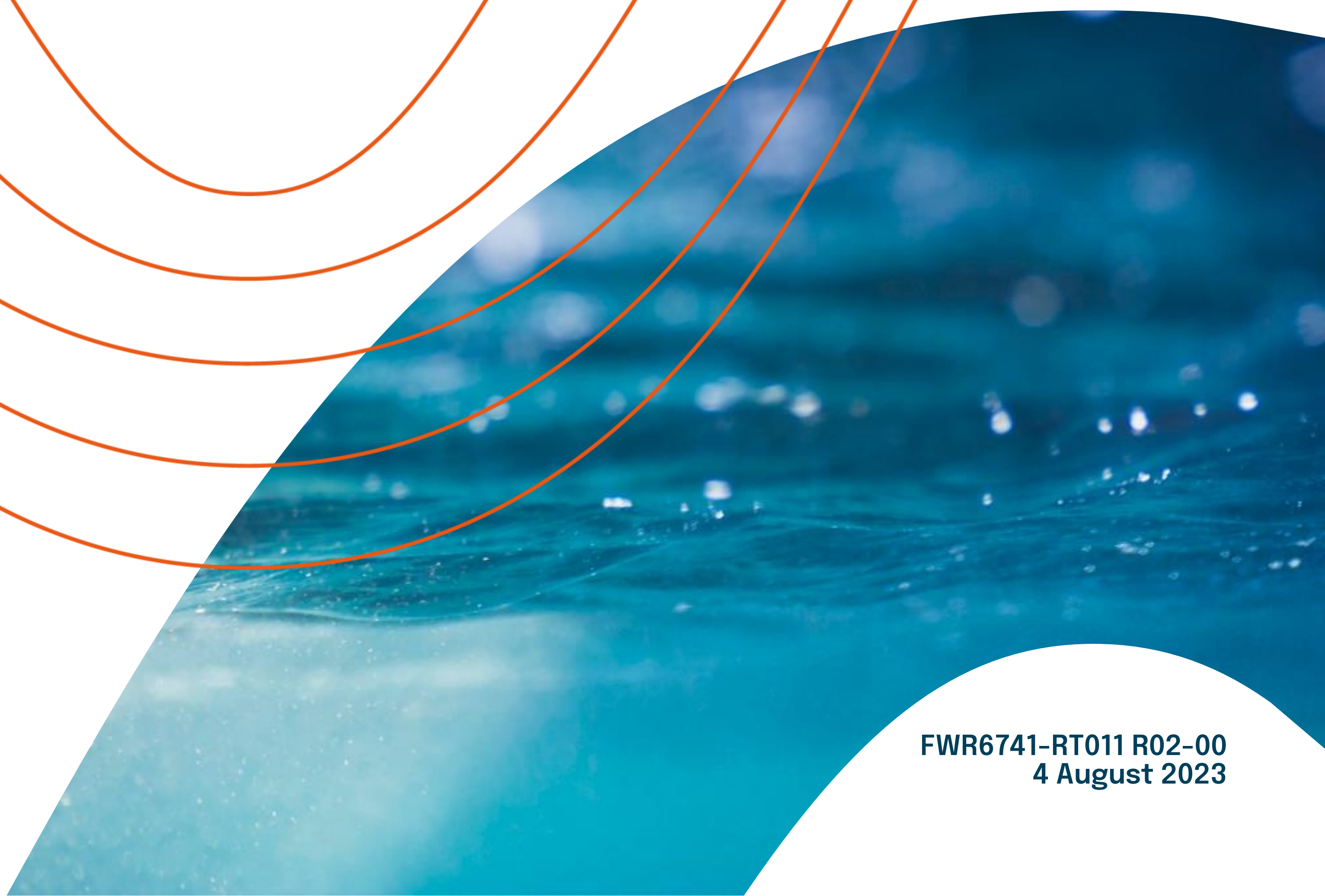
Groundwater monitoring for mapping aquifers in Belize as a tool for climate change adaptation planning

D-4.6 New River groundwater monitoring system design report



FWR6741-RT011 R02-00
4 August 2023

Document information

Document permissions	Confidential - client
Project number	FWR6741
Project name	Groundwater monitoring for mapping aquifers in Belize as a tool for climate change adaptation planning
Report title	D-4.6 New River groundwater monitoring system design report
Report number	RT011
Release number	02-00
Report date	4 August 2023
Client	Climate Technology Centre & Network (CTCN) (Contract No. UNEP/2022/319 (UMOJA #4700023827) RFP: 3100005103)
Client representative	Marisela Ricardez Garcia
Project manager	Azucena Rodriguez Yebra
Project director	George Woolhouse

Document history

Date	Release	Prepared	Approved	Authorised	Notes
4 Aug 2023	02-00	GFW	AZR	GFW	
29 Jun 2023	01-00	GFW	AZR	NW	

Document authorisation

Prepared	Approved	Authorised
George Woolhouse	Azucena Rodriguez Yebra	George Woolhouse

Executive summary

This report provides a design for a groundwater monitoring system for the Coastal Plains groundwater province located within northern Belize in the Orange Walk and Corozal districts, where the New River is located. The aim of this system is to provide long-term monitoring of groundwater level and quality for the monitoring of drought events and long-term trends, to inform sustainable management of groundwater resources in a changing climate.

Designing, maintaining, and using a monitoring system provides several benefits to protect water resources and communities. Groundwater is a vital resource and not readily accessible in contrast to surface water. Changes to groundwater quantity and quality can be slow processes. These changes are not easy to determine and require monitoring networks and data interpretation. The primary goal of aquifer management is to control the impacts of groundwater abstraction and contaminant loads, and monitoring aquifer response and quality trends provide key inputs for this goal (IGRAC 2020).

Background

This report is a deliverable under the project "Groundwater Monitoring for mapping aquifers in Belize as a tool for climate change adaptation planning" executed by the National Hydrological Service (NHS) of the Ministry of Natural Resources, Petroleum, and Mining and the National Climate Change Office of the Ministry of Sustainable Development, Climate Change, and Disaster Risk Management, with financial support provided by the Climate Technology Centre and Network (CTCN). The project delivery was led by HR Wallingford over the period October 2022 to September 2023.

Requirements for groundwater monitoring

Groundwater is a vital source of water supply in northern Belize for municipal, domestic, agricultural, and industrial purposes, sustaining health, livelihoods, and economic activities. However, the monitoring and management of groundwater is limited, and the resource is facing several challenges including:

1. Limited licensing and reporting of groundwater abstraction leading to uncertainty over the sustainability of groundwater exploitation with respect to environmental flows in rivers and wetlands;
2. Agricultural development and the application of agrochemicals which have the potential to contaminate groundwater;
3. Climate change projections which indicate warmer and drier conditions in the future, reducing groundwater recharge and increasing the risk of saline intrusion, coupled with sea level rise.

These issues have been highlighted in recent drought events and the eutrophication of the New River in 2019. Groundwater and surface water resources are likely to be closely linked in some areas, and the transboundary nature of the aquifer systems extending into southern Mexico and Guatemala adds further dimensions of complexity to the system.

At present there is no systematic monitoring of groundwater level and quality in Belize, and such a system is required to provide data for the effective and evidence-based management of groundwater resources as well as the following benefits:

- Resource Management;
- Protection of Ecosystems;
- Data-Driven Decision Making;
- Early Warning Systems;
- Public Awareness and Engagement;
- Scientific Research;
- Early Detection of Contamination;

- Regulatory Compliance;
- Cost Savings.

Monitoring system design

The proposed monitoring system in this report provides a basis for the structured collection of groundwater level and quality data across the northern Coastal Plains groundwater province. The NHS is the lead agency for implementing and operating the monitoring system, working collaboratively with other agencies including the Department of Environment, especially on water quality issues. Twenty manually operated and seven automatic monitoring stations are proposed for the long-term monitoring of groundwater level and quality. The use of existing wells is proposed to minimize capital costs.

At manually operated sites community groundwater observers will be employed to take measurements of groundwater level, temperature, and conductivity at defined intervals and report this back to the NHS.

At automatic sites, temperature, water level, and conductivity probes and dataloggers are proposed to provide continuous monitoring of these variables. Automatic monitoring is proposed in coastal areas where salinity is considered to be a risk factor.

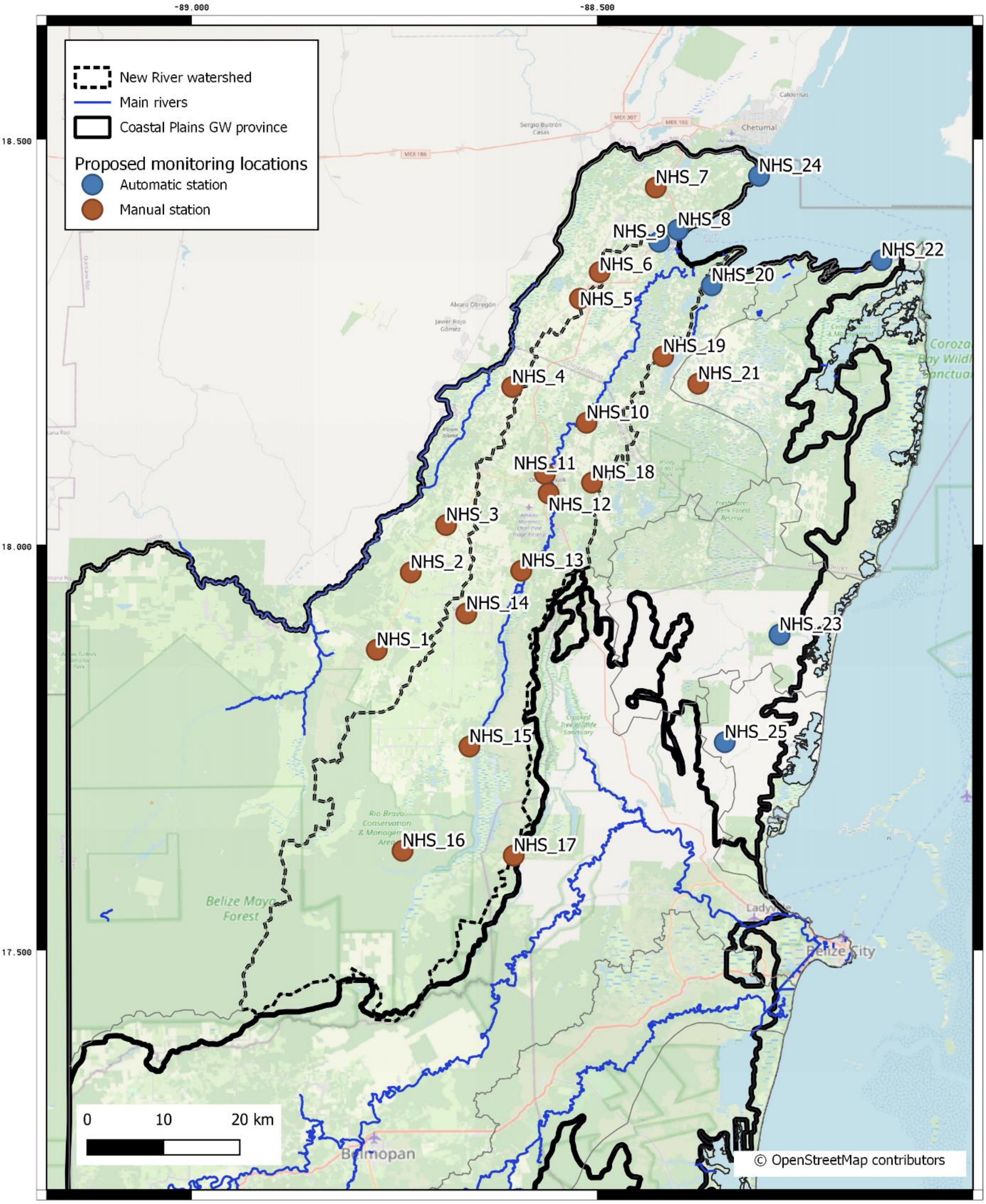


Figure 1: Map of proposed monitoring locations

At both manual and automatic sites, regular sample collection for water quality testing is proposed to be undertaken by NHS staff, on a quarterly basis for standard water quality parameters and on a less frequent basis for trace chemicals of concern, to balance cost and value.

The monitoring regime, both in terms of the location of sites and frequency of monitoring the various parameters should be reviewed annually to ensure effectiveness and optimise for cost efficiency.

<table>
<tr><th>Monitoring site type</th><th>Number of monitoring sites</th><th>NHS Site visit to monitoring station</th><th>Water level monitoring method</th><th>Field parameter monitoring method</th><th>Standard water quality laboratory analysis</th><th>Trace chemicals water quality laboratory analysis</th></tr>
<tr><td>Manual</td><td>20</td><td>Quarterly (year 1) then review.

Inspect well. Collect well level and field parameters using a handheld meter.
Take water quality sample.</td><td>Weekly.

Community representative collects water depth data using a well dipper.</td><td>Weekly.

Community representative collects temperature, conductivity, and pH data using a handheld meter.</td><td>Quarterly (year 1) then review.

Sample collected by NHS during the site visit.</td><td rowspan="2">Five sites sampled per year.

Sample collected by NHS during the site visit.

Adjust sampling depending on findings.</td></tr>
<tr><td>Automatic</td><td>7</td><td>Quarterly (year 1) then review.

Inspect well. Collect well level and field parameters using a handheld meter.
Take water quality sample.</td><td colspan="2">15 minute (year 1), then review.

Water level, temperature, and conductivity probe with logger.</td><td>Quarterly (year 1) then review.

Sample collected by NHS during the site visit.</td></tr>
</table>

Data management is proposed to be carried out by the NHS utilizing existing licenses for Water Information Systems by KISTERS (WISKI). Data quality assurance will be carried out by the NHS Hydrological Analyst, working with the monitoring technicians. An external consultancy is proposed annually to review data collected over the course of the year and recommend technical improvements. Once one full year of data has been collected, it may be appropriate to recruit a Hydrogeologist to provide data interpretation and derived products. A regular public briefing twice per year is recommended to give an update on groundwater status and trends, and this frequency may be increased during periods of drought where a closer interest in groundwater management is required.

Cost and implementation process

Capital and operational costs have been calculated including equipment, works at wellheads, staffing, training transportation, laboratory analysis, software, and hardware.

The capital costs associated with setting up the system in Year 1 of implementation are 300,850 Belize dollars and the ongoing operational costs are 277,197 Belize dollars.

The operational costs include the replacement of equipment at intervals of between 3 and 5 years for most items, reflecting the realities of the harsh conditions to which monitoring equipment is exposed to. Replacement costs form a significant component of ongoing costs, as do laboratory analyses for water quality.

The implementation process is based on setting up the monitoring system in Year 1, including recruitment of personnel, purchase of equipment, preparing existing wells for monitoring and installing equipment, training staff, and community observer training. At the end of Year 1, the system should be operationally collecting data from manual and automatic stations following agreed procedures. Thereafter, an annual review is proposed in which the operation of the system is reviewed and modified to ensure it is fit for purpose.

Contents

Tables

1 Introduction

1.1 Project summary

The National Hydrological Service (NHS) of the Ministry of Natural Resources, Petroleum, and Mining and the National Climate Change Office of the Ministry of Sustainable Development, Climate Change, and Disaster Risk Management, are executing a project to design a groundwater monitoring system for the management of aquifers in Belize, focusing on the New River watershed. The project commenced in October 2022 and will complete in September 2023. HR Wallingford Limited is leading the consulting team implementing the project and financial support is provided by the Climate Technology Centre and Network (CTCN).

This important project will help Belize to sustainably manage groundwater resources in the face of a changing climate and human pressures on the resource.

The main outputs include:

1. A communications plan and detailed work plan;
2. Stakeholder mapping and establishing a stakeholder working group;
3. An assessment of groundwater availability and demand, nationally and with a particular focus on the New River watershed;
4. Design of an integrated monitoring system that will enable Belize to manage groundwater resources in the priority area of the New River watershed;
5. Development of an implementation plan on the enabling factors for implementation, including financial, institutional setting and capacity building.

1.2 About this report

This report provides a design for a groundwater monitoring system for the New River area (as defined by the Coastal Plains groundwater province) under Output 4 above.

It provides the following:

- Definition of the area to be monitored;
- Description of information needs and monitoring objectives;
- The monitoring system description including:
  - Monitoring locations;
  - Monitoring variables and frequency of monitoring;
  - Monitoring methods;
  - Data management.
- Initial cost estimates;
- Institutional arrangements.

2 Benefits of groundwater monitoring

Designing, maintaining, and using a monitoring system provide several benefits to protect water resources and communities. Groundwater is a vital resource and not readily accessible in contrast to surface water. Changes to groundwater quantity and quality can be slow processes. These changes are not easy to determine and require monitoring networks and data interpretation. The primary goal of aquifer management is to control the impacts of groundwater abstraction and contaminant loads, and monitoring aquifer response and quality trends provide key inputs for this goal (IGRAC 2020).

Groundwater monitoring can be often considered expensive due to capital costs of network installation; sampling costs for instrumentation, personnel, and logistics; and analytical costs (for laboratory, data processing and storage (World Bank, 2023; Kim & Kim, 2019). However, monitoring groundwater provides numerous benefits and advantages that will often generate a beneficial investment. Amongst these, several can be highlighted in terms of benefits of groundwater quantity and quality monitoring, these have been summarised in Table 2.1 (Taylor et a., 2001; Environment Agency, 2007,2018; Kim et al., 2019; IGRAC 2020; Rau et al., 2020).

Table 2.1: Benefits of groundwater monitoring

Groundwater quantity monitoring	Groundwater quality monitoring
Resource Management	Early Detection of Contamination
Protection of Ecosystems	Regulatory Compliance
Data-Driven Decision Making	Data-Driven Decision Making
Early Warning Systems	Cost Savings
Public Awareness and Engagement	Public Awareness and Engagement
Scientific Research	Scientific Research

These benefits are detailed below:

- **Resource Management**: Groundwater monitoring systems provide valuable data on water levels and usage patterns. This information helps water resource managers make informed decisions regarding allocation, conservation, and sustainable use of groundwater resources.
- **Protection of Ecosystems**: Groundwater plays a crucial role in sustaining aquatic ecosystems, wetlands, and streams. Monitoring systems aid in assessing the impacts of groundwater pumping on these ecosystems, ensuring that appropriate measures are taken to protect and maintain their health.
- **Data-Driven Decision Making**: Groundwater monitoring systems generate a wealth of data that can be used for analysis and modelling. This data-driven approach enables informed decision making for water resource planning, pollution prevention, and remediation efforts.
- **Early Warning Systems**: By continuously monitoring groundwater levels, the system can provide early warnings of potential drought conditions or water scarcity. This allows for proactive planning and implementation of water management strategies to mitigate the effects of drought.
- **Public Awareness and Engagement**: Sharing the collected data from groundwater monitoring systems with the public fosters awareness and engagement in water resource management. It promotes transparency, facilitates public participation, and encourages responsible water use practices.
- **Scientific Research**: Groundwater monitoring data serves as a valuable resource for scientific research related to hydrogeology, water quality, climate change, and ecosystem dynamics. Researchers can utilize this data to enhance their understanding of groundwater systems and develop innovative solutions for water resource challenges.
- **Early Detection of Contamination**: By continuously monitoring groundwater quality, the system can detect any changes or contamination in groundwater resources early, which minimises the risks to public health and the environment, prompting actions to be taken.
- **Regulatory Compliance**: Many regions have regulations and standards in place to protect groundwater quality. A monitoring system helps entities, such as industries or agricultural operations, comply with these regulations by providing real-time data on water quality parameters and ensuring adherence to acceptable levels.
- **Cost Savings**: Timely detection and response to contamination incidents can help prevent costly clean-up efforts and damage to water supply infrastructure. Additionally, monitoring systems can assist in optimizing water usage, leading to cost savings through improved efficiency and reduced wastage.

Overall, a groundwater monitoring system provides critical information to protect water quality, manage resources sustainably, and make informed decisions for the benefit of both the environment and human populations.

3 Defining the area to be monitored

This task involves defining the area for which the monitoring system will be designed. This should reflect the hydrogeological characteristics and should also be replicable such that if the monitoring system is upscaled from the New River to a national scale it represents a logical spatial unit.

Two options have been considered as the area to be monitored:

1. The **New River watershed**. This represents the topographic boundary of the New River watershed. Given the very flat topography of the New River watershed and surrounding areas, and the unconfined and often karstic nature of the aquifer systems, the topographic boundary may not accurately reflect the groundwater divide. Therefore, in this case the watershed may not be the most relevant unit for monitoring.
2. The **Coastal Plains groundwater province** as defined in Hursthorn (1984) and provided by the National Hydrological Service (NHS) in shapefile format, covers a large part of northern Belize in the Corozal and Orange Walk administrative districts, and encompasses the New River and Rio Hondo catchments as well as the low-lying areas towards the coast. Within the province, numerous village and private wells tap into chalks and marls of Eocene age or younger. Beneath these Eocene deposits are older limestone formations of Cretaceous age (notably the Barton Creek and Yalbac formations). These formations outcrop in the Campur groundwater province to the south of the coastal plains where they provide reliable yields. These are presently not exploited, with the exception of a well at the Caribbean International Brewery at Carmelita village in the Orange Walk district which is around 238 m deep with artesian flow at 92 imperial gallons per minute from fractured dolomite at 236 m (based on drilling log provided by the NHS).

A map of these areas is provided in Figure 3.1 below.

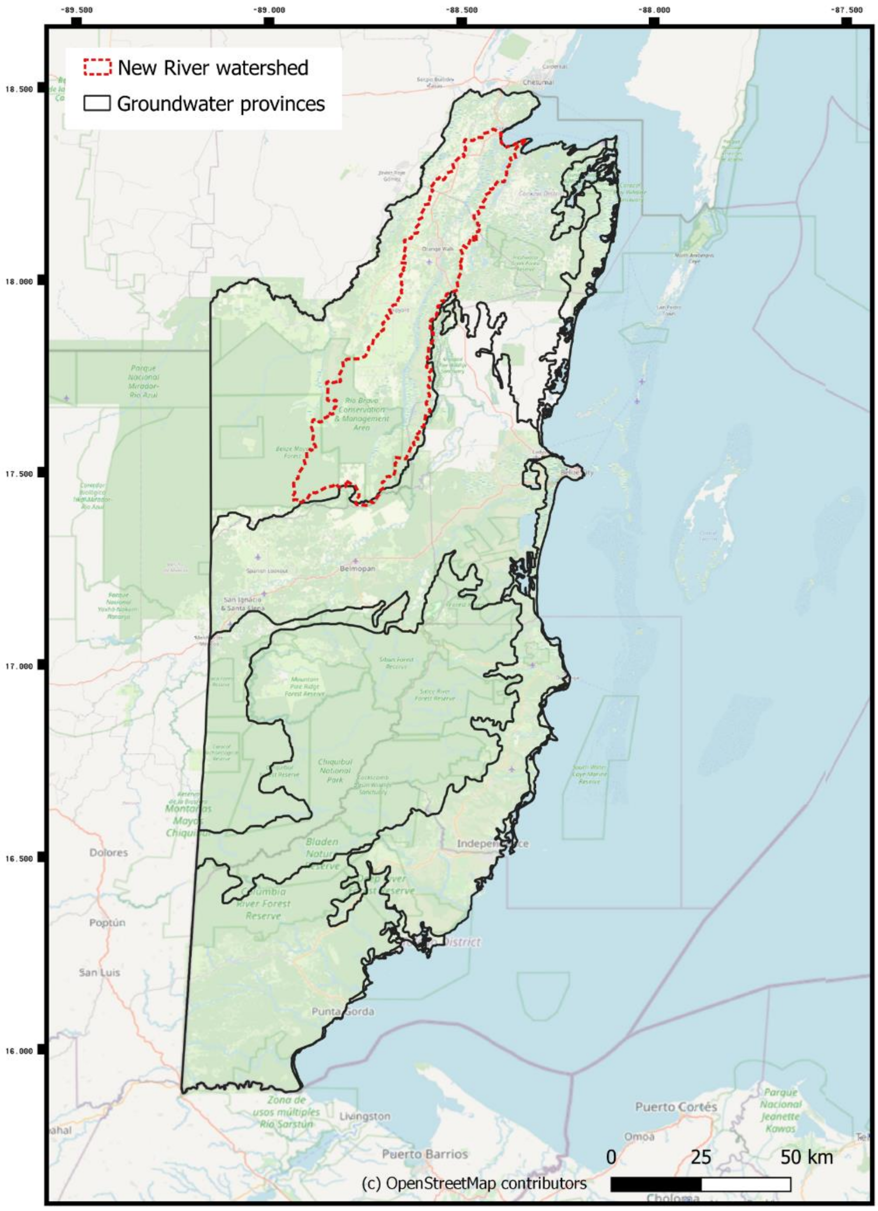


Figure 3.1: Belize groundwater provinces - data provided by the NHS (in black). Note that the Cayes are not included in the GIS shapefiles. New River watershed in red

The Coastal Plains groundwater province provides the most logical boundary for defining the area to be monitored as it represents an area of similar hydrogeological characteristics, and if future monitoring systems are required nationally, the other six provinces could be used as the basis for their design. Figure 3.2 shows the Coastal Plains groundwater province outlined in blue.

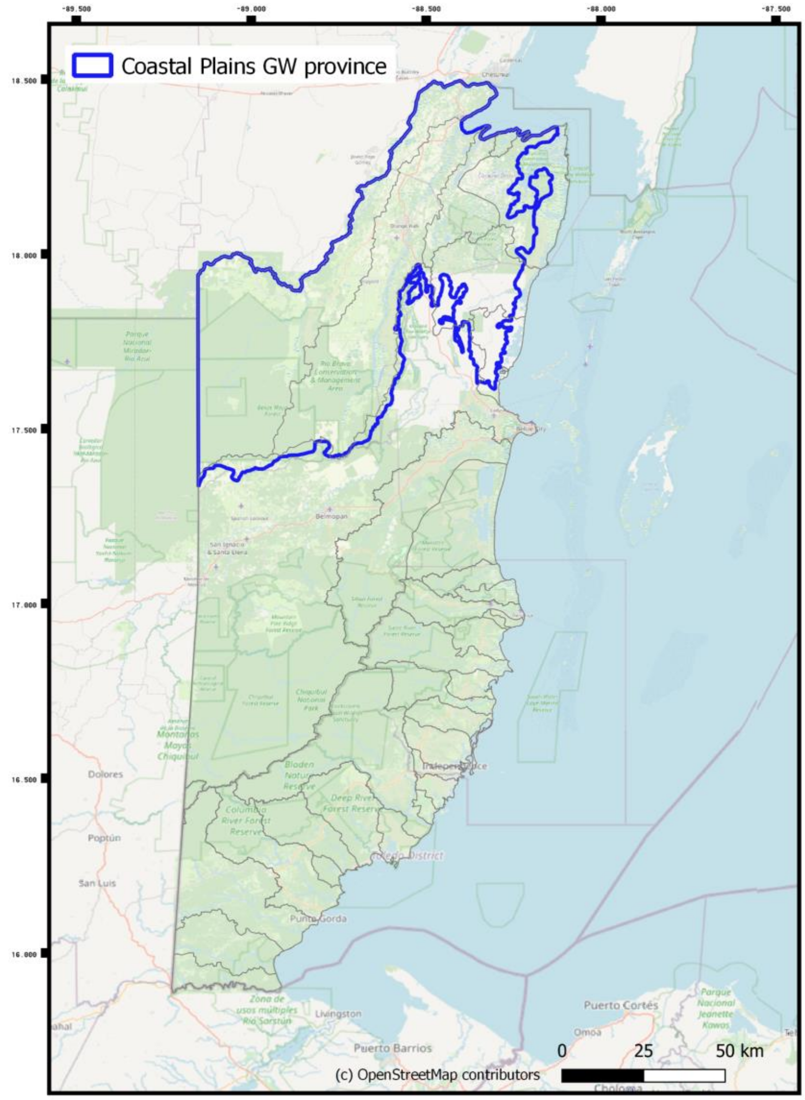


Figure 3.2: Coastal Plains groundwater province outlined in blue

4 Defining the information needs and monitoring objectives

Based on our review of available data and information, and discussions with stakeholders the information needs related to groundwater include both quantity and quality and represent both: one off data collection exercises as well as ongoing groundwater monitoring.

4.1 Information needs for stakeholders

The information needs for stakeholders are summarised below:

National Hydrological Service

The mission of the NHS is: *"To enforce the policy of the Government for the orderly and coordinated management, development and use, conservation and protection of our water resources to provide a safe, adequate and reliable supply for the present and future generations of Belizeans"*.

Based on its mission, the NHS is the most suitable organisation to lead on collection, management, and interpretation of groundwater monitoring data for the proposed system. Groundwater monitoring information will be needed by the NHS to inform government policy on the sustainable development and use of groundwater resources. This will be done by tracking trends in groundwater usage, levels, and quality over time, and improving knowledge on the characteristics and behaviour of aquifers through modelling studies and other analyses.

Improved groundwater monitoring information will allow the NHS to regulate groundwater abstraction to ensure sustainable management of the resource. It will also allow the NHS to advise other government agencies such as the Department of Environment on trends and emerging issues in water quality and quantity which may impact the environment or water users.

Other government ministries and departments

As a regulator of water resources, the NHS has a role to provide evidence and technical advice to other government departments on matters of water resources development, informed by groundwater monitoring activities, aiming to provide integrated water resources management.

Scientific research organisations

Groundwater monitoring data will also underpin scientific research to advance the state of the knowledge on groundwater resources in Belize. This can include data analysis or groundwater modelling to predict the impacts of future development, land use, population and climate change on groundwater and water resources.

4.1.1 Proposed institutional arrangements for groundwater monitoring

The NHS is considered the most appropriate organisation to operate a groundwater monitoring system for Belize. The NHS has experience in monitoring surface water resources through its river flow gauging activities. They are well placed to take on the role of groundwater level monitoring and there is no overlap with other institutional responsibilities for this variable.

In terms of groundwater quality monitoring, it is recommended that the NHS takes a lead role as their staff will already be responsible for operating groundwater level monitoring stations and can take groundwater quality data collection as part of this ongoing process. However, it will be important for the NHS to coordinate with other agencies, such as the Department of Environment (DoE) and other governmental and NGO organisations, the collection of surface water quality data as set out in the DoE's Final Comprehensive National Water Quality Monitoring Program and Protocol[1] document. In addition, cooperation across agencies at a technical level will also be beneficial in terms of sharing expertise and problem solving involved in water quality data collection.

4.2 Groundwater management information

A variety of different baseline and time-variant data are required for effective groundwater management (see Table 4.1 below). Groundwater monitoring typically comprises the 'time-variant data' component on the right-hand side of the table. Groundwater monitoring consists of three main elements: monitoring groundwater levels, abstraction rates and groundwater quality. The time varying supporting information (rainfall, river flows) are important but outside the scope of groundwater monitoring.

A comprehensive set of baseline data supports the design of a monitoring system, and conversely gaps in baseline data introduces uncertainties into monitoring system design. If this is the case, then a phased approach to monitoring may be required to fill information gaps over time.

[1] The Final Comprehensive National Water Quality Monitoring Program and Protocol. 30th September 2019. Prepared by CBCL Limited for the Belize Department of Environment

Table 4.1: Types of data required for groundwater management

TYPE OF DATA	BASELINE DATA (from archives)	TIME-VARIANT DATA (from field stations)
Groundwater Occurrence and Aquifer Properties	• water well records (hydrogeological logs, instantaneous groundwater levels and quality) • well and aquifer pumping tests	• groundwater level monitoring • groundwater quality monitoring
Groundwater Use	• water well pump installations • water-use inventories • population registers and forecasts • energy consumption for irrigation	• water well abstraction monitoring (direct or indirect) • well groundwater level variations
Supporting Information	• climatic data • land-use inventories • geological maps/sections	• riverflow gauging • meteorological observations • satellite land-use surveys

The status of the main types of groundwater information are summarised below.

Groundwater levels and quality

At present, no monitoring of groundwater levels is carried out by government agencies in Belize. Therefore, there is very little risk of overlap or duplication of data collection, and the mandate for collection of groundwater levels is with the National Hydrological Service of Belize.

Water quality monitoring from groundwater sources is currently carried out for drinking water compliance by both Belize Water Services (BWS) and the Ministry of Health. However, this monitoring does not necessarily cover the locations, variables, and time intervals of interest from a water resources management and protection perspective.

Surface water quality monitoring is carried out by the Department of the Environment (DoE) and other organisations as summarised in DoE's Final Comprehensive National Water Quality Monitoring Program and Protocol[2] document. Although it is understood that the DoE does not monitor environmental groundwater quality, there is a need to ensure that data collection efforts on surface water and groundwater are coordinated, and data is shared between organisations. Groundwater quality and surface water quality data together provide a more integrated picture of the status of water resources quality than each viewed in isolation.

Groundwater abstraction

Limited data exists on the location of groundwater wells and their abstraction rates. Abstraction rates for public water supply are available from the water utility BWS and can be estimated for rural and private supplies. Some data for industrial water users is available from the abstraction licence returns held by the NHS. However, no data on agricultural water consumption exists, although the location of farms with wells is recorded in the Ministry of Agriculture's BAIMS system.

Baseline data on aquifer characteristics

Geological mapping of Belize is available, providing a general overview of the geological formations, and qualitative information on those formations which are known to contain groundwater in viable quantities for abstraction. However, the extent and characteristics of

[2] The Final Comprehensive National Water Quality Monitoring Program and Protocol. 30th September 2019. Prepared by CBCL Limited for the Belize Department of Environment

aquifers within the Coastal Plains and Shelf groundwater provinces are not well understood. Groundwater from wells, that are typically less than 20 m deep, has historically been the main source of water for the population in the area, and drillers indicate that it is hard to predict well yields due to local variability in the underlying strata, although it is understood that at greater depths artesian aquifers are present in the limestone formations. A concerted effort to collect and catalogue well logs is required, and going forward more effort is required in obtaining well logs and carrying out pumping tests for newly drilled wells.

4.3 Groundwater monitoring objectives

Groundwater monitoring systems can be classed into three types: primary, secondary, and tertiary (as shown in Table 4.2):

- Primary Systems aim to detect general changes in groundwater flow and trends in groundwater quality, and bridge gaps in scientific understanding of the groundwater resource base.
- Secondary and Tertiary Systems aim to assess and control the impact of specific risks to groundwater.

In the case of Belize where no groundwater monitoring is carried out at present, a primary system is recommended to provide a general status of groundwater quality and quantity for water resources management. There are concerns around agricultural intensification, salinity in coastal areas, and potentially point sources of pollution which are reflected in the monitoring system design and location of monitoring boreholes. However, the current focus of the system is considered to be for general reference purposes to track seasonal and inter-annual changes in groundwater level and quality. Figure 4.1 shows the proposed monitoring locations and settlements as well as population concentration in relation to land use and particularly agricultural areas.

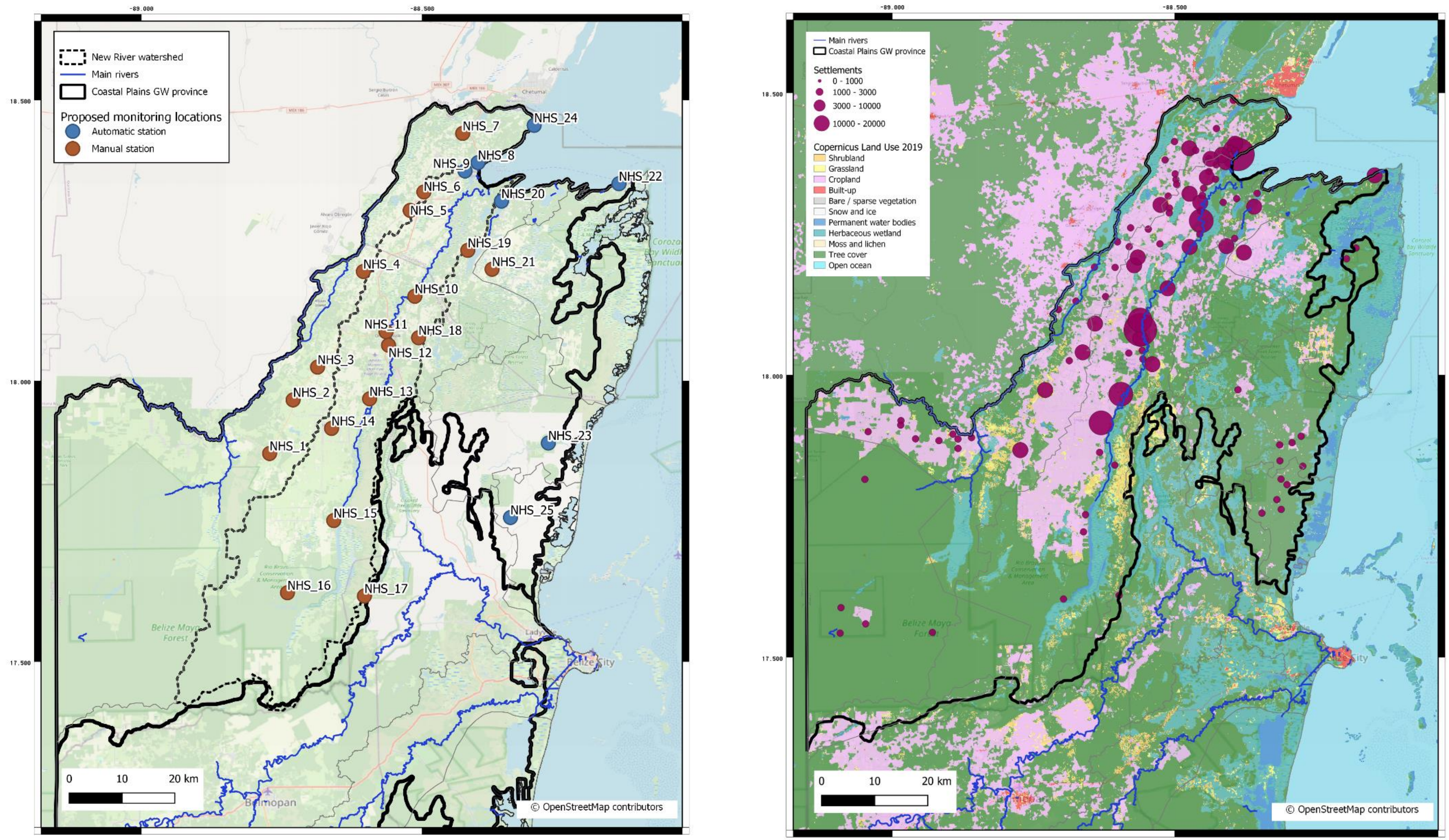


Figure 4.1: (a) Proposed monitoring locations and; (b) Settlements and land use in northern Belize

Table 4.2: Classification of groundwater monitoring systems by function (GW-MATE 2006)

SYSTEM	BASIC FUNCTION	WELL LOCATIONS
Primary (Reference Monitoring)	evaluation of general groundwater behavior: • trends resulting from land-use change and climatic variation • processes such as recharge, flow and diffuse contamination	• in uniform areas with respect to hydrogeology and land use
Secondary (Protection Monitoring)	protection against potential impacts of following: • strategic groundwater resource • wellfields/springheads for public water supply • urban infrastructure from land subsidence • archaeological sites against rising water table • groundwater-dependent ecosystems	• around areas/ facilities/ features requiring protection
Tertiary (Pollution Containment)	early warning of groundwater impacts from: • intensive agricultural land use • industrial sites • solid waste landfills • land reclamation areas • quarries and mines	• immediately down- and up-hydraulic gradient from hazard

4.3.1 Groundwater quantity monitoring objectives

Monitoring of groundwater levels at boreholes representative of regional aquifers is required in order to understand variability and trends, specifically to quantify:

1. Seasonal groundwater level variability in response to dry and wet seasons;
2. Long term trends in groundwater levels associated with groundwater exploitation and multi-year changes in climate including long term climate change.

The monitoring objective is a general reference purpose at aquifer scale, focusing both on reference areas (those not disturbed by human activity) and on those where groundwater is being exploited. However, monitoring of local drawdowns associated with individual abstraction boreholes is not proposed, unless a specific case can be made.

The monitoring objective is primarily focused on shallow aquifers which are presently being exploited for drinking water, industry and agriculture. However, a small number of monitoring boreholes into the deeper artesian aquifers would be useful to provide baseline reference values for those aquifers.

4.3.2 Groundwater quality monitoring objectives

The following monitoring objectives are proposed:

Monitoring of groundwater quality at locations representative of areas where groundwater is under pressure from abstraction, saline intrusion, and diffuse pollution, as well as reference areas for natural or baseline conditions, is required in order to provide baseline data and quantify any trends and seasonal fluctuations. Variables for monitoring should reflect the use of groundwater (drinking/agriculture/environmental) and the known quality issues (for example agricultural intensification). Specifically:

1. General characterisation of groundwater quality at locations representative of regionally important aquifers.

2. Monitoring of groundwater salinity in areas potentially influenced by saline intrusion.
3. Monitoring nitrates and phosphates in areas where diffuse pollution from agricultural fertilizers is a risk.
4. Monitoring pesticides, arsenic, fluoride, heavy metals, and other trace pollutants of concern.

Presently monitoring of groundwater quality for drinking water purposes is carried out by BWS and Ministry of Health (for Rudimentary Water Systems - RWS), and there may be opportunities to achieve some of these monitoring objectives by sharing of data and / or collaborating on monitoring programmes.

4.3.3 Recommendations to address other groundwater information gaps

Groundwater abstraction monitoring

Groundwater abstraction data for agricultural water use is not presently collected and a more systematic approach to assessing groundwater abstraction is required. This should focus on water use for agriculture, using a suitable sample of farms, collecting information on the water use and pumping rates for different types of farms and making estimates of agricultural water consumption and irrigation return flows. This will require periodic updating to track changes in agricultural land cover and farming practices.

Borehole logs and pumping tests

In addition to a groundwater quantity and quality monitoring system, improved aquifer characterisation is required to close the baseline data gaps on groundwater in Belize. This involves the following:

1. Using a more systematic approach to well logging and pump tests, for example through mandatory submission of drilling records to the NHS, by using a proforma to collect the necessary information.
2. A programme of pump tests to determine aquifer characteristics for a sample of representative boreholes across the province. This would focus on the shallow aquifers which are most heavily exploited, and if budget allows some testing of deeper boreholes which are not widely exploited at present.

This will likely also require training and engagement with drillers to move towards a more rigorous approach to data collection.

5 Proposed monitoring system description

This section sets out the proposed monitoring system. Principles for the development of the system:

1. Relevant to the interests of the users;
2. Targeted to the highest priority areas;
3. Timely reporting of data;
4. Appropriate technology;
5. Adaptable to allow updates/improvements/upscaling;
6. Financially and technically sustainable;
7. Clear institutional roles.

The system should not be overly ambitious given that Belize presently has no institutional experience with groundwater monitoring and considerable uncertainties still exist in aquifer characteristics. Once implemented, the system should be reviewed on a regular basis, preferably annually, in order to review the quality of the data being collected, revisit monitoring priorities and optimise the locations and frequency of monitoring. Lessons from this process should be adopted when considering upscaling to a national level monitoring network.

5.1 Proposed locations for monitoring

In order to meet the monitoring objectives, locations for monitoring groundwater levels and quality have been identified and are provided in Table 5.1. A map of the proposed monitoring locations is provided in Figure 4.1.

These have been identified on the basis of the following:

- A representative spread of locations across the monitoring area to be able to determine spatial variations in groundwater level changes and water quality changes over time.
- Locations have been selected in reference areas with minimum human disturbance to provide data on natural groundwater conditions to track drought and climate change without human influence.
- Locations have been selected in areas where agricultural development may influence groundwater levels (through abstraction for agriculture) and quality (through application of fertilizers and pesticides).
- Locations have been selected in areas where saline intrusion may pose a risk to public water supply in order to track changes in salinity over time.
- Most locations have been identified to coincide with the existing wells surveyed by the NHS and Table 5.1 identifies the primary choice of monitoring well and in some cases alternative nearby wells which may be suitable. Appendix B provides this table in Excel format together with the existing well survey data with a unique identifier for each of the surveyed wells. However, not all locations have existing wells within the NHS well survey database, and in such cases some fieldwork will be required to identify suitable nearby wells. An initial prioritisation has been carried out as part of this study, and further, more detailed fieldwork and engagement with well owners will be carried out to confirm their suitability for monitoring.

The use of automatic monitoring stations is proposed in coastal locations where a high-resolution record of water levels and quality are required in order to track potentially rapid changes in salinity, and manual monitoring at the remaining locations where community members can be engaged to collect data similar to the current approach the NHS uses for the collection of river level data.

Table 5.1: Proposed monitoring locations

Monitoring location reference	District	Settlement	Purpose	Type	Primary choice existing well (purpose, construction and status)	Primary choice existing well (depth of well (m))	Notes	Primary choice existing well from NHS survey (NHS survey reference)	Alternative existing well option from NHS survey	Alternative existing well option from NHS survey
NHS_1	Orange Walk	San Felipe	General monitoring of water level and quality	Manual station	Domestic/Open Well/Active	7.42		NHS_survey_205	NHS_survey_199	NHS_survey_204
NHS_2	Orange Walk	August Pine Ridge	General monitoring of water level and quality	Manual station	Domestic/Open Well/Active	5.47		NHS_survey_3	NHS_survey_5	NHS_survey_6
NHS_3	Orange Walk	Trinidad	General monitoring of water level and quality	Manual station	Domestic/Open Well/Active	6.3		NHS_survey_365	NHS_survey_360	
NHS_4	Orange Walk	San Luis	General monitoring of water level and quality	Manual station	RWS/Drilled/Active	not recorded	Primary choice active RWS well - need to check whether this can be monitored. If not identify suitable domestic well.	NHS_survey_250	NHS_survey_248	
NHS_5	Corozal	San Narciso	General monitoring of water level and quality	Manual station	Domestic/Open Well/Active	13.6		NHS_survey_256	NHS_survey_258	
NHS_6	Corozal	San Pedro	General monitoring of water level and quality	Manual station	Domestic/Open Well/Active	8.41		NHS_survey_275	NHS_survey_279	
NHS_7	Corozal	Chan Chen	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby.		
NHS_8	Corozal	Corozal	Monitoring groundwater salinity in coastal areas	Automatic station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby - purpose is to monitor salinity near BWS wells.		

Monitoring location reference	District	Settlement	Purpose	Type	Primary choice existing well (purpose, construction and status)	Primary choice existing well (depth of well (m))	Notes	Primary choice existing well from NHS survey (NHS survey reference)	Alternative existing well option from NHS survey	Alternative existing well option from NHS survey
NHS_9	Corozal	Ranchito	Monitoring groundwater salinity in coastal areas	Automatic station	Domestic/Open Well/Active	11.37		NHS_survey_172	NHS_survey_59	
NHS_10	Orange Walk	San Estevan	General monitoring of water level and quality	Manual station	RWS/Drilled/Inactive	not recorded		NHS_survey_125	NHS_survey_198	
NHS_11	Orange Walk	Orange Walk Town	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in immediate vicinity in the survey - need to identify suitable well nearby.		
NHS_12	Orange Walk	San Jose Palmar	General monitoring of water level and quality	Manual station	RWS/Drilled/Active	28.04	Primary choice is active RWS well, use alternative if not feasible.	NHS_survey_234	NHS_survey_233	
NHS_13	Orange Walk	Guinea Grass	General monitoring of water level and quality	Manual station	Agriculture/Well type not recorded/Inactive	46.07	Primary choice is Inactive BSI well, location not recorded.	NHS_survey_116	NHS_survey_118	
NHS_14	Orange Walk	Shipyard	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby.		
NHS_15	Orange Walk	Indian Church	General monitoring of water level and quality	Manual station	RWS/Drilled/Active	39	Primary choice is active RWS well, identify alternative if not feasible.	NHS_survey_121		
NHS_16	Orange Walk	Rio Bravo Conservation and Management Area (Hillbank Station)	Reference monitoring of water level and quality in undisturbed area	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby - possibly wells serving the Hillbank field station.		
NHS_17	Belize	Lemonal	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby -		

Monitoring location reference	District	Settlement	Purpose	Type	Primary choice existing well (purpose, construction and status)	Primary choice existing well (depth of well (m))	Notes	Primary choice existing well from NHS survey (NHS survey reference)	Alternative existing well option from NHS survey	Alternative existing well option from NHS survey
								note BWS has a well in Lemonal.		
NHS_18	Orange Walk	in vicinity of Honey Camp National Park	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby.		
NHS_19	Corozal	Progresso	General monitoring of water level and quality	Manual station	RWS/Drilled/Active	not recorded	Primary choice is active RWS well, use alternative if not feasible.	NHS_survey_162	NHS_survey_170	NHS_survey_166
NHS_20	Corozal	Copper Bank	Monitoring groundwater salinity in coastal areas	Automatic station	Domestic/Open Well/Active	7.74		NHS_survey_98	NHS_survey_93	NHS_survey_92
NHS_21	Corozal	Little Belize	General monitoring of water level and quality	Manual station	#N/A	#N/A		No wells in survey - need to identify suitable well nearby.		
NHS_22	Corozal	Sarteneja	Monitoring groundwater salinity in coastal areas	Automatic station	Domestic/Open Well/Active	2.07		NHS_survey_342	NHS_survey_344	NHS_survey_345
NHS_23	Belize	Bomba	Monitoring groundwater salinity in coastal areas	Automatic station	RWS/Drilled/Status not recorded	10.9	Primary choice is unused RWS well.	NHS_survey_17	NHS_survey_23	NHS_survey_22
NHS_24	Corozal	Consejo	Monitoring groundwater salinity in coastal areas	Automatic station	Domestic/Open Well/Active	3.17	Note primary and secondary choices are recorded as saltwater, may need to find more appropriate well.	NHS_survey_89	NHS_survey_88	
NHS_25	Belize	Rockstone Pond	Monitoring groundwater salinity in coastal areas	Automatic station	RWS/Drilled/Active	not recorded	Primary choice is active RWS well, identify alternative if not feasible.	NHS_survey_177		

Drilling and commissioning of new observation boreholes is expensive and represent a large sunk cost if in future the location of the observation well is found to be sub-optimal. Therefore, the use of existing wells for monitoring water levels is recommended at this stage. In future, once several years of data have been collected and evaluated, a case for investing in new monitoring boreholes may be stronger. Other potentially suitable wells may exist which are not in the NHS survey data. The Ministry of Agriculture's BAIMS database of farms indicates many farms which utilise wells as their water source (although not the specific location of the wells themselves), and this may be a basis to target additional areas for well surveys in the future.

The criteria for selecting an existing well to be part of the monitoring system include the following:

Essential criteria for manual stations

1. The well is accessible (physically/legally) and is likely to remain so;
2. The risk of vandalism, damage or other unplanned alterations to the well are low (for example dumping of garbage);
3. The owner of the well is willing to agree periodic access by NHS staff for monitoring activities (periodic water quality sampling/checking of probes and loggers);
4. The owner of the well is willing to take periodic water level readings or permit a nominated person to do so;
5. The well is suitable for water quality sampling (i.e. good contact between the well screening and the surrounding aquifer and ability to purge the well for sampling);
6. The well suitable for water level monitoring, i.e. can it reliably be manually dipped to obtain water depth measurements;
7. The groundwater table is likely to remain above the base of the well during periods of extended drought? – wells not at risk of drying out.

Additional essential criteria for automatic stations

8. The risk of vandalism or theft of equipment is manageable, and any protection measures can be installed (such as fences and signage);
9. The well is suitable for water level monitoring, i.e. can a probe be easily installed and removed without disrupting well operations, in the case of drilled boreholes.

Further considerations

10. Is the well nearby any potential sources of pollution/contamination which are not representative of the aquifer in general (e.g. proximity to soakaways/land fill etc), unless these are a specific monitoring objective?
11. Is the well nearby any significant groundwater abstractions which may impact on groundwater level measurements? – unless cone of depression of abstraction well needs to be determined;
12. Are the well construction and performance details known (geology, well screen, yield)?

5.1.1 Prioritisation of existing wells for use as monitoring stations

The NHS has surveyed 388 existing wells in the northern part of Belize (Williams, 2022). For each well the following data were collected:

1. District;
2. Village name;
3. Coordinates;
4. Construction (Drilled/Open/Standpipe (assumed standpipes are also drilled));
5. Depth to water (m) (from top of well casing);
6. Well casing height (m) (from surrounding ground level);
7. Water table (m) (depth to water from surrounding ground level);

8. Depth of well (m);
9. Water column (m) (depth of water in well);
10. Diameter of well (m);
11. Elevation (m above datum) (measured using handheld GPS);
12. Well purpose (Standpipe/Domestic/Agricultural/RWS);
13. Status (Active/Inactive);
14. Comments (general comments on state of repair, water quality and reliability of well yield).

While the above does not provide all the information required for selecting wells to be part of the monitoring system, it does provide a basis for an initial prioritisation exercise on the suitability of different types of wells for manual and automatic monitoring.

Different types of well represent different challenges and opportunities for monitoring. Note also the comments provide further observations of relevance for selecting wells, for example if wells are reliable in drought and whether they are in a poor state of repair or contain garbage and other objects.

RWS wells

These are drilled boreholes used for Rudimentary Water Systems and have been classified into active and inactive.

Inactive RWS boreholes may be suitable for long term monitoring if they are in good condition and are not likely to be recommissioned. The reason for their abandonment should be investigated to ensure it does not impact on suitability.

Eight inactive RWS boreholes are listed in the data:

- Carmelita (depth 18.25 m);
- Nuevo San Juan/Douglas (depth 27 m);
- August Pine Ridge (depth 23 m);
- Bomba (2 wells, one depth 4.8 m the other 10.9 m);
- San Estevan (depth not known);
- Libertad (depth not known);
- Santana (unclear if active or inactive, depth not known).

Active RWS wells may be suitable for manual or automated stations. However, care will need to be taken that they can be dipped, loggers installed and sampled without interfering with production. Care will also need to be taken to allow the well to recover when manually dipping. Thirty four (34) active RWS wells are within the survey.

Standpipes

These are drilled boreholes, typically drilled by the Dept. of Rural Transformation. Fifty nine (59) are listed as inactive, and 28 as active.

Inactive standpipes may be suitable for monitoring if the pump can be removed, and the well head converted for manual or automatic logger deployment. However, the depth and condition of these wells would need to be determined, and it would need to be confirmed that there are no plans to recommission the standpipe as a water source.

Active standpipes are unlikely to be suitable as the pump will preclude the ability to dip or install loggers.

Domestic wells

Of the 207 domestic wells, 180 are open, 6 drilled and 21 are not recorded. One hundred twenty nine (129) of the wells are active, 57 inactive and 21 not recorded. The majority of domestic wells are relatively shallow compared to drilled boreholes, and therefore they may represent a smaller depth of the aquifer than deeper boreholes (depending on screen arrangements). Shallow wells may, depending on the location, be more prone to drying out than deeper drilled boreholes.

Active open domestic wells may be suitable for both community led monitoring as long as the well can be dipped and samples taken readily and are not affected by the use of the well. These wells could also potentially be used for automatic logging, however, stilling tubes within the wells would be required to minimise disturbance.

Inactive wells could potentially be used for monitoring, however, there is a risk that these wells are in poor state of repair and may require rehabilitation and additional maintenance and supervision to avoid deterioration.

Agricultural wells

Only 16 of the wells in the survey are listed as agricultural.

There are three inactive agricultural wells, one of which is an inactive drilled BSI well at Guinea Grass with a depth of 46.07 m, which may be a useful monitoring station if agreement can be reached with BSI. The other two inactive wells are open wells in San Felipe where it is noted that the well caved in during excavation.

Of the 13 active agricultural wells, 7 are relatively shallow open wells which are likely to have similar characteristics to the domestic open wells above, 2 are drilled wells, and 4 of unknown construction. Unclear whether these offer a significant monitoring opportunity.

Based on the discussion above, the surveyed wells have been categorised into five classes based on their likely suitability for monitoring and summarised in the Table 5.2.

Table 5.2: Summary of well survey prioritisation

Class	Number of wells in class	Description
1	9	Inactive RWS wells and inactive BSI well at Guinea Grass. Drilled boreholes which may be suitable for both automatic and manual monitoring if in good condition and can be adopted for monitoring.
2	60	Wells marked as reliable in the survey comments (these are wells which the owners indicate have never dried out), they are almost all open domestic active wells. These may be suitable for manual dipping, or automatic monitoring if stilling tubes can be installed to protect loggers and the wells are suitable and agreement can be reached.
3	79	Inactive standpipes (drilled boreholes). These maybe suitable for automatic or manual monitoring if the pump can be removed (practically and supported by the community) and the well adapted for monitoring purposes.
4	34	Active RWS boreholes. Active RWS wells may be suitable for manual or automated stations. However, care will need to be taken that they can be dipped, loggers installed and sampled without interfering with production. Care will also need to be taken to allow the well to recover when manually dipping.
5	207	All other wells, considered a lower priority and less suited to monitoring.

5.2 Groundwater quantity monitoring approach

The selection of monitoring variables, frequency and methods is a balance between the resources invested and the value of the data obtained. This section discusses groundwater level monitoring proposed approach and frequency of sampling.

Groundwater level monitoring may be carried out by manual level reading using dippers or by deploying probes and loggers. The data from the logger is then periodically downloaded or may be transmitted to a central database via a telemetry system. The NHS has experience in manual stage measurement for surface water systems using a network or community observers who are paid a small stipend to record twice daily stage readings and submit them to the NHS. This has been an effective method for surface water data collection to date. The NHS is also currently expanding its capability with respect to groundwater data loggers and is currently in the process of setting up automated monitoring stations, both approaches have their advantages and disadvantages as set out in Table 5.3.

Table 5.3: Monitoring approaches

Manual well dipping	Automatic data logger
Advantages • Proven approach used for surface water monitoring which could be adapted for groundwater • Low capital cost to set up monitoring station once agreement in place and community representative trained in data collection and reporting • Predicable operational costs for data collection	*Advantages* • Frequency of monitoring can be very high (e.g. sub-hourly) if required • Operational costs are only associated with maintenance, data retrieval and checking • Does not require engagement with third parties for data collection
Limitations • Frequency of data collection lower than automatic data logger (weekly reading may be appropriate) • Need to ensure water levels have recovered if using production wells • Ongoing cost to pay for data on an ongoing basis.	*Limitations* • Initial capital cost of loggers and telemetry systems is high • May require costly well rehabilitation and site protection • Risk of theft, vandalism and breakdown of equipment resulting in data gaps and replacement costs • Wells must be suitable for installation of loggers (challenges with using production wells)

The use of both approaches is recommended in order to manage the risks and maximise the benefits of each approach. We have identified seven automatic monitoring stations for areas where salinity monitoring is required and 25 manual stations to provide spatial coverage with lower upfront capital costs.

Once the system has been running for one or two years the costs and benefits of each approach can be reviewed, and the balance of manual and automatic approaches adjusted.

Water level monitoring at automatic stations

For automatic stations an initial period of high frequency monitoring (15 minutes) may be useful to determine if there are any influences on water level from rapidly varying processes such as the operation of nearby boreholes or tidal influences. This could then be lengthened to daily once such processes have been established, depending on the battery life and revisit constraints of the loggers used. At a minimum, automatic monitoring stations will require a level probe (and it is suggested that a combined conductivity, temperature, and pH probe is utilised to maximise economies of scale), with logger and battery pack. Additionally, a telemetry system may be put in place which would send data to a receiver at the NHS office, powered by batteries or solar panels. Telemetry is more expensive, and may require more maintenance effort, but provides real time data for tracking drought events and flagging up issues early, which would only be known on download of data if a logger is used.

Water level monitoring at manual stations

For manual stations a weekly water level reading is likely to be a reasonable balance between resolution and cost. It will be important to ensure that if the well is used for production, the water level has recovered prior to measurement. It is proposed that a well dipper is provided to community observers to collect readings and send these to the NHS via text message or periodic posting of paper records to the NHS.

If a higher frequency of reading is required it may be possible to have community readings taken twice weekly, or even daily for the first year to help understand the response time of groundwater levels to precipitation events and determine the most appropriate monitoring frequency moving forward. However, this would incur additional budget for community observers for the first year.

5.3 Groundwater quality monitoring approach

Groundwater quality monitoring can be divided into three categories for the purpose of the proposed monitoring system: field parameters, standard laboratory, and trace laboratory. A recommended set of water quality parameters for each set are provided below:

1. Field parameters: These include temperature (T), pH, specific electrical conductance (SEC), oxidation reduction potential (ORP) and dissolved oxygen (DO) (IGRAC, 2008). These are measured in the field during a site visit to the monitoring location. These are typically measured using single or multi-parameter probes. Some probes also measure other parameters such as nitrate, ammonia and chloride using ion sensitive electrodes[3]. These probes require periodic calibration to maintain accuracy. The following parameters are considered the most straightforward to collect and the most useful for general reference purposes and are recommended for collection at both manual and automatic monitoring stations:

1. Temperature;
2. pH;
3. Specific electrical conductance (SEC).

2. Standard laboratory parameters: These include typical parameters which are routinely measured in Belize for drinking water compliance testing and can be measured in Belizean laboratories. The following are proposed for standard chemical analysis, and are aligned with the parameters analysed by BWSL in drinking water surveillance, with the addition of arsenic as this can be an issue in groundwater sources:

1. Total Alkalinity;
2. Chloride;
3. Fluoride;
4. Iron;
5. Hardness, calcium, magnesium and total;
6. Nitrates;
7. Phosphates;
8. Sulphate;
9. True colour;
10. Turbidity;
11. Ph;
12. Aluminium;
13. Conductivity;

[3] See for example the YSI ProDSS Multiparameter Digital Water Quality Meter https://www.ysi.com/prodss

14. Total dissolved solids;
15. Salinity;
16. Manganese;
17. Chlorine;
18. Arsenic;
19. Copper oxide.

In addition, the following biological parameters are recommended:

1. Total coliforms;
2. Fecal coliforms;
3. E. coli.

These can be analysed within Belize at a number of government and private laboratories.

3. Trace laboratory parameters: These include pesticides and similar trace compounds which are not typically monitored as part of drinking water surveillance. The Belize Pesticide Control Board have identified the following chemicals of interest, which are proposed for inclusion in the trace water quality analysis parameter set:

1. 2,4-D;
2. Ametryn;
3. Asulam;
4. Atrazine;
5. Chlorothalonil;
6. Chlorpyrifos;
7. Copper Oxide;
8. Diazinon;
9. Diuron;
10. Fenpropimorph;
11. Glyphosate;
12. Malathion;
13. Mancozeb;
14. Nicosulfuron;
15. Paraquat;
16. Paraquat Dicloride (Tehnical);
17. Pendimethalin;
18. Propanil;
19. Propineb;
20. Pyrimethanil;
21. Terbutryn;
22. Thiram;
23. Triflumuron.

It is understood that the University of Belize has recently upgraded its laboratory facilities, with the opening in January 2023 of the Hummingbird Laboratory, which has the facility for pesticide testing. This may offer an alternative to the requirement to ship samples to the US for testing.

Water quality monitoring programme for manual stations

At manual monitoring stations, it is proposed that the three priority field parameters are recorded on a weekly basis by community observers with the use of handheld meters at the same time as they are collecting water level readings. This will provide a weekly dataset of water level, temperature, pH, and conductivity. Community observers will require basic training in maintaining the meters and their calibration. In practical terms it is recommended that the approach for water level monitoring is used as the basis for community members recording and sending in readings on a periodic basis.

It is recommended that a quarterly site visit by NHS staff is carried out to undertake the following activities:

1. Measure field parameters in order to verify readings from community held meters.
2. Take water quality samples for standard laboratory analysis. Note that quarterly measurement is recommended initially, this may be adjusted depending on the results at each location.
3. Inspect the well and water monitoring equipment to ensure that it is fit for purpose and log any issues to be addressed.
4. Pesticide sample collection is recommended for five monitoring stations in total (both manual and automatic) per year in order to manage costs. If concerning concentrations of pesticides are detected the frequency of sampling may be adjusted in future.

Water quality monitoring programme for automatic stations

At automatic water level monitoring sites, multiparameter probes are recommended to collect high resolution data for field parameters. The most common multiparameter probes measure level, temperature and conductivity which would be reasonable in this context. These can be set to collect data at 15-minute intervals for the first year to capture any high resolution changes in these parameters associated with tidal influences or nearby production boreholes. These will require periodic inspection and calibration in line with the manufacturer's specifications.

It is recommended that a quarterly site visit by NHS staff is carried out to undertake the following activities:

1. Measure field parameters in order to verify readings from probes deployed in the well (note that pH is not recommended for automatic monitoring stations as it will not add sufficient value for the additional cost and calibration requirements).
2. Take water quality samples for laboratory analysis (both standard and trace parameters). Note that quarterly measurement is recommended initially, this may be adjusted depending on the results at each location.
3. Inspect the well and water monitoring equipment to ensure that it is fit for purpose and log any issues to be addressed.
4. Pesticide sample collection is recommended for five monitoring stations in total (both manual and automatic) per year in order to manage costs. If concerning concentrations of pesticides are detected the frequency of sampling may be adjusted in future.

5.4 Summary of monitoring system regime

Table 5.4 below provides an overall summary of the characteristics of the proposed monitoring system and sampling regime.

Table 5.4: Summary of monitoring system

Monitoring site type	Number of monitoring sites	NHS Site visit to monitoring station	Water level monitoring method	Field parameter monitoring method	Standard water quality laboratory analysis	Trace chemicals water quality laboratory analysis
Manual	20	Quarterly (year 1) then review. Inspect well. Collect well level and field parameters using handheld meter. Take water quality sample.	Weekly. Community representative collects water depth data using well dipper.	Weekly Community representative collects temperature, conductivity and pH data using handheld meter	Quarterly (year 1) then review. Sample collected by NHS during site visit.	Five sites sampled per year. Sample collected by NHS during site visit. Adjust sampling depending on findings.
Automatic	7	Quarterly (year 1) then review. Inspect well. Collect well level and field parameters using handheld meter. Take water quality sample.	15 minute (year 1), then review. Water level, temperature and conductivity probe with logger.		Quarterly (year 1) then review. Sample collected by NHS during site visit.	

5.5 Data collection, management and dissemination

5.5.1 Data collection

The fieldwork task of data collection is usually performed by technicians who have received special training in the use of the equipment (IGRAC, 2008). Information management can work well only if the necessary human resources and logistic support are in place. This requires training for users and budgetary support for operation and maintenance of data collection systems, IT, and software services (Ravenscroft and Lytton. 2022).

Groundwater levels are measured manually using a dipper or automatically by a pressure transducer. Automatic readings may be stored in a datalogger that is visited periodically and downloaded by field staff or sent automatically over the phone network to a database in a data centre (telemetry) (BGS, 2023). Manual readings can be sent through text messages, postal forms, open-source documents or existing methods already available in other manual measurements (e.g. river flow/stage).

In terms of how data can be collected and tested:

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 field testing for public health surveillance when high precision is not required, so only one or two parameters need to be tested quickly.

For manual stations the following monitoring equipment is required:

Water level meter, typically a dipper on a reel with an electronic buzzer which sounds when the dipper reaches the water level. These will be held and operated by both the community observers and the NHS technicians. They should, therefore, be simple to use and robust. For simplicity, it is recommended to issue the same model to community observers as NHS technicians.

Handheld water quality meter for temperature, pH, and conductivity. These will be held and operated by both the community observers and the NHS technicians. They should, therefore, be simple to use and robust. A variety of manufacturers and models are available at a wide range of costs. A balance must be struck between the cost of the units and their reliability, using well known and regarded manufacturers.

NHS technicians will also require a robust submersible pump, controller, and power source, in order to purge and sample wells for laboratory samples.

For automatic stations the following monitoring equipment is required:

Water level and conductivity probes (or single multi parameter probe), data logger, power source and telemetry (optional). Key factors to consider are compatibility with existing equipment, cost, robustness and ease of maintenance and security (to minimise vandalism risk). The NHS are presently aiming to standardise equipment using Campbell Scientific. The NHS has also reported issues of corrosion of probes used in the past, possibly as a result of deployment in saline conditions. Care must be taken to ensure that probes and loggers are resistant to high temperature, high humidity, and saline groundwater conditions. Most probes are constructed with stainless steel bodies, 904 grade stainless steel offers greater corrosion resistance than 316 grade. Some probes are also constructed with titanium or ceramic bodies, which may provide additional corrosion resistance.

Automatic monitoring systems are typically designed to be installed in drilled boreholes. The simplest situation is a drilled borehole with a simple well cap. The presence of pumps and the arrangement of any head works on the borehole will impact on the effect the installation of such equipment and care must be taken to avoid damaging or losing the monitoring equipment or pumps.

In situations where open wells are being used for monitoring, a stilling well will likely be required to protect the monitoring equipment and to provide a stable environment for mounting the equipment.

Protection of the site to minimise the risk of theft and vandalism are important considerations. Selecting secure private premises can offer some level of protection, as can the installation of security fences and appropriate signage.

5.5.2 Data management

A variety of software systems and approaches for data management are available for managing groundwater data. These range from bespoke database systems developed specifically for an organisation to proprietary software such as Water Information Systems by KISTERS (WISKI) or AQUARIUS Water Data Management Software by OTT. In its simplest form data management can utilise spreadsheet systems such as Microsoft Excel. Although Excel is widely used and available, it is not designed for proper quality assurance and data version control.

WISKI is currently in use at the NHS. WISKI is a software for managing, analysing and reporting surface water, groundwater, water quality, wastewater, drinking water and meteorological data, including forecast and warning (https://www.kisters.com.au/wiski.html). WISKI is specifically designed for hydrological data management and facilitates quality assurance of incoming data through validation and flagging and provides an audit trail for changes to data.

It is understood that WISKI licences are being shared between the NHS and Department of Environment, to share costs and maximise efficiencies. Also, in place is the setting up of administrator and user profiles across the agencies such that the access to and ability to edit NHS datasets is appropriately managed. Consideration should also be given to backup copies of data in the event of system failure or accidental deletion.

Beyond the functionality provided by WISKI, a variety of other software for exploring and analysing groundwater data exist, notably open source software, such as R (https://www.r-project.org/) or Python (https://www.python.org/), are potent tools with many available packages for data management, specifically used for hydrological and groundwater modelling and statistical analysis. However, these tools do require some level of programming skills in order to use with confidence.

5.5.3 Data dissemination

Use of the data within the NHS as part of strategic planning and decision making to support and advise government on the sustainable development of water resources at a national level will be a key benefit of the monitoring system. However, dissemination of data to third parties to inform decision making and raise awareness of water related issues is pivotal to realise the benefits of data collection. Examples of dissemination channels include:

- Regular briefings to government agencies and the public on the status of groundwater, for example to highlight drought impacts or inform other water dependent sectors such as agriculture.
- Access to raw data by government departments, researchers, and private companies/individuals for use in their own studies and plans.

How data and information are communicated to the public (e.g. website, reports, free downloading of data) is vital to highlight the importance of groundwater management. Data can also be disseminated by request (free or at a cost). Depending on the end user, data should be published in the most appropriate and useful way. Certain ministries or agencies might need metadata for further investigation whilst other ministries might need to disseminate these data as, for example, reports or bulletins with certain frequency (monthly, seasonally, annually).

Data can be also used to produce early warning systems and to create indices that highlight certain conditions (e.g. drought early warning system; flood alerts, etc). This will also depend on end users and what departments or ministries are disseminating the data and for what purpose.

At a minimum, a regular public briefing is recommended twice per year to present the recent trends in groundwater levels at a set of representative monitoring stations, and when sufficient historical data becomes available, to set this within the context of recent years. This could be presented simply as a map of stations indicating groundwater status as above normal, normal or below normal for that time of year. An example of a hydrological summary for the UK can be found here (https://nrfa.ceh.ac.uk/monthly-hydrological-summary-uk). The resources available in Belize for dissemination activities are obviously substantially less than in the UK, hence the scope of such dissemination would be reduced accordingly. One challenge with dissemination, is that it is viewed as a lower priority than data collection and therefore is frequently dropped where resources are limited and focused on solving data collection issues. The frequency of these updates could be increased during periods of drought where a closer interest in groundwater management is required.

5.6 Staffing and operational considerations

Trained technicians will be needed for installing and running the groundwater monitoring system, data collection and maintenance of the system. Based on the specifications of the monitoring system described above with 7 automated stations and 25 manual stations, two technicians dedicated to groundwater data collection will likely be required. Once the system is up and running with community observers who are familiar with data collection procedures and automatic monitoring stations working reliably then the fine tuning of ongoing staffing requirements can be carried out. These technicians will need transportation, communication devices, personal protective equipment, field monitoring equipment and tools necessary for basic system maintenance.

In order to quality assure (QA) incoming data, store and manage it in the WISKI database, support will be required from the hydrological analyst within NHS, who will either need to review and QA data entered by technicians, or QA and enter data into WISKI themselves. In order to utilise the data, for example for hydrogeological interpretation or production of derived products, either external support from a Consultant Hydrogeologist would be required, or recruitment of a Hydrogeologist into the NHS. The former option may be more appropriate in the first year or two of the system operation, moving to the latter when more data is available for interpretation and analysis.

6 Implementation plan

This section sets out the timeline of actions required in order to implement the monitoring plan from the point of budget approval to the point where groundwater data collection, storage and dissemination is an ongoing regular process. A Gantt chart showing the timing of each activity is provided in Figure 6.1 and Figure 6.2 and is provided electronically in Appendix C.

Year 1 of implementation focuses on setting up the data collection and management processes, with the aim of generating useful groundwater datasets from the majority of proposed monitoring sites by the end of the year. Setting up manual and automatic monitoring sites has been scheduled to run in parallel. If this is not possible due to resource constraints, then this could be balanced by either focusing on manual or automatic sites in year 1 and moving the other to year 2. Another option is to reduce the number of manual sites in year 1 to ten or fewer and using the experience to inform rolling out the approach to the full number of manual sites in year 2.

Year 2 focuses on data collection and consolidation of the monitoring network with an external review at the close of the year to take stock of the data collected, review the data collection and management protocols and adjust as necessary.

Year 3 again focuses on ongoing data collection with a consolidated monitoring network with the aim of maintaining continuity of records from the monitoring sites in order to monitor status and long term trends in groundwater level and quality, and to monitor the evolution of seasonal events such as droughts.

	Year 1											
Activity	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Staffing and logistics												
Recruit monitoring technician	■	■	■									
Purchase vehicle for site visits and computer equipment for technician	■	■										
Prepare monitoring sites												
Finalise monitoring sites and prepare a well information sheet for each monitoring well	■	■	■									
Prepare and execute access agreements with well owners.			■	■	■	■						
Identify and undertake rehabilitation works for monitoring wells as necessary						■	■	■	■			
Purchase monitoring equipment												
Purchase groundwater monitoring equipment						■	■					
Purchase database management software and develop protocols												
Purchase groundwater database management system			■									
Develop protocols for quality assurance (QA) and storage of automatic and manually collected monitoring data				■	■							
Develop protocols for periodic reporting of groundwater data (internally within NHS and externally)					■	■						
Commission manual monitoring sites												
Develop protocols and training material for community observers in data collection and sending data to the NHS							■					
Provide monitoring equipment and training to community observers at manual monitoring sites								■	■	■	■	■
Commission automatic monitoring sites												
Install monitoring equipment at automatic monitoring stations, test and validate data.								■	■			
Develop protocols for ongoing data collection and maintenance for automatic monitoring stations									■	■		
Ongoing data collection activities												
Community observers provide groundwater data (water level and conductivity) to NHS in line with protocols												
Data downloaded from data loggers at automatic stations on a regular basis, including field visit and inspection of equipment												
Water quality sampling as per schedule and agreed variables												
Data QA and entry into database												
Annual summary report of data collection activities												
Annual review												
External review once at least six months of data has been collected from the majority of monitoring sites. Review to example quality and relevance of data collected, and make recommendations on adjustments to number and location of sites, monitoring methods and data collection and management processes.												

Figure 6.1: Implementation plan – Year 1

Activity	Year 2				Year 3			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Staffing and logistics								
Recruit monitoring technician								
Purchase vehicle for site visits and computer equipment for technician								
Prepare monitoring sites								
Finalise monitoring sites and prepare a well information sheet for each monitoring well								
Prepare and execute access agreements with well owners.								
Identify and undertake rehabilitation works for monitoring wells as necessary								
Purchase monitoring equipment								
Purchase groundwater monitoring equipment								
Purchase database management software and develop protocols								
Purchase groundwater database management system								
Develop protocols for quality assurance (QA) and storage of automatic and manually collected monitoring data								
Develop protocols for periodic reporting of groundwater data (internally within NHS and externally)								
Commission manual monitoring sites								
Develop protocols and training material for community observers in data collection and sending data to the NHS								
Provide monitoring equipment and training to community observers at manual monitoring sites								
Commission automatic monitoring sites								
Install monitoring equipment at automatic monitoring stations, test and validate data.								
Develop protocols for ongoing data collection and maintenance for automatic monitoring stations								
Ongoing data collection activities								
Community observers provide groundwater data (water level and conductivity) to NHS in line with protocols								
Data downloaded from data loggers at automatic stations on a regular basis, including field visit and inspection of equipment								
Water quality sampling as per schedule and agreed variables								
Data QA and entry into database								
Annual summary report of data collection activities								
Annual review								
External review once at least six months of data has been collected from the majority of monitoring sites. Review to example quality and relevance of data collected, and make recommendations on adjustments to number and location of sites, monitoring methods and data collection and management processes.								

Figure 6.2: Implementation plan – Year 2/3

7 Costs for system set up and operation

Accurate groundwater resource monitoring is essential for a better understanding of aquifer dynamics and for creating robust climate change adaption strategies. An overview of the expenses related to installing and maintaining a groundwater monitoring system in Belize is given in this section. Using this information, stakeholders can more effectively plan and allocate resources of the necessary setup costs and ongoing operating costs.

7.1 Set up Costs

7.1.1 Equipment

The initial setup requires the procurement of essential equipment such as groundwater level monitoring devices,, data loggers, and associated installation materials. As stated in previous sections the recommendation is to have a minimum of twenty (20) manually monitored sites and seven (7) automatically monitored sites.

For the manually gauged stations, residents of the respective area will be commissioned to take and record readings using supplied equipment. The main pieces of equipment to be used are:

- Manual Well Dipper - used to measure the static water level in the well.
- Bailer - to collect water sample.
- Water quality probe meter – used to measure basic water quality parameters such as pH.
- Conductivity and Temperature.

As it relates to the automatic stations, the equipment list will comprise the following:

- Water level, conductivity and temperature probes, logger and telemetry equipment. It is understood that NHS prefer the use of Campbell Scientific as a supplier of equipment in order to ensure consistency across monitoring assets.

Equipment needs for NHS technicians will include:

- Portable submersible pump (~ 1 Hp).
- Portable electric power supply.
- Manual Well Dipper - used to measure the static water level in the well.
- Bailer: to collect water sample.
- Water quality probe meter – used to measure basic water quality parameters such as pH.
- Conductivity and Temperature.
- Pickup truck (4WD) to transport personnel and equipment to each site.

7.1.2 Site Preparation

Preparing the monitoring sites involves completing basic well information sheets for each location (see for example Appendix A), putting in place access and maintenance agreements with landowners. Minor works may be required to ensure proper well construction and retrofitting well heads to facilitate both manual and automatic measurement procedures and installing piezometers at automatic monitoring sites.

The drilling of new monitoring boreholes is not recommended due to its high initial cost and should only be utilised if no alternative existing boreholes are available in any critical data collection area. Other aspects of site preparation include checking the accessibility to the site – will there be a need to clear pathways (pedestrian, vehicular) in heavily vegetated areas.

7.1.3 Data Management Infrastructure

To effectively collect, store, and analyse groundwater data, an appropriate data management infrastructure is required. This may involve investing in a centralized database, secure servers, software licenses, and hardware components. Additionally, costs related to data validation, quality control, and backup systems should be considered. Currently, the NHS utilises a data management software (WISKI). The unit may also require an additional desktop computer dedicated for this groundwater monitoring initiative.

7.2 Operational Cost

7.2.1 Monitoring Personnel

Personnel are essential for the regular maintenance and operation of the groundwater monitoring system. For manually read system, the project has considered stipends for community observers and where necessary an access agreement fee for private property owners. The NHS also requires skilled technicians to conduct field visits, calibrate instruments, retrieve, and analyse data, and maintain the overall functionality of the system. The operational costs include salaries, training, and transportation allowances. For the purposes of this groundwater monitoring initiative, it is important that at least two (2) additional personnel are recruited by the NHS with backgrounds in hydrogeology and/or hydrometry.

7.2.2 Maintenance and Calibration

Regular maintenance, calibration, repair, and replacement of monitoring equipment are crucial to ensure accurate and reliable data. Budgets should be allocated for periodic servicing, instrument calibration, spare parts, and replacement if necessary. In the table, these annual costs are calculated as the depreciated value for the service life – which is usually 3 to 5 years. Annual fees for site maintenance are also included. This includes vegetation clearing and minor repairs to well head mechanisms.

7.2.3 Data Collection and Analysis

The collected data needs to be processed, analysed, and interpreted for meaningful insights and decision-making. This will involve periodically going out in the field to collect and verify data points. It is anticipated that field visits will be conducted on a quarterly basis to all sites (manual and automatic). These visits will require finances to cover the cost of hotel accommodations, fuel, per diem, vehicle maintenance as well as insurance and licencing.

7.3 Summary of costs

Summaries of both capital and operational costs for the proposed groundwater monitoring system are shown in Table 7.1 and Table 7.2. The costing spreadsheet is provided electronically as Appendix D to this report and provides an editable version for any fine tuning of budgets required in future.

Table 7.1: Capital costs for the monitoring system

Cost category	Cost (Belize Dollars)
Community managed water level monitoring	$46,350
Automatic water level monitoring	$142,450
Groundwater monitoring equipment for NHS technicians	$39,350
Data management	$12,500
Administrative and logistical	$60,200
Total capital costs	**$300,850**

Table 7.2: Operational costs for the monitoring system

Cost category	Cost (Belize Dollars)
Community managed water level monitoring sites	$31,602
Automatic water level monitoring sites	$50,125
Groundwater monitoring equipment for NHS technicians	$13,403
Groundwater quality laboratory analysis	$70,000
Data management	$30,500
Total operational costs	**$277,197**

8 References

Environment Agency, 2018. The Environment Agency's approach to groundwater protection.

GW-MATE. 2006. Sustainable Groundwater Management: Concepts and Tools GW-MATE Briefing Note Series. Note 9. Groundwater Monitoring Requirements for managing aquifer response and quality threats.

IGRAC, 2020. Groundwater monitoring programmes: A global overview of quantitative groundwater monitoring networks.

Johns, H., Ozdemiroglu, E., 2007. Assessing the Value of Groundwater - Environment Agency.

Kim, S.G., Kim, G.B., 2019. Are groundwater monitoring networks economical? Cost-benefit analysis on the long-term groundwater supply project of South Korea. Water (Switzerland) 11. https://doi.org/10.3390/w11040753.

Rau, G.C., Cuthbert, M.O., Post, V.E.A., Schweizer, D., Acworth, & R.I., Andersen, M.S., Blum, P., Carrara, E., Rasmussen, T.C., Ge, S., 2020. Future-proofing hydrogeology by revising groundwater monitoring practice Assurer l'avenir de l'hydrogéologie en révisant les pratiques de suivi des eaux souterraines La hidrogeología del futuro por medio de la revisión de la práctica de monitoreo de las agu 2963–2969.

Ravenscroft, Peter and Lytton, Lucy (2022), 'Practical Manual on Groundwater Quality Monitoring'. World Bank, Washington, DC.

Taylor, C.J., Alley, W.M., 2001. Ground-water-level monitoring and the importance of long-term water-level data. US Geol. Surv. Circ. 1–68.

Williams, R. 2022. Analysis Of Collected Groundwater Data For The Creation Of A Small-Scale Regional Groundwater Hydrological Monitoring Network In The Northern Districts Of Belize. GWP Caribbean (GWP-C), National Hydrological Service, Ministry of Natural Resources, Petroleum and Mining.

Appendices

A Monitoring well information sheet template

An example of a well information sheet template is provided below. This could be adapted and completed for each of the identified monitoring wells (both automatic and manual stations).

Community Groundwater Level Monitoring **Well Information Sheet**

Well Name: ____________ **Well Tag No.:** ____________

Completed By: ____________ **Date:** ________ **Well Log ID No.:** ____________

Well Location:

Well Address: ____________

Directions to Well: ____________

County: ____________

Tax Lot No.: ____________

Township: ________ N or S

Range: ________ E or W

Section: ________

Please draw a sketch of the well location here:

N

Please enter the GPS location for the well, if available.

Degrees / Minutes / Seconds

Latitude (N) ° ' "

Longitude (W) ° ' "

Decimal Degrees

Latitude (N)

Longitude (W)

Please attach map showing well location and photo(s) of the well, if available

Map: ☐ Tax Lot ☐ Google Earth ☐ USGS Quad (1:24,000) ☐ Other ____________

Please attach photo(s) of the well, if available

Well Use and History:

Use: ☐ Unused ☐ Domestic ☐ Irrigation ☐ Industrial ☐ Community ☐ Other ____________

Pump Type: ☐ None ☐ Submersible ☐ Turbine ☐ Other ____________

Pump Depth: ________ Well Depth: ________ Casing Diameter: ________

Enter all well logs connected to the well (include well logs for deepenings, reconditionings, or other well alterations).

Well Log Number	Well Log Type	Date Well Completed	Owner Name on Well Log

Property/Well Owner:

Name: ____________ Phone (H): ____________

Address: ____________ Phone (W): ____________

City / State / Zip: ____________ Phone Cell: ____________

Email: ____________

Oregon Water Resources Department 725 Summer Street NE, Suite A - Salem, OR 97301

B Well survey spreadsheet

See attached Excel spreadsheet containing proposed monitoring locations and existing well survey data.

C Implementation Plan Gantt chart

See attached Excel spreadsheet containing Implementation Plan Gantt chart.

D Costing estimates

See attached Excel spreadsheet containing cost estimates and build up.

hr wallingford

We design smarter, more resilient solutions across both the natural and built environment to help everyone live and work more sustainably with water.

HR Wallingford
Howbery Park
Wallingford
Oxfordshire OX10 8BA
United Kingdom

+44 (0)1491 835381

info@hrwallingford.com

www.hrwallingford.com