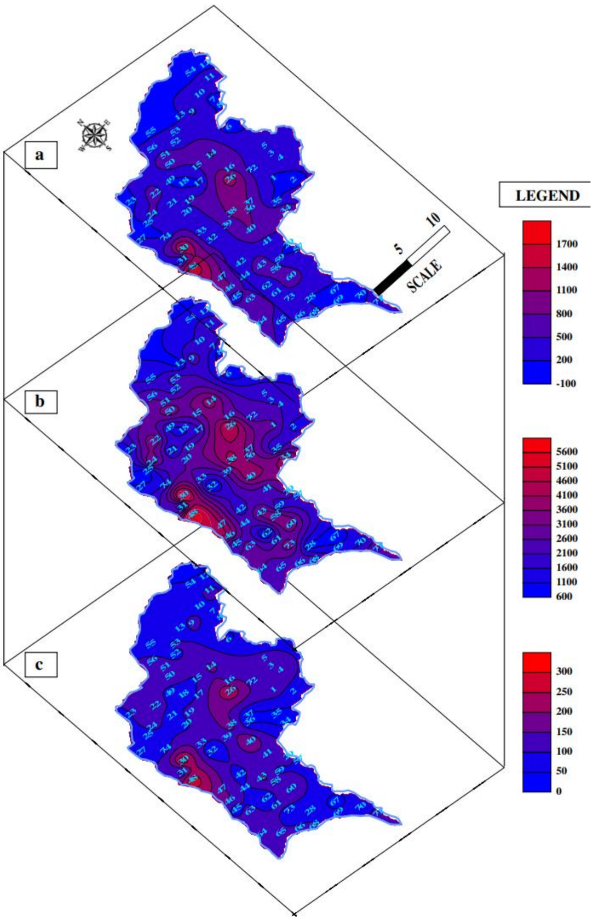


Figure 14: Spatial distribution map of a chloride, b EC, and c WQI of the study area during POM season. Extracted from Vasanthavigar et al. (2010)

Denmark: “Groundwater Monitoring in Denmark: Characteristics, Perspectives and Comparison with Other Countries”; Jørgensen & Stockmarr (2009)

Referring to Jørgensen & Stockmarr (2009), since 1988, Denmark has had a national groundwater-monitoring programme made of 74 well catchment areas and six small agricultural catchments with more than 1,500 screens at different depths for annual water quality sampling and assessment. Additionally, every 3–5years, water samples from 10,000 abstraction wells are analysed. These samples are analysed for the main components, inorganic trace elements, organic micro pollutants, pesticides, and their metabolites.

- **Step 1. Selection of parameters:** According to Jørgensen and Stockmarr (2009), the groundwater quality monitoring data from well catchments area and agricultural catchments collected until 2006 contains analyses for a total of 97 chemical parameters, including 26 main chemical/physical elements, 14 inorganic trace elements (heavy metals, etc.), 23 organic micro-pollutants and 34 pesticides and metabolites. Additionally, the compulsory quality control monitoring programme in 10,000 abstractions wells, contains five microbiological parameters, 28 main chemical and physical elements, 16 inorganic trace elements, 30 organic micro pollutants and 23 pesticides and metabolites. In Denmark, the main emphasis is on nitrate and phosphorus as wells as pesticides due to diffuse agricultural impact on groundwater. Further, the concentration and trends of other parameters such as nickel, arsenic and organic micro pollutants are reported.

- **Step 2. Data handling and reporting:** All data collected are stored in Danish national database, updated daily and freely availed online at www.groundwater.dk. While reporting, data from abstraction wells for drinking water production and data from the Danish Groundwater Monitoring Programme are distinguished. While abstraction wells intend to provide clean groundwater that only has to undergo simple treatment to give drinking water of a proper quality, the monitoring may have lower quality.
- **Step 3. Groundwater quality monitoring evaluation:** In 2002, the Danish Environmental Agency made a request for international evaluation by the European Topic Centre on Water (ETCW) was commissioned by the European Environment Agency. From the evaluation team, some remarks concerning the monitoring objectives, choice of parameters, locations, frequencies of sampling, data handling procedures, and the linkage to other sub-programmes were found adequate. The results are presented in the form of Figure 15.

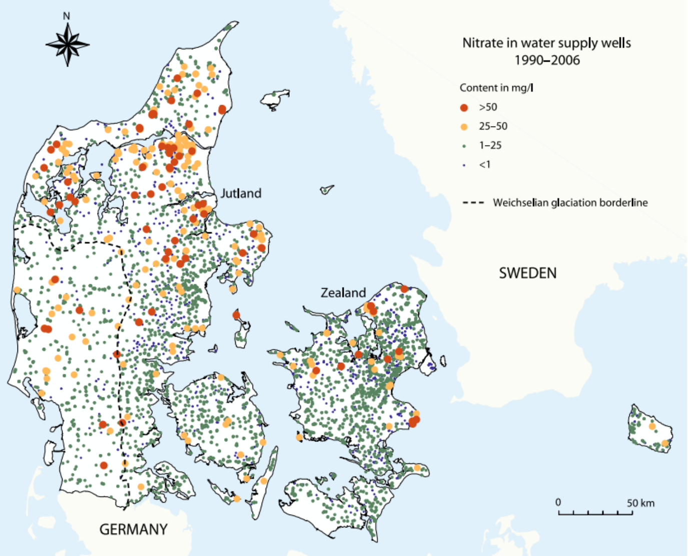


Figure 15: Distribution of nitrate in groundwater from abstraction wells for drinking water production(Jørgensen & Stockmarr, 2009)

Annex 2: Selected Chemical Parameters from the literature

The general parameters in set 1 are set based on the literature review and experiences in other countries (e.g., Babiker et al. (2007); Craig & Daly (2010b); Hansen et al. (2012); Muñoz Pardo (2009); Passarella & Caputo (2006); Todo & Sato (2002)). They are usually divided into sub-groups: main components (physical and chemical parameters, ions), micro-pollutants, and pesticides (Hansen et al., 2012; Muñoz Pardo, 2009; Passarella & Caputo, 2006; Todo & Sato, 2002). Groundwater level head could be also measured as an indicator of the hydrodynamic state of groundwater (Passarella & Caputo, 2006). The following table summarizes the main chemical parameters (Set 1) that are used in international examples.

Table 6: Chemical parameters in Set 1 from international case studies

Parameter / Country or directive	EU WFD Directive / Groundwater directive	Chile	Japan	Italy	Ireland	Denmark	SDG 6.3.2
Oxigen content (DO)	x						
pH-value	x						xx
Electrical conductivity	x			x	x		xx
Temperature	x						xx
Total Dissolved solids (TDS)		x	x				
Nitrates (NO3)	x	x	x	x	x	xx	xx
Ammonium (NH4)	x				x	x	x
Ammonia (NH3)				x			
Chlorides (Cl)	x	x	x	x	x	x	xx
Sulphates (SO4)	x	x	x	x	x	x	
Calcium (Ca)		x	x				
Sodium (Na)		x	x		x		
Magnesium (Mg)		x	x				
Feacal coliforms*							xx
Hardness				x			
Iron (Fe)				x		x	x
Manganese (Mn)				x			x
Phosphates					x		
Molybdate Reactive Phosphorus (MRP)					x		
Nitrites (NO2)					x		
Boron					x		
Individual pesticides					x		
Total pesticides					x	x	
Mercury	x				x		
Arsenic	x				x	x	x
Copper					x	x	
Lead	x				x		
Nickel					x	x	
Cadmium	x				x		
Chromium					x		
Aluminium					x		
Cyanide					x		
1,2-Dichloroethane					x		
Trichloroethylene	x						
Tetrachloroethylene	x						
Local parameters	x	x				x	

[1]: (Todo & Sato, 2002); [2]: (Muñoz Pardo, 2009); [3]: (Babiker et al., 2007); [4]: (Passarella & Caputo, 2006); [5]: (Craig & Daly, 2010); [6]: (Hansen et al., 2012). Double cross means highly important.

In Table 6, in green, the chemical parameters that are mostly used for the definition of the quality index in the reviewed international studies are shown. From this analysis, these are selected for the groundwater quality assessment and discussed in Section 4.2.

Annex 3: Overview of available guidelines for the implementation and improvement of monitoring networks

WFD guideline

The groundwater working group (WGC) of the Common Implementation Strategy (CIS) of the Water framework Directive (WFD) has developed guidelines to implement consistent groundwater monitoring network across Europe. Following are the summarised steps to establish and review the groundwater monitoring network (Grath et al., 2007):

- **Step 1.** Define the need for different groundwater monitoring networks (e.g., quantitative or qualitative monitoring network, surveillance monitoring network, operational monitoring network, etc.)
- **Step 2.** Develop a conceptual model/understanding of the groundwater system in which the general scheme of ‘recharge–discharge’ pathway is known. This provides a simplified representation and descriptions of the hydrogeological system being investigated
- **Step 3.** Quantify the amount of monitoring required (number of sampling site and sampling frequency) in each groundwater body. The network should have sufficient spatial and temporal density which considers the natural characteristics of the groundwater body (conceptual understanding) and the pollution risks, to help focus monitoring activities in areas where significant pressures combined with higher vulnerability exist.
- **Step 4.** Design and operate the groundwater monitoring network: boreholes and wells must be designed and operated to ensure that the environmental and monitoring objectives for each of the component bodies making up the network can be reliably achieved.
- **Step 5.** Refine the conceptual model and the understanding: groundwater bodies may be grouped for monitoring purposes provided that the monitoring information obtained provides a reliable assessment of the status of each body in the group. This involves the improvement and update of the conceptual model.
- **Step 6.** Network review and update: once the conceptual model is refined and the understanding of the hydrogeology and hydrochemistry of the groundwater system improves, the network design should be reviewed and adapted. The monitoring results obtained from the network must be interpreted regularly and the monitoring network and its operation must be reviewed at least once every six years but ideally more frequently. The network update should consider the observed variations in the natural processes and/or anthropogenic

activities influencing groundwater quality and quantity, the trends, and emerging phenomena.

IGRAC guideline

The International Groundwater Resources Centre (IGRAC) has developed a guideline on groundwater monitoring for general reference purposes and highlighted several steps to establish a groundwater monitoring network (Jousma et al., 2006):

- **Step 1.** Preliminary assessment of groundwater situation, conflicts, trends, and sustainable monitoring: this step aims to define the need to have systematic groundwater monitoring objective and scope of the monitoring programme(s), to have an overview of the groundwater situation, the actual problems, and a list of key concerns for monitoring.
- **Step 2.** Groundwater system analysis and development of conceptual model: This step involves the analysis of the groundwater system i.e., aquifer and flow systems and development of a conceptual model based on the available geological and hydrological information. This conceptual model serves as a technical guide for design of groundwater monitoring network.
- **Step 3.** Analysis of institutional setting: In this step, an inventory of the institutions (stakeholders) involved in groundwater exploitation, management and protection is conducted. This step also involves the analysis of each institutions' roles, mandates, tasks, related budgets, and human resources.
- **Step 4.** Inventory of data needs and specification of monitoring objectives: This step includes listing the users of groundwater data and assessing their data needs. Possible monitoring objectives include provision of data for assessment, development, management, and protection of groundwater resources.
- **Step 5.** Design of monitoring programme components for identified objectives: This step emphasizes on the analysis of the monitoring objectives and translates these objectives into components of the monitoring programme. Each of the monitoring objective leads to a monitoring component with its own specific requirements (i.e., area to be covered, preferential network set-up, parameters needed, frequency of sampling, etc.). Once the components of the monitoring are brought together, various functions and needs of the entire monitoring network become clear.
- **Step 6.** Specification of monitoring programme options: the groundwater monitoring options may differ with respect to the scope of the programme, the area covered, and properties involved (e.g., network density, frequency of observation, etc.). Specification of options to be considered must be done in close collaboration with the representatives of the stakeholders involved.
- **Step 7.** Specification of the required budgets expected performance and required institutional capacity for each option: this step includes the calculation of investment and annual costs involved in groundwater monitoring programme, analysis of each institutional capacity and limitations.

- **Step 8.** Assess the feasibility of monitoring program: This step encompasses evaluation of the applicability of the monitoring programme options based on financial and other organizational constraints.
- **Step 9.** Implement the selected monitoring programme: Based on feasibility analysis results, selected monitoring programme must be designed and implemented.

UNEP guideline

The United Nations Environment Programme (United Nations Environment Programme, 2022) has identified the following steps for implementation of new groundwater monitoring wells:

- **Step 1.** Define the purpose of the wells
- **Step 2.** Identify the sites of interest
- **Step 3.** Determine the site-specific geological succession
- **Step 4.** Assess the nature of the aquifers under observation
- **Step 5.** Evaluate the type and distribution of contaminants
- **Step 6.** Determine the depth of the borehole (i.e., drilled well)
- **Step 7.** Design the monitoring wells
- **Step 8.** Construct the monitoring wells

USEPA guidelines

The United State Environmental protection Agency (USEPA, 1992), identified the following steps for establishment of groundwater monitoring network.

- **Step1.** Define regulatory requirements and technical objectives
- **Step 2.** Conduct preliminary investigation
- **Step 3.** Develop an initial conceptual hydrogeological model as a basis for field investigation
- **Step 4.** Conduct field investigation
- **Step 5.** Refine the conceptual model as a basis for monitoring system design
- **Step 6.** Design groundwater monitoring system
- **Step 7.** Install groundwater monitoring system
- **Step 8.** Collect, analyse, and evaluate groundwater samples and data
- **Step 9.** Evaluate the groundwater monitoring system with respect to the regulatory requirements and technical objectives, refine the conceptual model, refine the groundwater monitoring system if necessary

World bank guideline

According to the World bank guideline (Ravenscroft & Lytton, 2022), reviewing of a groundwater network involves 7 seven steps:

- **Step1.** Consultation of stakeholders
- **Step 2.** Refine network objectives
- **Step 3.** Refine conceptual hydrogeological model
- **Step 4.** Re-define groundwater bodies and or management units, including stresses
- **Step 5.** Evaluate the adequacy of monitoring and identify gaps for each groundwater body unit
- **Step 6.** Design the monitoring wells
- **Step 7.** Construct the monitoring wells

DRDMW Guidelines

The Department of Regional Development, Manufacturing and Water of the Queensland government (Water Services of the Water Division, 2022) has developed a three-step methodology to review the groundwater monitoring network.

- **Step 1.** Review the priority and determine the specific purposes for monitoring in each groundwater unit where monitoring is currently occurring and other units where a risk is identified, and monitoring is not currently occurring
- **Step 2.** Review the priority of each currently monitored borehole within the groundwater unit
- **Step 3.** Provide recommendations based on the assessment under Part A and B, including a Gap Analysis and reasoning for frequency for manual measurements and loggers or telemetry sites.

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