

Groundwater monitoring for mapping aquifers in Belize as a tool for climate change

D 4.4 - Benchmarking of
methodologies for groundwater
monitoring

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Executive summary

The National Climate Change Office of the Ministry of Sustainable Development, Climate Change, and Disaster Risk Management, and the National Hydrological Service (NHS) of the Ministry of Natural Resources, Petroleum, and Mining are implementing a project to design a Groundwater Monitoring System for the New River Watershed with funding from the Climate Technology Centre and Network (CTCN). This report has been completed as part of Output 4 of the project and provides a benchmarking review of groundwater monitoring systems for both quantity and quality.

Background to groundwater quantity monitoring systems

Although groundwater quantity is monitored around the world, there is no systematic monitoring of groundwater at a global scale. Measurements of groundwater level, groundwater abstraction, and spring discharge are the best indicators of the condition of these resources and are also essential to understand groundwater availability and how groundwater interacts with surface water. There are a number of reasons why it is important to monitor groundwater levels such as the impact of climate change, looking for long-term trends of over exploitation, and for sustainable management of groundwater resources. Long-term data collection can also be used to develop groundwater models and even forecast trends. Studying these can provide groundwater data for the sustainable development of groundwater resources; determine the best location for abstraction; provide protection of the environment and protect against land subsidence caused by groundwater abstraction.

Groundwater is one of the main sources of water for drinking, industry, and irrigation in many countries however if its quality is not monitored contamination can go unnoticed to the point at which public water supply and ecosystems are put at risk, particularly for many rural communities around the world that depend on this resource. Tracking pollution can also be used to assess threats and provide an early warning system to communities. Analysis of groundwater quality can also provide insights into the impact of anthropogenic activities on groundwater systems, as well as the impact of climate change. Monitoring saline intrusion can prevent further deterioration as its negative impacts are also expected to increase because of climate-associated changes, such as sea levels rise, cyclones, and storm surges intensify; impacting water supply and food security.

Information requirements

It is important to set clear objectives when designing a monitoring system and information can be required at several levels. Different entities such as governments, environmental regulators, water users, health authorities or the public may have different requirements. Different types of information can be required: groundwater levels; groundwater quality; trends. The frequency of collection (e.g. weekly/monthly/annual) depends on the purpose of the monitoring system; regulation, compliance, public information, monitoring, etc. This will also affect the format in which the information will be displayed, ranging from reports to maps, apps, or websites.

Groundwater quality monitoring can also be used for protection monitoring – to protect strategic resources like wellfields, infrastructure, and sensitive ecosystems; and investigation of pollution contaminants – to provide early warning from known pollution risks from industry, waste facilities, mines, agriculture, from diffuse or point sources (Ravenscroft and Lytton, 2022; IGRAC, 2008); or determination of fresh-saline interface for coastal aquifers.

Methodology and data collection

There is no single best method, and that the accuracy of the data is a function of the selected methodology and the operational conditions. Both manually operated and automated recording instruments are available to monitor groundwater levels. And in terms of frequency, data should be collected at set locations and pre-determined regular time intervals, as far as possible. Frequency can vary from very short intervals of minutes or hours to longer intervals of monthly or yearly monitoring.

For quality, however, the sampling methods should be decided based on the type of monitoring (manual or in-situ monitoring) – such as downhole probes or logging tools. Compared to groundwater levels, groundwater chemistry typically changes slowly. Often groundwater quality programs carry out seasonal monitoring, for example during dry season and wet season conditions. The frequency of monitoring required can be based on the experience of contaminants in similar settings or how long a site can be left without monitoring. It is cost-effective to periodically review the monitoring frequency to avoid unnecessary sampling, for example, following an initial round of monitoring, the frequency may be reduced in areas of low concern and increased in areas where parameters are at or close to levels of concern.

Data can be collected in forms, drum charts, or data loggers. Forms are used to record manual measurements, whilst data loggers can be used to record and store digital data. This data must then be processed and analysed to allow the information to be interpreted, and disseminated. For water quality, samples can be analysed onsite or in a laboratory. If taken to a laboratory, they must be carefully preserved, transported, and stored. Field testing needs to be done when parameters could change during transport and storage and need to be measured as quickly as possible. Or for public health surveillance when high precision is not required, so only one or two parameters need to be tested quickly.

Case studies

The International Groundwater Resources Assessment Centre produced an overview report on groundwater monitoring programmes around the world in 2020, many countries did not respond to requests but an analysis to summarise data from countries with established groundwater monitoring programmes was done. At least 33 countries produce written reports, and 41 countries generate groundwater maps – not freely available in most cases. There was a large range in the frequency of monitoring, from 15 minutes to several times per year, largely related to whether automatic or manual measurements are carried out. They also provided groundwater monitoring profiles, with a few countries in the Caribbean region. This included: Mexico, El Salvador, Costa Rica, and Colombia. However, there was very little information on how groundwater monitoring systems were designed and what decisions were made in the process of design. A few common findings among these countries were: that there was limited information provided; monitoring was done during dry and wet seasons and; all used a combination of manual and automatic networks.

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1 Background

1.1 Project summary

In Belize, 56% of the population lives in rural areas where groundwater is a vital source for fresh water and represents almost 95 per cent of the fresh water supply in rural areas.

Groundwater is also used as a source of drinking water in all districts in Belize, using rural water systems and Belize Water Services Limited (BWLS) wells. However, the existing aquifers and their annual recharge rate have not been quantified.

Increase in demand for fresh water resulting from increasing population, greater economic activity and agricultural expansion are threatening the quality and availability of fresh water. Each year during low rainy seasons exists the possibility of droughts due to low recharge of aquifers.

Transboundary aspects and distribution of population are other factors that affect the water sector. For example, central and northern regions (Orange Walk and Corozal) have much larger populations and higher agriculture zones for water intensive crops, but less water resources.

Although there is a need for groundwater information across the country, the priority area includes the New River watershed.

The Nationally Determined Contribution (2022) indicated water resource assessment (especially groundwater) as part of the main actions to be implemented to build resilience.

The results of the prioritization of adaptation technology factsheets for the Water Sector documented in the technologies needs assessment (TNA) for adaptation (National Climate Change Office et al., 2017) include:

- Drought Monitoring System for Northern Belize with Specific Focus on Groundwater Resources;
- Water Efficient Fixtures and Appliances;
- An Integrated Management Strategy for Water Safety for Eight Rural Water Supply Systems in Belize.

The National Hydrological Service (NHS) is leading a process for building an inventory of existing data on groundwater. The objective is to identify and homogenize information that is currently available but spread among different agencies and institutions, and their various departments.

Requests have been made from the executive level of the Ministry (responsible for the NHS) to other ministries for sharing of relevant groundwater data. However, this is still a work in progress. Additionally, the Ministry of Rural Transformation has indicated that they do not geo-reference their wells.

Following the foreseen adaptation actions in the NDC and the TNA for Adaptation for the water sector, the National Climate Change Office of the Ministry of Sustainable Development, Climate Change, and Disaster Risk Management, and the National Hydrological Service (NHS) started conversations to develop a proposal for a Groundwater Monitoring System.

1.2 About this report

The purpose of this report is to benchmark the existing methodologies for groundwater monitoring, including among other things, groundwater observation wells, groundwater pumping wells, springs, and surface water observation points, as well as tools for water quality monitoring. Based on the results of the assessment of groundwater availability and demand (Output 3), as well as the definition of information needs, monitoring objectives, costs, and climate and hydrological data available in Belize, monitoring systems for groundwater quantity and quality will

be described and examples of case studies. This will lead to the prioritization of existing technologies and provide suggestions for the one(s) that would be more suitable for Belize.

2 Groundwater quantity monitoring systems

Background to groundwater quantity monitoring systems.

Groundwater monitoring is defined as the ‘scientifically-designed, continuing measurement and observation of the groundwater situation’ (IGRAC, 2008). Monitoring of groundwater poses more challenges than monitoring surface water due to higher initial investments; the requirement for larger, spatial representativeness of monitoring points due to hydrogeological heterogeneity and the limitations of remote sensing when monitoring groundwater (IGRAC, 2020). There are also difficulties through access, as aquifers are less visible than surface water.

Groundwater quantity is monitored around the world – through measurements of groundwater level, groundwater abstraction, and spring discharge – although there is no systematic monitoring of groundwater on a global scale (Kukuric and van Vliet, 2008).

Monitoring of water levels in wells provides the best indicator of the condition of the resource and is essential to understand groundwater availability and how groundwater interacts with surface water (Taylor and Alley, 2001). There are a number of reasons why it is important to study groundwater levels such as the impact of climate change, looking for long term trends of over exploitation and how groundwater and surface water interact. This is expanded upon in Section 2.1.2. Studying groundwater data can provide information for the sustainable development of groundwater resources; determine the best location for abstraction; provide protection of the environment and protect against land subsidence caused by groundwater abstraction (IGRAC, 2008). Long-term data collection can be used to develop groundwater models and even forecast trends (Taylor and Alley, 2001).

2.1.1 Programme location

Specific monitoring areas need to be defined by hydrological or hydrogeological criteria rather than political ones as surface water, groundwater, estuarine and coastal environments can be considered together. Understanding of the hydrogeological and hydrological setting is important to understand these interactions. As an example, using the river basin area or aquifer could be used to design a groundwater monitoring system (IGRAC, 2008).

2.1.2 Information requirements

What information is required and why it is required, needs to be decided early on when planning a groundwater monitoring programme. This will provide a better outcome and will allow the system the flexibility needed for each individual case and to adapt if required. IGRAC (2008) recommends a set of specific topics to be investigated prior to the design:

- Who wants to be informed?
 - For example, governments, environmental regulators, water users, health authorities, the public.
- What types of information?
 - Groundwater level; groundwater quality; trends.
- For what purpose?
 - Reconnaissance, regulation, compliance, effectiveness of measures, public information, monitoring.
- How accurate?
 - Time and spatial scale of observations, data aggregation, analytical results.

- How fast?
 - Does data need to be gathered on a weekly/monthly/annual basis?
- In what format?
 - Reports, maps, apps, websites.

Groundwater monitoring objectives must be defined before the system is designed and must be suitable for the needs of data-users, to allow for success. It can be useful to collate information from stakeholders and their data related needs. Several reasons why groundwater levels should be monitored have been identified and are outlined in Table 2.1.

Table 2.1: Examples of groundwater level monitoring objectives

What is being monitored?	Why is it being monitored?
Groundwater levels (at a local scale)	To investigate the impact of local drawdowns on groundwater levels, in the geology that is utilised as a resource.
Groundwater levels (at a regional scale)	To investigate the impact of variability (seasonal or interannual) and long-term climate change (droughts/changes in precipitation) on groundwater resources - this will need to be unaffected by pumping and irrigation (Taylor and Alley, 2001).
Groundwater levels (interaction with surface water)	Monitor levels along the river to investigate the interaction between a river and groundwater.
Groundwater levels (deep groundwater system)	To characterise the deep groundwater system and investigate the impact of climate change on deeper groundwater resources.
Groundwater flow direction	To characterise the groundwater system and identify possible trends in groundwater flow direction flow (e.g. is there flow from Mexico to Belize?).

2.1.3 Methods

Water level measurements are the most important data required to provide information on hydrological stresses on aquifers (Taylor and Alley, 2001). When deciding which method should be used to meet sampling objectives and needs, it should be noted that there is no single best method (Water Research Commission, 2017). Both manually operated and automated recording instruments are available to monitor groundwater levels. The accuracy of the data is a function of the selected methodology and the operational conditions (IGRAC, 2008).

2.1.4 Frequency

A groundwater monitoring programme must collect data at set locations and pre-determined regular time intervals, as far as possible (IGRAC, 2008).

Frequency in monitoring systems can vary from less than 15 mins, to hourly, daily, weekly, monthly, or a set number of times per year (IGRAC, 2020). As frequency is heavily controlled by economic considerations (Taylor and Alley, 2001), a network is likely to be more frequently monitored when automatic methods are used (IGRAC, 2020). Nixon (1996) recommends that initially sampling twice a year should be carried out during a period of high groundwater levels and a period of low groundwater levels. The frequency that data is collected should be determined with respect to expected water level fluctuations, although this is not always possible (IGRAC, 2020).

In the context of Belize, most of the aquifer systems being utilised are shallow unconfined aquifers in a carbonate and sometime karstic system. Therefore, water levels can be expected to fluctuate on short timescales in response to rainfall events. Therefore, monitoring frequency should be relatively short, weekly or monthly, to capture aquifer response to rainfall.

2.1.5 Sampling Points

A selection of wells used for observation must be selected for the groundwater monitoring programme. The number and location of needs to be representative of the local topography, geology, climate, and land-uses (Taylor and Alley, 2001). If the aquifer is multilayer, measurements will need to be completed at multiple depths. Additionally, there needs to be uninterrupted access to the chosen sampling points (IGRAC, 2008) and well that can be used for an indefinite length of time are preferable (Taylor and Alley, 2001).

The density of observation wells depends on the:

- The size of the area or country;
- The geology and hydrogeology of the area;
- Land use in the area;
- Admittance to certain areas;
- Existing monitoring systems;
- The objectives and time constraints of the network;
- Financial limitations for establishment and sampling through time (Nixon, 1996).

The proposed network should include selected sites based on existing national monitoring stations and should make sure that all nationally important aquifers are monitored. If production wells are used for groundwater level measurements, the drawdown cone caused by pumping can disturb measurements of groundwater levels. Measurements should only be taken once the pumping has been stopped or paused to allow groundwater levels to recover – this recovery can vary in length of time depending on aquifer characteristics, which can cause a problem to well users. Therefore, an agreement needs to be reached with the well user regarding frequency and time of measurements and the length of time that pumping will need to be paused (IGRAC, 2008).

If the recovery period is short, and only takes minutes or hours, then an agreement can be found with the well user to pause pumping before measurements. Alternatively, users measure levels just before pausing pumping, and then stop pumping for a short period and the recovery of groundwater levels measured over that period and extrapolated.

If the recovery period is longer, it may be necessary to measure groundwater levels with the pumps on and log the average pumping rate at the time of the measurement. Several measurements are likely to be required to find an average as the rates could be unstable (IGRAC, 2008).

2.1.6 Data collection, storage, and transfer

Data can be collected in forms, drum charts or data loggers. Forms are used to record manual measurements, whilst data loggers can be used to record and store digital data. The borehole can then be visited periodically by field staff or the user to download the data, or it can be sent automatically over the phone network (telemetry) (British Geological Survey, 2023). The data must then be processed and analysed to allow the information to be meaningfully interpreted, and then disseminated either through websites, reports, or free downloading of the data (IGRAC, 2020).

3 Groundwater quality monitoring systems

3.1 Background to groundwater quality monitoring systems

Groundwater is one of the main sources of water for drinking, industry, and irrigation in many countries (Ravenscroft and Lytton, 2022). Particularly in low- and middle-income countries, groundwater can be directly extracted and used untreated as drinking water for the rural populations. Groundwater quality can be described by a wide range of parameters, that can be physical, chemical, and biological (IGRAC, 2008).

Groundwater can be contaminated with faecal bacteria, agrochemicals, industrial waste disposal, and environmental contaminants such as pharmaceuticals, personal care products, flame retardants and chemical stabilisers. Groundwater problems generally increase with greater intensity of groundwater development (IGRAC, 2008). Additionally, it can be contaminated with naturally occurring chemicals including arsenic, fluoride, and uranium.

Monitoring groundwater quality provides several benefits:

- Accounting for resources by gaining knowledge on the quality of water sources, and their status and trends for the most important regional bodies;
- Tracking pollution plumes to assess threats and provide an early warning system (Ravenscroft and Lytton, 2022);
- Providing a historical record of groundwater resources and the impact of climate change and human activities on groundwater quality (Ravenscroft and Lytton, 2022; IGRAC, 2008);
- Determination of fresh-saline interface for coastal aquifers;
- Determination of the position of specific natural groundwater quality parameters which limit use (IGRAC, 2008).

3.1.1 Programme location

Before deciding upon objectives, it is important that the spatial boundaries of the monitoring zone is defined and aquifers and basins are divided into groundwater bodies. It is useful to define the regional groundwater bodies as this can be used to predict regional differences (IGRAC, 2008).

3.1.2 Information requirements

It is important to set clear objectives so that it is possible to decide the parameters that require monitoring, and the spatial and temporal scale that these should be monitored on. The objectives need to be practical given institutional and financial limitations, so communication with stakeholders through a multistakeholder platform is necessary. Information can be required for the following reasons:

- Reference monitoring – to evaluate general groundwater status, trends from climate and land-use change, diffuse pollution, and recharge;
- Protection monitoring – to protect strategic resources like wellfields, infrastructure, and sensitive ecosystems;
- Pollution contaminant – to provide early warning from known pollution risks from industry, waste facilities, mines, agriculture, from diffuse or point sources (Ravenscroft and Lytton, 2022; IGRAC, 2008);
- Determination of fresh-saline interface for coastal aquifers;
- Determination and observation of specific natural groundwater quality parameters limiting groundwater use (e.g. arsenic, fluoride) (IGRAC, 2022).

Examples of objectives and associated potential monitoring parameters are provided in Table 3.1.

Table 3.1: Examples of groundwater quality monitoring objectives for general groundwater reference monitoring applications

What is being monitored?	Why is it being monitored?
Basic field water quality parameters (pH, Redox Potential, Electrical Conductivity, Dissolved Oxygen, Turbidity, and temperature)	Water Quality - to observe seasonal and long-term trends.
Water quality (lab analysis of Ca, Mg, Na, K, NH ₄ , Fec, Mnc, SiO ₂ , HCO ₃ , SO ₄ , Cl, NO ₃ , PO ₄ (major ions))	Water Quality - to observe seasonal and long-term trends.
Pesticides	Water Quality - to observe the long-term trend of pesticides.
Saline intrusion	To investigate the impact of tidal influences on water quality, including rising sea level.
Concentration of microbes (typically coliforms and E.coli)	Water Quality - to detect the presence of contamination (for example from septic systems).

3.1.3 Methods

Samples can be analysed onsite or in a laboratory. For samples taken to a laboratory, they must be carefully preserved, transported and stored. Different types of analysis will require different bottles and preservatives. Laboratories should supply the prepared bottles with labels, barcodes, and pre-chilled boxes. Some examples of sampling procedures for specific compounds are found in Figure 3.1. Analysis of parameters required for drinking water surveillance may be straightforward to complete in country, while more specialist analysis for example for pesticides may require shipping to specialist laboratories at considerable cost.

The following parameters should be used to characterise an area and to provide a general overview: Ca, Mg, Na, K, NH₄, Fec, Mnc, SiO₂, HCO₃, SO₄, Cl, NO₃, PO₄ (major ions). In addition, direct measurements of pH, EC and temperature should be taken (IGRAC, 2008).

Field testing needs to be carried out in two instances:

- Some parameters need to be measured in the field as they could change during transport and storage, so they need to be measured as quickly as possible;
- Field testing for public health surveillance when high precision is not required, so only one or two parameters need to be tested immediately;
- The most common parameters to be measured in the field are pH (using a pH meter), alkalinity (field titration) and multiprobe measurements. Multiprobe measurements are carried out in a flow-through cell to record EC, temperature, pH, dissolved oxygen and Eh (Ravenscroft and Lytton, 2022).

Determinand group	Sampling procedure	Preferred materials	Storage time/temperature	Operational difficulty/cost
Major ions Cl, SO ₄ , F, Na, K	<ul style="list-style-type: none"> • 0.45-µm filter only • no acidification 	any	7 days/4 °C	minimal
Trace metals Fe, Mn, As, Cu, Zn, Pb, Cr, Cd, and so on	<ul style="list-style-type: none"> • sealed 0.45 µm filter • acidify (pH <2) • avoid aeration through splashing/head space 	plastic	150 days	moderate
N species NO ₃ , NH ₄ , NO ₂	<ul style="list-style-type: none"> • sealed 0.45 µm filter 	any	1 day/4 °C	moderate/low
Microbiological TC, FC, FS	<ul style="list-style-type: none"> • sterile conditions • unfiltered sample • onsite analysis preferred 	dark glass	6 hours/4 °C	moderate/low
Carbonate equilibria pH, HCO ₃ , Ca, Mg	<ul style="list-style-type: none"> • unfiltered well-sealed sample • on-site analysis (pH, HCO₃) (Ca/Mg at base laboratory on acidified sample) 	any	1 hour (150 days)	moderate
Oxygen status pE(Eh), DO, T	<ul style="list-style-type: none"> • on site in measuring cell • avoid aeration • unfiltered 	any	0.1 hour	high/moderate
Organics TOC, VOC, HC, ClHC, and so on	<ul style="list-style-type: none"> • unfiltered sample • avoid volatilization • direct absorption in cartridges preferred 	dark glass or Teflon	1-7 days (indefinite for cartridges)	high

Source: GW-MATE 2006a.

Note: As=arsenic; Ca = calcium; Cd = cadmium; Cl= chloride; ClHC = chlorinated hydrocarbons; Cr = chromium; Cu = copper; DO = dissolved oxygen; Eh = redox potential; F = fluoride; FC = fecal coliforms; Fe = iron; FS = fecal streptococci; HC = hydrocarbon; HCO₃ = bicarbonate; K= potassium; Mg = magnesium; Mn = manganese; N = nitrogen; NH₄ = ammonia; NO₃ = nitrate; NO₂ = nitrogen dioxide; Pb = lead; pE = redox potential; T = temperature; TC = total coliforms; VOC = volatile organic compounds; Zn = zinc.

Figure 3.1: Sampling procedures for specific compounds (Ravenscroft and Lytton, 2022)

The design and operation of different well types influence the characteristics of groundwater quality parameters as well as the quality of water extracted. Water collected is affected by changes in temperature or pressure when passing through a well and pump; different water qualities could mix inside the well and react with one another or the well materials (Ravenscroft & Lytton, 2022). Trace metals can be absorbed by rusted steel pipes and growth of bacteria can also occur in the inside of pipes and pumps (Ferguson et al. 2011). It is important to take these aspects into account when designing the monitoring system and deciding on the methods to be used.

3.1.4 Frequency

Compared to groundwater levels, groundwater chemistry typically changes slowly. Often groundwater quality programmes tend to follow administrative decisions on frequency initially. However, this should be reviewed as needed. The frequency of monitoring required can be deduced by answering the following questions:

- Length of time with regards to a contaminant reaching a receptor, how long is it appropriate and safe to wait for measurements to be done? Judgement will need to be made based on experience of contaminants in similar settings;
- What is the longest period that is acceptable to be with the adequate information? (Ravenscroft and Lytton, 2022).

At a minimum, when there is no specific need to monitor groundwater quality, measurements should be taken every five or ten years. This is more likely to be reasonable for deeper groundwater systems that have little anthropogenic impact. However, if the aquifer is shallow or under the impact of abstraction or changing surface water management, the frequency should be more regular (IGRAC, 2008).

With increasing data and knowledge, it should be possible to re-assess how frequently measurements need to be taken, with observed variations. Intervals can be estimated by modelling pollutant travel times; and the risk of contaminants reaching water supplies. If automatic in-situ probes are used, then measurements should be taken once a day, unless tidal fluctuations are of interest or in karstic systems where rapid changes in flow can be experienced. It has been suggested that a few automatic devices can be used and rotated between sampling points to determine short- to medium-term fluctuations (Ravenscroft and Lytton, 2022).

3.1.5 Sampling Points

A network of existing wells, dedicated monitoring wells, and natural discharge points (e.g. springs) should be used. Abstraction wells are important as they can sample a larger area of the aquifer – although this can lead to mixing of water from different levels – and can be used for a one-time survey to help characterise the area (IGRAC, 2008). However, this can mean that if a contaminant is found at a well, then a more detailed study should be carried out close to the source. Shallow monitoring wells can provide advance warnings of rising nitrate concentrations. (Ravenscroft and Lytton, 2022).

The spacing of wells in a monitoring system depends on whether the network has been developed for tracking an anthropogenic pollution incident or a routine resource monitoring (Ravenscroft and Lytton, 2022). Identification and observation from a pollution point source is not the first priority in the early stages of groundwater monitoring, as it is less likely to have a regional impact and would take a disproportional amount of time (IGRAC, 2008).

The most important factors in sampling point locations, is the distribution of existing wells, the geology, location of potable abstractions and other sensitive receptors. Directly spacing is not always feasible, but it can be helpful to specify the spatial density of sampling points (Ravenscroft and Lytton, 2022). Local clusters of wells should be avoided in regional monitoring programmes, unless there is a specific reason (IGRAC, 2008). Monitoring stations should be positioned where groundwater flow is concentrated, for example at a spring so the data reports information from a larger area of the aquifer (Ravenscroft and Lytton, 2022).

Whilst using existing wells may not be the best and most ideal option, they can reduce the cost of the programme. The following requirements are necessary if existing wells are to be used:

- The location of selected wells should be representative of regional groundwater (IGRAC, 2008);
- Construction material of the well must be known;
- Diameter of the well needs to be greater than 2 inches;
- For wells that are not in regular use, purging must be possible;
- Basic data such as depth, screen depth and length and exact location must be known.

3.1.6 Natural groundwater contaminants

Natural groundwater contaminants, such as arsenic and fluoride, are dangerous to public health and water quality, even at low concentrations. They are released from geological materials at any depth – and the problem can extend over large areas at varying concentrations, making regional monitoring difficult (IGRAC, 2008).

The position and extent of affected groundwater can be measured with a one-time sample at pre-existing boreholes in the area that may be at risk, if no changes are expected. If groundwater flow is expected to change, a monitoring programme will need to be set up to observe these changes (IGRAC, 2008).

3.1.7 Anthropogenic groundwater contaminants

Diffuse contamination of groundwater from anthropogenic sources can be problematic in upper, relatively shallow aquifers and can be caused by the application of agrochemicals (fertilisers and pesticides), atmospheric deposition of NO_x , SO_x , and metals, or local sources of pollution spread over large areas (e.g. urban areas). Groundwater chemistry impacted by pollution can be influenced by the type and load of pollutant, the hydrologic path, and the reactivity of the geological formations and groundwater aquifer characteristics (IGRAC, 2008).

Commonly, to monitor groundwater pollution, the source, path lines and affected receptors are considered (EU, 2000). This should be considered when designing the groundwater monitoring system, but often there is not enough information to make informed decisions. A simplification can use 'characteristic' or 'homogenous area types' based on land use and groundwater system vulnerability. Higher priority can be given to areas with a higher risk of being polluted, whilst deeper aquifers require less monitoring (IGRAC, 2008).

Identifying and proving diffusive pollution can be possible with a general reference network – but the wells chosen must be suitable and representative of the area. To show that the pollution is impacting the groundwater composition, sampling must be carried out in both affected and unaffected areas. Statistical analysis is possible when enough wells are monitored. The network can be improved over time, when more knowledge is gained (IGRAC, 2008).

Limits can be set to the chemical parameters that are monitored as this can reduce cost and increase efficiency. Additionally, reducing the frequency with which a well needs to be sampled to the minimum, can help reduce costs. For example, there can be a higher density of wells that are only monitored once every year or two years, whilst aquifers at a higher risk should only have a limited selection of wells which are monitored more frequently (IGRAC, 2008).

3.1.8 Fresh-saline interface

The need to monitor the interface between fresh and saline groundwater is required for coastal aquifers and aquifers with fossil saline water. The position is usually fairly stable, if only natural processes are involved. However, groundwater abstraction can result in sea water intrusion, so regular monitoring may be required (IGRAC, 2008). The sampling frequency depends on how fast the interface is likely to change and can vary from once every five to ten years to every month in rapidly changing situations (IGRAC, 2008).

Salinity can be monitored using a number of methods. In the field, specific electric conductivity (EC-value) and temperature can be measured and then EC-value for a reference temperature calculated. Alternatively, the total dissolved solids (TDS) or concentration of major ions can be determined in a lab (IGRAC, 2008).

The network for monitoring a fresh-saline interface depends on the location and requires an understanding of hydrogeology and groundwater flow systems. However, if there is little information on this, a preliminary design can be based on the Ghyben-Herzberg ratio (Ploessel, 2014) which helps to predict the shape of the interface. The wells should be positioned in (some)

rows perpendicular to the coast, although in less regular shaped estuaries this can be more complicated (IGRAC, 2008).

4 Groundwater monitoring case studies

4.1 General overview

The International Groundwater Resources Assessment Centre (IGRAC, 2020) have produced an overview report on groundwater monitoring programmes around the world. Their research included a literature review of all available information on the 108 countries involved in the Global Groundwater Monitoring Network (GGMN) and open requests for information to 62 countries that are not included in the GGMN. Some countries were not included as no contact details could be found, and only 10 countries responded to the open requests. The following analysis was carried out by IGRAC (2020) to summarise data from countries with established groundwater monitoring programmes and where information was provided.

IGRAC found that the most common reason for a groundwater monitoring network to be established was to “assess temporal and spatial variations of groundwater with respect to other environmental processes and human activities” (IGRAC, 2020). Additional purposes for a groundwater monitoring system include the “contribution of scientific information” and “monitoring compliance with regulation or standards”.

IGRAC (2020) reported that there was a large range in the frequency with which monitoring is carried out (Figure 4.1), from 15 minutes to several times per year, and this is largely related to whether automatic or manual measurements are carried out. Forty-two countries used automatic monitoring, although 28 of these countries used automatic monitoring alongside manual measurements – and these countries often reported a wide range of monitoring frequencies. Nine countries used manual measurements only and 30 countries did not specify the method of data collection, as shown in Figure 4.2.

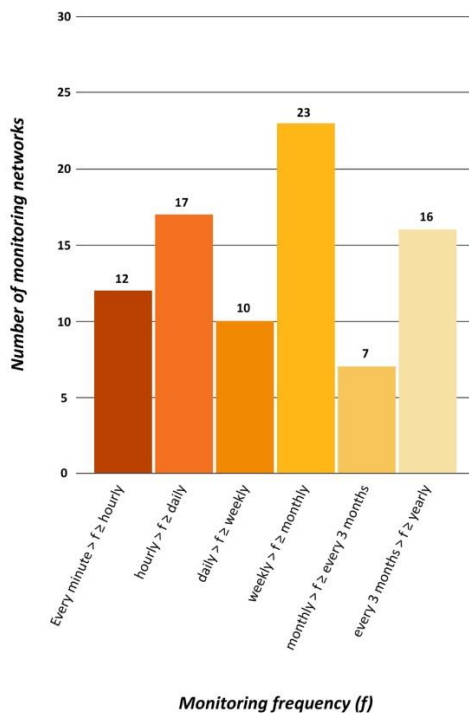


Figure 4.1: Monitoring frequency

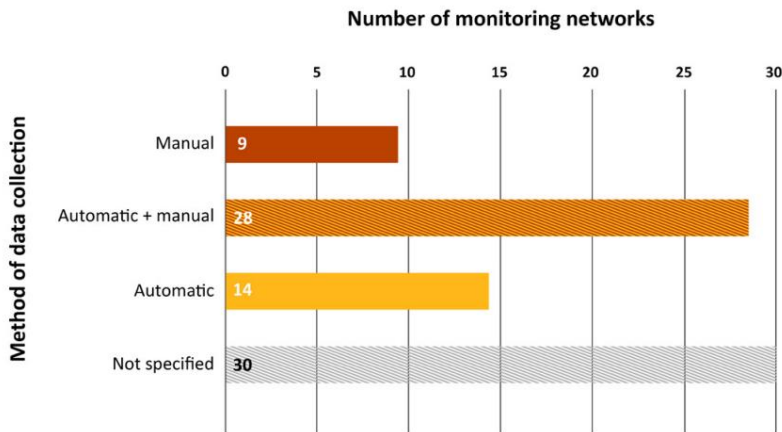


Figure 4.2: Methods of data collection

How countries processed the data was also collected, and this is summarised in Figure 4.3. The data was processed in different ways with at least 33 countries producing a written report and 41 countries generating groundwater maps. However, on multiple occasions, IGRAC was not able to access the reports or maps.

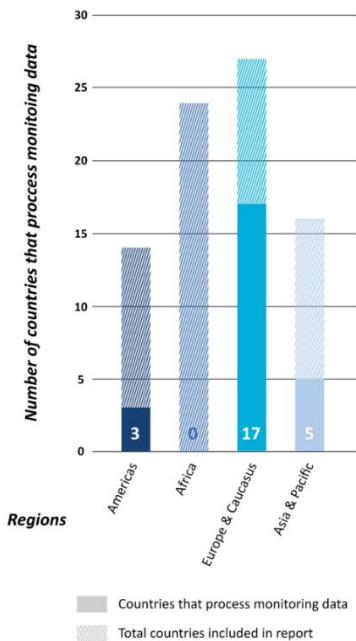


Figure 4.3: Number of countries that process monitoring data per region (IGRAC, 2020)

4.1.1 Country case studies

The National Groundwater Monitoring Programme’s report (IGRAC, 2020) also provided groundwater monitoring profiles on 81 countries. A summary of these programmes in countries with a similar geographical location, GDP or population to Belize is provided below. It was noted that there was very little information on how groundwater monitoring systems were designed and what decisions were made when designing the system (IGRAC, 2020).

4.1.2 Colombia

Groundwater monitoring in Colombia is managed by the Institute for Hydrology, Meteorology and Environmental Studies (IDEAM). IDEAM developed the national groundwater monitoring network to collect multipurpose information about the current status and long-term trends in groundwater quantity and quality. The monitoring of wells was not carried out by IDEAM, and an agreement with existing regional networks representatives was made. The wells used must be away from the influence of sources of groundwater contamination and must represent natural hydrogeological conditions. IDEAM aimed to have 1 station per 100 to 10000 km² (IGRAC, 2020).

Monitoring is carried out twice a year for groundwater quantity, aiming to capture the rainy and dry seasons, whilst groundwater quality is monitored once a year. Variables that are monitored include piezometric levels, total hardness, pH, temperature, electrical conductivity, total dissolved solids, dissolved oxygen, redox potential, alkalinity, and major ions (calcium, sodium, potassium, chloride, sulphate, nitrate, bicarbonate, magnesium and ammonia). There are 114 monitoring stations in various aquifer systems throughout the country (IGRAC, 2020).

4.1.3 Costa Rica

There are multiple groundwater monitoring networks in Costa Rica which are managed by the Water Directorate (DA) under the Ministry of Environment and Energy (MINAЕ), alongside the Costa Rican Institute of Aqueducts and Sewers (AyA) and the National Groundwater, Irrigation and Drainage Service (SENARA).

The automated network (SIMASTIR) is composed of an automated registration of data via telemetric transmission and semi-automated transmission. This monitoring programme began in 2016 in Costa Rica in the province of Guanacaste. This was extended to the Heredia and Alajuela provinces in 2020, resulting in 75 groundwater monitoring sites over the three provinces. Monitoring wells in some locations record hourly groundwater levels, temperature, and electrical conductivity.

In addition, there are 300 manual wells monitoring groundwater levels across Guanacaste and the Central Pacific area that are visited monthly.

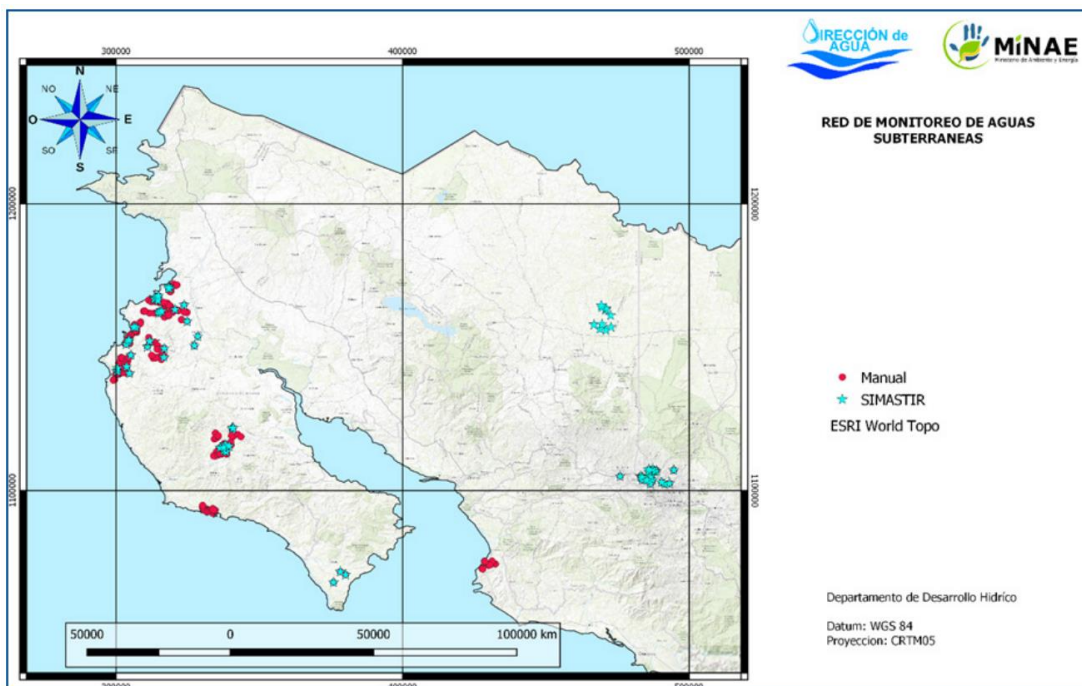


Figure 4.4: Groundwater Monitoring Network of Costa Rica (IGRAC, 2020)

4.1.4 El Salvador

Set up in 2007, as a collaboration of the Ministry of Environment and Natural Resources (MARN) and the European Union project Strengthening Environmental Management of El Salvador (FORGAES), the network of 32 monitoring wells, aims to provide data on the long-term status and trends of the national groundwater resources. The automatic data loggers provide data on groundwater levels every 8 hours. In 2018 and 2019, 15 new monitoring wells were drilled to perform automatic measurements of groundwater level and temperature.

In addition, there is a manual monitoring network of 100 hand-dug wells which measures groundwater levels twice a year (once during the dry season and once during the wet season).

4.1.5 Eswatini

Groundwater resources in Eswatini are monitored by the Ministry of Natural Resources and Energy in the Department of Water Affairs. Monitoring was initially set up to take place monthly. However, records are normally found only for the period immediately following borehole drilling. This is due to users of the borehole not taking on the responsibility of monitoring (IGRAC, 2020) and boreholes used for supply due to water shortages (SADC-GMI, 2023).

The monitoring programme is currently being revised, through the Southern African Development Community (SADC) Groundwater Management Institute (SADC-GMI) to monitor groundwater levels and quality.

4.1.6 Guinea-Bissau

Groundwater monitoring in Guinea-Bissau is managed by the Directorate General of Water Resources (DGRH). The data is stored on a national database, called mWater Portal and contains drilling logs, groundwater levels and groundwater quality. The project has been supported by UNICEF.

4.1.7 Lesotho

There are many privately owned boreholes in Lesotho, which are rapidly increasing in number, especially as groundwater is often the only source of potable water. Monitoring of a few springs in Lesotho began in the early 1990s (IGRAC, 2013).

Currently, the groundwater monitoring network in Lesotho is made up of 130 springs and 60 observation wells. However, due to a number of reasons, only 30 springs and 20 wells are operational and monitored. They are manually monitored every three months with water level dippers (IGRAC, 2020). Springs are also monitored for pH, temperature, EC, salinity, and redox potential once a year (IGRAC, 2013).

The Department of Water Affairs (DWA) in the Ministry of Energy, Meteorology and Water Affairs (MEMWA) were responsible for the monitoring of groundwater levels and quality. However, the responsibility is currently being shifted to local communities, with the DWA functioning as an advisory body. A project run by SADC-GMI was planning to expand the network in 2020, although no evidence was found confirming this had been carried out.

4.1.8 Luxembourg

Luxembourg began groundwater monitoring after a drought in 1976, by monitoring the flows from springs. In 2002, this was expanded to measure the flow, temperature, and electrical conductivity of nearly 200 springs every four months. The Water Management Administration was set up in 2004 to optimise the network of sources, and since then, piezometers and boreholes have been added to the scheme (The Luxembourg Government, 2023). There are seven operational automatic monitoring stations which record groundwater level and temperature, with the aim of

managing the legal and regulatory requirements for groundwater, in addition to manual monitoring (IGRAC, 2020).

4.1.9 Mexico

The national groundwater monitoring network is managed by the National Water Commission (CONAGUA) of Mexico. The aim of CONAGUA is to 'regulate, supervise and validate the study of groundwater as well as provide technical support, integrate and disseminate knowledge of the resource' (Gobierno de Mexico, 2023). The groundwater network is made up of more than 12,000 wells that monitor 370 aquifers (IGRAC, 2020). CONAGUA also manages the processing and dissemination of this data. Example of national water quality is shown in Figure 4.5 (CONAGUA 2021).

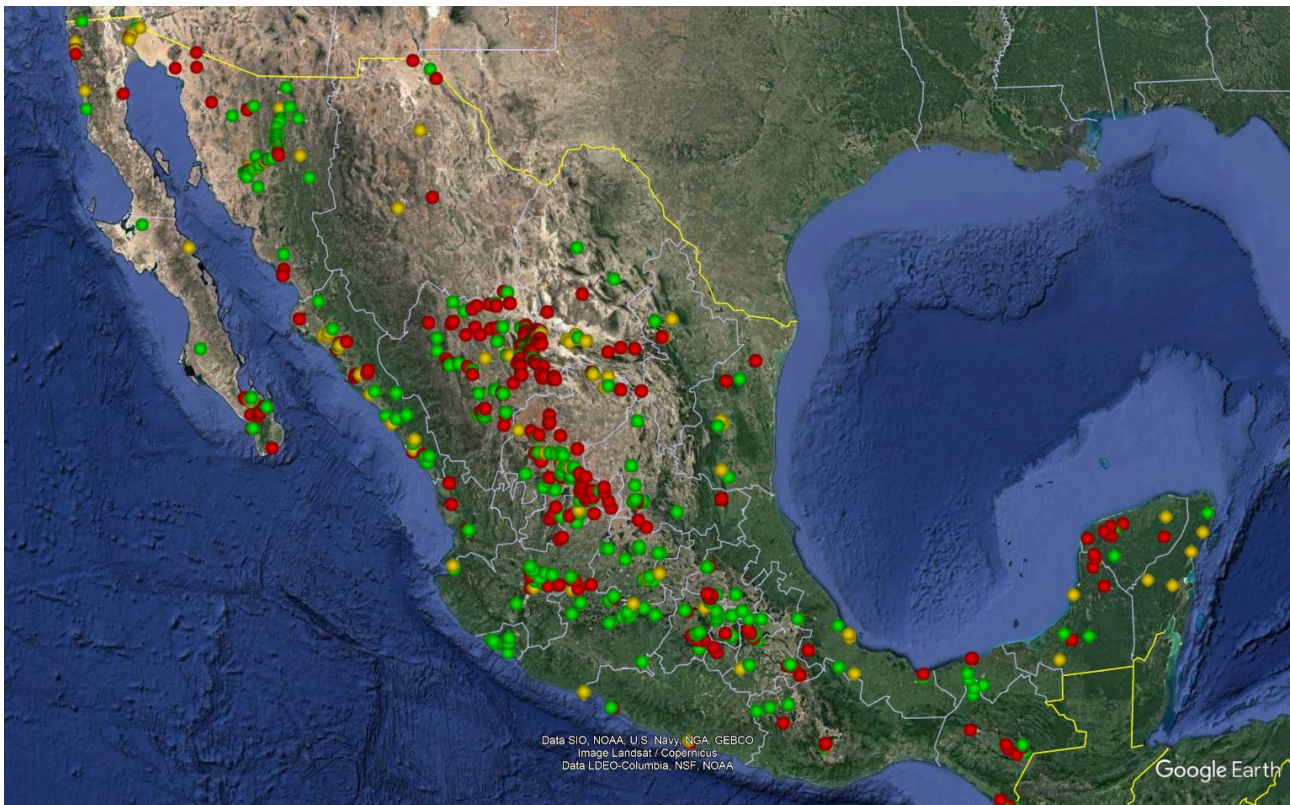


Figure 4.5: Water quality at the national level (CONAGUA 2021)

4.1.10 The Gambia

Groundwater management is overseen by the Department of Water Resources. The network was established between 2011 and 2015 with the aim of improving the assessment of resources for sustainable abstraction. A high number of data loggers have failed, so the DWR are trying to secure more funding to monitor more sites and replace the automatic data loggers. There are 38 groundwater monitoring boreholes, which are currently monitored manually. When the data loggers were functioning, they took measurements every 6 hours, but data was downloaded monthly or less frequently (IGRAC 2020).

5 Conclusions

This benchmark exercise provides an overview of the different options available for the design of a monitoring system. In the next deliverables, a preliminary system design will be developed based on the information gathered in this report and the particular needs of Belize and the New River area.

A key decision point for groundwater monitoring approach is the use of manual or automatic systems for collecting, storing, and transmitting data. The review of case studies indicates that most countries use both approaches. While it is difficult to determine the specific decisions which led to the adoption of either approach in the case studies, each approach is suited to a particular monitoring objective, and comes with its own risks and benefits. The use of both approaches offers some level of redundancy, for example if automatic systems fail, manual systems can offer some continuity. The capital intensive setting up of automatic monitoring systems appears to have been funded by donor projects in some cases, and therefore maintaining the sustainability of funding for the ongoing operation of the system is a key requirement. Conversely, manual approaches require either trained and motivated communities to undertake monitoring, or sufficient professional staff to make regular site visits for data collection. Automatic approaches provide high frequency data and if telemetry is used, offer the potential for near real time data. This may be important in some situations for example tracking of drought events or the effects of pumping regimes on groundwater level.

Automatic systems can monitor a limited range of parameters (groundwater level and field parameters – depending on the probes used and their regular recalibration), while manual sample collection for laboratory analysis is required for the majority of water quality parameters. Costly sample collection and analysis means that water quality analysis should be carefully optimised to avoid sampling which does not contribute to the monitoring objectives.

Below we show a table (Table 5.1) of potential options that we propose as a starting point to the monitoring system design.

Table 5.1: Technology options for groundwater quantity monitoring

Method	Advantages	Disadvantages
Manual	<ul style="list-style-type: none"> ● Low capital cost to set up network; ● Less risk of costly equipment failure; ● Experience of using similar approach for surface water measurement. 	<ul style="list-style-type: none"> ● Requires onsite visits if professional staff used; ● Requires training of community observers.
Automatic	<ul style="list-style-type: none"> ● High frequency of observations; ● Not reliant on third parties for data collection; ● Range of multiparameter probes available for water level, conductivity, temperature etc. 	<ul style="list-style-type: none"> ● More expensive to set up; ● Periodic recalibration of probes required (depending on parameter); ● Possibility of vandalism; ● Increased risk of failure and if electrical power is not possible will require solar panels or rechargeable packs.

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