GUIDANCE DOCUMENT ON GROUNDWATER DATA COLLECTION: FINAL DOCUMENT

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Ministry of Environment of Denmark
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WATER RESEARCH COMMISSION

TT 905/22

Guidance Document on Groundwater Data Collection

Report to the
Water Research Commission

by

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EXECUTIVE SUMMARY

Groundwater resources support many urban and rural communities within South Africa. To protect and ensure the sustainability of this resource, groundwater management approaches rely on effective data collection, collation, quality control, storage and management.

The guidance document provides individuals from all spheres, including government, consultancies, universities and communities, as well as stakeholders and citizen scientists, with the necessary tools to undertake accurate monitoring, where data is collected using the correct field procedures, captured consistently, quality controlled and stored appropriately for further interpretation and analysis.

The guidance document presents a set of standard procedures for all aspects of groundwater data collection, with an emphasis on groundwater monitoring (groundwater level, groundwater quality and groundwater abstraction) and groundwater development (well drilling and test-pumping).

The document emphasises the following:

- Important groundwater data that should be collected during groundwater level, groundwater quality, groundwater abstraction and spring monitoring.
- Groundwater monitoring is undertaken according to international best practice.
- Important groundwater-related data that should be collected during well drilling and test pumping.
- Steps to follow whilst recording, processing and storing data to ensure accuracy and usability.
- Importance of quality assurance and quality control processes which should be implemented when recording, processing and storing data.
- Recommendations on available data management systems for all types and scales of users.

The data collection procedures presented should be used in conjunction with additional available guidance documents on groundwater monitoring, collection and management, as mentioned in **Chapter 1.** Groundwater monitoring should be carried out on a regular basis to ensure sustainable use and management of the groundwater resource. A uniform, accurate and reliable set of procedures will ensure that data is collected to a known standard and is therefore comparable to other datasets.

Currently there are no guidelines for groundwater abstraction monitoring, and therefore this document outlines the best practice methods for effective groundwater abstraction monitoring. The document aims to educate groundwater users on the importance of groundwater monitoring which will lead to improved accuracy of groundwater data and therefore the management of the resource.

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ACRONYMS & ABBREVIATIONS

ºC	Degrees Celsius
CAPWV	Capillary bound fluid volume
CBWV	Clay bound fluid volume
CEC	Contaminants of emerging concern
COC	Chain of Custody
CoCT	City of Cape Town
bMR	Borehole Magnetic Resonance Response
DEM	Digital Elevation Model
DIS	Discrete Interval Sampler
DMS	Degrees, minutes and seconds
DO	Dissolved Oxygen
DSM	Digital Surface Model
DTM	Digital Terrain Model
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EC	Electrical conductivity
Eh	Oxidation-reduction potential
etc.	etcetera
ETL	Extract, Transform and Load
FAIR	Findability, Accessibility, Interoperability, and Reusability
FFV	Free fluid volume

GB	Giga Byte
GGIS	Global Groundwater Information System
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GRIP	Groundwater Resource Information Project
GRS	Geohydrological Report System
HGA	Hydro GeoAnalyst
IGRAC	International Groundwater Resources Assessment Centre
IGS	Institute for Groundwater Studies
InSAR	Interferometric Synthetic Aperture Radar
l/s	Litres per second
m	Metre
m^3	Metres cubed
m/day	Metres per day
magl	Metres above ground level
mamsl	Metres above mean sea level
mbd	Metres below datum
mbgl	Metres below ground level
meq/l	Milliequivalents per litre
Mg/l	Milligrams per litre
ml	Millilitre
mm	Millimetre
mS/m	Millisiemens per metre

MS	Microsoft
mV	Millivolt
NDVI	Normalised Difference Vegetation Index
NGA	The National Groundwater Archive
NIWIS	National Integrated Water Information System
NWA	National Water Act
pH	Potential of Hydrogen
ppm	Parts per million
QA	Quality Assurance
QC	Quality Control
QGIS	Quantum Geographic Information System
Q&M	Operation and Maintenance
REDOX	Oxidation-Reduction Reaction
RQD	Rock Quality Designation
SABS	South African Bureau of Standards
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community Groundwater Management Institute
SANAS	South African National Accreditation System
SANS	South African National Standard
SAR	Synthetic Aperture Radar
SAWQG	South African Water Quality Guidelines
SQL	Structured Query Language

TB	Terra Byte
TMWSA	Table Mountain Water Source Area
TPOR	Total Porosity
UTM	Universal Transverse Mercator
WARMS	Water use Authorisation and Registration Management System
WDP	Waterpoint Data Transmitter
WGS	World Geodetic System
WSCU	Water Sector Coordination Unit
WMAs	Water Management Areas
WMS	Water Management System
WRC	Water Research Commission
WSA	Water Service Authorities
WUL	Water Use Licence

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

Groundwater is an important water resource in South Africa and is often the primary water source in rural and arid areas. Groundwater accounts for approximately 15% of South Africa's total water use (DWS, 2016a). Due to the growing population and increased climate variability, the resource is increasingly coming under pressure. With the current droughts and future predicted droughts envisioned for South Africa, groundwater has become a crucial resource and has been considered an alternative option for future water supply (Mvandaba et al., 2019). To protect and ensure the sustainability of this resource, there needs ongoing improvements and refinements in the approaches used to manage it. Management of groundwater resources requires regular monitoring and assessment of groundwater characteristics (water level, water quality and quantity), its interaction with other components of the water cycle (rainfall, surface water, etc.), its relationship with socio-economic activities and environmental issues, as well as the legal and institutional setting in which it is governed (SADC-GMI, IGRAC, IGS., 2019). **Appendix A** highlights the challenges identified in South Africa related to groundwater management, monitoring, data collection, data collation, data storage and data management.

The National Water Act (Act No. 36 of 1998) (NWA) stipulates the need for data acquisition and monitoring as part of water resource management. To fully understand the properties and conditions of a groundwater resource, groundwater data is required at all levels and scales, from local users to national government. Groundwater data collection can be divided into two broad categories: groundwater monitoring and groundwater development. Groundwater monitoring consists of groundwater level, quality and abstraction monitoring, whereas groundwater development includes data collected during drilling and test-pumping of wells. These methods of groundwater data collection are discussed in detail in **Chapter 2**.

An important, and often overlooked, part of data management is what to do with the data after it has been collected. For groundwater management decisions to be made, the data needs to be easily accessible and accurate. These factors rely on data processing procedures which include data collation, validation and storage to an appropriate database. The steps undertaken, starting with data processing and ending with data storage, are discussed in detail in **Chapter 3.**

This guidance document summarises existing national standards and guidelines on groundwater data collection and outlines the techniques and processes of groundwater data collection. The techniques and processes are detailed in such a way that they can be applied to all scales of groundwater use and monitoring, and be used by all groundwater stakeholders, from local users to municipal supply schemes. The document outlines the methodology to:

- Collect groundwater data associated with groundwater monitoring and groundwater development.
- Process groundwater data in various formats.
- Develop a framework to store and manage collected groundwater data.

1.2 NATIONAL STANDARDS AND GUIDELINES

As per the National Standards Act (No. 8 of 2008), a standard is defined as a document that provides for common and repeated use, rules and guidelines for products, services, processes and production methods. Documents published by the South African Bureau of Standards (SABS) are called South African National Standard (SANS) documents and vary across various economic sectors. The SANS documents relevant to groundwater data and/or some relatable aspects to groundwater are listed in **Table 1-1**.

Table 1-1 SANS documents relevant to groundwater data.

SABS Document	Description
SANS 10299 Development, maintenance and management of groundwater resources	Outlines the minimum code of practice for well construction and pump-testing. The document details the standards for well siting, design, drilling and construction. The standards related to pump-testing includes the pump-test selection, installation and commissioning of pumping equipment. Furthermore, the document outlines the standards related to rehabilitation, management and decommissioning of a well.
SANS 5667 Water quality – sampling	The document contains the standards for sampling techniques, preservation and handling of different water samples (groundwater, rivers, lakes, effluent and contaminated water). The standard outlines the processes needed to avoid inaccurate results, prevent cross-contamination and ensure the safety of the staff conducting the sampling.
SANS 241 Drinking water	Outlines the minimum acceptable quality of drinking water for health risks with regards to physical, microbiological, chemical and aesthetic determinants.
SANS 10306 The management of potable water in distribution systems	Details the management of water in potable distribution systems with focus on calculation, determination, impacts, mitigation and corrective measures as well as prevention of water losses from a supply system. The approach to management, policy and monitoring systems are also outlined in the document.
SANS 1657 Bottled water of subterranean origin	Deals with the description, testing, treatment, bottling, packaging and labelling of waters that are subterranean in origin, i.e. spring or borehole water.
SANS 1529	Stipulates the characteristics and requirements of mechanical or electronic water meters for flow rate and volume measurement. This pertains to the accurate monitoring of a groundwater scheme.

In addition to the SANS documents, there are a number of international and national guidelines that focus specifically on groundwater data collection which are listed below. This guidance document incorporates their input to ensure that international best practices are employed.

- Water Resource Commission (WRC) (1993). The development of a Strategy to monitor groundwater quality on a national scale. WRC Report, (428/1/93).
- Water Resource Commission (WRC) (2007). Groundwater sampling: a comprehensive guide for sampling methods. Pretoria, South Africa. WRC Report No. TT 733/17
- Water Resource Commission (WRC) (2017). Groundwater Sampling Manual. Pretoria, South Africa. WRC Report No. TT 303/07.
- Department of Water Affairs and Forestry (DWAF) (1997). Minimum standards and guidelines for groundwater resource development for the community water supply and sanitation programme.
- Department of Water Affairs and Forestry (DWAF) (1996). South African Water Quality Guidelines (SAWQG) (second edition). Series:
    1. Domestic Water Use;
    2. Recreational Water Use;
    3. Industrial Water Use;
    4. Agricultural Water Use: Irrigation;
    5. Agricultural Water Use: Livestock Watering;
    6. Agricultural Water Use: Aquaculture Aquatic;
    7. Aquatic Ecosystems; and
    8. Field Guid.
- Southern African Development Community Water Sector Coordination Unit (SADC-WSCU) (2001). Guidelines for the Groundwater Development in the SADC Region. Development of a Code of Good Practice for Groundwater Development in the SADC Region. Bloemfontein, South Africa.
- Southern African Development Community Groundwater Management Institute (SADC-GMI), International Groundwater Resources Assessment Centre (IGRAC), Institute for Groundwater Studies (IGS) (2019). SADC Framework for Groundwater Data Collection and Data Management. SADC-GMI report: Bloemfontein, South Africa.
- European Commission (2007). Guidance on Groundwater Monitoring. Common implementation strategy for the Water Framework Directive (2000/60/EC). Guidance document, (15). Office for Official Publications of the European Communities, Luxembourg.
- International Groundwater Resources Assessment Centre (IGRAC) (2008). Guideline on: Groundwater Monitoring for General Reference Purposes. Utrecht, Netherlands.
- Sundaram B, Feitz A, Caritat P. de Plazinska A, Brodie R, Coram J and Ransley T (2009). Groundwater Sampling and Analysis – A Field Guide. Geoscience Australia, Record 2009/27.
- Ravenscroft, P. and Lytton, L. (2022). Practical Manual on Groundwater Quality Monitoring. World Bank, Washington, DC.

CHAPTER 2: METHODOLOGY OF GROUNDWATER DATA COLLECTION

2.1 GROUNDWATER MONITORING DATA

Groundwater monitoring is defined as the process of collecting time-variant groundwater data such as groundwater levels, groundwater quality and groundwater abstraction data. The monitoring of groundwater levels, quality and abstraction is important to understand trends in resource development and use, and to define effective management interventions (SADC-GMI, IGRAC, IGS., 2019). Regular and continuous monitoring provides the data needed to manage groundwater, and the resource as a whole, sustainably in response to increasing populations and climate change. Data typically collected when conducting groundwater monitoring is outlined in **Table 2-1**.

Table 2-1 Types of data to be collected when conducting groundwater monitoring.

Data	Definition	Water level	Water quality	Abstraction
Site/Station ID	Site/Station ID refers to the unique identification name/code/number that has been assigned to the monitoring site (see **Section 3.1** for further details).	x	x	x
Date and Time	Date and Time is important for collecting time-variant groundwater data and should be captured using a common datetime format: • dd/MM/yyyy hh:mm:ss	x	x	x
Location	Location refers to the position of a well (i.e. borehole, piezometer, well-point), spring, etc. Location data consists of: • Coordinates – latitude and longitude / eastings and northings / x and y • Elevation – elevation recorded in metres above mean sea level (mamsl) / z value.	x	x	x
Site/Station type	Site/Station type refers to the type of station the groundwater is sourced from. The most common groundwater station types are wells, springs and hand-dug wells.	x	x	x
Datum height	The datum is the monitoring point on a well, spring, river, etc. A datum point should clearly be marked to ensure monitoring readings are always taken from the same point. Datum height refers to the height of the datum above or below ground level.	x	x	x

Data	Definition	Water level	Water quality	Abstraction
Groundwater level	Groundwater level is the depth of the water table. Groundwater level can be split into static or dynamic water level. • Static water level – the water level in a well under normal, undisturbed, no pumping conditions. • Dynamic water level – the water level in a well where the water level is changing in response to pumping of the well or nearby wells. Water levels can be measured manually, typically with a dip-meter or automatically with data loggers.	x	x	x
Artesian pressure	Water pressure in an aquifer causes the groundwater level to rise above surface level in the well, daylighting. Artesian pressure is typically measured in bar or kbar. Artesian pressure can be converted to groundwater level by the following relationship ~1 bar = 10 m	x	x	x
Field water quality parameters	Field parameters refers to the basic water quality measurements recorded in the field. These measurements are required to be done on site to preserve sample integrity and to ensure data accuracy. This typically includes: • Water temperature • Electrical conductivity (EC) • pH • Dissolved oxygen • Oxidation-reduction potential (Eh)		x	
Sampling method	Sampling method refers to the technique used to sample the well. Typical sample techniques include: • Tap • Bailer • Low-flow pump • High-flow pump • Discrete Interval Sampler (DIS)		x	
Odour	Odour refers to the distinct smell of the groundwater sample.		x	
Turbidity	Turbidity is a measure of the relativity clarity of a water sample. This can vary from high turbidity (many individual particles such as mud or silt in the		x	

Data	Definition	Water level	Water quality	Abstraction
	sample) to low turbidity (the water sample appears relatively clear to the naked eye).			
Sample depth	This is the depth in the well where a groundwater sample is retrieved from. The sample depth helps indicate which portion of an aquifer is sampled, e.g. fracture zone or screen zone.		x	
Flow / abstraction rate	Flow rate is the amount of fluid that flows in a given time. Flow meters are equipped to abstraction boreholes and indicate the flow rate at any given time and the total volume of groundwater that has been abstracted.	x		x
Discharge	Springs refer to the natural discharge/daylighting of groundwater at surface. These are the points/areas where groundwater head equals or exceeds the atmospheric pressure. Spring discharge is determined by the rate of water flow from the spring. Spring discharge can be measured manually from a weir or discharge pipe, or automatically with the use of flow meters or data loggers.	x		x

2.1.1 Location

Groundwater monitoring involves repeated measurements at determined **locations** at a chosen frequency. It is important that positions of monitoring sites are recorded correctly so that monitoring locations can be identified and that the measurements reflect the correct area.

A geographic position is referenced by its latitude and longitude values. These are angles measured from the Earth's centre to a point on the Earth's surface. Latitude and longitude values are typically measured in decimal degrees or in degrees, minutes and seconds (DMS). In South Africa latitude will be a negative value (Southern Hemisphere) and the longitude will be a positive value (east of the prime meridian, also known as the Greenwich meridian) (DWAF, 2004) (**Figure 2-1**).

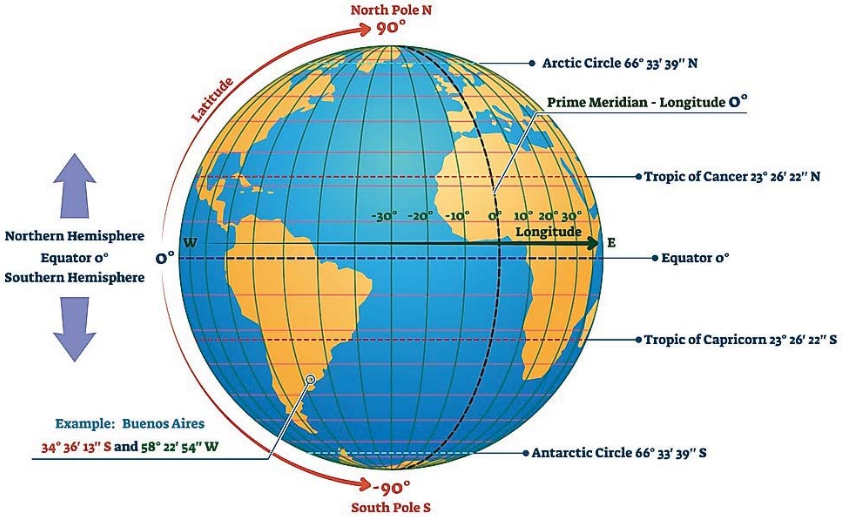


Figure 2-1 **The world as a globe showing the circles of latitude and longitude (Nag et al., 2022). The east-west lines represent lines of equal latitude, the north-south lines represent lines of equal longitude.**

A projected coordinate system is based on a geographic coordinate system and is defined on a flat, two-dimensional surface. A projected coordinate system has essentially constant lengths, angles and areas across the two dimensions. Locations are identified by **x** and **y** coordinates on a grid, with the origin at the centre of the grid (DWAF, 2004). Representing the earth's surface in two dimensions causes distortion in the shape, area, distance or direction of the data, therefore a map projection uses mathematical formulae to relate spherical accordance on the globe to flat, planar coordinates (DWAF, 2004). Different projections cause different types of distortion (**Figure 2-2**), therefore the projection should be recorded when measuring coordinates.

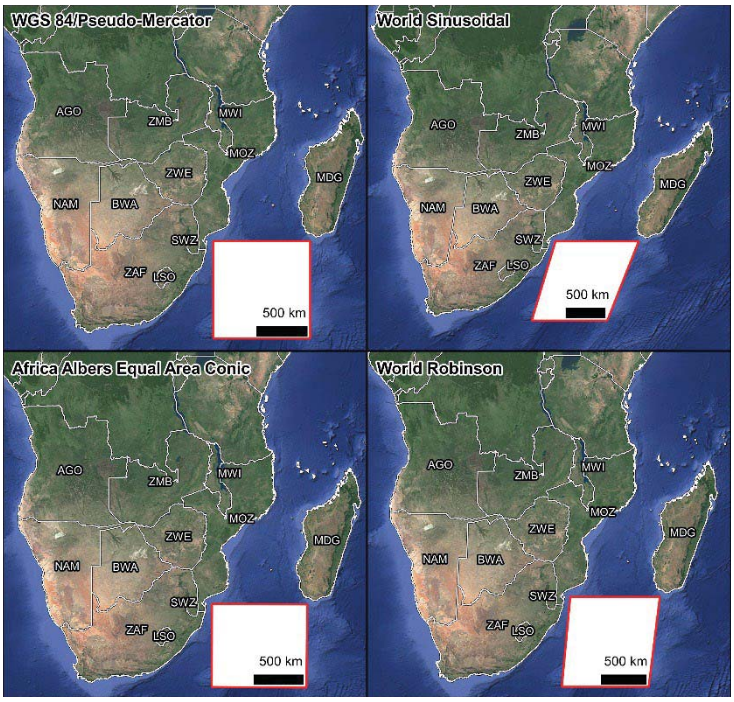


Figure 2-2 **Various map projections showing the different distortions of the earth's surface. Mercator maintains true shape, Sinusoidal maintains true area, Equal-Area Cylindrical maintains true area, Robinson does not preserve any properties but is widely used because it makes the Earth's surface and its features "look right". White block highlights the changes in geometry between projections.**

2.1.1.1 Methods to Determine Coordinates

There are three methods typically used to determine the coordinates of a specific point/location. These include maps, computer programmes and satellite navigation systems which are detailed in **Table 2-2**. The accuracy of these methods varies significantly and therefore the required object needs to be considered prior to selecting a method.

Depending on the map scale, the uncertainty of the coordinates can be greater than 50 m. Maps can be used to gather rough estimates of locations when conducting field activities, but they should not be used to determine the final location of a site (e.g. well location). The accuracy of computer programmes can vary from moderate to high, depending on software and the input data. Coordinates generated for computer programmes must always be verified with on-ground measurements using satellite navigation systems. The accuracy of satellite navigation systems can vary from moderately high to high, depending on the device, the satellite configuration and use of surveying techniques.

Typical handheld Global Navigation Satellite System (GNSS) receivers or smartphones with built in GNSS have a horizontal accuracy within 5 m under open sky conditions, however, their accuracy can decline due to satellite coverage, signal blockage, network coverage, atmospheric conditions, etc. (GPS.GOV, 2022). The vertical accuracy (i.e. elevation) of these handheld GNSS devices is generally not provided by the manufacturers but is typically 1.7 times the horizontal accuracy (Juniper Systems, 2022). Some GNSS receivers have built-in functions, i.e. waypoint averaging, which refine the location by averaging the coordinate for a period of time through short-term averaging or multiple-sampling averaging. Short-term averaging is averaging the waypoint once for only a few minutes (5 to 10 minutes), whereas multi-sampling averaging involves taking multiple short-term measurements (Garmin, 2022). The multi-sampling averaging is the most accurate method of averaging a location. The user manual for the GNSS device should be used for detailed instructions on how to use these features. GNSS devices used for surveying purposes are more accurate than handheld GNSS devices and can have an accuracy to a few mm. It is recommended that coordinates (latitude, longitude and elevation) be measured using GNSS. If multiple coordinates have been generated for a site, the most accurate measurement must be recorded.

Table 2-2 Methods to determine the coordinates of a geographic features.

Method	Application
Maps	Geographic positions can be plotted, and the coordinates determined from the coordinate references on the map (latitude and longitude or eastings and northings). When in the field, locations are identified on maps by orientating the location with features identified on the map. Elevation can be estimated by examining the contour lines on a map. These can also be used to create vertical cross sections of an area.
Computer Programmes	Computer based programmes such as Google Earth, Google Maps, ArcGIS and QGIS have built in coordinate reference systems (i.e. geographic coordinate systems, projected coordinated systems and vertical coordinate systems) used to determine the coordinates and elevations of geographical features. These programmes are able to import Digital Elevation Models (DEMs), Digital Surface Models (DSMs) and Digital Terrain Models (DTMs) which represent elevation data (AEVEX Aerospace, 2022): • A DEM represents the bare-Earth surface, removing all natural and built features. • A DSM captures both the natural and built/artificial features of the environment. • A DTM typically augments a DEM, by including vector features of the natural terrain, such as rivers and ridges. DEMs, DSMs and DTMs are the most common basis for digitally produced maps, allowing for accurate elevations of geographic features to be determined.
Satellite Navigation Systems	GNSS are satellite-based navigation systems made up of satellites which transmit unique signals and orbital parameters. Receivers (Survey GNSS devices, handheld GNSS (e.g. GPS, smartphones, etc.) decode and compute these signals to determine their location (latitude, longitude and elevation) to high precision.

2.1.1.2 Coordinate Reference Systems and Reference Datums

The Hartebeesthoek94 (WGS84) Datum has been the official coordinate reference system for South Africa since 1 January 1999 (DWAF, 2004). The coordinate system is based on the World Geodetic System 1984 ellipsoid, commonly known as WGS84 (DWAF, 2004). Previously, the Cape Datum reference system was used in South Africa, therefore a large number of maps still reflect the Cape Datum as a reference. The difference between the WGS84 and Cape Datum reference systems may vary up to 300 m (DWAF, 2004). It is recommended that the WGS84 datum is used when measuring the coordinates of points in South Africa.

Furthermore, coordinates of groundwater sources (i.e. boreholes, well-points, springs, etc.) that are recorded using the Cape Datum should be resurveyed using the WGS84 reference datum. The resurveyed coordinates should replace the old coordinates in the database system where the station information is stored to ensure accurate use and analysis.

The Universal Transverse Mercator (UTM) coordinate reference system has its origin on the equator at a specific longitude. The UTM coordinate reference system is a global map projection. To avoid distortion of angular conformity, distance and area, the world is divided into 60 equal zones that are all 6 degrees wide in longitude from east to west (QGIS, 2022). South Africa is covered by four UTM zones to minimise distortion. The zones are called UTM 33 S, UTM 34 S, UTM 35 S, UTM 36 S (see **Figure 2-3**). For example, the coordinate of the AOI (red cross in **Figure 2-3**) is located within the UTM 35 S zone, therefore UTM 35 S zone should be used as the coordinate reference system. The position of a coordinate in UTM south of the equator must be indicated with the zone number (35) and with its northing (y) value and easting (x) value in metres. The northing value is the distance of the position from the equator in metres (QGIS, 2022).

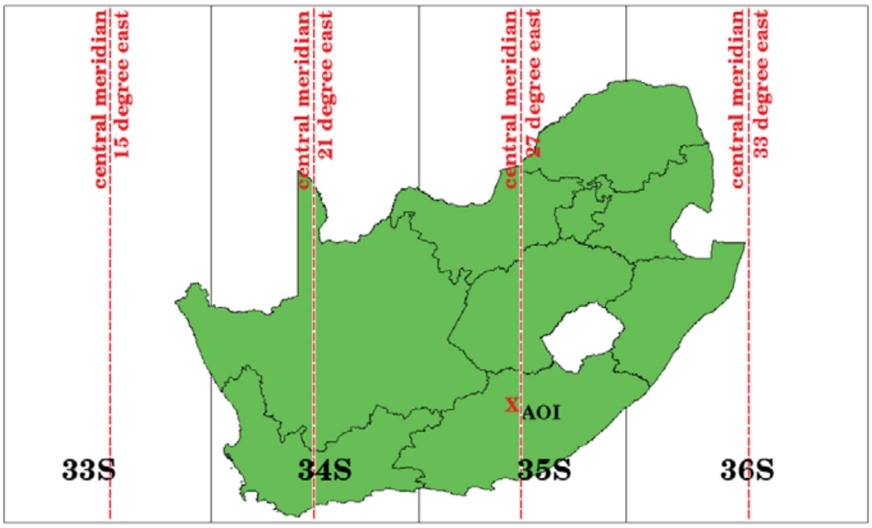


Figure 2-3 UTM zones 33S, 34S, 35S, and 36S with their central longitudes (meridians) used to project South Africa (QGIS, 2022).

2.1.2 Groundwater Level Monitoring

Groundwater levels as defined in **Table 2-1**, are the depth of the water table and can be divided into static water level (water level under normal undisturbed conditions) or dynamic water level (water level under influence of pumping). Whether the water level is static or dynamic, it is important to understand when monitoring groundwater levels, as this will influence the water level measurement (**Figure 2-4** and **Figure 2-5**). When monitoring groundwater levels, the static water level should be measured, this represents the natural groundwater level that is not influenced by other factors such as abstraction from the well or nearby wells.

Groundwater level measurements can provide information on lateral and vertical head distribution and hydraulic gradients within individual aquifers and between aquifers in layered aquifer systems. Groundwater levels can also provide information on groundwater flow directions.

Long-term monitoring of groundwater levels is important for understanding the temporal responses of the aquifer to rainfall, abstraction and other factors (Sundaram et al., 2009).

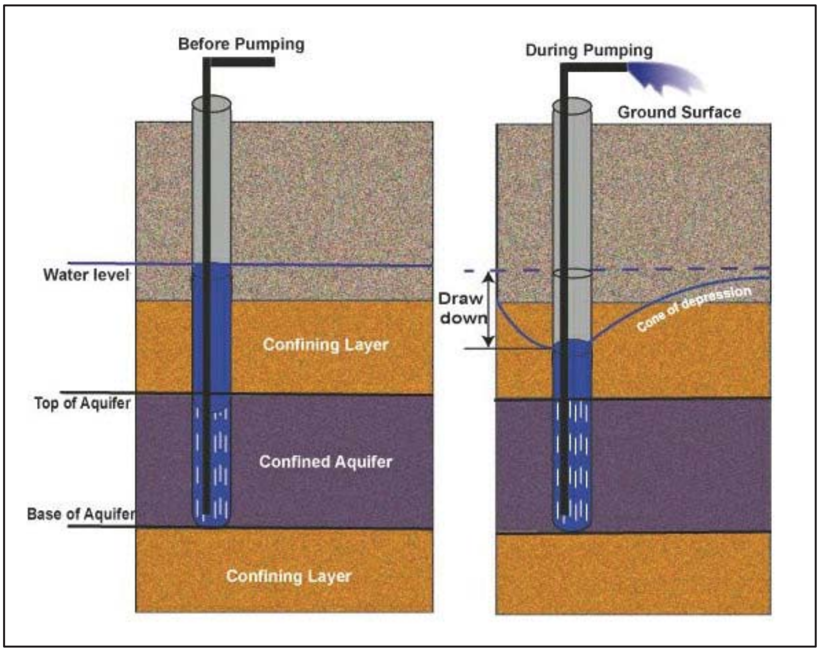


Figure 2-4 The influence of pumping on the water level in the borehole. The drawdown represents the dynamic water level that changes during pumping. Modified after Groundwater Dictionary, 2022.

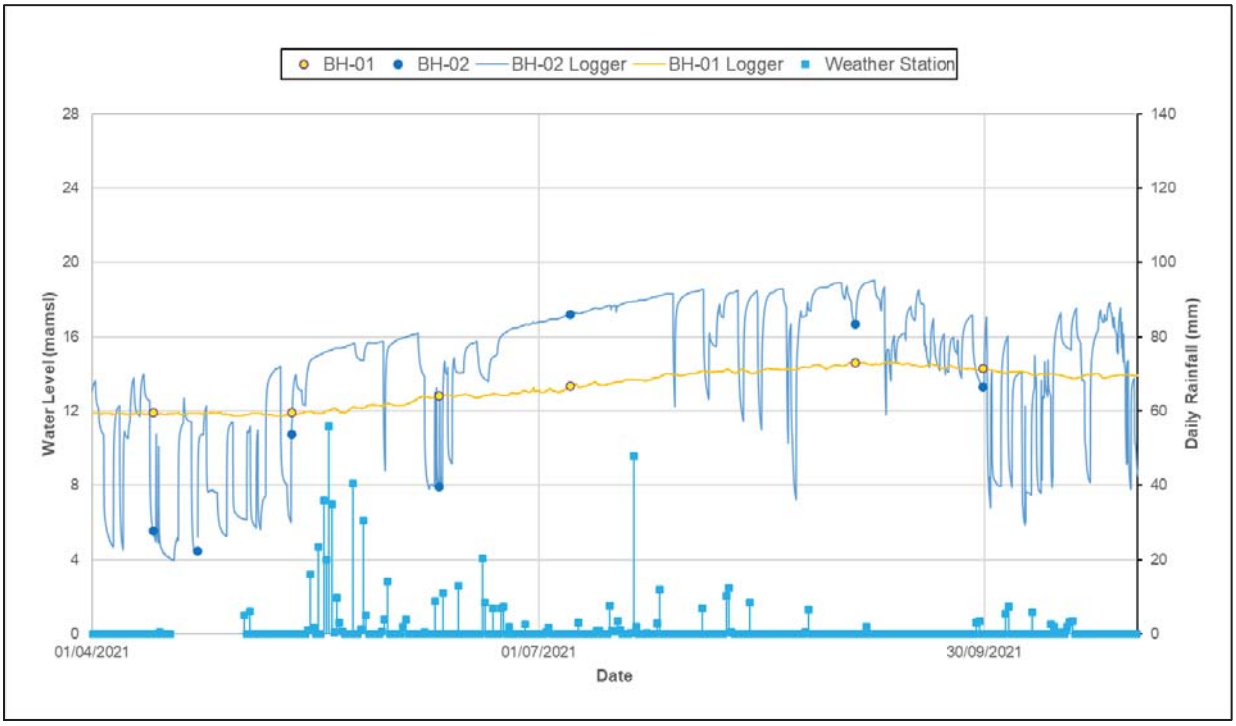


Figure 2-5 Example of logger and manual water level readings to compare the difference between water levels under the influence of abstraction and water levels that are not. BH-01 illustrating the natural groundwater level fluctuations, not influenced by abstraction; BH-02 showing daily fluctuations of water levels due to abstraction.

Water level is measured in a well (i.e. borehole, wellpoint or piezometer) as the depth to the water below the ground surface. Groundwater level is often measured in metres below ground level (mbgl); however, a water level can also be measured as metres below datum (mbd), i.e. measuring point, thereafter it can be converted to mbgl. If a datum point is used to measure the water level at a well, it is important to first establish the datum point.

Datum Point = A point which serves as a reference or base for all measurements, this is regarded as the zero point when taking a measurement.

The datum point on a well is the fixed point on the well from where all measurements are recorded. This can either be the top of the casing, the dip tube, top of a manhole, etc. The datum point must be clearly marked, and the position of the point needs to be measured in reference to ground level (i.e. height above or below ground level) (see **Figure 2-6**).

The formula below is used to convert a water level reading from mbd to mbgl. If the datum point is positioned above ground, the height of the datum above ground needs to be subtracted from the water level reading in mbd. Vice versa, if the datum is positioned below ground, the measured difference between the datum and ground level needs to be added to the water level reading in mbd.

Water Level (mbgl) = Water Level (mbd) – Collar Height (m)

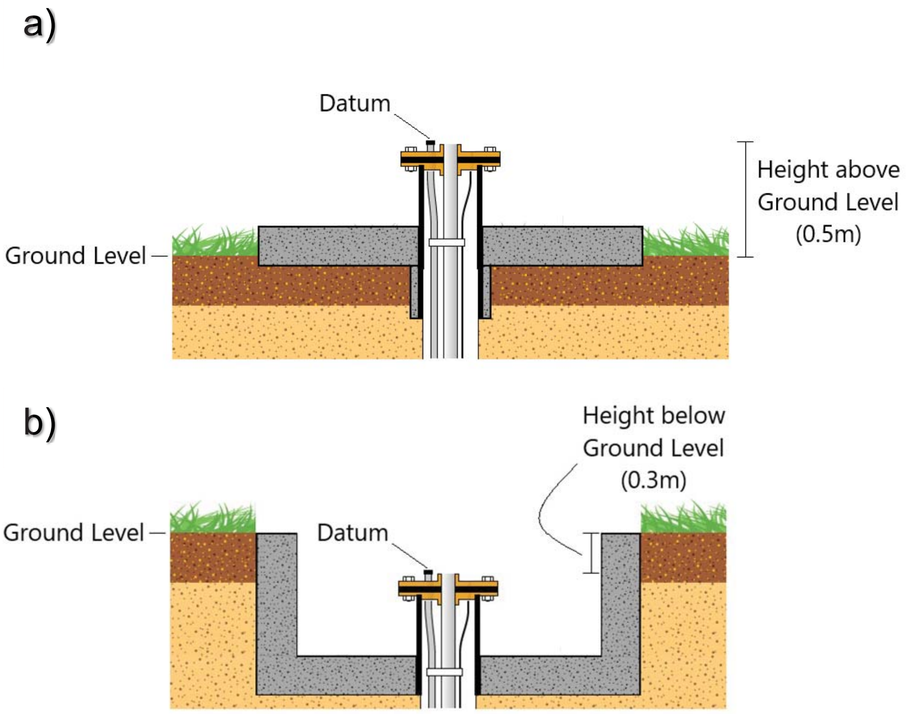


Figure 2-6 **Schematic of a well showing the datum point in reference to ground level. a) Datum positioned above ground level; b) datum positioned below ground level.**

The measured groundwater level in mbgl can be converted to metres above mean sea level (mamsl) by accounting for elevation, using the equation below. Groundwater levels in mamsl are useful to determine the changes in groundwater level over a large area by accounting for changes in topography (see **Figure 2-7**). When comparing more than one well, the water level must be in mamsl to account for these changes. To determine the elevation of a well/measuring point, see **Section 2.1.1**.

Water Level (mamsl) = Elevation (m) – Water Level (mbgl)

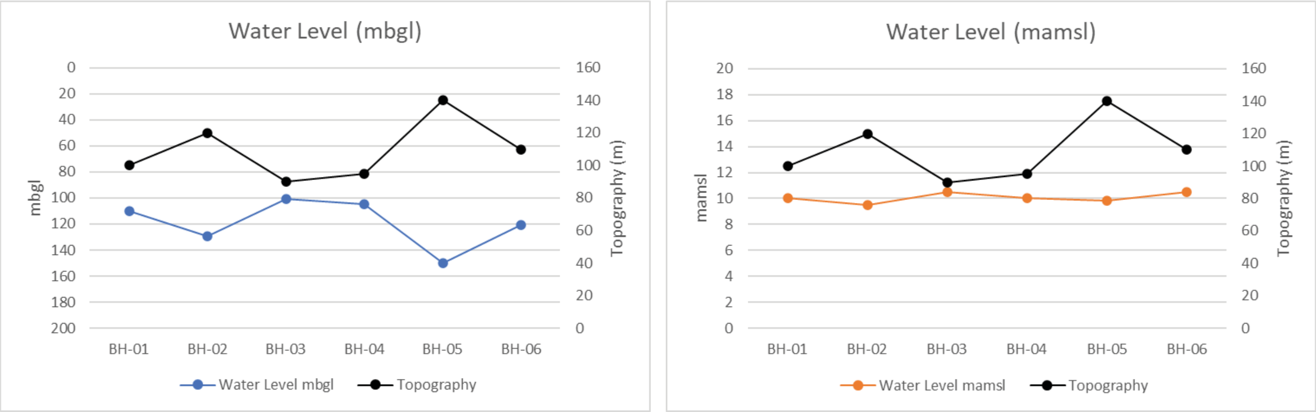


Figure 2-7 **Visual representation of groundwater levels recorded in mbgl vs mamsl. Note apparent large differences in water levels recorded in mbgl compared to the same measurements converted to mamsl to account for elevation. The measurements in mamsl show minor changes in water level.**

2.1.2.1 Manual Water Level Measurements

2.1.2.1.1 Chalked Tape

The chalked tape or wetted tape method has been one of the most commonly used methods to measure water level in the past (IGRAC, 2008). It consists of a steel tape with a small lead weight attached. The lower few metres of the tape are covered with carpenter's chalk or pastes that change colour. To measure the water level, the weight is lowered into the well until it is a few metres below the water surface. A reading is made at the datum point at surface and the tape is removed and the water mark recorded. The water level is obtained by subtracting the two measurements. This method is accurate up to 100 m (IGRAC, 2008). There are a few disadvantages using this method: water on the sides of the casing or cascading water may wet the tape resulting in incorrect measurements, the measurements may be difficult if an estimated water level is not initially known, and the wetted chalk mark may dry before the tape is retrieved from the well.

2.1.2.1.2 Electronic Water Level Meter – Dip Meter

Water level is typically measured manually using a dip-meter (see **Figure 2-8**). A dip-meter is an electronic water level meter that consists of a probe attached to a conductor wire in a measuring tape. When the probe comes into contact with the water, the dip-meter will “beep” as a result of the circuit being closed due to the conductive properties of water. The water level reading is taken directly from the tape at the datum point. The process is repeated to ensure high reliability. Some electronic water level meters are also capable of measuring other parameters such as conductivity and temperature.

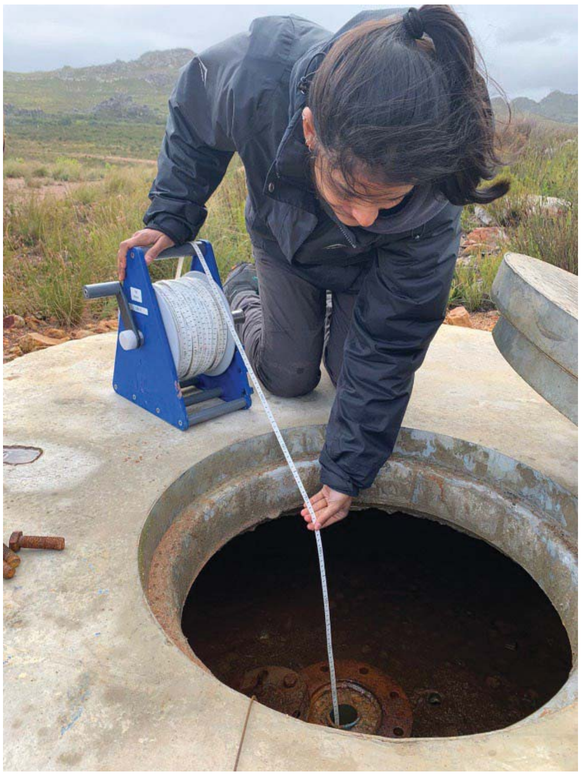


Figure 2-8 Dip meter used to measure groundwater levels.

2.1.2.1.3 Plopper Method

The plopper or popper method uses a metal cylinder/cup with an open end at the bottom that is attached to a measuring tape (see **Figure 2-9**) (Sundaran et al., 2009). The plopper is lowered into the well until it comes in contact with the water surface, producing a “plopping” noise. The water level is recorded from the tape at the datum. The process is repeated to ensure high reliability.

Figure 2-9 Plopper used to measure groundwater levels (Sundaran et al., 2009).

2.1.2.1.4 Sonic Water Level Meter

A sonic water level meter consists of a control unit connected to a probe (see **Figure 2-10**). The probe transmits a sonic pulse into the well and measures the return time of the pulse after contacting the water (Solinst, 2022). The water level readings are displayed on the control unit. Sonic water level meters are able to measure other parameters such as well-diameter, temperature, etc.

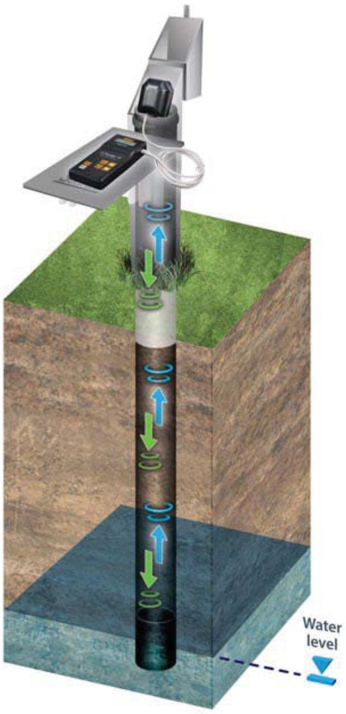


Figure 2-10 Schematic of sonic water level meter (Solinst, 2022).

2.1.2.2 Artesian Pressure

When a well is drilled through an overlying impervious layer into a confined aquifer, water can rise in the well to a level above the top of the aquifer. The water level in the well represents the confining pressure at the top of an aquifer (Driscoll, 1986). When the confining pressure in a well is sufficient, the water will free flow out of the well to the surface, known as artesian pressure. Wells that are under artesian pressure are fitted with pressure gauges. When conducting groundwater monitoring of wells under artesian pressure, the pressure is simply read directly off the pressure gauge and recorded in a field sheet (see **Figure 2-11**). The artesian pressure at a well can be converted to the apparent water level above ground level. The formula below is used to convert artesian pressure to groundwater level, where the artesian water level is recorded as metres above ground level (magl). When measuring artesian pressure in magl, positive measurements indicates that the water level would be above the ground level and vice-versa for negative measurements (for negative measurements the pressure in the well is not sufficient to raise the water level above ground). Water level in magl can be converted to mamsl by adding the surface elevation.

Water Level (magl) = pressure (bar) x 10.2

Figure 2-11 Pressure gauge fitted to a borehole that is under artesian pressure.

2.1.2.3 Water Level Monitoring Field Sheets

Manual water levels need to be recorded in field sheets. The following information should be recorded when conducting water level monitoring:

- Project Name/Project Number
- Site/Station ID
- Well coordinates, coordinate system and coordinate reference datum
- Date and time of measurement
- Name of field technician or person measuring the water level
- The time since pumping has stopped, if well is used for abstraction
- Height of datum above/below ground level
    - Height of datum above ground level should be recorded with positive values
    - Height of datum below ground level should be recorded with negative values
- Water level measurement
    - The unit of measurement should be recorded, i.e. mbgl, mbd, etc.
    - It is recommended that final groundwater level measurements be recorded in mbgl and mamsl
    - Artesian pressure and correct unit should be recorded, i.e. Pa, kPa, bar, etc. and converted to water level during data processing
- Type of water level, i.e. static or dynamic water level
    - Static water levels should be recorded
- If a logger is present, the time the logger is removed and put back should be recorded
- Field observations
    - Comments should be made of any field observations which may have an influence on the groundwater levels or the ability to monitor a well, these include:
        - pumping of wells nearby
        - sprinklers being used
        - weather conditions
        - changes in datum height
        - blockages in the well
        - vandalism

2.1.2.4 Automatic Water Level Measurements

Water level dataloggers are used for automatic long-term and continuous groundwater level measurements. These loggers measure the pressure above the logger sensor. The loggers typically measure water pressure above the sensor or both water pressure and atmospheric pressure. Water level dataloggers can be grouped into two primary types, vented and non-vented.

Vented water level loggers only measure water pressure. They include a built-in vent tube that enables the loggers to automatically compensate for atmospheric pressure changes (see **Figure 2-12 a**) (Onset, 2022).

Non-vented water level loggers measure both water and atmospheric pressure, they do not use vent tubes, therefore the water level data needs to be barometrically compensated. Non-vented loggers must be used in conjunction with barometric loggers to allow for barometric compensation (see **Figure 2-12 b**)*. C*ompensation is done by using the datalogger software.

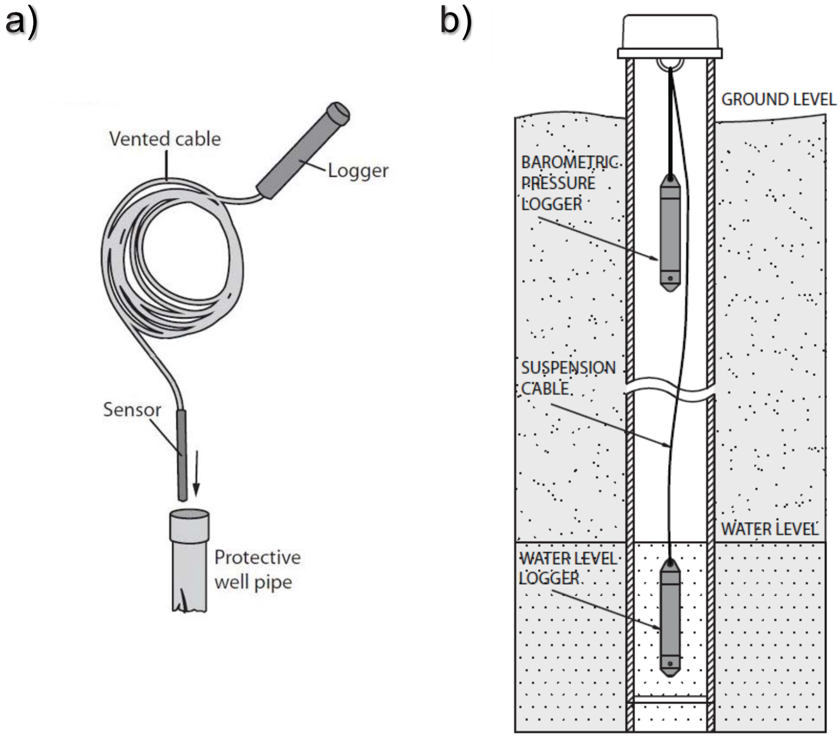


Figure 2-12 Primary types of water level dataloggers. a) schematic of a vented water level datalogger; b) non-vented water level datalogger schematic showing the water level logger and barometric logger setup (Onset, 2022).

2.1.2.4.1 Datalogger Installation

- Water level dataloggers should be installed below the lowest expected water level for a well to ensure continuous recording.
- Loggers are installed by using either a suspension line or a direct read communication cable. The instruments are suspended from the top of the well to the desired depth.
    - The suspension line should be stainless stell wireline or Kevlar cord to prevent the line from stretching over time, altering the accuracy of the measurements.
    - The length of the suspension line or communication cable should be measured and recorded.
- The frequency of logger readings can typically be set for each logger by using the logger software. The frequency should be set depending on the requirements for the investigation. For continuous long-term groundwater level monitoring, loggers are typically set to *half-hour* or *hour* intervals.
- A manual water level measurement should be recorded once a logger has been installed. The manual water level measurement is used to confirm and calibrate logger water levels.
    - The point where the logger is installed/hung from should be used as the datum point for all manual water level measurements at wells which have loggers installed.
- Barologgers should be installed above the water level, in a similar thermal environment to the water level loggers (Onset, 2022).
    - Barologgers can typically cover a 30 km radius and/or 300 m elevation change. Water level loggers cannot be compensated by a barologger if they are outside the radius of coverage of the barologger.

2.1.2.4.2 Logger Download and Data Processing

Logger data can either be download directly from the logger by using logger laptop/app interfaces (see **Figure 2-13**) or they can be downloaded remotely by using telemetry systems. Routine weekly or monthly manual water level measurements should be recorded to ensure that the water level loggers are recording correctly.

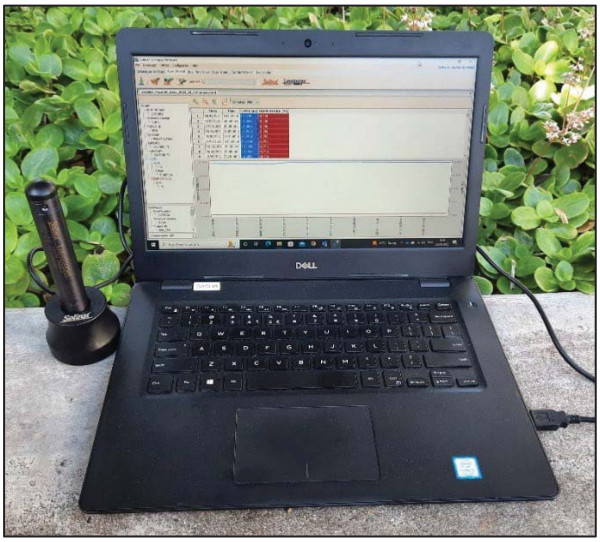


Figure 2-13 **Manual water level datalogger download using logger docking station.**

Once water level loggers have been downloaded and compensated, if necessary, the water level logger data should be plotted graphically with the corresponding manual water levels. This allows for the data to be cleaned by removing any unnatural spikes in the data (e.g. from when a logger was removed from the water for downloading) and also allows for the logger water levels to be QC'd against the manual water levels. The raw water level logger data needs to be archived separately to the processed water level logger data that should be upload to a database system after the data has been QC'd (see **Section 3.1**)

2.1.2.5 Groundwater Level Quality Assurance

Groundwater level quality assurance (QA) is a set of operating principles, procedures and actions that ensures that the measured groundwater level data is reliable and accurate. Groundwater level measurements are the most basic parameter measured in groundwater monitoring and are essential for any groundwater monitoring undertaken. Important routine QA measures for groundwater monitoring include:

- Always measuring groundwater levels in relation to the established datum point. The datum point must be clearly marked and the details (e.g. height above ground level and elevation) must be recorded on the field form and in the database.
- The correct units should be captured when recording groundwater levels and artesian pressures (e.g. mbgl, mbd, mamsl, bar, kPa, etc.)
- Groundwater level changes observed during monitoring must be evaluated to determine the cause, e.g. the water level at a monitoring well may be influenced by abstraction from a neighbouring well.
- When interpreting measured groundwater levels, information regarding aquifer types, well construction, etc. should be assessed. For example, the groundwater levels in two wells within a few metres of each other can vary by several metres if they are drilled into different underlying aquifers that are separate by an impermeable layer.
- Dataloggers must be calibrated and processed according to the software specifications.
- All groundwater dataloggers must be calibrated and checked against manual measurements.

2.1.2.6 Summary

Figure 2-14 below outlines the general operational flow to ensure that groundwater level monitoring is conducted according to best practice principles to prevent rudimentary errors.

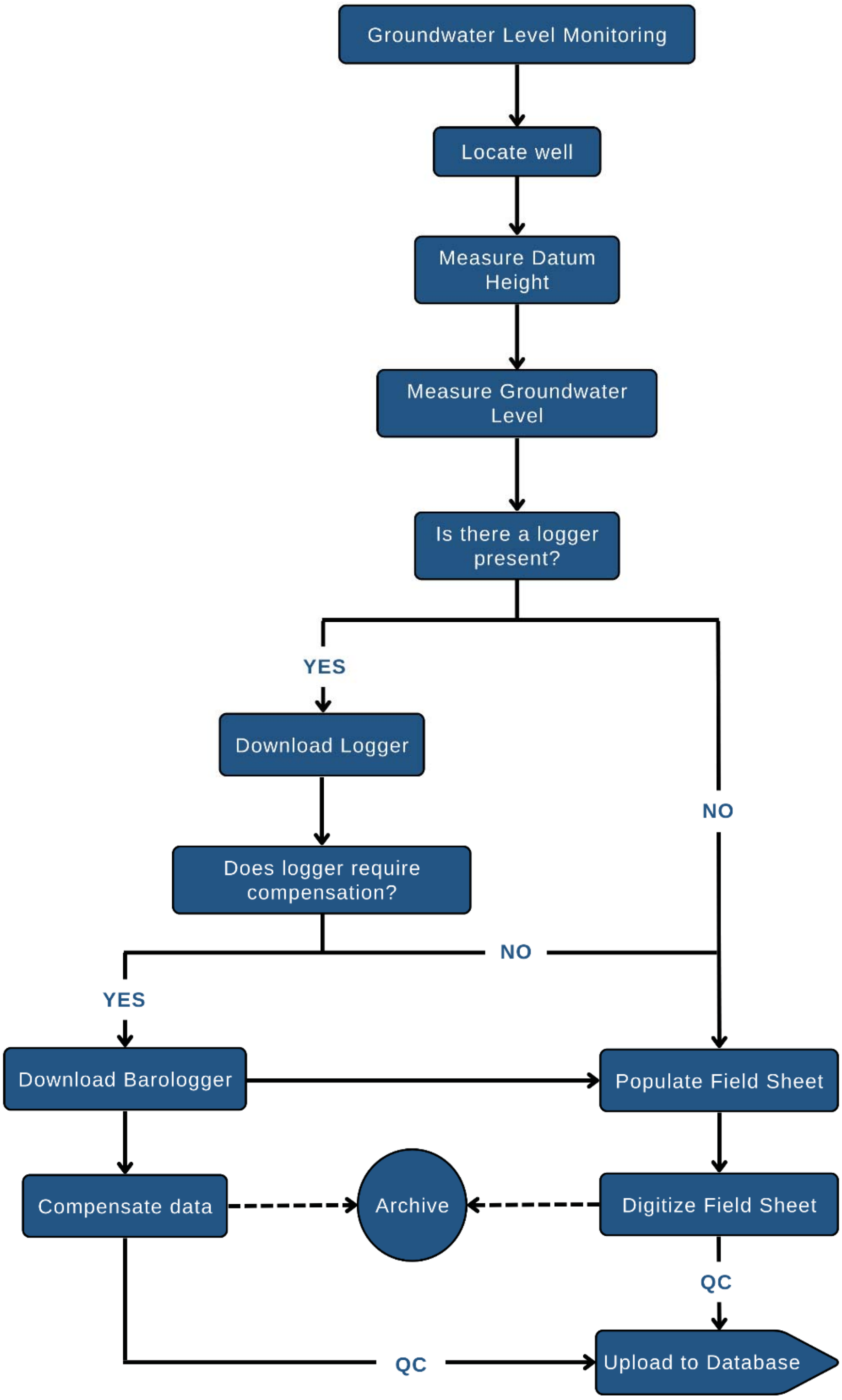


Figure 2-14 Operational flow for conducting groundwater level monitoring, illustrating the general steps in groundwater level monitoring from collecting groundwater data in the field to processing the data and uploading to a database for storage and future use.

2.1.3 Groundwater Quality Monitoring

> "A lack of monitoring has resulted in a gap in our knowledge concerning temporal changes in groundwater quality in South Africa. Known cases of groundwater contamination, particularly those related to non-point sources, are therefore limited. The lack of both spatial and temporal information concerning groundwater quality on a national scale makes it difficult to manage the country's groundwater resources" – WRC (2017)

Groundwater quality monitoring can be undertaken for a variety of reasons such as assessing the water quality for use, to understand the hydrogeology of an aquifer, determining the surface water-groundwater interactions, identifying contaminants, assessing the impact of land use activities on groundwater, etc. Water quality monitoring requires that the correct sampling methods are used to ensure that the sample is representative of the groundwater *in situ* in the aquifer. The collection of "representative" samples which reflect in situ groundwater conditions at the time and location of sampling is a key objective of groundwater quality monitoring. This ensures that the chemical and microbiological properties of the groundwater sample reflect those in the aquifer adjacent to the sampling point (CL:AIRE, 2008). A representative groundwater sample has experienced no mixing of water from different aquifer horizons within the well; minimum disturbance of temperature and pressure; and no reaction with any part of the well (Ravenscroft and Lytton, 2022).

When selecting wells for groundwater quality monitoring it is important to evaluate whether the well will provide a representative sample for the purpose of monitoring, by assessing the well construction details and drilling logs. This includes assessing the depth of screeded zones and the type of casing material. For groundwater quality monitoring wells, the casing material must be inert. Some casing material such as mild steel and some grades of stainless steel are susceptible to corrosion, which can release iron, manganese, copper, lead, cadmium, nickel, chromium and molybdenum into the water (Nielsen and Nielsen, 2006). Thermoplastic well casing, such as PVC casing, is resistant to corrosion, does not release metals into water and is unlikely to absorb trace metals and metalloids (Ravenscroft and Lytton, 2022) (see **Table 2-3**). However, if wells are to be sampled for volatile or semi volatile organics, pesticides and pharmaceuticals, the plastic material needs to be scrutinised because some common organic contaminants are solvents that can leach chemicals from plastic (Ravenscroft and Lytton, 2022). The advantages and disadvantages of different common monitoring well materials are summarised in **Table 2-3**.

The parameters selected for analysis during groundwater quality monitoring depend on the purpose of the groundwater investigation. **Table 2-4** outlines which parameters should be measured in the field, and which should be analysed by the laboratory for the various types of groundwater investigations. It is important that all samples are analysed by a South African National Accreditation System (SANAS) accredited laboratory. Water quality sampling, monitoring and assessments should be undertaken in accordance with applicable national guidelines and standards (see **Section 1.2**).

Table 2-3 **Comparison of common well construction materials (modified after Weight, 2008).**

Material	Advantage	Disadvantage
Stainless steel 304 and 316	Least reactive with organic chemicals; high strength.	Heavy; may corrode in heavy metal acid mine drainage waters; higher costs than plastic.
PVC	Lightweight; resistant to acids, alkalis, alcohols and oils.	Can absorb VOCs or react with ketones or esters.
Mild steel	Low-cost; high strength.	Heavy; not as chemically resistant as stainless steel.
Polypropylene	Lightweight; resistant to acids, alkalis, alcohols and oils.	Weak, flexible and difficult to make slots for screens.
Teflon	Resistant to most chemicals; lightweight.	Lower wear resistance and tensile strength.

2.1.3.1 Well Purging

Various processes affect the groundwater quality inside a well (see **Figure 2-15**), therefore it is important that a well is purged correctly. Well purging is the process of removing stagnant water from the well before a sample is taken, to ensure a representative groundwater sample can be retrieved. Well purging typically involves the removal of water until the field chemistry parameters (pH, EC, temperature, dissolved oxygen and Eh) stabilises. This usually involves removing three times the well volume (WRC, 2017).

It is usually recommended that at least three times the well volume be removed during purging (WRC, 2017; Sundaram et al., 2009; WRC, 2007), however, the well may be over-purged and dewatered, causing cascading, aeration of the formation, loss of gasses and volatiles and increased sample turbidity (CL:AIRE, 2008; WRC. 2007). On the other hand, the time required for field parameters to stabilise during purging can vary significantly between wells (CL:AIRE, 2008). Some field parameters may require several hours of pumping before stabilisation which can also result in the well being over-purged. Therefore it, is recommended that each well be looked at individually.

NOTE: When purging a well, it is good practice to consult well drilling logs to identify the depth of the main water strikes. The water level should be monitored during purging (see **Section 2.1.2.1**) to ensure that the water level is not dropped below the main water strikes to prevent dewatering or below the top of the screened section to prevent bringing oxygen into the aquifer which could result in biofouling.

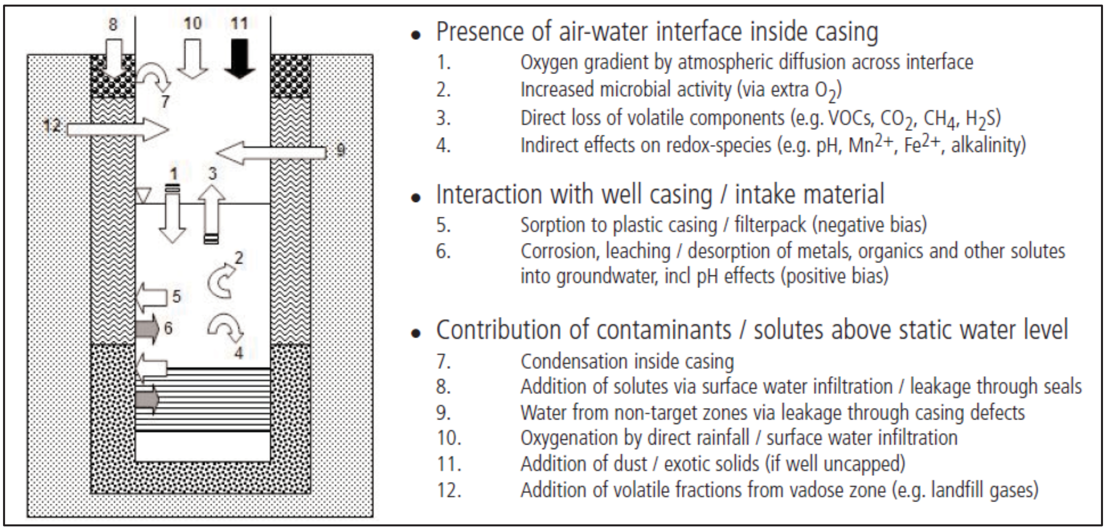
Table 2-4 **Detailed sampling guide for selecting determinants (Modified after WRC, 2017).**

Aim	Application	Field Measurement[1]	Parameters to be analysed in the Laboratory
Water quality specifications for intended use	Household consumption	EC, pH	SAWQG for Domestic Use and SANS 241:15 Drinking Water Guidelines
	Livestock drinking	EC, pH	SAWQG for Agricultural Water Use: Livestock watering
	Irrigation	EC, pH	SAWQG for Agricultural Water Use: Irrigation
	Industrial usage	EC, pH, Eh	SAWQG for Industrial Water Use

Aim	Application	Field Measurement[1]	Parameters to be analysed in the Laboratory
Hydrogeochemistry for groundwater investigations	Major hydrochemistry	EC, pH, Eh, Temp	Cat/An and project specific parameters
	Trace elements	EC, pH, Eh, Temp	Cat/An and project specific parameters
	Radioactivity		Project specific
	Isotopes	pH, Temp, Dissolved oxygen (DO)	Project specific
	Artificial recharge	pH, Eh, Temp, DO	Cat/An, DOC, microbiology, phenols and DOX
	Waste disposal sites	pH, Eh, Temp, DO	Cat/An, DOC, DOX and toxic substance of interest
Groundwater pollution investigations	Agricultural contamination	pH, Eh, Temp, DO	Identified target herbicides, pesticides and fertilizers, as well as nitrates, phosphates and potassium. Cat/An
	Acid mine drainage	pH, Eh, Temp, DO	Cat/An and identified trace elements
	Industrial waste pollution	pH, Eh, Temp, DO	Determined by the process, total and dissolved metals.
	Sewage disposal	pH, Eh, Temp, DO	Cat/An, DOC and microbiology
	Underground fuel storage tanks		Volatiles and semi-volatiles, DOC, identified substances, e.g. petroleum compounds
	General suspected pollution	EC, pH, DO	Cat/An, DOC, DOX

1 – Field EC should be measured for all sampling. However, field EC meters are often less accurate, therefore the laboratory EC measurement should be used later for interpretation.

Cat/An – full analysis of major cations and anions.



- Presence of air-water interface inside casing
  1. Oxygen gradient by atmospheric diffusion across interface
  2. Increased microbial activity (via extra O_2)
  3. Direct loss of volatile components (e.g. VOCs, CO_2, CH_4, H_2S)
  4. Indirect effects on redox-species (e.g. pH, Mn^{2+}, Fe^{2+}, alkalinity)
- Interaction with well casing / intake material
  5. Sorption to plastic casing / filterpack (negative bias)
  6. Corrosion, leaching / desorption of metals, organics and other solutes into groundwater, incl pH effects (positive bias)
- Contribution of contaminants / solutes above static water level
  7. Condensation inside casing
  8. Addition of solutes via surface water infiltration / leakage through seals
  9. Water from non-target zones via leakage through casing defects
  10. Oxygenation by direct rainfall / surface water infiltration
  11. Addition of dust / exotic solids (if well uncapped)
  12. Addition of volatile fractions from vadose zone (e.g. landfill gases)

Figure 2-15 **Processes affecting the quality of groundwater inside a monitoring well (CL:AIRE, 2008).**

2.1.3.2 Sampling Methods

The methodology to be followed when sampling groundwater for laboratory analysis is summarised below. This includes the use of a submersible pump, low-flow pump, bailer and DIS.

2.1.3.2.1 Submersible Pump

- Measure depth to water table to calculate water column using depth of well (obtained from well construction details or measured manually at the well). Use equation below to calculate well volume.

$$\mathbf{V=\pi \times r^2 \times h}$$

V = volume of standing water in metres^3 (x 1000 to get litres)

$\pi = 3.1416$

r = inside radius of well casing in metres

h = well depth in metres minus water level in metres

- Lower pump to level above the screening if depth known. If not, place ~2 m below groundwater level.
- Roll lay-flat pipe downslope of well and connect to electricity (generator if in field).
- When using submersible pump, at least three times well volume (calculated above) needs to be removed (purged), with stabilization of groundwater indicator parameters (pH, EC and temperature). Ensure discharge of water is downgradient. Measure flow using bucket and stopwatch.
- Measure the water level to ensure the water level does not drop below the main water strikes.
- When stabilisation of indicator parameters and three volumes removed, drop pump by 0.5 m and sample.
- NOTE: monitor flow and if flow begins to slow/aerate, drop pump another 2 m; but never right to the base of the well where sediment can be pulled in.

2.1.3.2.2 Low-flow pump

The low-flow pump sampling method abstracts water from the screened portion of a well without disturbing the stagnant water column above. This is achieved by pumping the well at a low rate to induce laminar flow within the screened portion, drawing in fresh water from the aquifer, and reducing drawdown in the well (Sundaram et al., 2009; WRC, 2017). This method does not require three times the well volume to be removed prior to sampling. Stabilisation of groundwater parameters are used to indicate when a sample can be collected.

The following procedure is followed when using the low-flow pump method:

- Measure the static groundwater level.
- Lower the pump to the middle of the screened portion of the well or at groundwater flow zones (i.e. fractures or water strikes). These depths are gathered from the well drilling log and construction details.
- Set the pumping rate to a level that is within minimum drawdown, typically between 0.5 to 2 l/min. Continuously measure the water level to ensure the water level is stable. Reduce the pumping rate if drawdown occurs.

- Monitor field parameters to ensure stabilisation before collecting samples.

2.1.3.2.3 Equipped Wells

Abstraction wells are equipped with pumps, typically have higher yields and are used for extended periods every day (Sundaram et al., 2009). When sampling from an abstraction well that is not routinely operated daily, the well should be purged following the procedures for a submersible pump (see **Section 2.1.3.2.1**). However, if abstraction wells are continuously pumped during the day, there is no need for purging, but sampling should consider the wells operational times to ensure that the sample is representative.

2.1.3.2.4 Hand pumped Wells

Wells equipped with hand pumps typically have low pumping rates and relatively short screened sections (3 – 6 m). These wells are best sampled after the well has been in operation for ~1 hour, to avoid the need for purging and to avoid the effects of leaking casing joints. When sampling a hand pumped well that has not been in continuous use before sampling, **three pumps of the handle for each metre of depth** of the well is often appropriate for removing stagnant water from the well. Hand pumped wells are appropriate when sampling for chemical parameters, however they are unsuitable when sampling for microbiology because faecal bacteria can survive and grow inside pumps even when largely absent in flowing groundwater (Ravenscroft and Lytton, 2022). A limitation of hand pumped wells is that it is not often possible to measure the groundwater level without removing the pump, which is time-consuming and can result in damages to the pump.

2.1.3.3 Non-Purging Methods

Alternative sampling techniques can be used to obtain representative groundwater samples from discrete depths in a well without having to apply purging techniques (WRC, 2017). Samples can be retrieved from discrete depths where laminar flow occurs in a well, this includes open or screened portions of the well where groundwater flows into the well. The location of these flow zones should be gathered from the drilling log and well construction details prior to sampling.

2.1.3.3.1 Bailers and Discreet Interval Samplers

Bailers are one of the most common sampling techniques used for groundwater quality monitoring. Bailers are typically made of inert materials such as stainless steel, Teflon, polyvinyl chloride, polypropylene and polyethylene. There are various types of bailers such as single check-valve and double check-valve. Bailers allow groundwater samples to be retried from distinct levels in the well, i.e. screened portion or water strike.

A DIS device is another technique used to collect groundwater samples from distinct levels in a well. A DIS is a device that can be pressurised and depressurised to allow for samples to be retrieved from distinct groundwater flow zones without the sample interacting with other water in the water column.

Bailers and DIS devices can be used to purge wells with small volumes, however it is difficult to ensure that all stagnant water is removed when attempting to purge using a bailer. Therefore, these devices are used to sample directly from groundwater flow zones. The following steps are used to collect groundwater samples using bailers or a DIS.

- Measure the static water level.

- Determine the sampling depth by identifying the wells screened portion or water strike by consulting well drill logs and well construction details.
- Lower the sampling device to the determined sampling depth and retrieve a sample.
- If multiple sampling runs are required to fill the sampling containers, the procedure is to be repeated. To limit impacts, each sample is to be retrieved at least 1 m deeper than the previous (ensuring the sampling deceive remains within the screened interval).
- The device should be thoroughly cleaned after use and rinsed with deionised water.

2.1.3.4 Cross Contamination

To avoid cross contamination between monitoring sites, it is important that sampling devices are properly cleaned between sites. Decontamination is especially essential for microbiological, organic and pesticide sampling (Trick et al., 2008). Proprietary cleaners should be used to clean the inside and outside of the sampling device. All cleaning should be undertaken away from a well to ensure no direct contamination (wellhead protection zone). After sampling devices have been cleaned, they should be rinsed with deionised water to ensure no residual contamination remains.

2.1.3.5 Sample Containers, Preservation and Storage

The way a sample is prepared, handled, stored and transported to the laboratory, is directly related to the quality of the results delivered (WRC, 2017). Sample containers required are specific both to the parameters to be measured and the laboratory being used for analysis. As a result, this needs to be predetermined through discussions directly with the selected laboratory.

NOTE: Sample bottles which have been sterilised by the laboratory or bottles which contain preservatives should not be rinsed prior to sampling. If sample bottles have not been prepared by the laboratory, they should be rinsed three times with the sampled water.

To prevent particulates dissolving or precipitating, some samples require filtering through a 0.4-0.45 µm cartridge, often using a syringe, however care must be taken to prevent air exposure for redox-sensitive elements such as arsenic, iron, manganese and metals (Ravenscroft and Lytton, 2022). It is important to understand the reason for filtration, and when and how to filter a sample. The consideration for filtration are dependent on the purpose of sampling and the site hydrogeological conditions. WRC (2007), WRC (2017) and Ravenscroft and Lytton (2022) provide comprehensive guides on when and how to filter samples for laboratory analysis.

The sample container types, preparation, preservation and storage has been summarised in **Appendix B** after WRC (2017).

2.1.3.6 General Field Procedure

Measurements of field parameters are to be taken at the time of sampling using an appropriately calibrated multiparameter hand-held meter and recorded on field forms. Field parameters are those parameters which must be measured in the field before or during sampling. These parameters are unstable and are likely to change before reaching the laboratory. The most common and important field parameters include pH, EC, temperature, Eh, dissolved oxygen and alkalinity. A copy of historic measurements and the expected parameter range should be available during sampling for comparison so that these measurements may act as an early warning of any potential water quality concerns or non-functional equipment.

Clean disposable nitrile gloves are to be used at all times during sampling and must be changed between sampling locations in order to minimise the potential for cross contamination.

Prior to sampling, containers are to be labelled with:

- Sampler's company name
- Project Name/Project Number
- Site/Station ID
- Sample Depth
- Date and Time
- Name of field technician or person conducting the sampling

Sampling Procedure:

- Measure groundwater level and record in field sheet (see **Section 2.1.1.2**)
- Select sampling method as described above (see **Section 2.1.3.2** and **2.1.3.3**), purge well if required
- Collect groundwater sample into sample containers by following the procedure and best practices below:
    - Sample with the bottles up-wind, as perfumes/sunscreen, etc. may affect the results
    - Any concerns of air quality at the time of sampling should be noted. An example is heavy smoke, dust, etc. This is especially necessary when sampling for volatiles and when sampling for contaminants of emerging concern (CEC) which contain parameters with very low detection limits
    - Awareness to not introduce any contamination to sampling equipment or sampling bottles
    - Avoid contact with the sampling device (e.g. submersible pump outlet, bailer, etc.) and dirt/dust by keeping it off the ground
    - Use clean gloves at each location, and if the gloves get dirty, re-apply new gloves. Nitrile gloves should be used
    - Sampling bottles need to be handled carefully and should therefore be stored on a clean black bag or clean paper towel during sampling. Samples are never to be placed on any other surface to avoid contamination
    - Contact between sampling bottles and any clothing should be avoided

    - Sampling devices are cleaned between sites. Proprietary cleaners should be used to clean the inside and outside of the sampling device as described in **Section 2.1.3.4**
    - Any excess water on a sampling device should be wiped with a paper towel to prevent contamination of the sample bottle
    - Plastic sample bottles are to be filled to base of neck, glass sample bottles/vials are to be filled at a positive meniscus (as per laboratory requirements)
    - Filter sample if required
    - Add preservatives as required. Samples with preservatives are to be caped and inverted 5 times
    - Sample bottles with preservatives are **NOT** to be rinsed
- Measure groundwater field parameters
    - pH
    - EC (mS/m)
    - Water temperature (ºC)
    - Eh (mV)
    - Free chlorine (mg/l)
    - Total dissolved solids (mg/l)
    - Salinity (ppm)
    - DO (mg/l)
- Record groundwater sampling information into field sheet

Groundwater Sampling Field Sheets

All information regarding field measurements and observations during groundwater sampling need to be recorded in field sheets. Ensure that all the required fields on the appropriate field forms have been fully completed, legibly before leaving site, including notes on surrounding activities and conditions. The station name recorded in the field sheet should be consistent with the registered station name used in the database management system.

The following information should be recorded when conducting groundwater quality sampling:

- Manual water levels.
    - Site/Station ID
    - Date and time of measurement
    - Height of datum above/below ground level
    - Static water level reading before sampling
    - Groundwater level after sampling
    - Depth of well

    - If a logger is present, the time the logger is removed and put back should be recorded
- Sampling information
    - Site/Station ID
    - Sample technique
        - Purging method and purging field sheet
    - Site/Station type, i.e. borehole, wellpoint, spring, etc.
    - Number of samples collected
    - Sample bottle type and laboratory
        - Type of preservation substance used
    - Screened interval (from and to)
    - Sampling depth (from and to)
    - Observations
        - Sample colour
        - Sample turbidity
        - Sample odour
        - Contamination observations such as oil/sheen
- Standard field parameter measurements and units
- Field observations
    - Comments should be made of any field observations which may have an influence on the results or the ability to monitor a well, these include:
        - Pumping of wells nearby
        - Sprinklers being used
        - Weather conditions
        - Changes in datum height
        - Blockages in the well
        - Vandalism.
        - Potential contamination sources

2.1.3.7 Post Field Procedure

After samples have been collected, filtered (if required), labelled and preserved (if required), the samples need to be placed immediately on ice as per laboratory preservation requirements (Karklins, 1996) (see **Appendix B**). Samples are to be kept cool, below the required preservative temperature, but above freezing, through storage, handling and shipping.

Breakable sample containers (e.g. glass vials) should be individually bubble wrapped. Placing samples in a plastic bag can help minimise the possibility of cross-contamination among samples should a container break (Karklins, 1996).

All field forms are to be scanned and the data captured to the database being used. The field sheets should be updated and uploaded to the database as described in **Section 3.1**.

2.1.3.7.1 Chain of Custody

Chain of Custody (COC) form is a document that lists all the persons that have access to the samples. The COC is generated by the sampler and handed to the designated laboratory personal with the samples, who in turn hands it to the personal required to carry out the various analyses. All persons that handle the samples are required to sign the COC form (WRC, 2007; WRC, 2017). Courier companies that transport the packaged samples to the laboratory make use of waybills to keep track of delivery details.

Field COC procedures are provided by Wisconsin Groundwater Sampling Manual (Karklins, 1996), and are summarised below:

1. Limit sample collection and handling to as few people as possible. If sample transfers are necessary, use signed receipts of possession. The chain of custody record must accompany the samples. Keep a copy of the chain of custody record for your own records.
2. If the samples are known or suspected of being hazardous, give a receipt for each sample collected to the property or facility owner(s). The property or facility owner may request split samples.
3. If the samples are known or suspected of being hazardous (e.g. explosion or corrosion hazard), special shipping procedures may be required by the mail carrier. Check with the mail carrier for restrictions and procedures.
4. Record field measurements and other important data in a field notebook, on field measurement data sheet or on modified data sheets that meet site-specific needs. For legal purposes, indelible ink should be used for recording all data and errors in field records should be crossed out with one line and initialled.
5. When required or applicable, document sample locations, pollution sources, violations, etc. with photographs. If possible, use cameras that print the date of when the photographs were taken.
6. Maintain physical possession and sample integrity of the collected samples until they are properly transferred to the laboratory custodian or the mail carrier.
7. Obtain a sample possession transfer receipt (a copy of the dated and signed chain of custody record) after transferring possession of the samples to the laboratory custodian or the mail carrier.

2.1.3.8 Field-base Quality Assurance and Quality Control Procedures

Quality Assurance (QA) and Quality Control (QC) procedures must be employed to ensure the validity of groundwater sampling data.

Incorrect sampling practices can lead to errors in results. Data that is not correct has no value and is often worse than not collecting data at all, as this can guide incorrect decision making. Sampling QC measures assess sampling accuracy and precision, typically using sample blanks and duplicate samples. These samples are used to assess for sample contamination, quality of preservation methods, equipment decontamination procedures and performance of laboratory analyses (CL:AIRE, 2008).

2.1.3.8.1 Quality Assurance

QA is the policies, procedures and actions established to provide and maintain a degree of confidence in data integrity an accuracy. A thorough programme of checks, comparisons and communication must be implemented to ensure consistent data collection by following a QA system (Sundaram et al., 2009). A systematic approach to developing a QA programme for groundwater sampling is provided in **Figure 2-16** below. The QA programme should also include training of field staff, standardised field procedures, peer reviews, QC measures (i.e. trip blanks and duplicate samples), regular maintenance of field equipment, calibration of field equipment before use and continuous review of the field sampling plan.

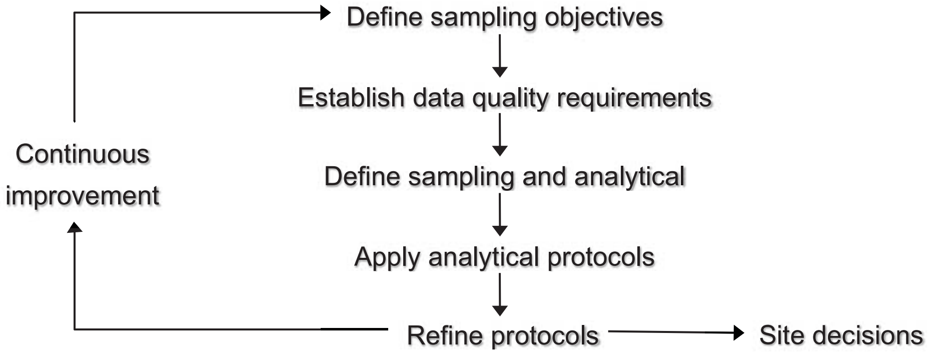


Figure 2-16 QA framework for groundwater sampling (from Sundaram et al., 2009, adapted after Puls and Barcelone, 1996).

2.1.3.9 Quality Control

QC is a sample or procedure used to verify the accuracy and precision of results. The type and number of QC samples collected is dependent on the purpose of the investigation. The confidence in the validity and accuracy of the results is dependent on the number of QC samples. The most common types of QC samples include trip blanks, field blanks and field duplicate samples:

Trip Blank

These blanks are used to monitor potential contamination during shipping and storage. These blanks are sent from the laboratory with empty bottles and remain with other samples throughout the sampling trip. A trip blank is never opened in the field. The trip blank identified areas of exposure such as shipping temperatures and pressures, laboratory preparation of field samples and laboratory preparation of field samples for analysis. Trip blanks are to be included when sampling for volatiles.

Field Blank

The field blank is analyte free water, typically deionised water, that is poured into a sampling container in the field. The same procedure for filling bottles with sampled water is used to prepare the field blank. The field blank is used to assess any contamination which many occur during sampling. The field blank should be analysed for the same parameters as the samples. At least one field blank should be collected and analysed for each monitoring programme.

Duplicate Samples

Duplicate samples are used to assess the precision of the analytical process of the laboratory. A duplicate sample is prepared by collecting double the sample from the same well and split into two different bottles/ sampling sets; the duplicate samples are labelled differently. The duplicate sample must be recorded correctly on the field sheet. The duplicate sample is treated as a normal sample and analysed for the same parameters at the laboratory. A second set of duplicate samples can be prepared and sent to a separate laboratory for QA.

Anion-Cation Balance

Another simple way to check the accuracy of the laboratory analyses is by calculating the anion-cation balance. Because water is neutrally charged, the sum of the anions should equal the sum of the cations (Sundaram et al., 2009). The percentage error (difference between analysed cations and anions) is calculated using the following equation, an error of ± 5% in the ion balance is considered acceptable (CL:AIRE, 2008):

$$\boldsymbol{Ion\ Balance} = \frac{(\sum \boldsymbol{meq/l\ Cations} - \sum \boldsymbol{meq/l\ Anions})}{(\sum \boldsymbol{meq/l\ Cations} + \sum \boldsymbol{meq/l\ Anions})} \times \mathbf{100}$$

Where $\sum Cations$ is the sum of the cations and $\sum Anions$ is the sum of the anions.

Concentrations of cations and anions are expressed as milliequivalents per litre.

2.1.3.10 Automatic Water Quality Monitoring

Automatic dataloggers are able to measure parameters in the well with minimal disturbance, since no pumping is required. Dataloggers are able to measure a suite of parameters such as EC, pH, temperature, Eh, turbidity, DO, chloride, etc.

Dataloggers can be installed at wells for monitoring of groundwater parameters as well as for operational monitoring for abstraction wells. For example, EC concentration is often used as an operational condition where the concentration at the abstraction well cannot exceed a threshold value. In this case automatic data loggers are installed to monitor changes in EC concentration during pumping. Continuous measurements are transmitted via telemetry to the pump operators. Data loggers can also be downloaded routinely in the field directly from the logger by using logger laptop/app interfaces.

Dataloggers can also be used to create vertical downhole profiles of parameters, see **Figure 2-17** for an example of an EC vertical profile. A downhole profile is done by lowering a datalogger down a well and taking recordings at predetermined depths or programmed time intervals. For vertical profiling, the depth is either measured by a pressure sensor (see **Section 2.1.2.4**) or using a logger attached to a measuring tape. It is important to calibrate downhole dataloggers before doing field investigations as per the manufacturer instructions. WRC (2007) provides a comprehensive guide on operating downhole loggers. Below are key points when conducting downhole logs:

- Calibrate loggers before doing a test.
- Do not sample or purge the well before conducting a test as this will disturb the water column and affect the results.

- At the start of logging, once the water logger is submersed, hold the logger in place to ensure that the sensors stabilise.
- Lower the logger at a steady pace.
- Stop the logging at least one or two metres above the bottom of the well.
- Data collected while pulling the logger out of the well should be rejected as disturbances of the water column can affect the results.

Data retrieved from dataloggers must be uploaded to the selected database system. All raw files should be saved separately from processed files and archived (see **Section 3.3.2**).

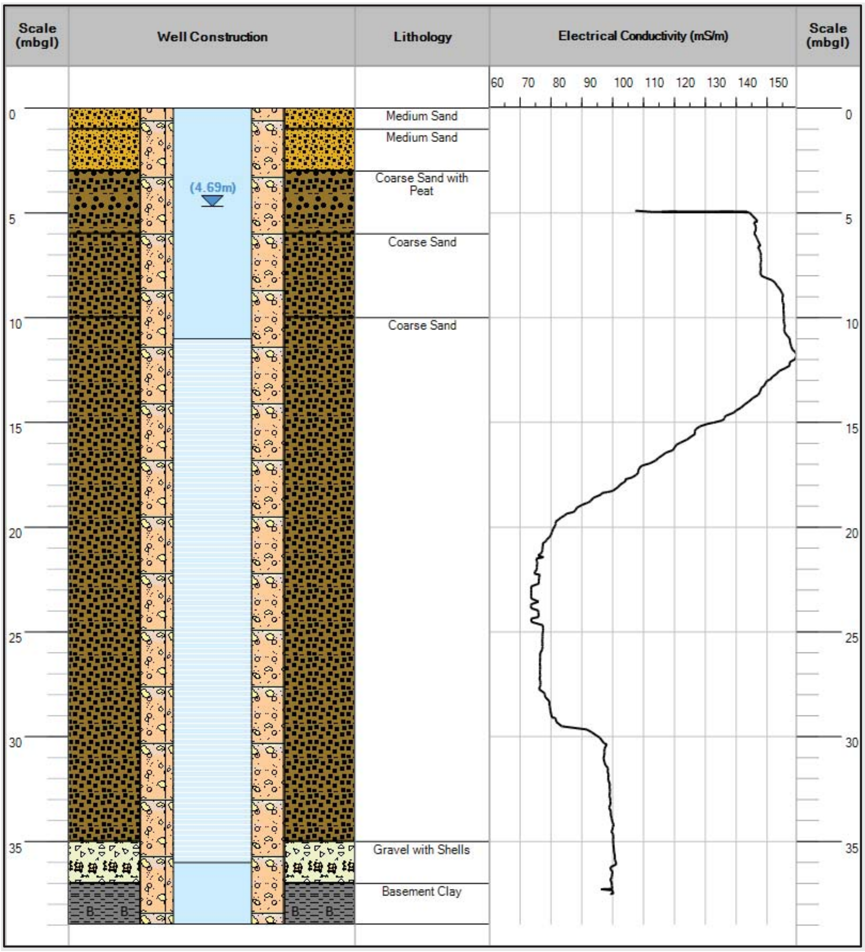


Figure 2-17 **Example of a downhole vertical EC log with the well log, showing the change in EC concentration with depth.**

2.1.3.11 Summary

Figure 2-18 outlines the general operational flow to ensure that groundwater quality monitoring is conducted according to best practices. This includes QA and QC to ensure the validity of groundwater sampling data. Incorrect sampling practices lead to errors in results which ultimately leads to incorrect decision making. **Figure 2-18** also includes the processing of laboratory results (**Section 3.1.1** for further details).

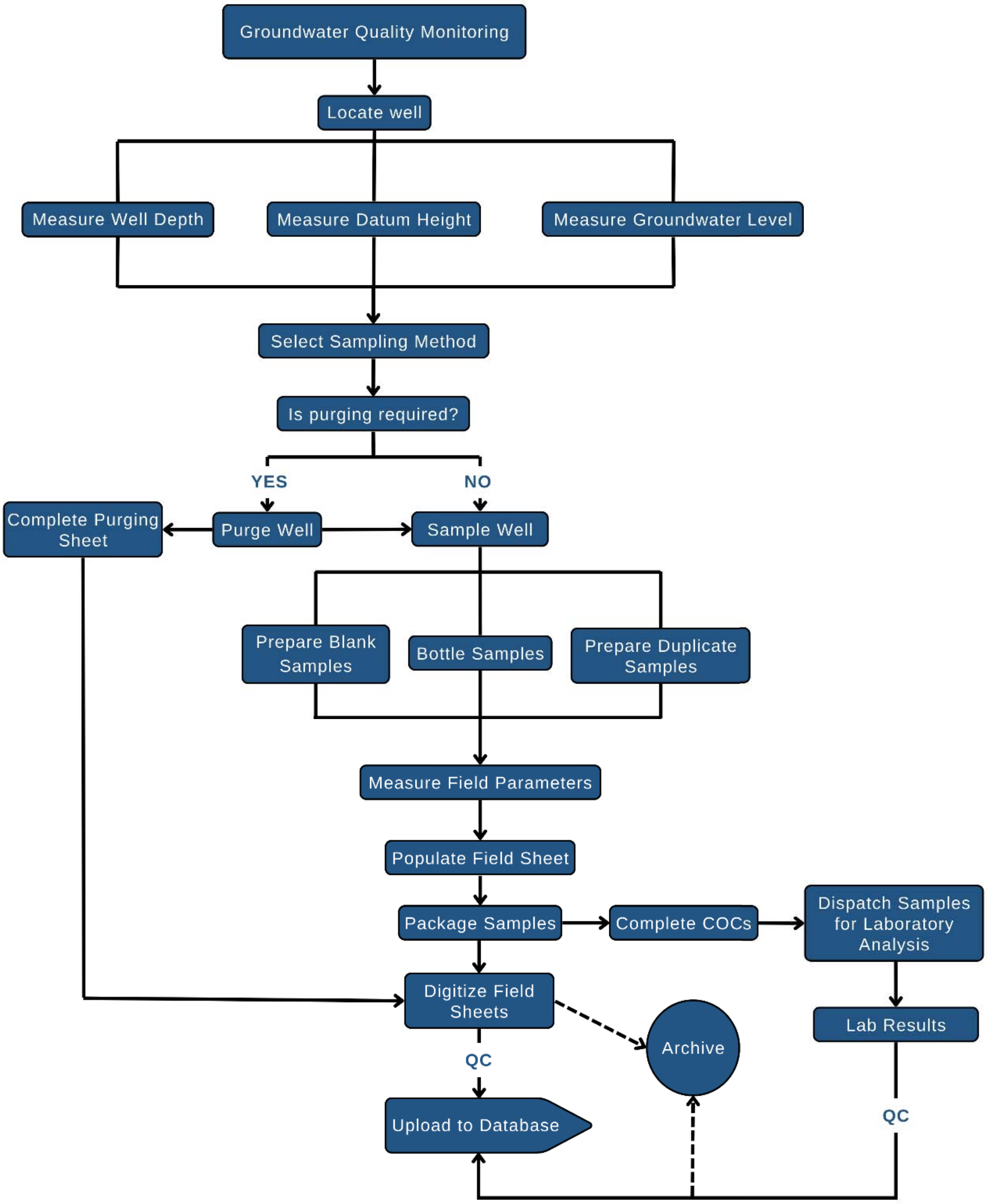


Figure 2-18 **Operational flow for conducting groundwater quality monitoring, illustrating the general steps in groundwater quality monitoring from collecting groundwater data in the field to processing the data and uploading to a database.**

2.1.4 Groundwater Abstraction Monitoring

Groundwater abstraction refers to the volume of water being removed from the aquifer typically from pumping or discharge under pressure in the case of a spring or artesian well. Groundwater abstraction data is an important parameter for sustainable management of the resource. There is a lack of effective monitoring, compliance and control systems regulating groundwater abstraction in South Africa (DWS, 2016a). The lack of effective monitoring of groundwater abstraction leads to over abstraction and the depletion of the groundwater resource.

2.1.4.1 Groundwater Users

Groundwater is an important resource used by various sectors including agriculture, water supply services, mining, industry, recreation, aquaculture and power generation (DSW, 2016a). Groundwater users can be separated into Schedule 1 Users and Licenced Users, depending on several factors such as the type of use and the volume of use. A Schedule 1 user typically has a single well with an abstraction volume within the Section 21(a) General Authorisation (GA) volumes. Licenced groundwater users include farms, mines, industries, private owners and municipalities. Licenced users often have more than one well or abstract large volumes.

It is the responsibility of the landowner to ensure groundwater abstraction is monitored in accordance with the NWA (Act. 36 of 1998). The NWA GA (2016 Revision) stipulates that a water user who takes groundwater at more than 2 l/s on property or piece of land in terms of the Section 21(a) GA must measure and record the volume of water that is taken (DWS, 2016c). The volume of water taken must be measured and recorded at the end of each month. The records must be kept for a minimum of five years and be available to officials of the responsible Water Service Authorities (WSA) upon request (DWS, 2016c).

Schedule 1 users whose abstraction is less than 2 l/s are not required to measure groundwater abstraction volumes, however these users should be encouraged to register the water use and conduct basic monitoring of water levels (see **Section 2.1.1.2**) and have flow meters installed at pumping wells to monitor abstraction volumes (see **2.1.4.2**). The data collected by the Schedule 1 users should be uploaded to national database systems and provided to the WSA. The WSA should review the Schedule 1 users use to ensure the abstracted volumes still comply with Schedule 1 use and that there is no detrimental impact to the water resource.

WUL conditions of Licenced users, specify what monitoring activities are required, depending on the intended use and licence. Licenced users are meant to undertake and report compliance monitoring (water level, quality and use) according to the conditions of the water use licence. Compliance monitoring of groundwater use (abstraction volumes) requires the installation of flow meters to record abstraction volumes. Compliance monitoring is however, not regularly undertaken. Compliance monitoring data should be uploaded to the relevant national database system and be provided to the WSA so that water resources can be managed sustainably.

A lack of groundwater monitoring data prevents authorities, such as municipalities and the DWS, from determining the overall use from a water resource and they are therefore unable to be proactive in acting against over abstraction. Due to limited monitoring data, the DWS are unable to sustainably allocate and control the use of groundwater.

2.1.4.2 Methods to Determine Groundwater Abstraction Volumes

Abstraction volumes from wells equipped with motorised pumps can be measured directly using various techniques such as flow meters, power consumption, dataloggers, etc. Groundwater abstraction and water use volumes can also be estimated for regional and local scales by using techniques such as GNSS, remote sensing imagery and GIS. These techniques will be discussed in more detail below. In the cases of hand-pumps and hand-dug wells, the measurement of abstraction volumes is difficult and abstraction volumes have to be estimated based on local knowledge, e.g. how many containers are filled daily.

2.1.4.2.1 Flow Meters

Flow meters are the most effective method of measuring groundwater abstraction from a well. Flow meters measure the flow rate and cumulative volume of water that passes through a pipe or outlet. The volume of water that passes through a meter is typically displayed in metres cubed (m^3). The installation of flow meters should be compulsory when new abstraction wells are drilled and equipped. WRC (2011a), *Integrated Water Meter Management*, provides an overview of flow meter selection and management based on their advantages and disadvantages.

Flow meters either record groundwater abstraction electronically with flow meters connected to software or they can be recorded manually by reading the displayed abstraction volumes on the flow meter (see **Figure 2-19**).

The South African Trade Metrology Act (Act No. 77 of 1973) requires consumer flow meters of sizes 15 to 100 mm to comply with the requirements of SANS 1529. The Act also stipulates that municipalities must ensure that all meters are kept in a verifiable condition at all times. Flow meters must be verified by a qualified and registered Verification Officer in a SANAS Accredited Test Laboratory in terms of SANS 10378 (WRC, 2011a). A flow meter that does not comply with the accuracy requirements specified in SANS 1529, must not be used.

Flow meters are generally classified based on the mechanism used to measure the flow passing through it, i.e. mechanical, electromagnetic or ultrasonic. Mechanical meters have moving parts that detect the flow, whereas electromagnetic and ultrasonic meters detect the flow through using electromagnetic principles or ultrasound waves (WRC, 2011a). Typical flow meters used to measure groundwater abstraction from wells include:

- Mechanical flow meters
    - Volumetric flow meters
    - Single-jet flow meters
    - Multi-jet flow meters
    - Rotary piston flow meters
    - Woltmann flow meters
- Electromagnetic flow meters
- Ultrasonic flow meters

Figure 2-19 **Examples of typical flow meter installations to measure groundwater abstraction from abstraction wells.**

2.1.4.2.2 Pump Power Supply

Estimated groundwater abstraction volumes can be measured indirectly through the collection of indicative data such monitoring the power supply of an electric pump. This method can be used when a well is on a detailed pumping schedule. The method involves monitoring the electrical supply to determine the pumping state (on and off) (Botha, 2017). The hours of pump operation are multiplied by the average pumping rate to estimate the groundwater abstraction volume.

2.1.4.2.3 Thermo-Loggers

Temperature data loggers can be used to measure groundwater abstraction by monitoring the temperature of the groundwater abstraction pipe. This method uses the variations to determine the pumping state (on and off) (Botha, 2017). Thermo data loggers are able to capture the measured data and transfer the data to a computer. As with monitoring the power supply to a pump, the hours of pump operation can be determined from the variations in temperature, and this multiplied by the average pumping rate to estimate groundwater abstraction volumes.

2.1.4.2.4 Hand Pump Waterpoint Data Transmitter

The monitoring of abstraction volumes from hand-pumps and hand-dug wells is challenging and abstraction volumes are estimated. Due to low outputs, varying pressure and relatively wide apertures, direct flow measurement devices are not suited to operate with handpumps (Hope and Foster, 2012). To overcome this challenge, a Waterpoint Data Transmitter (WDT) can be installed to provide real-time data on handpump usage which can be used to estimate groundwater abstraction. The WDT uses an accelerometer attached to the handpump to monitor the number of strokes made in operating the hand pump and then transmits this information over the global system for mobile communications, or GSM, network (see **Figure 2-20**). This provides an estimate of the volume of water pumped and can also show daily to seasonal demand levels, including critical under- or over-usage information (see **Figure 2-21**) (Hope and Foster, 2012). The methodology of using WDT for monitoring groundwater use at a handpump is described in detail by Hope and Foster (2012).

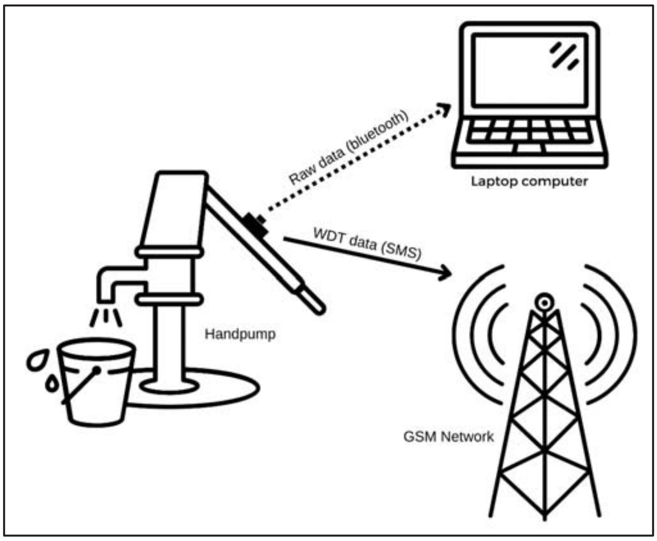


Figure 2-20 Water Point Data Transmitter setup to a rural groundwater handpump (modified after Hope and Foster, 2012).

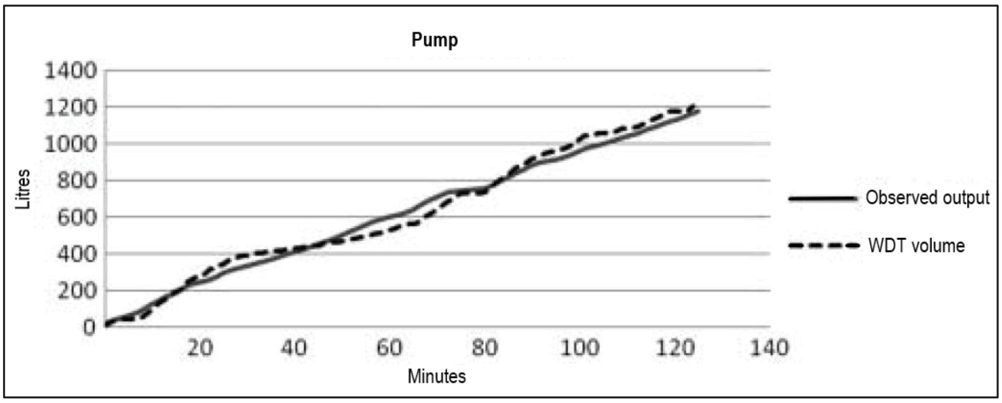


Figure 2-21 WDT volume estimate vs observed pumping volumes (from Hope and Foster, 2012). The estimated WDT volumes are similar to the observed pumping volumes, indicating that the WDT can provide accurate abstraction volume estimations.

2.1.4.2.5 GNSS

In certain contexts, GNSS data can be used to monitor effects of groundwater abstraction (or injection) on an aquifer (see WRC, 2013 and Wonnacott et al., 2015 for details) and measure seasonal fluctuations in groundwater storage. GNSS receivers installed on or near to abstraction wells can be used to record the effects of hydrological process which produce minor deformation of the Earth's surface (hydrological loading), and thus can measure the aquifer flux caused by abstraction (or natural discharge) and recharge (natural and artificial). Under typical conditions groundwater abstraction may cause subsidence in the aquifer which then rebounds during recharge events. However, hydrological loading when an aquifer is over abstracted causes the aquifer to not rebound to the base level which results in permanent compression of the aquifer and permanent loss of storage (**Figure 2-22**). The use of GNSS allows for tracking of sustainable abstraction. GNSS allows for measurement of rebound and subsidence at cm level, for near real time (6 – 12 hours) monitoring which can act as an early warning system for unsustainable abstraction, represented as limited rebound. It should be noted that GNSS only provides surface motion information at the GNSS site, and comparisons to other GNSS sites will require interpolation and technical experts. Further GNSS will also measure any tectonic deformation that occurs in the resource area, which is relevant as tectonic deformation may change aquifer characteristics.

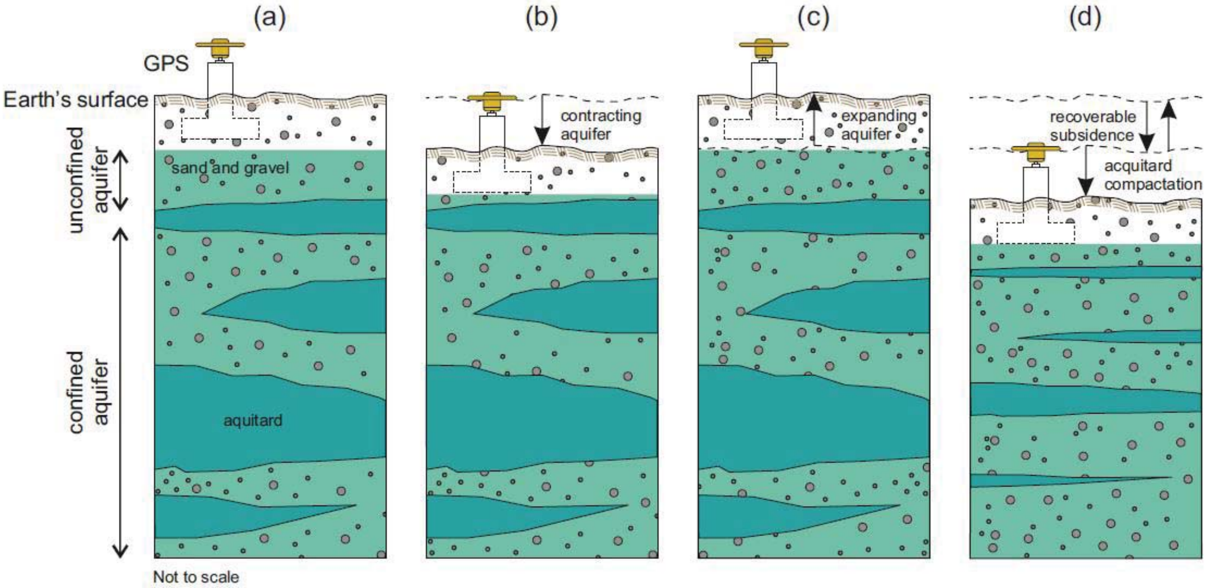


Figure 2-22 **Schematic of using GNSS to monitor aquifer subsidence (contraction) and rebound (expansion). Under equilibrium, the land surface remains stable (a). During a discharge period (e.g. abstraction), groundwater volume decreases, and the GNSS records a negative change in elevation (z-value) (b). During a recharge period (e.g. rainfall), groundwater volume increases, and the GNSS records a positive change in elevation. A difference in averaged elevation may indicate permanent subsidence due to compaction (d). Over a hydrological period, the GNSS may record cyclical subsidence and rebound. From Ferreira et al., (2019).**

2.1.4.2.6 GIS and remote sensing

Difficulties may arise when using direct quantification methods (i.e. flow meters and power consumption data) to calculate groundwater abstraction on a regional or water resource scale, particularly when trying to determine the impact of large-scale agricultural use (Castaño et al., 2009). The use of earth observation approaches such as satellite based optical imagery (e.g. multispectral from Sentinel-2 and Landsat 9 platforms), radar-based imagery (e.g. synthetic aperture radar [SAR] Sentinel-1) and gravity measurements (e.g. gravity filed anomalies data from GRACE) can provide indirect measurements of groundwater use and aquifer surface expression changes. The accuracy and validity of remote sensing analysis must be ascertained through in situ field measurements, validation and verification and ground-truthing activities. An example of such an approach is given by Castaño et al. (2009), where multitemporal and multispectral satellite images are used to quantify irrigation as a proxy for groundwater abstraction. Satellite imagery is used to create detailed classification of land use (e.g. crop type) which is combined in Geographic Information System (GIS) with auxiliary geospatial data (i.e. surface water features) and knowledge of agricultural practices (i.e. local irrigation methods; water conservation strategies) for validation and verification to increase accuracy of the estimated crop irrigation.

Castaño et al. (2009) outlines the method as:

1. The irrigated crops are identified and classified by the multitemporal analysis of images obtained by multispectral sensors on satellite platforms, comparing the phenological evolution of the crops with the evolution of the Normalised Difference Vegetation Index (NDVI).
2. The surface area for each crop is then quantified by entering the data in a GIS. Based on the surface area of each crop and the knowledge of the water requirements they have, the theoretical amount of water needed for those crops to reach the stage of development visible in the images is calculated.
3. When the surface of crops which are dependent on groundwater abstraction and the true state of the agricultural practices in the region are known, a correction coefficient is applied to translate the theoretical amount of water to real values applied to each crop in the area.
4. All the information generated (distributed over space and time) is then integrated in a hydrologic information system, which allows the relationships among all the elements of the water balance to be identified.

In conjunction with multispectral (or hyperspectral) approaches, radar imaging from earth observation satellites can be used to measure surface deformation as an aquifer subsides and/or rebounds (Amelung et al., 1999). By using Interferometric Synthetic Aperture Radar (InSAR) surface-deformation time series analyses, the ground motion of an aquifer area can be measured at millimetre scale depending on the technique used and at regular intervals, depending on the sensors used (Radutu et al., 2017). At regional and longer-term scales, gravity measurements can be used to quantify long-term changes in groundwater storage (Chen et al., 2016) thereby providing important context for local and study specific observations in groundwater changes.

2.1.5 Spring Monitoring

Springs are the natural outlet of groundwater at surface. These are the points/areas where the groundwater head equals or exceeds the atmospheric pressure (SADC-WSCU, 2001). Springs hold important groundwater information and support many sensitive ecosystems and therefore require routine monitoring.

2.1.5.1 Spring Discharge

The discharge (i.e. flow) of a spring determines the volume that supports ecological requirements and baseflow and then what remains as potential for supply. Springs form important sources of water supply if the flow is sufficient and consistent throughout the year (SADC-WSCU, 2001). The flow of a spring depends on the recharge area of the spring, the magnitude and frequency of groundwater recharge and the storage capacity and saturation level of aquifers (SADC-WSCU, 2001).

Spring discharge can vary from relatively low discharge rates to high discharge rates. The technique used to measure the discharge of a spring varies depending on the discharge rates and the outlet.

The volumetric method is used to calculate the discharge rate for springs with moderate to low discharge. The water from the spring is channelised using material such as a pipe. The discharge is measured at an outlet pipe using a stopwatch to record how long the water takes to fill a container with a known volume (e.g. bucket or drum). It is important to use a measuring container that has been calibrated to determine the volume of the container. To measure the discharge, place the container to capture the spring water flow and start the stopwatch immediately. Measure the time it takes to fill the container and calculate the discharge using the equation below.

$$\mathbf{Discharge}\ (\mathbf{l}/\boldsymbol{s}) = \frac{\mathbf{Volume}\ (\mathbf{l})}{\mathbf{time}\ (\boldsymbol{s})}$$

The process should be repeated at least three times to determine an average (if the three measurements are very different, repeat the measurements again). The measured discharge must be recorded in a field sheet, digitized and uploaded to a database.

For springs with higher discharge, a V-notch weir can be installed to measure discharge. The discharge is calculated based on the theoretical relationship between flow and the water level. To measure the discharge using a V-notch weir, measure the height of the water from the tip of the V-notch (i.e. the head) (see **Figure 2-23**). The head of water changes with discharge and is measured using a measuring tool, e.g. ruler. The discharge can be determined from the measured head using a reference table, **Table 2-5**, which has been calculated from the equation below for a 90º V-notch. There are six standard angles for V-notch weirs: 22º, 30º, 45º, 60º, 90º and 120º. The coefficient varies depending on the V-notch angle.

$$\boldsymbol{Discharge}\ (\boldsymbol{l}/\boldsymbol{s}) = \mathbf{1365}\ \times\ \mathbf{Head}\ (\mathbf{m})^{\mathbf{2.5}}$$

Where coefficient of 90º V-notch = 1365

For example, if the measured head is 105 mm, go to the first column, then come down the column until you read 100, then across to the right, to the column that indicates 5. The discharge is 4.9 l/s. The measured head (water level) and discharge must be recorded in a field sheet, digitised and uploaded to a database.

The discharge at a V-notch weir can also be measured using a water level datalogger installed at the base of the V-notch weir (see **Section 2.1.2.4**). The water level retrieved can then be converted to discharge. Logger readings at a V-notch weir must be cross checked with regular manual measurements at the weir.

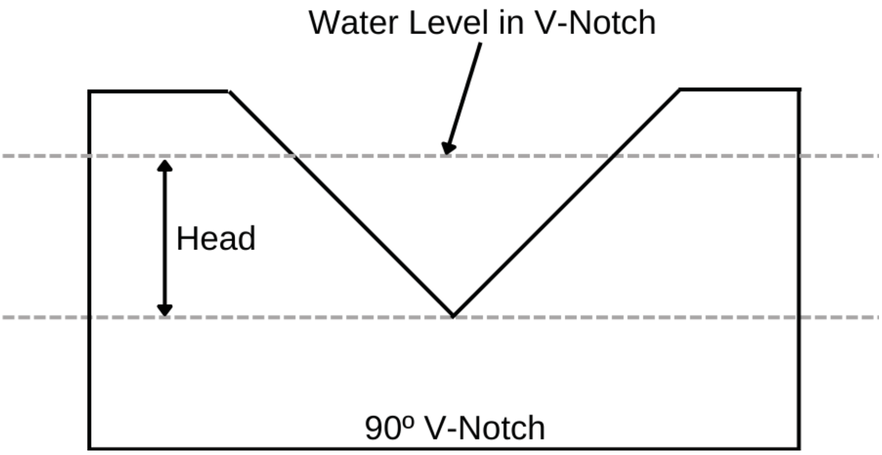
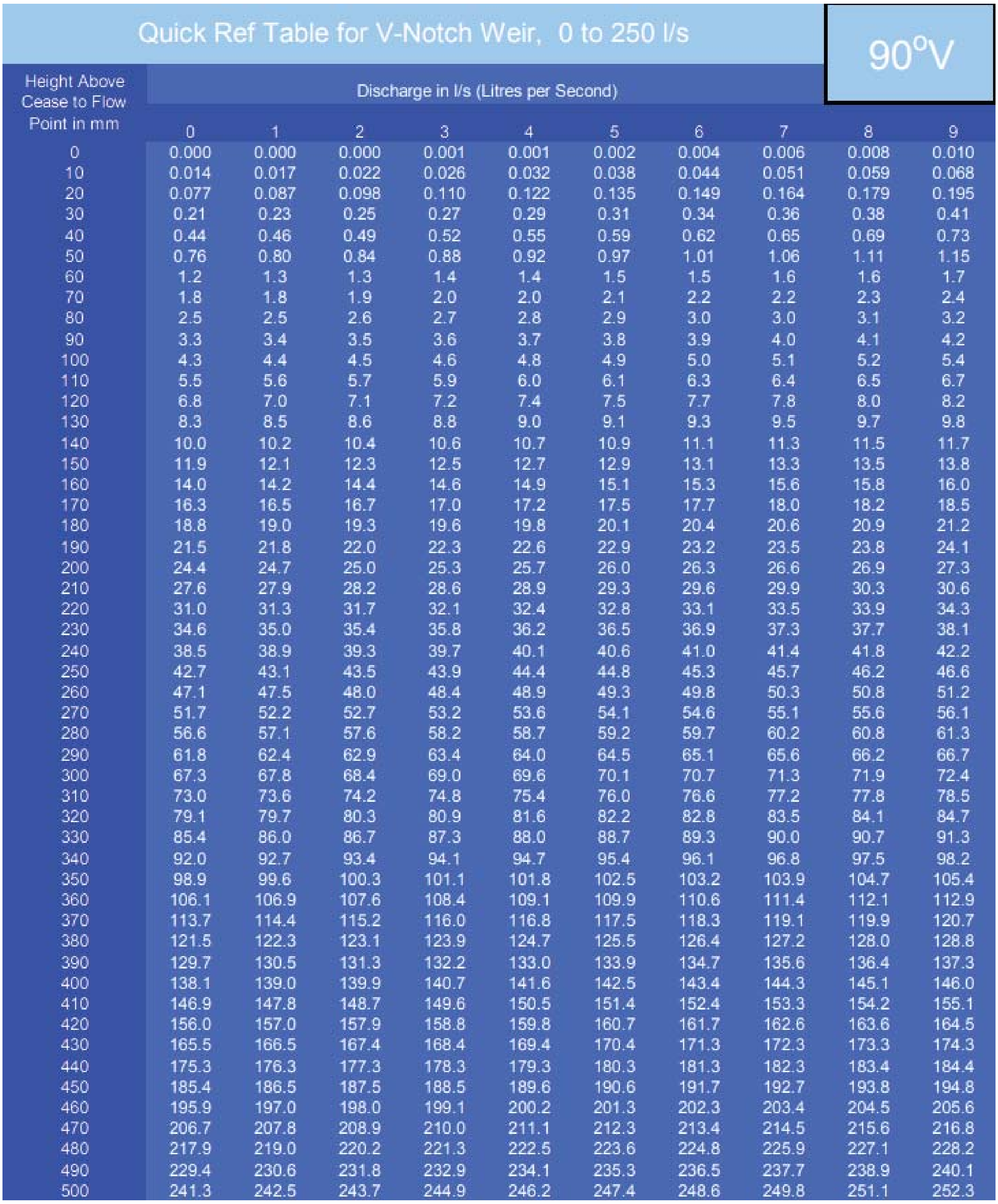


Figure 2-23 Schematic of a 90º V-notch.

Table 2-5 **Reference table for 90º V-Notch Weir, from ACE (2022), using the formula Discharge = 1365 x $\text{Head}_m^{2.5}$.**



Quick Ref Table for V-Notch Weir, 0 to 250 l/s

90°V

Height Above Cease to Flow Point in mm	Discharge in l/s (Litres per Second)									
	0	1	2	3	4	5	6	7	8	9
0	0.000	0.000	0.000	0.001	0.001	0.002	0.004	0.006	0.008	0.010
10	0.014	0.017	0.022	0.026	0.032	0.038	0.044	0.051	0.059	0.068
20	0.077	0.087	0.098	0.110	0.122	0.135	0.149	0.164	0.179	0.195
30	0.21	0.23	0.25	0.27	0.29	0.31	0.34	0.36	0.38	0.41
40	0.44	0.46	0.49	0.52	0.55	0.59	0.62	0.65	0.69	0.73
50	0.76	0.80	0.84	0.88	0.92	0.97	1.01	1.06	1.11	1.15
60	1.2	1.3	1.3	1.4	1.4	1.5	1.5	1.6	1.6	1.7
70	1.8	1.8	1.9	2.0	2.0	2.1	2.2	2.2	2.3	2.4
80	2.5	2.5	2.6	2.7	2.8	2.9	3.0	3.0	3.1	3.2
90	3.3	3.4	3.5	3.6	3.7	3.8	3.9	4.0	4.1	4.2
100	4.3	4.4	4.5	4.6	4.8	4.9	5.0	5.1	5.2	5.4
110	5.5	5.6	5.7	5.9	6.0	6.1	6.3	6.4	6.5	6.7
120	6.8	7.0	7.1	7.2	7.4	7.5	7.7	7.8	8.0	8.2
130	8.3	8.5	8.6	8.8	9.0	9.1	9.3	9.5	9.7	9.8
140	10.0	10.2	10.4	10.6	10.7	10.9	11.1	11.3	11.5	11.7
150	11.9	12.1	12.3	12.5	12.7	12.9	13.1	13.3	13.5	13.8
160	14.0	14.2	14.4	14.6	14.9	15.1	15.3	15.6	15.8	16.0
170	16.3	16.5	16.7	17.0	17.2	17.5	17.7	18.0	18.2	18.5
180	18.8	19.0	19.3	19.6	19.8	20.1	20.4	20.6	20.9	21.2
190	21.5	21.8	22.0	22.3	22.6	22.9	23.2	23.5	23.8	24.1
200	24.4	24.7	25.0	25.3	25.7	26.0	26.3	26.6	26.9	27.3
210	27.6	27.9	28.2	28.6	28.9	29.3	29.6	29.9	30.3	30.6
220	31.0	31.3	31.7	32.1	32.4	32.8	33.1	33.5	33.9	34.3
230	34.6	35.0	35.4	35.8	36.2	36.5	36.9	37.3	37.7	38.1
240	38.5	38.9	39.3	39.7	40.1	40.6	41.0	41.4	41.8	42.2
250	42.7	43.1	43.5	43.9	44.4	44.8	45.3	45.7	46.2	46.6
260	47.1	47.5	48.0	48.4	48.9	49.3	49.8	50.3	50.8	51.2
270	51.7	52.2	52.7	53.2	53.6	54.1	54.6	55.1	55.6	56.1
280	56.6	57.1	57.6	58.2	58.7	59.2	59.7	60.2	60.8	61.3
290	61.8	62.4	62.9	63.4	64.0	64.5	65.1	65.6	66.2	66.7
300	67.3	67.8	68.4	69.0	69.6	70.1	70.7	71.3	71.9	72.4
310	73.0	73.6	74.2	74.8	75.4	76.0	76.6	77.2	77.8	78.5
320	79.1	79.7	80.3	80.9	81.6	82.2	82.8	83.5	84.1	84.7
330	85.4	86.0	86.7	87.3	88.0	88.7	89.3	90.0	90.7	91.3
340	92.0	92.7	93.4	94.1	94.7	95.4	96.1	96.8	97.5	98.2
350	98.9	99.6	100.3	101.1	101.8	102.5	103.2	103.9	104.7	105.4
360	106.1	106.9	107.6	108.4	109.1	109.9	110.6	111.4	112.1	112.9
370	113.7	114.4	115.2	116.0	116.8	117.5	118.3	119.1	119.9	120.7
380	121.5	122.3	123.1	123.9	124.7	125.5	126.4	127.2	128.0	128.8
390	129.7	130.5	131.3	132.2	133.0	133.9	134.7	135.6	136.4	137.3
400	138.1	139.0	139.9	140.7	141.6	142.5	143.4	144.3	145.1	146.0
410	146.9	147.8	148.7	149.6	150.5	151.4	152.4	153.3	154.2	155.1
420	156.0	157.0	157.9	158.8	159.8	160.7	161.7	162.6	163.6	164.5
430	165.5	166.5	167.4	168.4	169.4	170.4	171.3	172.3	173.3	174.3
440	175.3	176.3	177.3	178.3	179.3	180.3	181.3	182.3	183.4	184.4
450	185.4	186.5	187.5	188.5	189.6	190.6	191.7	192.7	193.8	194.8
460	195.9	197.0	198.0	199.1	200.2	201.3	202.3	203.4	204.5	205.6
470	206.7	207.8	208.9	210.0	211.1	212.3	213.4	214.5	215.6	216.8
480	217.9	219.0	220.2	221.3	222.5	223.6	224.8	225.9	227.1	228.2
490	229.4	230.6	231.8	232.9	234.1	235.3	236.5	237.7	238.9	240.1
500	241.3	242.5	243.7	244.9	246.2	247.4	248.6	249.8	251.1	252.3

2.1.5.2 Spring Sampling

When sampling from a spring, it is important to sample water that is flowing and not stagnant, to ensure a representative groundwater sample is collected. Samples can be collected from outlet pipes and weirs which are installed at the springs (see **Figure 2-24**). For springs that do not have any infrastructure installed, the best way to reduce contamination is to install a well sampling pump as close to the spring outlet as possible. Spring sampling should be undertaken as per the standard of groundwater sampling described in **Section 2.1.3**.

Figure 2-24 Groundwater sampling directly from spring outlet pipe.

2.1.6 Monitoring Frequency

The frequency of monitoring activities is dependent of the type, scale and purpose of monitoring. Each monitoring objective leads to a monitoring component with its own specific requirements. Factors to consider when determining the frequency of monitoring activities includes seasonal variations, this is especially relevant to water level and spring discharge monitoring, as well as aquifer characteristics (Ravenscroft and Lytton, 2022). **Figure 2-25** provides an overview of factors to consider when determining the frequency of monitoring groundwater levels, the frequency of measurement should be adequate to detect short-term and seasonal groundwater level fluctuations of interest and to discriminate between the effects of short and long-term hydrologic stresses (Taylor and Alley, 2001).

To determine the exact requirements for groundwater quality monitoring, specialist knowledge is required to determine which constituents to analyse, as this depends largely on the chemical characteristics of the hosting aquifer, the hydrochemical processes in the aquifer and the process or expected contaminant to be monitored (SADC-GMI, IGRAC, IGS (2019). The frequency of groundwater quality monitoring will vary depending on the aforementioned factors and determined by the specialist. Barcelona et al (1985); U.S. EPA (1989); U.S. EPA 2009; Timms et al. (2009); SADC-GMI, IGRAC, IGS 2019); Sundaram et al. (2009); and Environment Agency (2003); provide guides for groundwater quality and water level monitoring frequency.

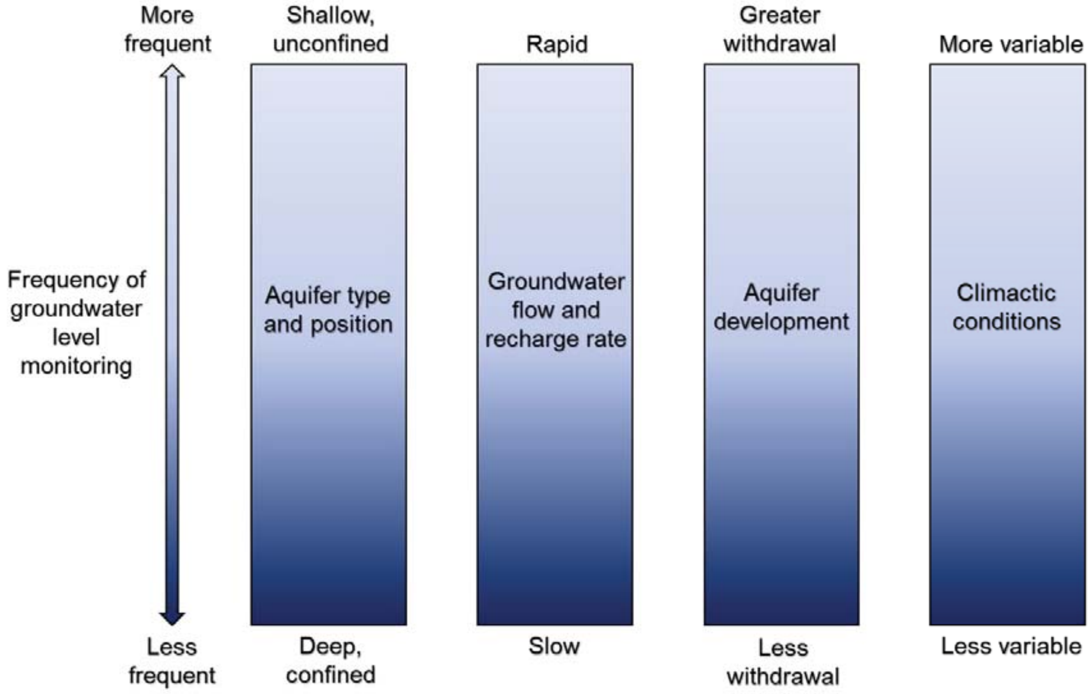


Figure 2-25 **Common factors influencing the frequency of groundwater level monitoring (modified after Taylor and Alley, 2001).**

For groundwater quality monitoring, a distinction should be drawn between routine monitoring, in which no particular risk is being guarded against, and purposive monitoring, which typically responds to regulatory requirements following anthropogenic pollution or a natural risk to abstraction wells to provide an early warning (Ravenscroft and Lytton, 2022). As more time-series data are collected, the frequency of monitoring can be adapted. Monitoring intervals can also be estimated by modelling pollutant travel times from a potential contamination source by assessing how quickly a well might be contaminated (Ravenscroft and Lytton, 2022).

The monitoring frequency for various groundwater level and quality monitoring objectives are summarised in **Table 2-6**. For groundwater abstraction monitoring and compliance monitoring, abstraction volumes should be recorded monthly or quarterly, in line with typical general WUL conditions.

Table 2-6 **Proposed monitoring frequency for various groundwater monitoring objectives (modified after Sundaram et al., 2009; adapted from Timms et al., 2009).**

Purpose for Monitoring	Groundwater Level	Groundwater Quality Indicator (e.g. EC, temperature, pH)	Groundwater Quality Parameters
Basic resource monitoring	Quarterly	Annually	As required**
Resource monitoring at sensitive sites (e.g. significant drawdown, well head protection zone, risk of groundwater quality impacts.	Daily	Monthly	Quarterly**
Recharge processes and rainfall response.	Daily or Hourly	Monthly or hourly	As required**
Measure aquifer confinement and specific storage.	Hourly or 15 minutes*	-	-
Point source contamination - Potential Impacts***	Quarterly	Quarterly	Half-yearly**
Diffuse source contamination - Potential impacts	Half-yearly	Half-yearly	Annually**

* Including barometric pressure measurement at the well.

** Selection of appropriate water quality parameters for testing depends on the purpose of monitoring, possible contaminants and constraints based on the cost of analyses.

*** Depending on the groundwater quality protection zone level.

2.2 GROUNDWATER DEVELOPMENT

2.2.1 Well Drilling

Wells are drilled for various purposes, including groundwater exploration, water supply, monitoring groundwater behaviour and composition, and contamination assessments. Wells are to be drilled in accordance with SANS 10299 *Development, maintenance and management of groundwater resources*. Collecting data from well drilling and test pumping is essential to develop a conceptual understanding of aquifer systems by gaining insight into groundwater availability, quality and use. The collected data is used to successfully develop and manage groundwater resources. It is crucial to capture and store all data collected during the various steps of drilling and test pumping a well. Regardless of if a well was successful, low yielding or dry, all wells provide meaningful data.

This section does not describe the drilling process and drilling techniques but outlines the important information that must be recorded during the drilling of a well.

Before a new well is drilled, site investigations are required to determine the best location of the well in terms of groundwater potential, access and use. Well siting investigations consist of desktop assessments, field investigations and geophysical investigations. The steps to be followed during the siting process and data and information to be collected during each step are summarised in **Table 2-7**.

Table 2-7 **Steps in borehole siting process with data and information to be collected at each step (modified after SADC-GMI, IGRAC, IGS, 2019).**

Activity	Objectives	Key data and information to be collected
Desktop assessment	• Develop a preliminary conceptual understanding of the hydrogeology of an area.	• Records of existing wells within a specific radius from the area of interest, including borehole construction, water strikes, lithology, quality, yields, groundwater levels, etc. • Types of aquifers which occur in the area • Geological controls of groundwater occurrence
Hydrocensus and field mapping.	• Identify and understand groundwater use within the area. • Identify geological, hydrogeological and hydrological features in the area. • Confirm the findings of the desktop assessment.	• Location of surrounding wells (latitude, longitude, elevation) • Groundwater levels and field groundwater quality parameters (EC, pH, temp) • Well use in terms of volume and purpose (potable, irrigation) • Recorded well yields • Geological, hydrogeological and hydrological data • Identify locations for geophysical survey • Identify potential drilling sites
Field geophysical survey	• Locate suitable drilling target using an appropriate geophysical method(s).	• Location of geophysical profile • Data of the investigated geophysical parameters • Identify potential drilling sites, water strike and drilling depth

All data and information gathered during drilling must be recorded in the appropriate drilling field sheets, this includes a daily log of the drilling activities (i.e. drilling techniques, depths, diameters, casing type and depths, water strikes, etc.), a geological logging form for detailed logging of drilling material (chips or core), and penetration rate form. The field sheets and all data collected during drilling must be digitized and the data uploaded to a database. The following data must be recorded during drilling:

- Name and address of the well owner and the drilling contractor
- Well coordinates, coordinate system and coordinate reference datum (the appropriate technique should be used to obtain the drilling coordinates, see **Section 2.1.1**)
    - Latitude, longitude and elevation
- Dates of drilling
- Drilling methods employed
- Total depth of wells
- Drilling diameter and depth of changes in diameter
- Penetration rate per metre
- Depth of water strikes
    - Blow yield per water strike. Blow yield at a well can be measured from a discharge pipe or V-notch installed at the well (see **Section 2.1.5.1**)
    - General groundwater parameters per water strike (pH, EC, temperature, etc.)
- Well construction details
    - Casing type
    - Casing diameter
    - Casing depth
    - Screen type
    - Screen diameter
    - Screen aperture
    - Screen depths
- Depth of sanitary seal, if applicable
- Gravel pack information, if installed
    - Type of gravel pack and size
    - Installation interval
    - Quantity
- Type and installation interval of any other materials installed in the annular space (i.e. backfill)
- A clear description of the datum (reference point) for all depth measurements (see **Section 2.1.1.2**)
- Depth to static water level on each day of drilling and after finial completion of the well, with reference to the datum point (see **Section 2.1.2.1**)

- Well development duration
- Finial blow yield
- Geological log
    - Depth of formations
    - Description of drilling material
        - Rock type
        - Size of drilling chips
        - Colour (use standardised colour charts such as the *Munsell Colour Chart*)
        - Fractures
        - Fracture frequency
        - Fault orientation
        - Core recovery parameters
        - Rock Quality Designation (RQD)
        - Degree of weathering
        - Mineralisation
        - Sorting
        - Roundness
- For wells that are to be used for supply (domestic use, irrigation, industrial use, etc.), groundwater samples should be collected after the completion and construction (i.e. after development) for analysis by a SANAS accredited laboratory (see **Section 2.1.3**)
- Drilling field forms
    - Daily drilling logs
    - Drilling chip logs
    - Penetration rate form
- Well completion information including the installation of a borehole cap, locking mechanism and/or manhole

Following well drilling, a report needs to be generated detailing the results. The report should document the entire drilling processes. Analyse well data obtained and develop an initial conceptual understanding of the aquifer where the well has been drilled. This should include lithological logs, location of main flow zones (water strikes), aquifer thickness, groundwater levels, etc.

2.2.2 Well Test-pumping

Pumping tests are the most important technique for groundwater investigations (WRC, 2002). They are conducted to test well performance, estimate sustainable yields and to calculate the aquifer hydraulic properties (hydraulic conductivity, transmissivity) (SADC-GMI, IGRAC, IGS., 2019). The sustainable yield is important to understand how much water can be abstracted without drying up the well or detrimentally impacting the water resource. The hydraulic parameters are important for management purposes, i.e. interaction between abstraction wells, operating conditions and pollution management (WRC, 2002).

The basic concept of test pumping involves water being abstracted from a well causing the water level to be lowered (drawdown). The water level in the abstraction well and the pumping rate are monitored over time (see **Figure 2-26**). The response of the water levels to pumping is then analysed to derive information about the performance of the well and the hydraulic properties of the aquifer (Dross, 2011). For detailed information on conducting aquifer pumping tests, data analysis and interpretation, see SADC (2001), Kruseman and de Ridder (1991) and WRC (2002).

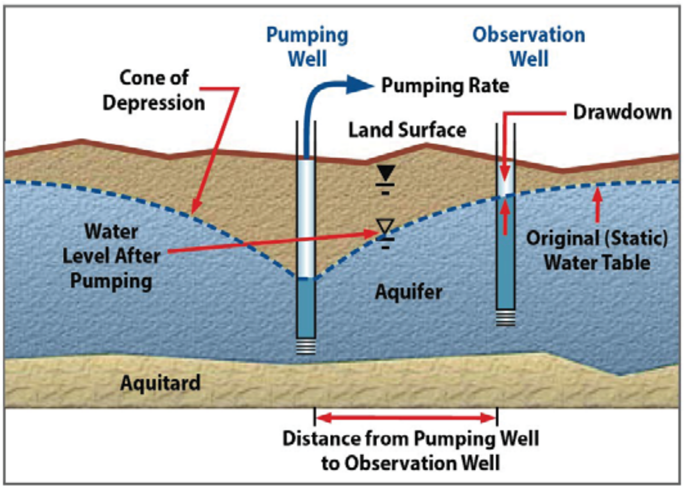


Figure 2-26 **Cross-section illustrating the impacts of conducting a pumping test in an unconfined aquifer. As water is pumped from the well, drawdown causes the static water level to be lowered forming a cone of depression surrounding the well, lowering the water level in the observation well.**

During test pumping, the maximum amount of drawdown in the well should be achieved so that the parameters and characteristics of the entire well can be determined. If the pumping rate is too low during the test, no strain will be placed on the aquifer and constraints (no flow boundaries) might not be picked up. If the pumping rate is too high, the water level inside the well will drop rapidly and it will reach the pump intake before the true characteristics of the well and aquifer can be assessed (WRC, 2002).

The following data should be collected during test pumping:

- Testing well location (latitude, longitude, elevation)
- Site ID and location of any observation wells (latitude, longitude, elevation)
- Date of the pumping test
- Type of pumping test
- Duration of the pumping test

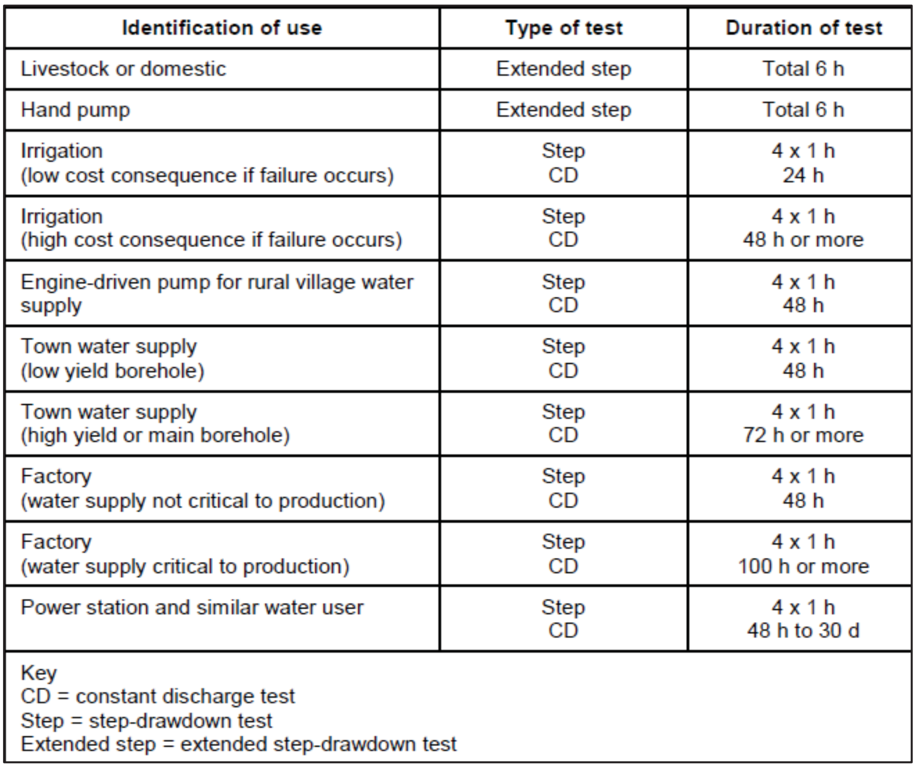
- Well screen depths
- Pump inlet depth
- Static water level before testing
- Water level drawdown against time in pumping well and observation wells
- Pump discharge rate against time
- Well recovery against time
- Pumping test field sheets

Following test pumping, a report needs to be generated detailing the analysed results. The report should include the well performance (well efficiency and specific capacity), the recommended sustainable yield and hydraulic characteristics of the aquifer such as hydraulic conductivity, transmissivity, storability, specific yield, etc. The report should also include operation conditions such as an operating water level and schedule to avoid dewatering strikes and fluctuating the water level within the well, which may induce biofouling.

2.2.2.1 Types of Test Pumping

The type of test and the duration is based on the intended water use. **Table 2-8** gives the minimum requirements regarding the type and duration of the test for various types of water use (SANS 10299-4:2003).

Table 2-8 Types of test pumping and their duration (SANS 10299-4:2003).



Identification of use	Type of test	Duration of test
Livestock or domestic	Extended step	Total 6 h
Hand pump	Extended step	Total 6 h
Irrigation (low cost consequence if failure occurs)	Step CD	4 x 1 h 24 h
Irrigation (high cost consequence if failure occurs)	Step CD	4 x 1 h 48 h or more
Engine-driven pump for rural village water supply	Step CD	4 x 1 h 48 h
Town water supply (low yield borehole)	Step CD	4 x 1 h 48 h
Town water supply (high yield or main borehole)	Step CD	4 x 1 h 72 h or more
Factory (water supply not critical to production)	Step CD	4 x 1 h 48 h
Factory (water supply critical to production)	Step CD	4 x 1 h 100 h or more
Power station and similar water user	Step CD	4 x 1 h 48 h to 30 d

Key
CD = constant discharge test
Step = step-drawdown test
Extended step = extended step-drawdown test

2.2.2.1.1 Slug Test

Slug tests are used to estimate the potential yield and hydraulic conductivity of wells, they are commonly applied to low-yielding wells that are not ideal to perform large scale pumping tests on (Vivier et al., 1995). The results may assist in assessing if other tests are feasible and warranted. The slug test involves measuring the change in water level in a well when water is rapidly displaced. The displacement will either cause a rise in the water level when the slug is introduced below the static water level, or a drop in the water level caused by the removal of a quantity of water from the well. The rate of recession or rise provides an indication of the yield of the well (DWAF, 1997). Dataloggers can be used to record the changes in water level, these are especially useful in high-yielding wells that recover quickly (Lubbe et al., 2022). It is recommended to set dataloggers to record at short intervals, e.g. half second intervals. According to a recent study by Lubbe et al. (2022), slug tests cannot be used to determine an exact potential yield but can rather be seen as an estimation tool to determine ranges of potential yield. Furthermore, it was determined that the use of simple homogenous models can be used to determine the possible transmissivity for slug tests and relate that to a potential yield.

2.2.2.1.2 Calibration Test

When there is no drilling report and information on water strikes and yields, a calibration test can be conducted to determine the optimum rates for test pumping. Water is pumped from the well at three or more different pumping rates over short sequential periods of time, usually 15 minutes. The response of the water level to each known pumping rate is measured and recorded as per prescribed time schedule. The water levels are recorded in a calibration test data sheet (see **Table 2-9**). The information gathered from the calibration test determines the correct pumping rates for a stepped drawdown test and a constant-rate pumping test (WRC, 2002).

Table 2-9 Example of a calibration test data sheet.

Time (minutes)	Drawdown (m)	Time (minutes)	Drawdown (m)
1		9	
2		10	
3		11	
4		12	
5		13	
6		14	
7		15	
8			

Steps to conduct a calibration test:

- Record the date and time of the test
- Record the datum
- Record the static water level
- Start the pump

- Make sure the capacity of the pump is known. Strain the pump so that ~ 1/3 of the capacity will be discharged during the first run
- Make sure that the discharge pipe is not leaking
- Measure drawdown in the well with the dip-meter as per the prescribed time intervals in the data sheet
- Measure the discharge from the pump at the beginning and end of the first run
- Stop the pump after the prescribed time has ended
- Begin measuring the recovery as soon as the well has stopped pumping
- Measure the recovery as per the prescribed time intervals in the data sheet
- Allow the water level to recover to more than 90% of the original static water level
- Repeat the test for 2/3 capacity of the pump
- Repeat the test for full capacity of the pump
- Using the gathered information, the test pumping contractor/hydrogeologist can determine the pumping rates for the step drawdown and constant-rate tests

2.2.2.1.3 Step Drawdown Test

The step drawdown test is a single-well test and is performed to evaluate the productivity of a well (WRC, 2002). The short-term relationship between yield and drawdown for a well is determined from the step drawdown test. It consists of pumping the well in a series of sequential steps, each at a different discharge rate, usually with the rate increasing at each step. The steps should be designed that the last step approaches the maximum yield of the well (Dross, 2011). The results from the step drawdown test will indicate whether the well is judged to be sufficiently weak (yield < 0.5 l/s) to make a utilisation recommendation without further testing (WRC, 2002). If the results from the stepped discharge test is positive, further test pumping through a constant-rate test must be performed.

The step drawdown test is done by pumping the well at a low constant discharge rate until the drawdown stabilizes. The constant discharge rate is then increased and the well is pumped until the drawdown stabilises again. The pumping rate is then increased again, and the process is repeated (WRC, 2002). The time per pumping rate should be between 60 and 120 min. The drawdown in the well in response to each of the pumping rates must be measured and recorded in accordance with a prescribed time schedule (WRC, 2002). The results from the step drawdown test must be recorded in a data sheet (see below **Table 2-10**). At the end of the pumping steps, the recovery water level should be recorded for the same period.

Table 2-10 **Example of a step drawdown test sheet.**

Time	Step 1 - x l/s	Step 2 - x l/s	Step 3 - x l/s	Recovery
(minutes)	(m)	(m)	(m)	(m)
0				
1				
2				
3				
5				
7				
10				
15				
20				
30				
40				
50				
60				

Steps to conduct a step drawdown test:

- Record the date and time of the test
- Record the datum
- Record the coordinates of the well and any observation wells
- Record the static water level
- Start the pump
- Make sure that the discharge pipe is not leaking
- Measure drawdown in the well with the dip-meter as per the prescribed time intervals in the data sheet
- Measure drawdown in the observation wells
- Measure the flowrate throughout the test
- Measure the discharge from the pump at the prescribed time intervals (see **Table 2-10**)
- Measure the temperature, EC and pH before the end of the step
- After the prescribed time, increase the rate of the pump to the second constant discharge rate increment
- Measure the second constant discharge rate at the same intervals as above
- Repeat the steps for the desired number of steps
- Switch off the pump after the final step has ended
- Begin measuring the recovery as soon as the pump is switched off
- Measure the recovery in the testing well and observation wells as per the prescribed time intervals in the data sheet
- Allow the water level to recover for the same period of time as the length of pumping or until it reaches 90% of the static level

- Determine the pumping rate for the constant rate pumping test

2.2.2.1.4 Constant-rate Test

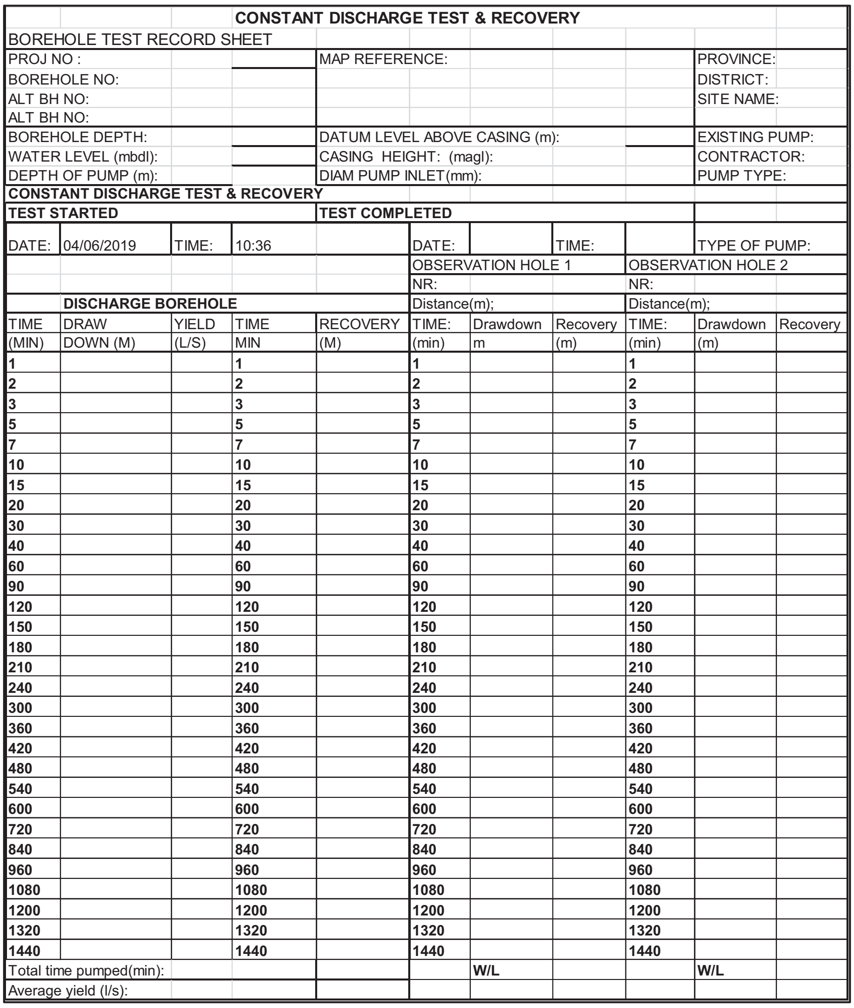
The constant-rate test is primarily designed to provide information on the hydraulic characteristics of the aquifer. Information on the aquifer storage coefficient can be deduced only if data are available from suitable observation wells. The optimum yield for long- and medium-term utilisation of the well can be determined from the constant-rate test. A constant-rate test is done at a single pumping rate for an extended period of time. It is critical that the pumping rate stays as constant as possible for the duration of the test. The pumping rate should be at a yield which will be able to be maintained for the duration of the test, and able to utilise more than 70 percent of the available drawdown (WRC, 2002). The available drawdown should not be exhausted. The drawdown should be monitored in the well as well as observation well if available.

The actual pumping rate maintained during the test should be measured and recorded regularly. The pumping rate must be checked and adjusted, if necessary, after 7, 15, 60, 120 and 180 min. From then on, the pumping rate should be checked whenever the water-level measurements are taken. At the end of the constant rate test, the recovery inside the well should be measured (WRC, 2002).

Steps to conduct a constant-rate test:

- Record the date and time of the test
- Record datum
- Record the coordinates of the well and any observation wells
- Record the static water level
- Start the pump
- Make sure that the discharge pipe outlet is down gradient from the well and that the outlet is far enough to not recharge the aquifer and compromise the test
- Make sure that the discharge pipe is not leaking
- Measure drawdown in the well with the dip-meter as per the prescribed time intervals in the data sheet (see **Table 2-11**)
- Measure the flowrate throughout the test
- Measure drawdown in the observation wells
- Measure the discharge from the pump at the prescribed time intervals
- Collect a water sample just before the end of the constant-rate test
- Stop the pump after the prescribed time has ended
- Begin measuring the recovery as soon as the pump has been switched off. Measure recovery in the testing well and observations wells
- Measure recovery for the same time intervals used for pumping, until (SANS 10299-4:2003):
    - The water level recovers to less than 5% of the total drawdown during the constant discharge test, or
    - At least three readings taken in succession are identical, or
    - a time equal to the total time taken for the constant discharge test has elapsed

Table 2-11 **Example of a constant-rate discharge test sheet.**



			CONSTANT DISCHARGE TEST & RECOVERY							
BOREHOLE TEST RECORD SHEET										
PROJ NO :				MAP REFERENCE:					PROVINCE:	
BOREHOLE NO:									DISTRICT:	
ALT BH NO:									SITE NAME:	
ALT BH NO:										
BOREHOLE DEPTH:				DATUM LEVEL ABOVE CASING (m):					EXISTING PUMP:	
WATER LEVEL (mbdl):				CASING HEIGHT: (magl):					CONTRACTOR:	
DEPTH OF PUMP (m):				DIAM PUMP INLET(mm):					PUMP TYPE:	
CONSTANT DISCHARGE TEST & RECOVERY										
TEST STARTED				**TEST COMPLETED**						
DATE:	04/06/2019	TIME:	10:36		DATE:		TIME:		TYPE OF PUMP:	
					OBSERVATION HOLE 1			OBSERVATION HOLE 2		
					NR:			NR:		
	DISCHARGE BOREHOLE				Distance(m);			Distance(m);		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME: (min)	Drawdown m	Recovery (m)	TIME: (min)	Drawdown (m)	Recovery
1			**1**		**1**			**1**		
2			**2**		**2**			**2**		
3			**3**		**3**			**3**		
5			**5**		**5**			**5**		
7			**7**		**7**			**7**		
10			**10**		**10**			**10**		
15			**15**		**15**			**15**		
20			**20**		**20**			**20**		
30			**30**		**30**			**30**		
40			**40**		**40**			**40**		
60			**60**		**60**			**60**		
90			**90**		**90**			**90**		
120			**120**		**120**			**120**		
150			**150**		**150**			**150**		
180			**180**		**180**			**180**		
210			**210**		**210**			**210**		
240			**240**		**240**			**240**		
300			**300**		**300**			**300**		
360			**360**		**360**			**360**		
420			**420**		**420**			**420**		
480			**480**		**480**			**480**		
540			**540**		**540**			**540**		
600			**600**		**600**			**600**		
720			**720**		**720**			**720**		
840			**840**		**840**			**840**		
960			**960**		**960**			**960**		
1080			**1080**		**1080**			**1080**		
1200			**1200**		**1200**			**1200**		
1320			**1320**		**1320**			**1320**		
1440			**1440**		**1440**			**1440**		
Total time pumped(min):						**W/L**			**W/L**	
Average yield (l/s):										

2.2.3 Down Hole Geophysics

Various downhole geophysical techniques are used to survey wells once they have been completed. These techniques are used to determine aquifer parameters; namely natural gamma, water quality and Borehole Magnetic Resonance Response (bMR). Geophysical techniques can also give an indication of well construction details such as diameter and screened intervals.

Natural gamma logging can be used for lithology identification, stratigraphic correlation, or recognising different facies. bMR provides information relating to pore size distribution of a rock or sediment from which storage and flow properties can be determined. bMR only begins recording once the saturated zone is encountered and is specifically tuned to sense the pore network fluids only, enabling precise determination of total porosity, free fluid content (which can be interpreted as specific yield), and bound fluid content (specific retention). Water quality data is obtained using a downhole water quality probe (pH, EC, temperature, oxygen saturation, etc.). Caliper probes are used to determine the drilling diameter and can also obtain information regarding collapsing zones and fractured zones (CoCT, 2020). An example of the data output from downhole geophysics is shown in **Figure 2-27**. Data generated during downhole geophysical investigations must be processed and uploaded to the database system (see **Section 3.1**). All raw files should be saved separately from processed files and archived (see **Section 3.3.2**).

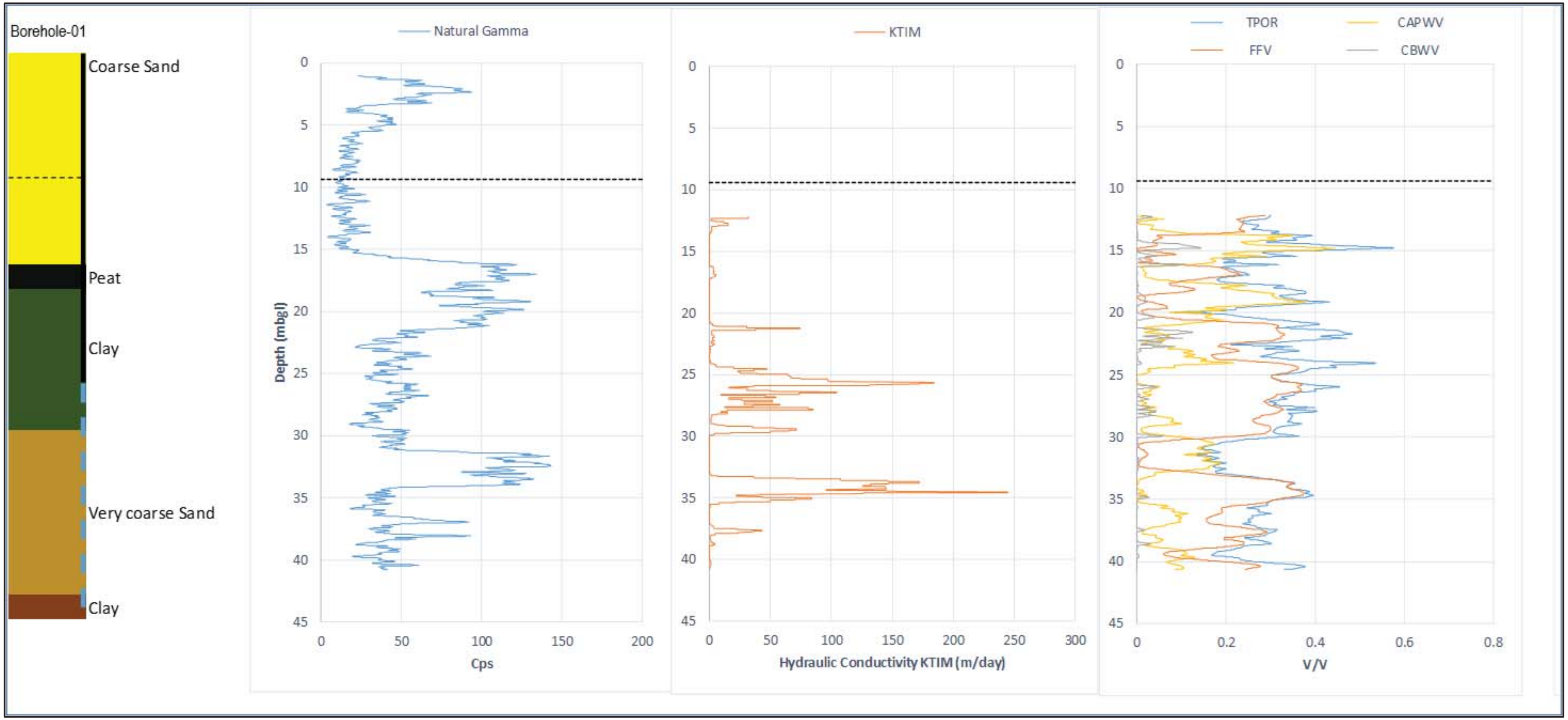


Figure 2-27 **Example of bMR logging results. The results include: Generalised lithological log (mbgl), Natural Gamma (count per second), Hydraulic conductivity based on permeability – KTIM (m/day), Total Porosity (TPOR), free fluid volume (FFV), capillary bound fluid volume (CAPWV) and clay bound fluid volume (CBWV). PVC casing is indicated next to the generalised log, blue dash lines indicate screened casing, and black solid lines indicate solid casing. Dashed black line represents the water level encountered during the geophysical survey (from CoCT, 2020).**

CHAPTER 3: GROUNDWATER DATA MANAGEMENT

Groundwater data management is the process of collating, processing, organising and storing groundwater data, within the bounds of policy and regulation, to maximise data integrity and information quality for analysis. An effective data management system is essential when working with large quantities of data, and when implemented correctly, ensures that:

- Appropriate QA and QC protocols are being adhered to
- Data is being organised and stored into the relevant databases and archives
- Data is made accessible for analysis and interpretation (SADC-GMI, IGRAC, IGS; 2019).

Monitoring and field teams tasked with data collection and collation are required to have a working knowledge of best-practice data management techniques and are responsible for the proper application of the procedures associated with data processing, data validation and data storage.

3.1 DATA PROCESSING

This section outlines how groundwater data, once collected, should be processed to ensure best-practice data processing and provides a set of guidelines that ensure a high degree of data integrity for use across data platforms. All data processing should meet the principles of findability, accessibility, interoperability, and reusability (i.e. FAIR data) or the best standard data practice at the time.

Data processing involves the collation and modification of various raw datasets into a predefined data structure. Workflows for data processing vary depending on the data source. Data capture template sheets should be designed to reflect the data captured in physical field sheets. These sheets can be designed to include built-in format/unit conversions, drop-down list options and auto-fill functionalities to ensure consistency in the formatting of various data types (e.g. predefined list options for routine groundwater quality monitoring, wellfield names, station types, etc.).

For groundwater data collection, digital capture templates can be broken down into data categories, each with specific data inputs depending on the purpose. Examples of data categories include:

- Station information
    - The Station Information category stores all the station location information such as station types, coordinates, elevation, installation date, etc. It is the most important category as all other categories are related to a specific station, therefore, any data that needs to be attributed to a unique station.
- Well construction details
    - Used to capture all construction related information regarding well (screen, casing, fill, drilling method, depth, water strikes, etc.).
- Monitoring Data
    - Designed to capture data and data-information from various field sources (i.e. field measurements, manual groundwater levels, hydrochemical sample information and results, logger information and results, etc.) – some of which are done manually and others by “external” means (i.e. laboratory or automated data gathering).

- Hydrogeologic description
    - The Hydrogeologic description category houses all hydrogeological data for a given site. This includes aquifer names and descriptions, transmissivity values, specific storage, saturated thickness, recommended yields, etc.
- Aquifer test information
    - The aquifer test category is used to capture general information on an aquifer testing event such as pumping rates, water levels (static and dynamic), pump information, etc.

3.1.1 Data Capturing

Data capture involves the process of extracting various physical or electronic datasets into a predefined data structure for further analysis. Data capture workflows vary depending on the source of the data, these include:

- Manually collected field data
- Sensor downloads
    - Telemetric
    - Manual
- Chemical results from laboratories
- External data sources
    - Contractor provided
    - Sourced
- Legacy data

Manually collected field data must be transferred into a digital format using the appropriate digital capture sheets. During data capture, it is important to ensure that all relevant data in the physical sheets are recorded in the appropriate columns with the correct information (see **Figure 3-1**). Special attention should be drawn to the station name and the SI units when capturing data. The SI units used to record field measurements should match the data capture sheets, this may involve converting the SI units. The station name recorded in the field sheets and digital capture sheets should be consistent with the registered station name. Field staff are encouraged to refer to station information/metadata in order to adhere to naming conventions and unit specifications.

Common mistakes when naming stations:

- Adding a stations “purpose” to a station name (purposes can change over time)
    - MON01 can change from a monitoring to an abstraction site
- Inconsistent formats – using a mixture of font cases (stick to one style)
    - Mon01, MON01
- Adding an unnecessary descriptor to the station name
    - MON01 (Bailer), MON01 (lowflow), MON01_NEW, MON01_Duplicate, etc.

Sensor downloads from online sources, manual sensor downloads or data received from telemetric systems should be transformed to match the appropriate digital capture sheets. The original data file (now considered “raw” data) should be archived appropriately (see **Section 3.3.2**).

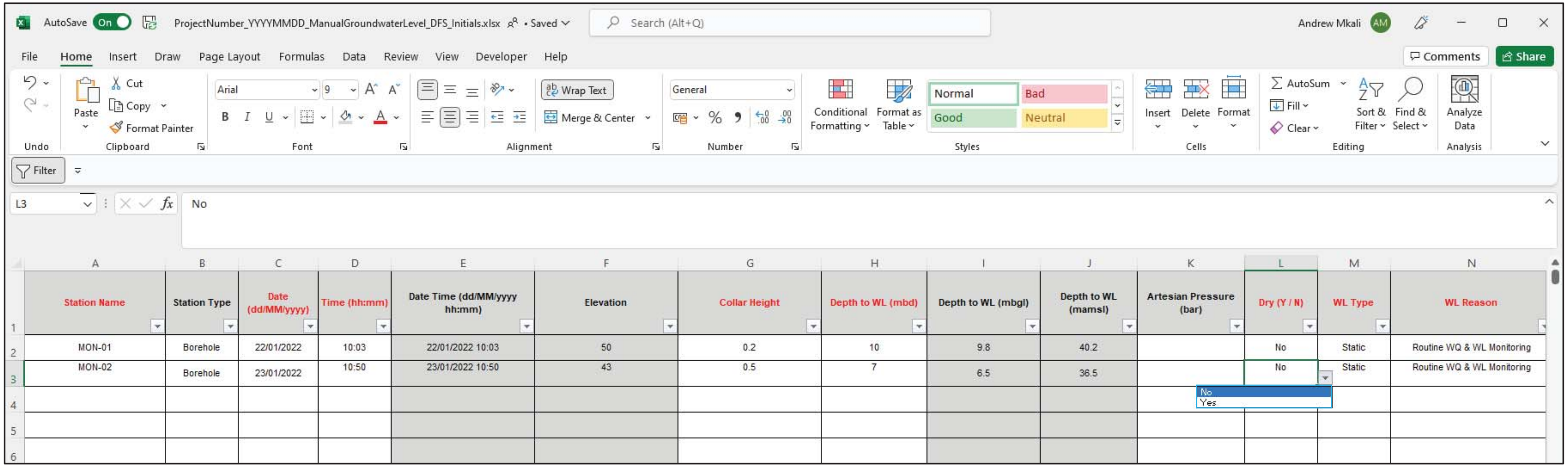
Both external and legacy data must be transferred into the relevant structure using the appropriate digital capture sheets. This includes water quality results whose formats may not be suitable for analytical purposes (e.g. PDF).

Once data has been collected and transformed into its respective data capture template sheets, both the digital capture sheets and the field data capture sheets are to be scanned and archived in their appropriate file locations and under an identifiable naming convention.

3.1.2 Data Transformation

Data transformation is comprised of changes to the format, structure, or values of a dataset according to a predefined set of specifications. The process of data transformation can also be referred to as the extract/transform/load (ETL) process. The extraction component involves identifying and pulling data from the various source systems and consolidating the data to a single repository. Next, the raw data is cleaned, if needed. The data is then transformed into a target format that can be loaded into various software to be used in analysis.

Digital capture templates may contain columns with auto-conversion functionalities to account for data transformations. This may include the conversion of units based on SI units and generation of unique identifiers. Therefore, it is important for field staff to understand *how* these conversions relate to the datasets (e.g. coordinates, elevation, depth, etc.).



Station Name	Station Type	Date (dd/MM/yyyy)	Time (hh:mm)	Date Time (dd/MM/yyyy hh:mm)	Elevation	Collar Height	Depth to WL (mbd)	Depth to WL (mbgl)	Depth to WL (mamsl)	Artesian Pressure (bar)	Dry (Y / N)	WL Type	WL Reason
MON-01	Borehole	22/01/2022	10:03	22/01/2022 10:03	50	0.2	10	9.8	40.2		No	Static	Routine WQ & WL Monitoring
MON-02	Borehole	23/01/2022	10:50	23/01/2022 10:50	43	0.5	7	6.5	36.5		No	Static	Routine WQ & WL Monitoring

Figure 3-1 **Example of a data capture template indicating important features. Red text indicates mandatory data columns; grey columns indicate data columns with data "checks", auto-conversions or auto-fill functionalities; and the blue box indicates a data field with an attached "list" option.**

3.2 DATA VALIDATION

Data validation is a process of ensuring that data has undergone the necessary QA and QC steps required to meet a predefined data standard. A variety of data validation tools can be used to complete this process. These include:

- Field sheets designed with built-in QA and QC considerations to assist field staff in capturing all required and relevant information.
- Digital capture sheets designed with built-in QA and QC considerations, containing validation rules, constraints, and checks.
- Data validation software can be used to assess the captured data and flag entries that do not meet the predefined constraints.

Data validation typically happens in two ways depending on the requirements of the investigation and the type of database system used. The first phase of data validation is conducted by field staff through a process of manual data checks, data capture, transformation reviews, as well as passing the dataset through any data validation software. Once these are completed, the dataset can be used for data analysis.

The second data validation step depends on the database system used. For a relational database designed using SQL, this data validation step is inherently contained inside the relational database, as SQL databases are designed with a pre-defined data schema. During data upload, datasets are evaluated using several validation criteria. These include:

- Formatting: Data entries are checked for case sensitivity, value delimiters, date and number formats, value vs text, etc.
- Duplicates: Datasets are checked for duplicate records against the established project database (i.e. same date, time, site, parameter, etc.)
- Constraints: Checking for data entries that fall outside a defined range for that site/station and data type.

3.2.1 Quality Assurance and Quality Control

QA and QC is important in data processing as data needs to be checked and verified before data is imported to a database. QA is a set of operating principles, procedures and actions ensuring that reliable data is collected. QC is a set of procedures and actions intended to ensure that groundwater data collected meets its objectives and requirements (SADC-GMI, IGRAC, IGS, 2019). QA and QC measures validate the accuracy and precision of groundwater data. Key processes to check groundwater data include (WRC, 2011b):

- Checking of raw data for completeness and correctness
- Checking of raw data against other measurements
- Correcting of raw data
- Validation of corrected data
- Storing of validated data

To reduce errors in data and to improve the consistency in data collection, different QA measures are available. These measures have been compiled from SADC-GMI, IGRAC, IGS (2019) and are summarised in **Table 3-1**.

Table 3-1 **Measures to reduce errors and improve consistency in data collection (from SADC-GMI, IGRAC, IGS (2019).**

QA Measures	Description
Training and capacity development	• It is important that all personnel responsible for collecting groundwater data (i.e. field staff) are well trained and are informed of international best practices and available guidelines and manuals. Private groundwater users that collect their own data should consult and adhere to national standards and national and international guidelines for groundwater data collection. • All staff involved in the coordination, supervision and interpretation of groundwater data must have an understanding of the hydrogeological meaning of the data to be able to distinguish if the data is correct or not. It is therefore important that personnel tasked with QC of the data and information have a background in groundwater. Ad-hoc additional professional training through courses and workshops may be required to improve the skills and knowledge in specific fields and to keep up to date with new advances and developments. • External parties involved with different groundwater sectors (i.e. drilling contractors, test-pumping contractors, consultants, laboratories) must adhere to minimum professional standards. Formal certification of professionals is another mechanism to improve quality assurance.
Data collection forms	• Standardised data collections forms/templates, to be used by field staff and private groundwater users for collecting different types of data. • Standardised forms will help ensure systematic and consistent collection of data irrespective of who is collecting the data and when. • Mobile applications (apps) can be used to record data in the field. Mobile apps can assist in preventing simple mistakes by making use of built-in logical data checks and by eliminating data entry errors resulting from illegible data forms (see **Appendix C**).
Equipment calibration	• All equipment needs to be calibrated and used according to the manufacturer's specifications and guidelines. • Regular maintenance needs to be done on equipment to ensure that it is operating at the optimal capacity. • Automated dataloggers need to be calibrated and checked with manual field measurements, routinely.
Data QC	• QC measures should be in place when collecting groundwater data to check the correctness of the data. This involves groundwater quality QC checks such as sample blanks and duplicates.

3.2.2 Other Routine QA and QC Steps

To ensure, and maintain data fidelity and validity, several actions can be undertaken. Data QA and QC is the responsibility of all personnel handling data and should be done to ensure the relevant QA and QC processes have been undertaken. Routine QA and QC are outlined below:

- Repeated Values
  - If values are consecutively repeated several times, they should be flagged as a potential “flatlining” issue and reported.
- Data Evaluation
  - Required to re-align data values that have been logged with obvious set differences to reality. An example is the syncing of logger data for water levels to reliable manual dip readings, or sudden changes in data values to a different range of values following an event.
- Routine Data Checks
  - Correcting potential errors or flagging outliers to project specific or established scientific standards (e.g. SANS 241 Water Quality Standards, or average water level at a site).

3.3 DATA STORAGE

Data storage is a fundamental component of any data management system. Once groundwater data/information has been processed and validated, all data must be stored in a central location to allow for data accessibility, usability and recovery of data (should data be lost).

A database is an organised collection of structured data/information which are typically stored electronically in a computer-based data management system or application. There are several types of databases that can store groundwater data. These databases can range from simple excel spreadsheets arranged in well thought out folder structures, to more complex software programs hosting multiple relational databases.

Groundwater databases may vary from private owned data management systems (used by private users and consultancies) to national database systems that are accessible to the public.

When selecting an appropriate groundwater database, two factors need to be considered:

1) the volume of data to be sorted.
2) the human capacity and skills required to maintain and manage the system.

For small-scale groundwater users such as Schedule 1 users and small rural groundwater schemes, a spreadsheet database can be used. However, appropriate digital capture sheets should be used which have been optimised for integration to national database systems. A server-based relational database is recommended for larger datasets, i.e. for national database systems. **Table 3-2** provides an overview of groundwater database options.

Table 3-2 Overview of database options (Modified after SADC-GM, IGRAC, IGS, 2019).

Database Functions	Database Types		
	Spreadsheet	Desktop Relational	Server Based Relational
Software examples	MS Excel, Apple Numbers, LibreOffice	MS Access, OpenOffice Base, LibreOffice Base	MS-SQL Server, MySQL, Apache Derby
Maximum number of users at a time	1	255 (theoretically, MS Access)	32 676 (Ms SQL-Server)
Maximum database size	Low (2 GB – MS Excel)	Low (2GB – MS Access)	High (524 272 TB – Ms SQL-Server)
Query/filtering functionality	Basic	Advanced	Advance
Logical checks on data entry	Basic	Advanced	Advance
Data quality control process	Very basic / impractical	Possible	Advanced
Audit trail	No	No	Possible (must be part of the database architecture)
Backup	External hard-drive or internet cloud	External hard-drive or internet cloud	Dedicated backup procedures are required
User roles and authorisations	Only 2 roles can be defined using a password for the spreadsheet	Different user roles and authorization levels can be set.	Advanced management of user roles and authorisation levels possible (required)
User interface	Not required but possible	Not required, but easy to develop	Required and custom made
Integration of various tools (processing, analysis, visualization, reporting)	Basic	Moderate (custom made)	Advanced (custom made)
Human capacity needed	• End-users require only basic understanding of spreadsheet software • Person setting up and maintaining the spreadsheet requires additional basic understanding	• End-users may need basic training in the use of the database • Development and maintenance may be done by staff with more advanced experience/training in the use of desktop databases	• End-users will require training in the use of the database interface and the specific tools they will be authorised to use (differentiated training) • Database developer(s) and administrator(s) needed with specialised knowledge on database

Database Functions	Database Types		
	Spreadsheet	Desktop Relational	Server Based Relational
	of relational database concepts and (optional) programming in Visual Basic	and concepts of relational database	management and server-maintenance, etc.
Financial implication	- Software: little to none (most people already have the software) - Training: very little - Hardware: no additional hardware required apart from backup drives	- Software: limited - Training: limited for users - Hardware: no additional hardware required apart from backup drives	- Software: Costly - Training: extensive - Hardware: additional hardware required (server, server room) and related infrastructure, which all require maintenance (recurring costs)

3.3.1 Relational Databases

The main feature of relational databases' is that it is structured around unique key-identifiers and has the ability to not only organise and store datasets, but to recognise relationships between stored items of information. These databases are built with a table-based data structure and have a strict, pre-defined, schema design which allows for a more robust data management process. Primary Keys (PKs) are used as the unique identifiers in a relational database table where only one PK is allowed per table.

A PK constrain is a column or group of columns that uniquely identifies every row in the table of the relational database management system. It cannot be a duplicate, meaning the same value should not appear more than once in the table. Additionally, a table cannot have more than one primary key. A foreign key (FK) is a column that creates a relationship between two tables. The purpose of the FK is to maintain data integrity and allow navigation between two different instances of an entity. It acts as a cross-reference between two tables as it references the PK of another table (see **Figure 3-2**).

Datasets should only be uploaded into a projects' relational database after undergoing the relevant data validation sets outlined in **Section 3.2**. The personnel in charge of data management (and the associated processes) should use the appropriate data upload method and match the relational database schema. Ideally, only QC'd data should be uploaded to the project database but, if required, data can be manually edited or updated inside the project database, however, this level of access should be managed to prevent errors in the database.

Different database systems allow for a variety of data records to be accessed and viewed simultaneously. **Figure 3-2** outlines a basic relational database structure.

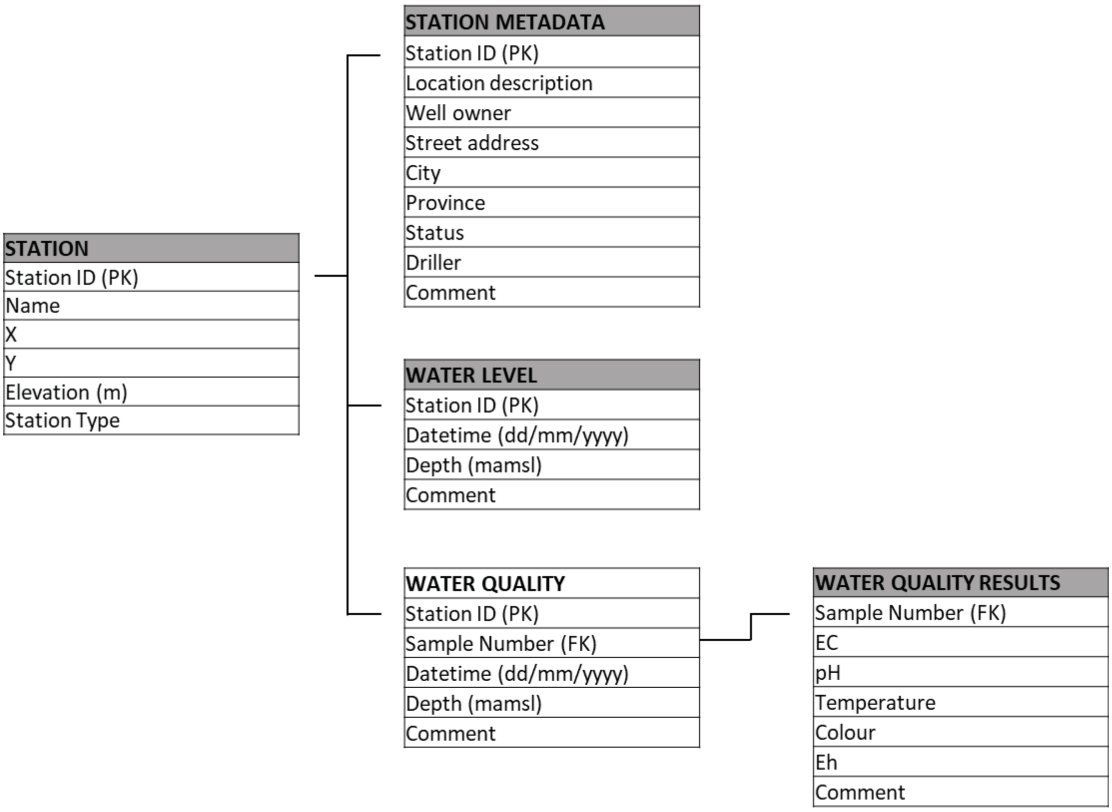


Figure 3-2 **Schematic of a basic relational database displaying data tables and their relationships based on unique identifiers.**

3.3.2 Data Archiving

Data archiving is the practice of identifying data that is moving out of the “active” data processing/analysis system, into a long-term data storage system. Implementing a structured archiving system assists in maintaining a secure data repository, ensuring data accessibility and disaster recovery, and maintaining a record of processed and analysed datasets for future reference (i.e. FAIR data).

Forms can either be archived as hardcopy files in a filing room or electronically as softcopy files on a computer or central server. It is recommended that forms be archived as both hardcopy and softcopy files. It is good practice to keep original hardcopy files in case the digital files are corrupted as it moves through the data management process. Original files are also useful for querying erroneous results and to QC data that has been transformed into digital formats. **Figure 3-3** provides a basic overview of the data archiving process.

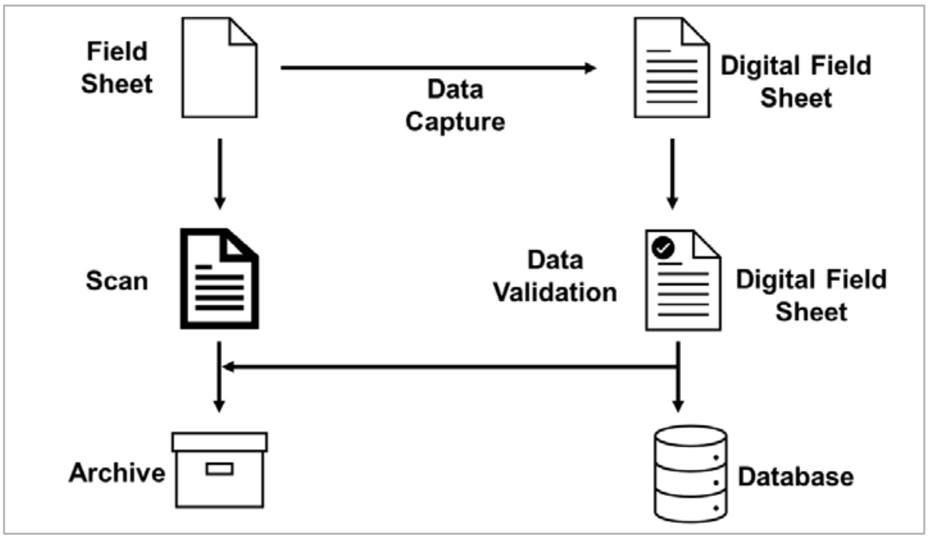


Figure 3-3 **Data archiving workflow displaying the basic components of the archiving procedure including the digitalisation of hardcopy/physical field sheets, hardcopy scans, validation of digital data and the archiving of scans and digital data once uploaded to the relevant database.**

3.3.3 Data Storage in South Africa

There are various database systems used in the private and public sectors in South Africa to store and access groundwater data. These database systems are used for a variety of purposes spanning from local groundwater users that track monthly water level data, to national databases used to manage large scale monitoring data. A list of currently available database systems in South Africa and the groundwater related data that can be uploaded and/or accessed from the databases are shown in **Table 3-3**.

3.3.3.1 National Groundwater Databases

Four national groundwater databases have been created to manage the data collected from monitoring programmes of South Africa's groundwater resources (see **Table 3-3**). This data, hosted by the DWS, is available to the public and can be accessed by registering via the online portals or by making direct requests to the DWS.

The **National Groundwater Archive** (NGA) is a digital database system that allows capturing, viewing, modifying and extraction of national groundwater information. The longstanding database includes comprehensive groundwater information ranging across South Africa dating back to the 1960s. Improvements in groundwater monitoring technology, such as dataloggers, which automatically record groundwater levels at daily, hourly, or even on the second intervals, meant that datasets were rapidly increasing in size. Due to the databases data storage limitations, it was no longer able to host the influx of large data. To solve this problem, in 2004 the DWS commissioned a new data management system called **Hydstra**. Sites that were no longer being monitored remained in NGA as an archive and data from NGA (pre ~2004) for sites that were still being monitored post 2004 were migrated to Hydstra, which was completed in 2015 (DWS, 2016b). All groundwater level data must be submitted to the DWS with the geosite location so that it can be uploaded to Hydstra.

Water use registration for both surface and groundwater, as required by the National Water Act, is captured within the **Water Use Authorisation and Registration Management System** (WARMS) database, administered by DWS (DWS, 2016b). There are various water uses which include bulk water supply, domestic use, irrigation, industry, power generation, watering of livestock, and recreational purposes. The registration and licencing of these uses is governed by the NWA. All groundwater use, regardless of the amount, should be registered on WARMS.

Water Management System (WMS) provides information for water resource monitoring and management with an emphasis on water and environmental quality. Groundwater quality data is stored on the WMS and is linked to the NGA. Groundwater quality data from sites that are monitored twice a year, by DWS personnel, (before and after the rainfall season [October and April]) are stored on the database. The database includes a variety physio-chemical properties such as pH, EC and temperature, macro-chemical determinants, micro-biological parameters, metals and trace elements. To ensure data points align across the different databases, the site names are consistent with the NGA and WARMS databases. All groundwater quality data must be submitted to the DWS to be uploaded to the WMS.

Table 3-3 Groundwater databases in South Africa (Du Toit, 2012; DWS, 2016a; WRC, 2014; GGIS, 2022; DWS, 2022; CapeFarmMapper, 2022; Ribeka, 2022; Waterloo Hydrogeologic, 2022; Aquabase, 2022; Earthsoft, 2022).

Database	Description	Data
Public Groundwater Database		
National Groundwater Archive (NGA)	The NGA is a web enabled database system that allows capturing, viewing, modifying and extraction of groundwater related data by registered users.	• Geolocation Type (borehole, spring, dam, etc.) • Geolocation ID • Geolocation coordinates • Well construction • Lithology • Water strike depth • Blow yield • Field based water quality • Test pumping and abstraction data • Groundwater levels
DWS Hydstra	A national groundwater database that stores continual groundwater level measurements (i.e. data loggers recording water level at daily and hourly time intervals). Data from NGA (pre ~2004) for sites that were still being monitored post 2004 were migrated to Hydstra such that complete records are now available in Hydstra.	• Groundwater levels (manual groundwater level and logger groundwater level data.

Database	Description	Data
Water Management System (WMS)	Database system that provides information for water resource monitoring and management with an emphasis on water and environmental quality. Groundwater quality data is stored on the WMS and is linked to the NGA. GIS is used to graphically display water resource information.	• Hydrochemistry (surface and groundwater) • Ecosystem data
Water Use Authorisation and Registration Management System (WARMS)	National database system that stores information regarding registered and licenced water uses in South Africa.	• Registration details • Date water use licence was registered • Water volume licenced • Geolocation coordinates • Resource type (borehole, spring, dam, etc.) and location • Water use sector (e.g. irrigation, industrial use, domestic use)
National Integrated Water Information System (NIWIS)	NIWIS is an experimental dashboard managed by the DWS that gives an overview of groundwater related data on maps.	• Water level • Climate data • Surface water conditions
Geohydrological Report System (GRS)	GRS is a DWS database that contains groundwater related technical reports.	• Drilling reports • Groundwater monitoring reports • Water quality reports • Geological reports • Hydrogeological reports
The Groundwater Resource Information Project (GRIP)	GRIP was initiated in 2002 to improve data and information by providing access to unpublished or private data and reports (DWS, 2016a). GRIP is a systematic approach to gather, verify, upload and use field data from wells and equipment to provide site-specific information on already developed infrastructure. The database includes 15 500 wells and more than 6 000 constant discharge tests. GRIP has been fully implemented in the Limpopo Province, where it has been successful, but is not as advanced in other provinces where there is a lack of budget.	• Well data • Geolocation coordinates • Water levels • Basic hydrochemistry • Test pumping data • Hydrogeological parameters
CapeFarmMapper	CapeFarmMapper is a web mapping application that was developed by the Western Cape Department of Agriculture which provides a wide variety of spatial data sets and tools.	• Properties (erfs, farms) • Climate

Database	Description	Data
		• Land cover • Soils • Topography • Water resources (water management areas, catchment areas, drainage patterns, strategic water source areas for groundwater and surface water, etc.)
Table Mountain Water Source Area (TMWSA) Dashboard	The dashboard was developed to inform residents, environmental scientists and practitioners about the status of groundwater in Cape Town. The dashboard is part of a bigger project by the Table Mountain Water Source Partnership and was funded by the Danish Embassy through WWF South Africa. This is an easily understandable dashboard to present groundwater information of the TMWSA on a map, which is derived from an up-to-date groundwater database set up and maintained from various sources of data. This database was built using Aquabase.	• Geosite locations and IDs. • Well depth • Well blow yield • Groundwater levels (manual groundwater level and logger groundwater level data • Groundwater type (borehole, wellpoint, spring, etc.) • Groundwater chemistry. • Hydrology (dams, lakes, rivers, quaternary catchments). • Rainfall stations
The Global Groundwater Information System (GGIS)	GGIS is an online platform which allows groundwater data and information to be shared and distributed worldwide. The GGIS supports the sharing of map layers, well and groundwater monitoring data on one profile which is accessible to anyone around the world. Groundwater data that is available in South Africa is available on GGIS.	• Groundwater monitoring • GIS data
Private Groundwater Databases		
Hydro GeoAnalyst (HGA)	HGA is a comprehensive and easy-to-use environmental data management system. It is a customisable database that has tools for data interpretation, statistical analysis, GIS mapping, data charting, and 2D and 3D visualisation.	• Groundwater monitoring – groundwater levels, water quality, etc. • Well data – lithological logs, penetration rates, well construction, etc. • Geophysics data • Soil analysis

Database	Description	Data
		• Groundwater modelling • Hydrogeological analysis • Climate data • Hydraulic properties
Aquabase	Aquabase is a water resources management software with data entry, management and presentation tools for groundwater.	• Groundwater monitoring – groundwater levels, water quality, etc. • Well data – lithological logs, penetration rate, well construction. • Well status • Groundwater quality data • Downhole geophysics data • Climate data • Basic graphing
EQuIS	EQuIS is an advanced environmental data management and decision support system. It is used to manage data pertaining to environmental chemistry, biology, geology, geotechnical, hydrology, limnology, air, and associated compliance monitoring activities.	• Field monitoring data • Georeferenced data
GW-Base	GW-Base is a data management system to collect data related to water resources and water use such as geological information and well data. It is designed for all well and water extraction point operators.	• Water levels (manual and data loggers) • Discharge and runoff • Hydraulic properties • Well data (lithology, construction and completion). • Climate data • Water quality and quantity • Data mapping • Hydrogeological analysis

CHAPTER 4: CONCLUSION

To protect and ensure the sustainability of groundwater resources, groundwater management approaches, which rely on effective data collection, collation, QC, storage and management, need to be improved. This document presents the methodology for groundwater data collection outlining the processes from data acquisition during groundwater monitoring or development, to data processing, QA and QC and uploading to a database.

A set of standard procedures for different aspects of groundwater data collection are presented with a focus on groundwater level, groundwater quality, groundwater abstraction and spring monitoring; the last two of which are not regularly monitored nationally. Additionally, this document highlights important groundwater data that should be collected for each monitoring objective as well as important groundwater related data that should be collected during well drilling and test pumping. The document further details operational flows and QA and QC measures to ensure the validity of groundwater data collection as well as outlining the steps and recommendations for data storage. The collection, processing, storage and management of groundwater data is quintessential for groundwater resource management.

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Appendix A –

Overview of gaps identified in groundwater management, monitoring and data management in South Africa.

Gap Identified	Description
Gaps related to legislation	
Non-registration of Schedule 1 Use	The non-registration of groundwater users that fall under Schedule 1 results in data gaps and impacts to the water resource. Data gaps include groundwater abstraction volumes, groundwater levels, groundwater quality and extent of groundwater users. This leads to a misrepresentation of groundwater abstraction and usage from a resource which makes sustainable planning and distribution impossible.
Information for licensing	Limited data such as high confidence reserve determination, water resource classification, and resource quality objectives exist. This prevents the DWS and regulators making accurate and sustainable decisions.
WUL application time	The processing time for a water use licence is notoriously long and there are many backlogs in applications. The Water Use Licence (WUL) processing time has been reduced to 90 days; however, the application process still takes long due to the specialist studies required. These factors result in people becoming impatient and going ahead with unregulated groundwater use.
Borehole drilling regulation	There are no regulatory controls on borehole drilling and construction. Moreover, boreholes and borehole equipment are not listed. These factors result in poor borehole construction resulting in contamination, gaps in monitoring data and limited knowledge of the extent of groundwater use from a water resource.
Illegal groundwater use	Illegal groundwater use is an issue, as only twenty percent of groundwater use is verified. The limited capacity within regulators makes this a challenging task to address.
Lack of licenced groundwater users	Lack of licenced groundwater users. A lack of groundwater monitoring data prevents municipalities and the DWS from acting against over abstraction. Due to limited data, the DWS are unable to sustainably allocate and control the use of groundwater.
Compliance monitoring	Regulations and standard operating procedures for compliance monitoring are not enforced by the DWS.
Lack of capacity in municipalities	The sustainable development and management of municipal groundwater resources in South Africa is hindered by the lack of capacity in municipalities where they do not have the capacity to comply with WUL conditions or carry out sufficient Operation and Maintenance (O&M).
Standards and guidelines	• There are standards and guidelines in place that refer to groundwater data such as borehole drilling, testing and groundwater sampling. However, these standards are not always followed. • There is also limited legislation describing how groundwater levels and abstraction monitoring should be undertaken. • There are national and international guidelines available outlining groundwater monitoring and data collection, but these are not being followed effectively.

Gap Identified	Description
	• The guidelines and standards for groundwater monitoring and management that are in place are outdated.
Gaps related to groundwater governance	
Management within WMAs	The lack of management within all Water Management Areas (WMAs) results in gaps in national groundwater monitoring data and leads to data gaps and misinformation regarding the current state of groundwater resources across the country. The lack of management leads to the exploitation and degradation of the water resource.
Shared resource	Groundwater resources are not restricted to individual properties or municipal boundaries which is problematic when there is a lack of cooperation between municipalities. This results in discrepancies of who is responsible for monitoring and managing the resource which leads to a lack of effective monitoring and ultimately the deterioration of the resource.
Jurisdiction Responsibilities	There is an uncertainty on the jurisdiction and responsibilities between stakeholders regarding groundwater monitoring and O&M.
National Groundwater Leadership	The National Groundwater Leadership is inadequate to deal with the coordination of institutional arrangements at national, regional and local levels.
Leadership and skills	There is a lack of skills and leadership in hydrogeology to drive the understanding and acceptance of groundwater from a national level down to a local management level.
“Invisible resource”	The water management strategies and policies focus on the coordination of land-based activities and limited consideration is made to the uniqueness of the subsurface.
Groundwater quality management	There is a lack in implementing the policy and strategy for Groundwater Quality Management in South Africa which was developed in 2000 (DWS, 2016b).
Lack of support from DWS	Lack of support from DWS. This is linked to insufficient budget and capacity to implement a groundwater monitoring network and regulate compliance of groundwater users.
Stakeholder participation	There is a lack of effective stakeholder participation in WMAs. It is stated in Section 8 (5) of the National Water Act 36 of 1998 that a catchment management strategy must enable the public to participate in managing the water resources within its WMA. Stakeholders provide valuable insight into groundwater knowledge and data from monitoring initiatives. Their lack of participation is a loss to data gathering, insight and the overall understanding and protection of the water resource.
Mismanagement of funds	The mismanagement of funds due to corruption results in a degradation of management and infrastructure. As a result, money is spent on the drilling of boreholes, but this infrastructure is never implemented in reality, leaving communities destitute. Strict regulations are required to this.
Special management initiatives	No special or management initiatives have been formalised to protect vulnerable aquifers (dolomitic aquifer systems and coastal aquifers) resulting in the degradation of these resources.
Gaps related to groundwater data collection	

Gap Identified	Description
Spatial density of monitoring boreholes	The spatial density of monitoring boreholes within WMAs is not sufficient to accurately represent the groundwater characteristics, and often leads to a bias in the data.
Insufficient groundwater monitoring locations	Insufficient groundwater monitoring locations results in the loss of important groundwater data impacting on groundwater management decisions.
Lack of sufficient groundwater monitoring data	Lack of sufficient groundwater level and groundwater quality monitoring both temporally and spatially.
Spring monitoring	Springs hold important groundwater information and support many sensitive ecosystems. These require routine monitoring, but the current number of springs monitored is insufficient.
Outdated techniques for data collection	Techniques used for data collection are outdated, new techniques could gather more data, faster and at less cost. e.g. remote sensing.
Resources	There are limited resources for effective groundwater monitoring to take place across the country.
Groundwater abstraction	There is a lack of effective monitoring and regulation of groundwater abstraction which does not allow for a true understanding of the available resource or impacts already happening. The DWS is responsible for awarding and regulating groundwater abstraction across the country, but this is rarely done due to a lack in funds and capacity.
Skills and training	There is a lack of training and organisational skills of monitoring personnel. This results in errors in the collected data which ultimately results in poor decision making and management as this relies on the data.
Standards	There is a lack of monitoring standards. This leads to questionable/invalid data being gathered and used for interpretation and decision making.
Interpretation of groundwater data	Lack of regular interpretation of groundwater data, such as reporting. Analysed groundwater data allows groundwater users and management to make informed decisions regarding groundwater, for example identifying sources of contamination, groundwater protection zones or noting over abstraction at an early stage.
Long-term monitoring	There is a lack of long-term groundwater monitoring. Long-term monitoring allows for trends in the groundwater to be observed.
Historical records	Data gaps in historical records. Historical groundwater data allows for baseline values to be determined for areas. Old boreholes that do not have data uploaded (lithological logs and well construction) results in a loss of that data and wasteful expenditure as boreholes are redrilled to gather that data.
Database systems	Groundwater data often does not make its way to national database systems where the data can be easily accessible. Data is often stored on private databases or not uploaded at all and remains on hardcopy sheets. If done, this would assist in national groundwater management and effective and sustainable groundwater management.

Gap Identified	Description
Vandalism	Vandalised, damaged or faulty monitoring infrastructure. This prevents monitoring from occurring at these sites resulting in important data being lost. Vandalised or damaged sites are not reported or rehabilitated which prevents ongoing long-term monitoring of these sites.
Compliance monitoring	Compliance monitoring is not conducted regularly. Compliance monitoring includes groundwater level, quality and abstraction to ensure groundwater use complies to the water use licence conditions issued to the user. These conditions, when issued require regulation to ensure that they are undertaken and support the management of the water resource.
Lack of O&M	Lack of O&M. Monitoring sites are abandoned when boreholes are not correctly maintained or rehabilitated reducing the monitoring network. The failure of groundwater schemes is often not related to a lack of supply but rather poor maintenance of abstraction boreholes.
Quality of abstracted groundwater	Little effort is made to monitor the quality of abstracted groundwater in some municipalities. Microbiology is often not monitored due to the misinformation that groundwater is free from microbial contamination, but groundwater can be contaminated from human or animal activity especially in unconfined aquifers, e.g. typhoid outbreaks.
Regulations for borehole drilling and test pumping	There are standards for borehole drilling and test-pumping however there are no technical regulations regarding the collection of data from them. There is a loss of valuable data from contractors not uploading drilling and pump testing data which would allow for better management and reduce wasteful expenditure if information for a certain area is already known.
Professional supervision of borehole activities	Boreholes drilled without the supervision of a professional hydrogeologist leads to lithology either being logged incorrectly or not logged at all.
Stakeholder engagements	There is a lack of stakeholder engagements which can provide valuable insight into groundwater knowledge and data from the minutes of stakeholder meetings and monitoring initiatives by stakeholders.
Gaps related to groundwater data management	
Lack of trained personal	• Lack of trained monitoring personal leads to inaccurate data being recorded. • Lack of trained personal to handle data and ensure data is uploaded regularly, captured correctly and processed.
Lack of QA and QC	Insufficient QA and QC is undertaken before data is uploaded to a database. Data that is not correct has no value and is often worse than not collecting data at all, as this can guide incorrect decision making.
Upload of groundwater data	• Privately drilled boreholes not recorded on any national database. • The NGA is not regularly updated or is updated with minimal data.
Historical data	Gaps in historical data due to groundwater use not being regulated before 1998.

Gap Identified	Description
Inhouse database systems	Limited data sharing resulting in a lack of a full comprehensive understanding of the water resources in South Africa. All data should be collated to one system to allow for effective and sustainable management.
Data sharing	Data sharing issues related to confidentiality agreements and competition in the industry.
Data validity	Lack of reliable groundwater data being uploaded to databases, either resulting in insufficient spatial and temporal coverage of data or misinforming decision making.
Data on groundwater infrastructure	Lack of data on the status of water supply infrastructure.
Funding	Lack of budget in municipalities and the DWS to effectively collect data, monitoring and manage groundwater resources.
National databases are not user friendly.	National databases are not user friendly It is difficult to access data and upload data on national databases such as the NGA and WMS.

Appendix B – Sample container types, preparation, preservation and storage for common determinants.

Summarised information on sample container types, preparation, preservation and storage of samples for common determinants. From WRC (2017), Weaver et al. 2007; Sundaram et al. 2009; Ohio Environmental Protection Agency 2012, GW-MATE 2006 and U.S. EPA 2015.

Determinant	Container	Preparation	Preservation	Maximum Holding Time
Inorganic Chemistry Determinants				
Major ions	P or G	Filter if phosphate is a critical determinant	Cool storage (0-6 ºC)	28 days
Acidity	P or G	NSP	Cool storage (0-6 ºC)	14 days
Ammonia	P or G	NSP	Cool storage (0-6 ºC); H_2SO_4 to pH<2	14 days
Ammonium	P or G	NSP	Cool storage (0-6 ºC)	14 days
Bromide	P or G	NSP	NR	28 days*
Chloride	P or G	NSP	NR	28 days*
Chlorine	P or G	NSP	NR	Analyse immediately (within 15 minutes)
Cyanide	P or G	NSP	Cool storage (0-6 ºC); add NaOH to pH>12, ascorbic acid if oxidants (e.g. chlorine is present)	14 days
Hardness	P or G	NSP	HNO_3 to pH<2; H2SO4 to pH<2	6 months
Fluoride and iodide	Brown glass bottle	NSP	Cool storage (0-6 ºC)	28 days*
Kjeldahl and organic nitrogen	P or G	NSP	Cool storage (0-6 ºC); H_2SO_4 to pH<2	28 days
Nitrate	P or G	NSP	Cool storage (0-6 ºC)	48 hours
Nitrate-nitrite	P or G	NSP	Cool storage (0-6 ºC); H_2SO_4 to pH<2	28 days
Sulphate	P or G	NSP	Cool storage (0-6 ºC)	28 days
Sulphide	P or G	NSP	Cool storage (0-6 ºC), add zinc acetate plus sodium hydroxide to pH>9	7 days
Sulphite	P or G	NSP	NR	Analyse immediately (within 15 minutes)
Total metals	P or G	NSP	Cool storage (0-6 ºC); HNO_3 to pH<2 at least 24 hours prior to analysis	6 months
Dissolved metals	P or G	Filter through 0.45 µm membrane filter	Cool storage (0-6 ºC); HNO_3 to pH<2 at least 24 hours prior to analysis	6 months

Determinant	Container	Preparation	Preservation	Maximum Holding Time
Trace metals	P	Sealed 0.5 µm filter, zero head space	Acidify to pH<2	150 days
Chromium VI	P or G	Filter through 0.45 µm membrane filter	Cool storage (0-6 °C); add sodium hydroxide and ammonium sulphate buffer solution to pH 9.3 to 9.7 to extend holding time to 28 days	24 months
Mercury	P or G	Filter through 0.45 µm membrane filter	Cool storage (0-6 °C); HNO_3 to pH<2	28 days
Nutrients	P or G	Filter through 0.45 µm membrane filter	Freeze	28 days
Organic Related Determinants				
Volatiles	G, Teflon-lined cap	NSP	Cool storage (0-6 °C); 0.008% Na_2S2O_3; HCl to pH<2, Ensure no head space in the sample	14 days
Acrolein and acrylonitrile	G, Teflon-lined cap	NSP	Cool storage (0-6 °C); 0.008% Na_2S2O_3, adjust pH to 4-5	14 days
Dioxins and Furans	G, Teflon-lined cap	NSP	Cool storage (0-6 °C)	30 days until extraction, 45 days after extraction
Oil and grease	G	NSP	Cool storage (0-6 °C); H_2SO_4 or HCl to pH<2	28 days
Phenols	G, Teflon-lined cap	NSP	Na2S2O3	7 days until extraction, 40 days after extraction
PCBs	G, Teflon-lined cap	NSP	Cool storage (0-6 °C)	1 year
Pesticides	G, Teflon-lined cap	NSP	Cool storage (0-6 °C); pH 5-9	1 year
Microbiological Determinants				
Total coliforms; Faecal coliforms; E. coli; Enterococci; Heterotrophic Bacteria; or Coliphage	125- or 150 ml plastic bottles	Sterilise the bottles, do not filter	Add sodium thiosulfate if sample is chlorinated and cool storage (0-6 °C), make sure they don't freeze	8 hours for compliance samples, 30 hours for drinking water samples, 48 hours for coliphage samples
Giardia and Cryptosporidium	Plastic containers or equivalent	Sterilize the bottles	Cool storage (0-6 °C), make sure they don't freeze	96 hours
Other Common Determinants				
Radiological Alpha, beta, and radium	G, Teflon-lined cap	NSP	HNO_3 to pH<2	6 months

Determinant	Container	Preparation	Preservation	Maximum Holding Time
Radioactive Isotope-Tritium	G, Teflon-lined cap	Fill bottle directly from pump discharge hose. Leave 1 cm air-gap for expansion	Cool storage (0-6 ºC)	+
Dissolved gasses	Non-permeable bottle, Gas bags, flask	Fill according to instruction	Cool storage (0-6 ºC)	+
Stable Isotopes-Deuterium, Oxygen in water	P or G with tightly fitting caps.	Fill to the top and ensure no air bubbles, seal tightly	Cool storage (0-6 ºC)	+
Stable Isotopes-Sulphur, Oxygen in Sulphate	High Density Polyethylene (HDPE) bottle	Filter through 0.45 µm membrane filter	Add 1-2 ml of acid (HNO_3, HCl), shake and let react, then add 10 g barium chloride to precipitate barium sulphate.	+
Nitrogen-15	P or G with tightly fitting caps.	Fill to the top and ensure no air bubbles, seal tightly	Treat samples with acid, chloroform, HCl or Hg_2Cl_2 (consult the laboratory) or freezing the sample, Cool storage (0-6 ºC)	+
Carbon-14	Brown glass	NSP	Keep samples cool and in the dark. If biological activity is expected, preservation (with NaN_2 or $HgCl_2$**) is required.	+
Chlorine-36	Brown glass	Filter through 0.45 µm membrane filter	Cool storage in dark (0-6 ºC)	+

NSP – No Special Preparation

NR – Not Required

P – Polyethylene (plastic)

G – Glass

* The preservative and holding times may vary with sampling procedures, method analysis and selected laboratory.

**Maximum holding time includes waiting time in the laboratory.

\+ Could not be found from literature.

Appendix C – Mobile Phone Apps for Groundwater Data Collection.

Description of mobile apps that can be used for groundwater data collection. From WRC (2019), SADC-GMI, IGRAC and IGS (2019).

Objective	App	Website	Freeware/ Paid licence
Create personalised field forms for collection of data	AKVO Flow	To collect, manage, analyse and display geographically-referenced monitoring and evaluation data through the use of mobile phones and internet connectivity.	
		https://akvo.org/products/akvoflow/#overview	Paid
		http://flowsupport.akvo.org/container/show/akvo-flow-app	
	GeoPaparazzi	To do qualitative engineering/geological field surveys.	
		https://www.osgeo.org/projects/geopaparazzi/	Free
	Go-Canvas	App to create field-forms and capture data for any type of survey (e.g. monitoring or borehole siting/drilling/testing data). Allows manual data entry, capturing of coordinates and pictures and reading of barcodes.	
		https://www.gocanvas.com/	Paid
	mWater	App for monitoring any kind of data: physical sites like water points and facilities (schools, hospitals), non-geographic targets like grants and projects. The basic version of the app is free, but the full functionality requires a paid licence.	
		https://www.mwater.co/	Free / Paid
	KoboToolbox	Data can be accessed through API and synchronized via SSL (secure).	
		https://www.kobotoolbox.org/	Free / Paid
Edit GIS projects in the field	Collector	App to collect and update data (points, lines or polygons) using the map or GPS, download maps to mobile device to work offline, create map-driven forms, attach photos, use professional-grade GPS receivers, search for place and features.	
		https://www.esri.com/en-us/arcgis/products/collector-for-arcgis/resources	Paid
	Qfield	QField helps users to collection geodata in the field for use in QGIS projects (QGIS is a freely available GIS package). It is QGIS desktop compatible, and has a switchable use paradigm (Display, Digitise, Measure, Inspect). Qfield and QGIS are open source.	
		https://www.qfield.org/	Free

Objective	App	Website	Freeware/ Paid licence
Register groundwater monitoring data	FieldLogger	App to register new stations in the field (capture coordinates) and add (monitoring) data to the locations. Stores values on phone in csv-format, and allows sharing data by e-mail or FTP.	
		http://www.artesia-water.nl/software/fieldlogger/	Free
	GGMN App	App to geo-reference, register groundwater monitoring stations and capture groundwater level monitoring data, with the option of submitting the collected data to the Global Groundwater Monitoring Network (GGMN) Portal.	
		https://play.google.com/store/apps/details?id=com.vesselstech.ggmn&hl=en	Free
	GW-Mobil	App for groundwater monitoring. Field data are imported from the mobile device directly into the (commercial) groundwater management system GW-Base 9.0 or higher (only option available). It includes tools for planning and managing routes and barcode scans of the monitoring site to automatically connect data to site.	
		https://www.ribeka.com/en/products/gw-mobil/	Paid
	MyWell	App for monitoring groundwater data, as well as rainfall and check dam readings. In addition to the groundwater levels the user can store and display additional information (text / photograph), as well as historical and village level data for simple comparison and analysis.	
		https://vesselstech.com/mywell.html	Free
Collect stratigraphic data during fieldwork	LithoHero	Application to collect, record, and display sedimentological and stratigraphic data during fieldwork. The application can be used to describe outcrops or cores.	
		http://lithohero.com/	Free
Measure groundwater levels	Mobile Water Management (MWM)	App for groundwater monitoring. The app uses the smartphone (speaker and microphone sonar) to measure groundwater levels, up to 20m deep and with an accuracy of 1 cm. Data can be exported to a Water Information System (WIS). The basic version of the app is free, but the full functionality requires a paid licence.	
		https://www.mobilewatermanagement.nl/	Free / Paid
		https://play.google.com/store/apps/details?id=com.mobilewatermanagement.sensor&hl=en	
	CrowdWater	App for collecting hydrological data. Data collected are: water level & streamflow, soil moisture and flow condition of a temporary stream.	

Objective	App	Website	Freeware/ Paid licence
Collect complementary hydrological data		https://www.crowdwater.ch/en/welcome-to-crowdwater/	Free