GROUNDWATER MANAGEMENT INSTITUTE

SADC Framework for Groundwater Data Collection and Management

April 2019

igrac
International Groundwater Resources Assessment Centre

UNIVERSITY OF THE FREE STATE
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This report emanates from the project Capacity Building for Groundwater Data Collection and Data Management in SADC Member States (GWdataCoM) commissioned by the Southern African Development Community Groundwater Management Institute (SADC-GMI), and executed by the International Groundwater Resources Assessment Centre (IGRAC) and Institute for Groundwater Studies (IGS).

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This report is accessible online through SADC-GMI website: www.sadc-gmi.org

Citation: SADC-GMI, IGRAC, IGS (2019) SADC Framework for Groundwater Data Collection and Data Management. SADC-GMI report: Bloemfontein, South Africa.

Editorial and Layout: Southern African Research and Documentation Centre (SARDC)

CONTENTS

Tables

Figures

Boxes

ACRONYMS

ACWI	Advisory Committee on Water Information
AFD	Agence Française de Développement
CRD	Constant Rate Drawdown
DPSIR	Driver-Pressure-State-Impact-Response Framework
EEA	European Environmental Agency
EU	European Union
FAO	Food and Agriculture Organisation of the United Nations
FEC	Fluid Electrical Conductivity
GEF	Global Environmental Facility
GGRETA	Governance of Groundwater Resources in Transboundary Aquifers Project
GMI	Groundwater Management Institute
GPS	Global Positioning System
GSM	Global System for Mobile Communications
GWdataCoM	Groundwater Data Collection and Data Management
GWHC	Groundwater Hydrology Committee
GWML	Groundwater Mark-up Language
IAH	International Association of Hydrogeologists
IBE	Ion Balance Error
ICT	Information and Communication Technology
IGRAC	International Groundwater Resources Assessment Centre
IGS	Institute for Groundwater Studies
IHP	International Hydrological Programme
IPCC	Intergovernmental Panel on Climate Change
MCCM	Multi-Country Cooperation Mechanism
NGO	Non-Governmental Organisation
NGWMN	National Groundwater Monitoring Network
OGC	Open Geospatial Consortium
ORASECOM	Orange-Senqu River Commission
QA	Quality Assurance
QC	Quality Control
RBO	River Basin Organisation
SADC	Southern African Development Community
SDC	Swiss Agency for Development and Cooperation
SDI	Spatial Data Infrastructure
SOGW	Subcommittee on Groundwater
STAS	Stampriet Transboundary Aquifer System
SWCI	Shared Watercourse Institution
TBA	Transboundary Aquifer
TDS	Total Dissolved Solids
TM	Transverse Mercator
UFS	University of the Free State
UNECE	United Nations Economic Commission for Europe
UNESCO	United Nations Education, Scientific and Cultural Organisation
UNICEF	United Nations International Children's Emergency Fund
UPS	Uninterruptable Power Supply
USEPA	United States Environmental Protection Agency
WMS	Web Map Service
WRC	Water Research Commission
WSCU	Water Sector Coordination Unit

ACKNOWLEDGEMENTS

Development of the SADC Framework for Groundwater Data Collection and Data Management required strong collaboration from all the SADC Member States at various levels.

The authors express sincere appreciation to members of the **SADC Sub-Committee on Hydrogeology** for identifying the need for the Framework, following on the numerous challenges that they experience in their respective countries. Without the dedicated facilitation and support from the members of the SADC Sub-Committee on Hydrogeology, who also serve as focal points for groundwater development in their respective countries, this exercise would not have been accomplished. In this regard, special thanks is given to Mr Manuel Quintino, Angola; Mr Kedumetse Keetile, Botswana; Mr Cyrille Masamba, Democratic Republic of Congo; Mr Trevor Shongwe, Kingdom of eSwatini, Ms Christinah Makoae, Lesotho; Mr. Luciano Andriavelojaona, Madagascar; Ms Zione Uka, Malawi; Mr Pokhun Rajeshwar, Mauritius; Ms Ana Isabel Fotine, Mozambique; Ms Maria Amakali, Namibia; Mr Frankie Jose Dupres, Seychelles; Mr Zacharia Maswuma, South Africa; Ms Mwanamkuu Mwanyika, United Republic of Tanzania; Mr Frank Ngoma, Zambia; and Mr Robert Mutepfa, Zimbabwe.

Additionally, the authors thank all other professionals from the **Member States** who contributed to the project by providing ideas and feedback, in particular the 145 professionals from various organisations who contributed to the over-all project through interviews, and the senior officials from the Member States and young professionals involved throughout the project and in workshops.

Special appreciation is given to the **SADC Groundwater Management Institute** team comprising of Mr James Sauramba, Executive Director; Mr Brighton Munyai, Senior Groundwater Specialist; Mr Thokozani Dlamini, Communications and Logistics Knowledge Management Specialist; Ms Nyakallo Khoabane, Administration and Finance Officer; and Ms Mampho Ntsheke, Grants and Procurement Officer for making this project possible and for their technical and logistical contributions.

The contribution of all institutions and individuals who supported the development of the Framework through ideas and comments and may not have been credited by name, is greatly appreciated.

EXECUTIVE SUMMARY

Southern Africa has at least 70 percent of its population dependent on groundwater as the primary source for drinking, domestic use, and support for livelihood activities. Applications of groundwater are broad and important for urban water supply, irrigation, watering livestock, and for industrial use. It also provides base flow to rivers and supports ecosystems.

The demand for water is expected to rise due to growing population, changing lifestyle-patterns and climate. If well managed, groundwater in southern Africa is a resource which, could ensure long-term water supply to meet the increasing demands brought by the anticipated climate variability. There are more transboundary aquifers in southern Africa than there are transboundary river basins.

While groundwater is an abundant resource in the region, its potential remains subdued by limited amount of data on aspects of availability, quality, quantity and abstraction. The limited capacity to predict hydrogeological behaviour and water resource development in sufficient detail over long periods of time affects extents to which groundwater as a resource is appreciated and therefore managed. Proper and adequate groundwater data collection and data management, is therefore crucial for effective groundwater management.

The assessment carried out by the International Groundwater Resources Assessment Centre and the Institute for Groundwater Studies of the University of the Free State in 2017/2018, on the state of groundwater data collection and data management in SADC, confirms challenges the region is currently facing. The constraints include limited human resources, equipment and financial capacity appropriate for collection, analysis, management, retrieval, and sharing of data; inconsistence in data collection and routine quality control; data storage in different formats and difficulty in data access, use or interpretation.

It is observed that while policies, strategies and technical guidelines on groundwater data collection are available in the SADC Region, there is need to connect the policies with the existing technical guidelines which are not being effectively utilised due to lack of clear direction on how to use them. There is no appropriate organisational and planning framework for use of the technical guidelines to implement the existing policies and strategies on water resources that include groundwater. Thus, the SADC Framework for Groundwater Data Collection and Data Management serves as an instrument to drive implementation of policies and strategies making use of the existing technical guidelines.

The Framework is targeted at officials who have a coordinating role in groundwater data collection and data management. These are usually senior level professionals who coordinate field technicians as well as interact with managers and directors of departments.

The overall objective of the Framework is to **provide organisational and planning structures for collection and management of groundwater data in strategic, innovative and cost-effective ways**. Specific objectives are to:

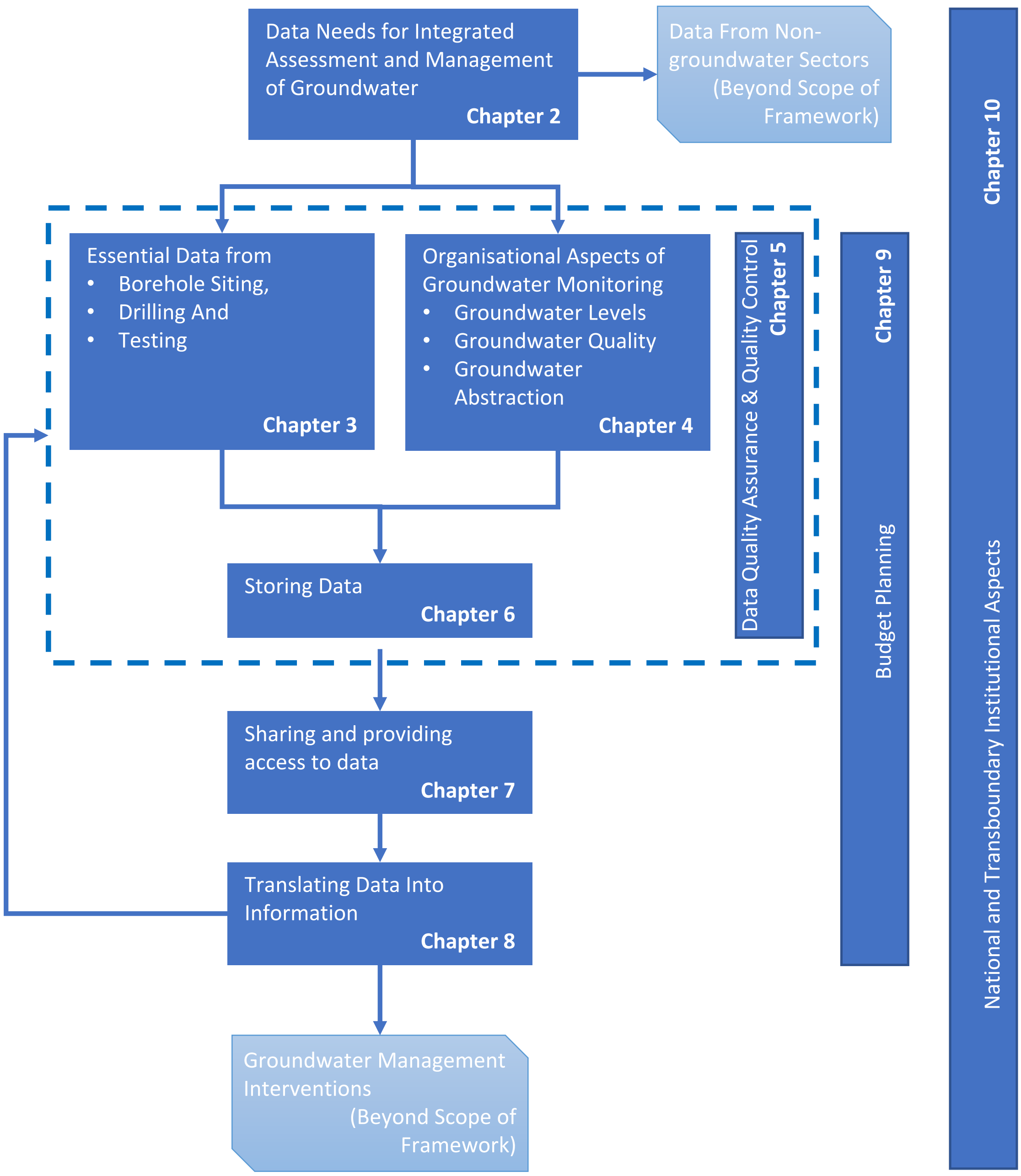
- **Assist SADC Member States which are currently facing difficulties in groundwater data collection and data management to develop adequate procedures at national level that match their financial and human capacity and level of development; and**
- **Enhance transboundary and regional cooperation through harmonisation of practices across Member States in terms of data collection and management and facilitate data exchange.**

The Framework addresses various aspects of groundwater data collection and data management, such as borehole siting, and drilling, groundwater monitoring, field data collection, databases, and data sharing and reporting.

The Framework assists in implementing priority actions in the work programme for groundwater in the SADC Regional Strategic Action Plan for Integrated Water Resources Management

(RSAP IV, 2016–2020). Institutional and technical capacity to implement national strategies can be strengthened using the Framework for guidance. The Framework will also facilitate cooperation in the management of shared aquifers in the region, towards implementation of the Revised SADC Protocol on Shared Watercourses and river basin agreements across the region.

The Framework is divided into 10 chapters as shown in the figure below.



Chapter 1 provides the **rationale of the Framework**; positioning the Framework in relation to regional processes, and the specific **target group.**

Chapter 2 provides insights in the **data needs for integrated assessment and management of groundwater**. The data needs go beyond groundwater, and cover data from other sectors such as agriculture that use or potentially pollute groundwater, and data from meteorological and ecological sectors that provide information needed to understand the hydrogeological system.

It underscores the importance of reliable and up-to-date groundwater data as the only way to develop a good conceptual understanding of aquifer systems and the dynamics or trends in groundwater resource development. Key to the chapter is the need for groundwater departments and other sectors to cooperate and exchange relevant data and information required for integrated groundwater resource assessments and the development of integrated policies.

Chapter 3 deals with the importance of collecting essential **data from borehole siting drilling and testing** to be able to develop a conceptual understanding of aquifer systems and to successfully develop and sustainably manage groundwater abstractions. The chapter provides focus on the essential data that need to be properly recorded during the drilling and construction phase, and be stored in more widely compatible formats in structured databases for future use.

Groundwater departments need to initiate activities to encourage and/or compel stakeholders to submit the essential data from drilling, testing and siting of boreholes. Capacity building in environmental law enforcement should include (enforcement of) collection of essential groundwater data.

Chapter 4 deals with the **organisation and planning aspects of groundwater monitoring.** Monitoring of groundwater levels, quality and abstraction is essential to understand trends in resource development and to define effective management interventions. The chapter highlights that for **cost-effective monitoring,** the right choices on methods (manual and data loggers), regular maintenance, re-evaluation and optimisation of the networks are required. It notes that **groundwater monitoring is not just a technical exercise**, it requires organisation and planning at various levels within the organisations. This includes allocating capacity and budgets for incidental investments and recurring costs for data collection and maintenance. The chapter presents the potential of **community-based groundwater data collection** as a cost-effective measure, with the added benefit that it can trigger community participation in groundwater management.

Chapter 5 focusses on the importance of **data quality assurance and quality control** (QA/QC). The need to build capacity in QA/QC and benefits of modern technology are underscored. This includes developing and conducting vocational training programmes for groundwater technicians to improve the quality and efficiency of groundwater data collection; use of modern technologies such as digital field forms in mobile phone applications and data loggers; The chapter emphasises the need to conduct (computer aided) routine checks to verify the quality of the data before it is captured in databases.

Chapter 6 highlights the need to **store data** in a structured way, in digital formats that can be easily processed, to enable efficient and cost-effective access, retrieval and processing for future studies. The choice of database software should be based on the expected amount of data to be stored as well as available human capacity and skills to manage the data and the database systems.

The chapter recommends the use of advanced server-based database solutions that provide the most robust solutions, though at relatively high cost. There is need to consider the high setup and maintenance costs as well as the cost of sustaining the advanced server-based database solutions. Otherwise if there are insufficient resources, the best would be to use more simple solutions. Well-designed spreadsheets can be an adequate and highly cost-effective alternative to advanced desktop or server-based database solutions.If the data are well-structured, migrating the data to more advanced database systems at a later stage when needed, is relatively straightforward, allowing for progressive development.

Chapter 7 presents the **importance of sharing and providing access to data** to promote awareness and stakeholder involvement in groundwater management. Data sharing enables informed decisions in planning and management of national and transboundary aquifer resources. The chapter promotes cooperation between and among data custodians. It also promotes use of modern technology on data sharing. For example, using open data standards allows for seamless access to data from other organisations whilst eliminating the need to manage the data in multiple places and organisations.

Chapter 8 highlights that **data needs to be turned into information** to communicate key messages to stakeholders and to develop fact-based interventions. The chapter takes note of different stakeholders which require information to be presented differently. Of much importance is data analyses and interpretation for development of policies and management interventions. Additionally, and importantly, analyses and interpretation also assist in identifying data gaps and data quality issues that may lead to reassessment of data needs and data collection and/or management procedures.

Chapter 9 underscores the need for **budget planning** and to understand the various costs involved in data collection and management activities. Funding for groundwater data related activities can be sourced in different ways. External funding may be suitable for initial investments, but budget for continued management and maintenance should as much as possible come from national financial resources.

Chapter 10 concludes the Framework by presenting **national and transboundary** institutional aspects of groundwater data collection and data management. This covers the need gradually implementing transboundary programmes of groundwater data collection and data management, starting with an initial assessment based on gathering, harmonising and combining existing datasets from the countries, before moving on to joint monitoring. The chapter underscores the need to harmonise the collection and storage of national data in such a way that it can be used at transboundary and regional levels. Though data may be collected through national organisations, transboundary and international institutions such as Lake and River Basin Organisations (L/RBOs) or the SADC Groundwater Management Institute (SADC-GMI) are well positioned to provide support to or even lead transboundary programmes of groundwater data collection and data management.

1 INTRODUCTION

1.1 Rationale for the SADC Framework for Data Collection and Data Management

Groundwater is important throughout the Southern African Development Community (SADC) region, especially for rural water supply. It is estimated that at least 70 percent of the 327.2 million people living in Southern Africa rely on groundwater as their primary source of water for drinking and domestic use, and to support livelihood activities (SADC, 2016a). Groundwater use for other purposes such as urban water supply, irrigation, watering livestock or for industry, although differing from country to country, is also significant.


Credit: Oliver Karstel

Groundwater is an important source for domestic water throughout Southern Africa

Water demand in the region is increasing as a result of population growth and socio-economic development. Climate extremes frequently result in floods and prolonged periods of droughts, making surface water less reliable for year-round water supply. The Intergovernmental Panel on Climate Change (IPCC) has predicted that Southern Africa is expected to experience more frequent droughts, generally longer dry spells and more variable rainfall than before with a decrease in annual precipitation of as much as 20 percent by 2080 (IPCC 2014). As a result, sustainable groundwater utilisation and management become crucial.

While groundwater is an important resource in the region, it remains somewhat hidden due to limited amount of data on its availability, quality and use, which hinders an accurate assessment of groundwater status and trend. Without proper knowledge of the resource and sound governance principles, this huge resource can be rapidly and irreversibly degraded.

Studies on transboundary aquifers and regional groundwater studies on the impacts of climate variability and change, as well as socio-economic developments, require regional data and information to be compiled, harmonised and made easily accessible.

As part of the project *Capacity Building on Groundwater Data Collection and Data Management in SADC Member States* (IGRAC and IGS, 2019a) an assessment was carried out in 2017 and 2018 on the state of groundwater data collection and data management in SADC Member States.

The assessment involved literature review, consultations with 145 groundwater experts through interviews, and engagement of young professionals from SADC Member States to understand the capacity needs on groundwater data collection and management in the region.

Information obtained through the assessment was synthesised into a report on the State of Groundwater Data Collection and Data Management in SADC Member States (IGRAC and IGS, 2019b). The report provides a detailed assessment per Member State and for the entire SADC region. The main conclusion is that all SADC Member States, to different extents, have challenges in effectively organising groundwater data collection and data management. Some of the major issues identified are:

- Lack of staff numbers and skills capacity and equipment;
- Lack of clear objectives and procedures for groundwater monitoring;
- Inconsistencies in collection of data. The spatial and temporal distribution of data is low or uneven (many data gaps);
- Insufficient quality assurance and quality control of data;
- Few functional digital databases. Data are stored in different places in different formats which further compromises the usability of the data;
- Limited data backup strategies, sometimes non-existent and data are at risk of being lost;
- Complicated access to the data, sometimes even within the government, departments and data sharing is very limited both at national and regional levels; and
- Limited capacity to interpret groundwater data and production of information for effective decision-making.

These issues show weaknesses in the whole chain of data collection and data management and, as a result, little up-to-date information on groundwater is produced to support decision-making in the region. Interviewees often reported that the challenges emanate from the lack of funds. This is in line with the SADC Regional Water Strategy (SADC, 2006) that also reports that the region has difficulty in mobilising adequate funds for developing and managing groundwater resources. Notwithstanding that groundwater data collection and data management programmes need more funding, they also need to be optimised according to available and limited budgets.

Policies, strategies and technical guidelines on groundwater data collection and data management are available but there is a need to connect the policies with the technical guidelines such as the Guidelines for the Groundwater Development in the SADC Region (SADC, 2001), which are not being effectively used due to a lack of clear and appropriate organisational and planning of data collection and management. It is upon this background that the SADC Framework for Groundwater Data Collection and Data Management was developed.

1.2 Objectives and Scope of the Framework

The aim of Framework is to fill the gap between the SADC-wide, regional strategies and policies and the technical guidelines and manuals that already exist, as illustrated in Figure 1.1, by providing organisational and planning structures for collection and management of groundwater data in strategic, innovative and cost-effective ways. It acknowledges differences between Member States capacity, challenges and needs in terms of groundwater data collection and data management. In consideration of this disparity, the Framework provides strategic and organisation support for various levels and types of groundwater data collection and data management.

The specific objectives are as follows:

Objective 1: Assist Member States which are currently facing difficulties in groundwater data collection and data management to develop adequate procedures at national level that match their financial and human capacity and level of development;

Objective 2: To enhance transboundary and regional cooperation through harmonisation of practices across Member States in terms of data collection and management and facilitate data-exchange.

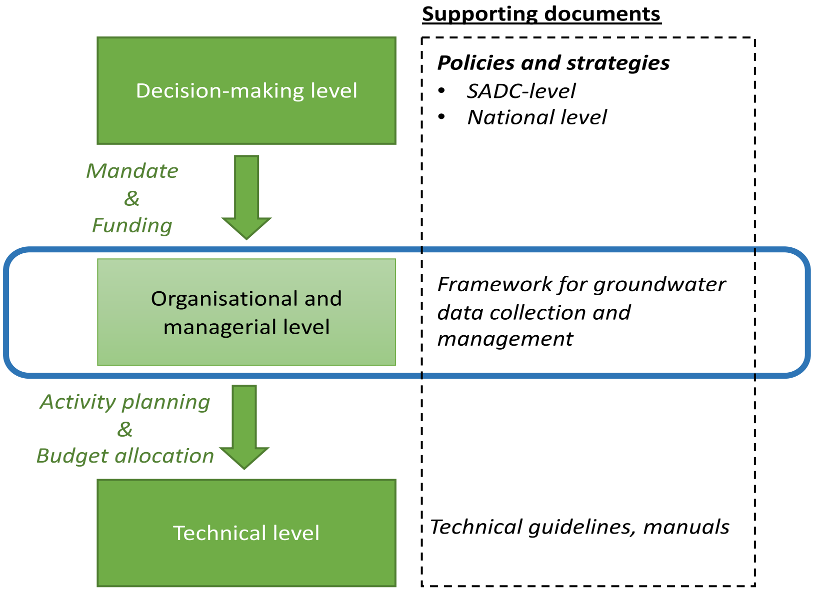


Figure 1.1 Position of the Framework within existing SADC groundwater instruments

The aim is for Member States to benefit from the Framework, irrespective of their levels of implementation of groundwater data collection and data management. The Framework addresses many aspects of groundwater data collection and data management, from borehole siting to groundwater monitoring, from field data collection to databases and data sharing. Focus is on data which are collected and archived on a regular basis either via dedicated monitoring programmes or via regular activities such as drilling and developing new boreholes (*See* Box 1.1 and 1.2). Data which are collected at incidental basis (e.g. in hydrogeological mapping or specialised research) are not covered in this Framework. The Framework is therefore not designed to guide technical expects but is mainly to strengthen capacity of groundwater managers in their organisation and planning for data collection and management.

There is need for improving safe access to clean water in Southern Africa

Box 1.1 Definition of terms

In this Framework, groundwater data collection, groundwater monitoring and groundwater data management are defined as follows:

Groundwater data collection is the collection of groundwater field data under the responsibility of groundwater departments. Data can be grouped in two main categories: borehole siting, drilling and testing data, and monitoring data.

Borehole siting, drilling and testing are the activities performed to create new boreholes. Many relevant data are collected during these activities that provide significant insight on groundwater availability, quality and use.

Groundwater monitoring is the process of collecting time-variant groundwater data, such as groundwater levels, groundwater quality data and groundwater abstraction data in a predesigned network and at set intervals, with the purpose to observe and analyse trends.

Groundwater data management is the whole process of using groundwater data after their collection. It encompasses quality assurance and quality control (QA/QC) of those data, the storage of those data in archives and databases, sharing/providing access to data, analysis and interpretation of the data, and finally the dissemination of resulting groundwater information.

1.3 Position of the Framework in Relation to Regional Processes

The SADC Framework for Groundwater Data Collection and Data Management will contribute significantly to the implementation of regional protocols and strategies in the SADC region. For instance, it will contribute to fulfilling the article on sharing of hydrogeological data and information envisaged in the SADC Revised Protocol on Shared Watercourses (SADC, 2000). This in turn feeds into findings of the project Groundwater Governance (FAO 2016c), which emphasises the importance of good groundwater information as indicated in Box 1.2.

The Framework will contribute to fulfilling the targets in the SADC Regional Water Policy (SADC, 2005), one of which is for Member States to establish water resources information systems as well as ensuring that the general public has access to relevant and easy to understand information on water resources impacting on their health or safety and on economic interests, as indicated in Box 1.3.

In addition, the Framework will contribute to Programme 6.2.2 (c) of the Regional Strategic Action Plan on Integrated Water Resources Development and Management Phase IV: 2016-2020 (SADC, 2016b), which states the need to strengthen groundwater monitoring and data management systems to support SADC Member States.

Groundwater spring in Motlhaka, South Africa indicates presence of aquifers beneath

Box 1.2 Groundwater Governance: key deficiencies, definition and aspects of data management

Groundwater governance – key deficiencies identified in 'global diagnostic'

- Inadequate Leadership from Government Agencies;
- Limited awareness of Long-Term Groundwater Risks;
- No Measurement of Groundwater Resource Status;
- Non-Performing Legal Systems on Groundwater;
- Insufficient Stakeholder Engagement in Groundwater Management; and
- Limited Integration of Groundwater in Related National Policies.

Groundwater Governance – a definition

Groundwater governance comprises the promotion of **responsible collective action** to ensure control, protection and socially-sustainable **utilisation** of groundwater resources and aquifer systems for the **benefit of humankind and dependent ecosystems.** This action is facilitated by an enabling framework and guiding principles.

Groundwater governance has four components:

- An effective and articulate legal and regulatory framework;
- Accurate and widely-shared knowledge of the groundwater systems concerned, together with awareness of the sustainability challenges;
- An **institutional framework** characterized by leadership, sound organisations and sufficient capacity, permanent stakeholder engagement, and working mechanisms to coordinate between groundwater and other sectors; and
- **Policies, plans, finances and incentive structures** aligned with society's goals.

Organising data collection, information generation and knowledge sharing

- Good aquifer management requires good information;
- Information will include both snapshots of static features and monitoring of dynamic changes;
- Information needs to be converted to knowledge in order to enable stakeholders to take informed management decisions;
- The resulting information and knowledge should be shared widely with all Stakeholders;
  the four information and knowledge tasks – data acquisition, analysis, information sharing; and
- Dissemination of useful knowledge – are key steps to guide groundwater management

Source:
Groundwater Governance Project (www.groundwatergovernance.org):

- Global Diagnostic on Groundwater Governance (FAO, 2016a)
- A Shared Global Vision for 2030 (FAO, 2016b)
- Global Framework for Action to Achieve the Vision on Groundwater Governance (FAO, 2016c)

Building capacity of young professionals in groundwater issues is vital

Box 1.3 SADC-wide policy statements on Water Resources Information Management

Policy statement:

(e) Water Resources Information and Management

Data and Information Acquisition and Management

(i) Member States shall establish water resources data and information acquisition and management systems in their territories in an integrated manner at regional, river basin and national levels to meet all water resources management needs.

(ii) Member States shall adopt compatible systems for data and information acquisition and management.

Information Sharing

(i) Member States shall timeously share relevant available information and data regarding the hydrological, hydro-geological, water quality, meteorological and environmental condition of shared watercourses.

(ii) Member States shall ensure that members of the public in the region have access to relevant and understandable information regarding water resources impacting on their health or safety and on economic interests.

(iii) SADC, SWCIs as well as Member States shall establish mechanisms for regular interpretation and dissemination of essential information on water resources so that the public is regularly informed.

Source: SADC Regional Water Policy (SADC, 2005)

1.4 Target Audience for the Framework

Groundwater data collection and data management are quite technical in nature. This Framework however, does not aim to be a guideline for the technically oriented staff going out in the field to collect data (field technicians). The existing guidelines, handbooks of best practices, and templates of field forms available in the region are appropriate for the technical staff.

The Framework is mostly targeting officials who have a coordinating role in the groundwater data collection and data management, usually at a more senior level; professionals who interact with or coordinate with field technicians as well as with managers and directors of departments.

It is intended to be an instrument for improving flow of data from the field into adequate and accessible databases, resulting in data being used for development of groundwater policies and management interventions. The Framework is meant to improve existing working procedures, as well as create more awareness on importance of data collection, management as well as taking into account capacity and budget requirements.

1.5 Development of the Framework

The SADC Groundwater Management Institute (SADC-GMI) contracted the International Groundwater Resources Assessment Centre (IGRAC) to execute the project *Capacity Building for Groundwater Data Collection and Data Management in SADC Member States* (SADC-GWdata-CoM) under contract CS2017/05 of 1 September 2017. The project, which ran from September 2017 to April 2019, was executed by IGRAC in close cooperation with the Institute for Groundwater Studies (IGS) of the University of the Free State (UFS) in South Africa. Development of this Framework was one of the project components, in addition to analysing the state of groundwater data collection and data management in SADC Member States and capacity building of young professionals from the region.

The project team drafted the Framework in regular consultation with SADC-GMI staff, making use of existing guidelines and documented similar initiatives. A zero draft of the Framework was discussed in a workshop held in November 2018 in Johannesburg attended by senior staff members from groundwater departments of SADC Member States, with experience in groundwater data collection and data management. Technical aspects of the Framework were discussed, and this provided valuable input to the report. An updated draft was shared with SADC-GMI focal persons in the Member States for further feedback via the SADC-GMI steering committee in April 2019, after which the Framework was completed.

Development of groundwater related policies must involve stakeholders at all levels

1.6 Report Outline

Chapter 2 explains the importance of collecting and managing groundwater data, along with other groundwater-related data. It describes the wider context of groundwater data dealt with in this Framework. Chapter 3 describes the essential data to be collected from siting, drilling and testing of boreholes. Chapter 4 deals with organisational aspects of groundwater monitoring, including a section on the potential for community-based groundwater data collection. Chapter 5 deals with aspects of quality control and quality assurance, while the following chapters deal with data storing (Chapter 6), sharing (Chapter 7) and processing (Chapter 8). Chapters 9 discusses budgetary issues and Chapter 10 completes the Framework with institutional considerations on data collection and data management at the national and transboundary levels. Figure 1.2 provides an overview of the aspects covered in the Framework.

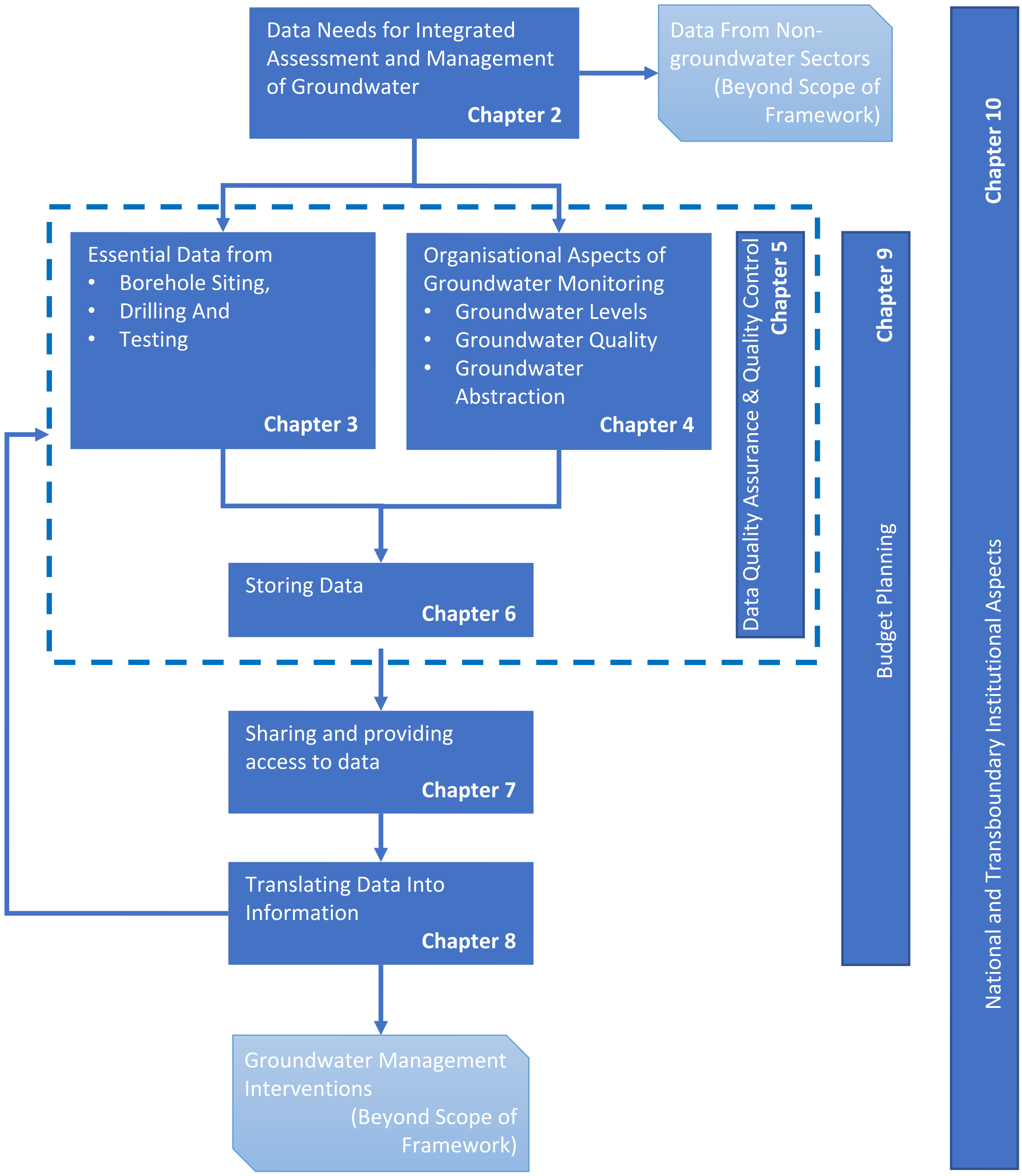


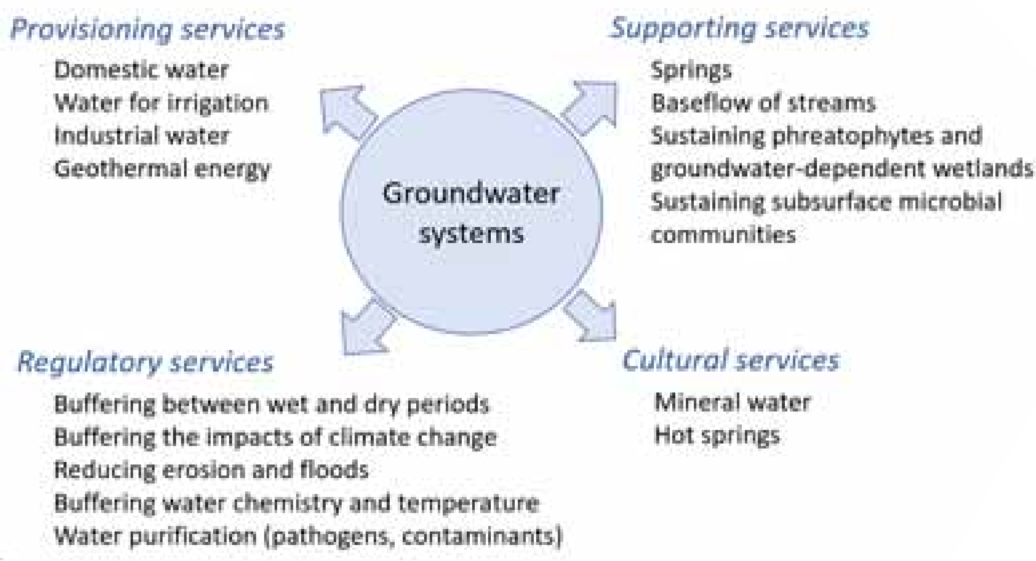
Figure 1.2 Framework Overview

2 DATA NEEDS FOR INTEGRATED ASSESSMENT AND MANAGEMENT OF GROUNDWATER

2.1 Introduction

Groundwater is an important resource for domestic use, agriculture (irrigation and watering live-stock) and industry. Groundwater is also crucial for several ecosystems, for example in sustaining springs and baseflow to rivers. Due to generally large buffering capacity of aquifers, groundwater systems can be used to store water (naturally or artificially) during wet periods to be abstracted in dry periods. These and other functions of groundwater are referred to as groundwater system services (Bergkamp and Cross, 2006). Figure 2.1 provides an overview of different groundwater system services or functions. To maintain these services, proper management of groundwater is required.

Groundwater is a key resource for agriculture in the face of climate change



Source: Van der Gun, J. (2018), Unpublished document for IGRAC

Figure 2.1 Groundwater services

2.2 Data Needs

Management of groundwater resources requires assessment and regular monitoring of the state of the resources (quantity and quality), its interaction with other components of the water cycle (e.g. surface water, rainfall and evaporation), its relationship with socio-economic activities and environmental issues, as well as the legal and institutional setting in which it is governed. To assess these interactions and to establish trends, data on all these processes are required. Table 2.1 lists the data required for integrated assessment of groundwater resources that can be used to describe the general state of groundwater resources. It was developed for the assessment of transboundary aquifers but can also be used for the assessment of national aquifers. Not all data are required under all circumstances and the list of parameters in the table is not comprehensive. Most importantly, it highlights the multitude of data required for integrated management of groundwater resources.

Training of young professionals on data collection

Table 2.1 Data to be collected for assessing transboundary aquifers

Parameters, variables and information to be collected	
A. Physiography and climate	C.9. Discharge by springs
A.1. Temperature*	**D. Environmental aspects**
A.2. Precipitation*	D.1. Groundwater quality (suitability for human consumption)
A.3. Evapotranspiration	D.2. Groundwater pollution
A.4. Land use*	D.3. Solid waste and wastewater control
A.4.1. Groundwater-fed agricultural land	D.3.1. Wastewater being collected in sewerage systems
A.4.2. Groundwater-irrigated land	D.3.2. Wastewater treated
A.4.3. Groundwater-supported wetlands and ecosystems	D.3.3. Solid waste being stored in controlled fields
A.4.4. Areas with land subsidence	D.4. Shallow groundwater table and groundwater-dependent ecosystems
A.5. Topography: elevation data*	**E. Socio-economic aspects**
A.6. Surface water network (rivers, lakes, swamps, reservoirs, canals, etc.)	E.1. Population (total and density)*
B. Aquifer geometry	E.2. Groundwater use
B.1. Hydrogeological map	E.2.1. Total volume groundwater abstraction
B.2. Geo-referenced boundary of the Transboundary Aquifer	E.2.2. Groundwater abstraction for domestic use
B.3. Depth of water table/piezometric surface	E.2.3. Groundwater abstraction for use in agriculture and livestock
B.4. Depth to top of aquifer formation	E.2.4. Groundwater abstraction for commercial and industrial use
B.5. Vertical thickness of the aquifer	E.3. Surface water use*
B.6. Degree of confinement	E.3.1. Total volume of surface water use
B.7. Aquifer's cross section	E.3.2. Surface water for domestic use
C. Hydrogeological characteristics	E.3.3. Surface water use for agriculture / livestock
C.1. Aquifer recharge	E.3.4. Surface water for commercial and industrial use
C.1.1. Natural recharge	E.4. Dependence of industry and agriculture on groundwater
C.1.2. Return flows from irrigation	E.5. Percentage of population covered by public water supply
C.1.3. Managed aquifer recharge	E.6. Percentage of population covered by public sanitation
C.1.4. Induced recharge	**F. Legal and institutional aspects****
C.1.5. Extent of recharge zones	F.1. Transboundary legal and institutional framework
C.1.6. Sources of recharge	F.2. Domestic legal and institutional framework
C.2. Aquifer lithology	F.2.1. Ownership of groundwater
C.3. Soil types	F.2.2. Water resource planning
C.4. Porosity	F.2.3. Groundwater resource abstraction and use
C.5. Transmissivity and vertical connectivity	F.2.4. Abatement and control of groundwater pollution
C.6. Total groundwater volume	F.2.5. Other water resource protection measures
C.7. Groundwater depletion	F.2.6. Government and non-government water institutions
C.8. Natural discharge mechanism	F.2.7. Implementation, administration and enforcement of the legislation

* National or local data can be used; estimates are also available from global datasets.
** The legal and institutional aspects are assessed by questionnaires.

Source: IGRAC, UNESCO-IHP (2015)

The majority of the data required for integrated assessment of groundwater resources is not collected by groundwater departments but comes from other sectors such as meteorological services, land use planning, agriculture and statistics offices. This implies a clear need for active and frequent exchange of data and information between the different sectors enabling integrated groundwater resources assessments and the development of truly integrated policies.

Data regularly collected under the responsibility of groundwater departments can be grouped in two main categories:

- Borehole siting, drilling and testing data: They comprise all relevant data produced during the activities related to the installation of new boreholes. These activities provide two sorts of data: hydrogeological data on the aquifers, e.g. dimensions and hydraulic properties, which are usually provided by geophysical investigations, lithological logs and pumping tests; and data on the boreholes, which provide insight on the use of groundwater. Whether borehole siting, drilling and testing activities are carried out by the departments themselves or by other stakeholders, data should be collected and stored for future use (*See* Chapter 3); and
- Groundwater monitoring data: They result from repeated measurements at determined locations and at - chosen frequencies. The most common time-variant data typically being monitored are groundwater levels, groundwater quality and groundwater abstraction. In the SADC region, monitoring of groundwater quality and abstraction is very limited and often inadequate. Unlike borehole siting, drilling and testing data that are collected only once whenever new boreholes are created, the collection of groundwater monitoring data is planned and organised by the groundwater departments and therefore requires different approaches in terms of organisation and planning (*See* Chapter 4).

Data from borehole siting, drilling and testing as well as from groundwater monitoring are all crucial data to understand aquifer systems, the status and trends of groundwater resources. Reliable and up-to-date groundwater data are essential to develop fact-based management interventions and groundwater policies. This Framework aims to contribute to improving the collection and the management of these two categories of data.

2.3 Main Messages

- **Reliable and up-to-date groundwater data are the only way to develop a good conceptual understanding of aquifer systems and the dynamics or trends in groundwater resource development; and**
- **Groundwater departments and other sectors need to cooperate and exchange relevant data and information required for integrated groundwater resource assessments and the development of integrated policies.**

3 ESSENTIAL DATA FROM BOREHOLE SITING, DRILLING AND TESTING

3.1 Introduction

Boreholes are drilled for many purposes, including water supply, exploration and groundwater observation. In many cases, in particular boreholes drilled for public water supply, the drilling target (location and depth estimate) will be determined through borehole siting activities, usually implying geophysics. After drilling, boreholes are usually tested. Testing can be done to determine the safe yield for pumping or to determine the hydrogeological properties of the aquifer.

It is crucial to capture and store borehole siting, drilling and testing data, as they provide significant insight on the aquifers and on groundwater use. With that respect, it doesn't matter if the borehole was successful, low yielding or dry. All boreholes provide meaningful data. Attention should be given to borehole drilling data, because they can't be collected afterward. Siting and testing data can be collected twice, but it is definitely not a cost-efficient option.

This chapter provides guidance on how to organise the collection of data from borehole siting, drilling and testing activities. Annexes A, B and C describe in detail the steps to be undertaken in siting, drilling and testing new boreholes, and the data coming out at each step. This chapter determines what the most important data are that must be stored for future use. It also explores how groundwater departments (or relevant authorities) can get hold on borehole siting, drilling and testing data collected by other stakeholders.

3.2 Relevant Borehole Siting, Drilling and Testing Data

During borehole siting, drilling and testing, data are collected on the hydrogeological setting and on the borehole itself, like for instance:

- Depth and extent of aquifers;
- Hydrogeological relevant features such as 3-dimensional insights on geological formations, fractures, faults and dikes, obtained from the geophysical survey;
- Detailed lithological logs describing the different rock types which have been drilled through, information on water strikes and the water quality, obtained during drilling; and
- Well performance and/or aquifer hydraulic properties obtained from borehole testing.

All this information is crucial in any groundwater study such as for the siting of new boreholes, groundwater modelling studies and detailed research studies. The whole process of siting, drilling and testing is a costly process and it is important that the right data are collected and stored in structured database or data archives for future use.

3.2.1 Borehole Siting

Locating the right position for drilling new boreholes usually includes site investigations. Depending on the drilling objectives and the budget, site investigations can consist of simple field visits or involve multiple geophysical methods. The borehole siting process consists of five distinct steps covering the following key aspects:

- The objectives for each step;
- What has to be done in each step;
- An overview of equipment required; and
- Data and information to be collected.

Geophysical surveys provide important information for siting of boreholes

Table 3.1 provides detailed information on steps to be followed during the borehole siting process and data and information collected in each step. Steps 1, 2 and 3 are preparatory steps, making use of prior existing data (for example from national databases). New data are generated and processed In Steps 4 and 5.

The following data from Steps 4 and 5 have to be captured and stored in (national) databases at the groundwater departments or other relevant authorities:

- Raw data from the geophysical survey, including exact locations and date of the survey; and
- Report with the outcomes (interpretations) from the geophysical survey, including data on the techniques and equipment used as well as the contractor / crew doing the survey.

Extra care is needed to ensure that raw data and the report for each geophysical study can be linked in the database through some sort of unique identifier, and/or geographical place marker (*see* also Box 3.1).

Table 3.1 Steps in borehole siting process with data and information collected in each step

Activity	Objectives	Key data and information to be collected
1. Desktop study	• Develop a preliminary conceptual understand ing of the hydrogeology of the area	Have a general understanding of: • Records of existing boreholes, e.g. location of boreholes in a specific radius of influence from the area of interest (e.g. 2 km radius), water strikes, lithology, yields and groundwater levels • Geological controls of groundwater occurrence • Types of typical aquifer occurring at regional scale and at local scales if there are any
2. Hydro-census and site walk	• Identify and understand groundwater use activities within the area of interest • Confirmation of information gathered in step 1	• Borehole location data (x, y, z) • Borehole use data • Records of yields for boreholes installed with water meters • Have an initial idea about layout of traverses for the geophysical survey
3. Interim report	• Plan for field geophysical survey	• Decide/recommend on the type of equipment suited for field geophysical survey based on the understanding of site conditions

		• Design the traverses' layout on the map for the geophysical survey.
4. Field geophysical survey	• Locate the suitable drilling target using an appropriate geophysical method(s) and equipment recommended in interim report (Activity 4)	• **Data of the investigated geophysical parameters,** • **Coordinates of start and end points of traverses,** • Identified potential drilling sites
5. Borehole siting report	• Give a detailed description of the borehole siting work and the main findings (Activity 1-5)	• Data and analysis to motivate the selected target • Coordinates of the drilling target, • Description of the drilling target, e.g. geological features being targeted like fault, fractures etc., • Estimated depth of water strikes and overall drilling depth, • Provisional basic well design can be part of this phase • **Report inclusive of all activities (1-5).**

Bold text indicates data which should be stored in databases or data archives.

Box 3.1 Unique identifiers for data from siting, drilling and testing of boreholes

Data identification:

To ensure that data can easily be found in a data archive or database and can be connected to a specific borehole location, data need to be stored under a unique and preferably logical identifier, and if the database allows it should also be possible to perform a geographic search.

Geographic names are often used to identify data from hydrogeological studies. Using geographic names is however not the most robust method as the location is not very accurate and in case different spellings exist it can be very hard to find the data in the database (*See* Box 3.2).

For data from drilling the preferred identifier is the national borehole number, and the coordinates act as another tool to locate the data from a map. The borehole number should also be used for data from borehole (or aquifer) testing. In case multiple boreholes are used to observe changes in piezometric head for aquifer testing purposes, the pumped borehole would be the preferred identifier.

For data related to borehole siting, the identifier is not as obvious as often the borehole number will not yet be available / assigned. If borehole siting data are related to a specific borehole then the borehole number should be used as much as possible. In case a geophysical study covers a larger area, which resulted in the siting of multiple boreholes, the coordinate of the central point from the (geophysical) siting study could be used as identifier. Depending on the functionality of the database more advanced geographical features such as the bounding box of the geophysical traverses can additionally be used to located data.

3.2.2 Borehole Drilling

Like in siting of a borehole there are multiple steps in the process of drilling. Annex B gives an overview of the different steps, including responsibilities of the driller and of the supervisor and the key data to be collected in all steps of the drilling process.

Data which must be stored in national databases at the groundwater departments or other relevant authorities include:

- Location and date;
- Borehole construction (e.g. geometry, materials, screening, pump);
- Lithological log: a record of the lithologies encountered while drilling (depth vs. type of

formation, texture, colour, state of weathering);
- Penetration rates per depth;
- Depth of water strikes, permeable/preferential groundwater flow zones;
- Blow yield of each water strike;
- Quality of water from each strike (e.g. pH and EC as indicators);
- Actual borehole designs and dimensions;
- Borehole construction details – casing, screen and gravel/sand packed depth;
- Optional: Site description with photographs; and
- Drilling report.

Table 3.2 highlights the key data to be collected in each phase. Steps 4 (borehole drilling), 5 (borehole construction) and 8 (documentation) are the steps in which essential data are collected which must be stored in (national) databases at the groundwater departments or other relevant authorities. Drilling data are crucial to understand the groundwater systems.

As an example, Figure 3.1 shows the lithological log of a borehole with two distinct water strikes, together with the interpreted hydrogeological conceptual model. In this case: an unconfined aquifer separated from a deeper confined aquifer by a confining layer.

Measuring the water level in the open borehole will not capture the difference in piezometric heads (and the potential vertical flow) between the two aquifers. The example shows clearly that piezometers will need to be placed in each aquifer to correctly measure (trends in) groundwater heads in each aquifer.

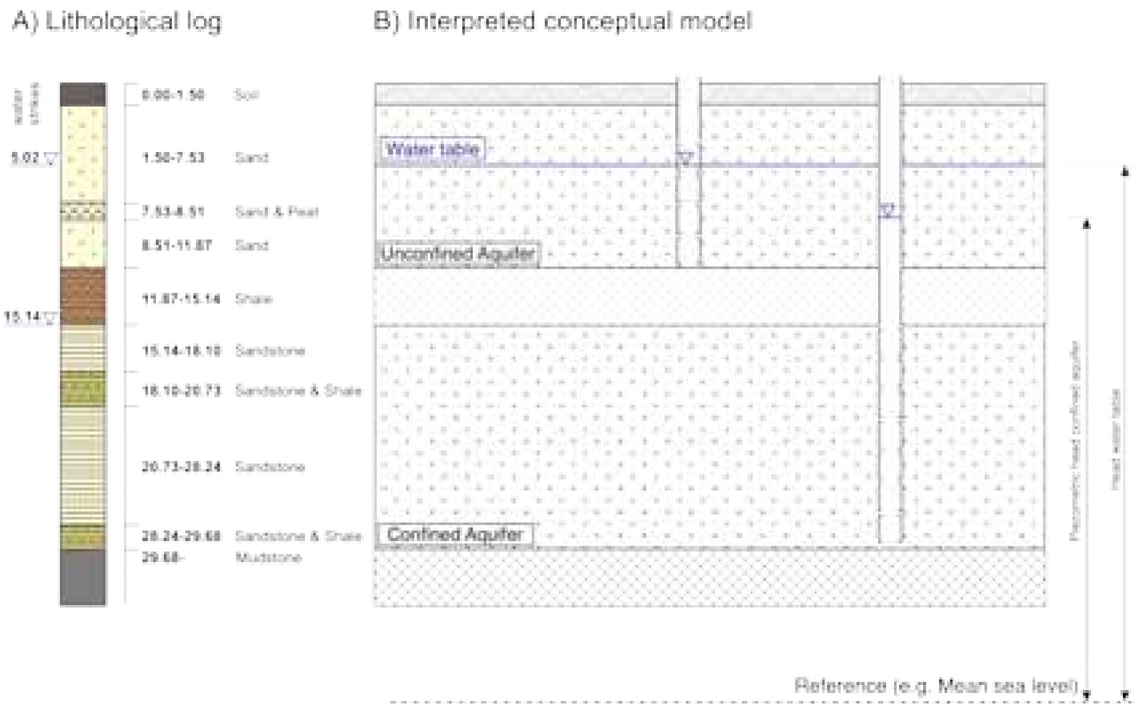


Figure 3.1 Example of lithological log from borehole drilling and conceptual hydrogeological model, interpreted from the drilling results

Care should be taken to link all data to the correct borehole. This is usually done by assigning a unique borehole identification number to each borehole (*See* Box 3.1). If not collected properly during the drilling and the construction of the borehole, data like the lithological log, water strike depths and borehole construction data might be lost forever, because they are very expensive to collect afterward. For instance, re-collecting the lithological log in a borehole equipped with a casing will require drilling a new borehole.

Table 3.2 Steps in borehole drilling process with data and information collected in each step

Borehole drilling supervision phases	Key data to be collected phase
1. Sourcing for the appropriate driller	• Initial quotation for services of the drilling contractor for drilling, construction, development and completion
2. Pre-mobilisation	• Most cost effective and capable driller selected for appointment • Indication of satisfaction with the quality of material and also capacity of the driller, if not: • Make recommendations to driller for improvements, • If not satisfied with material, communicate with the driller and procure separately if possible what you regard as most appropriate
3. Mobilisation	• The community leaders are aware about the presence of the drilling team and have given their consent, • The driller has arrived on the site and ready for the drilling,
4. Drilling	• **Date of drilling** • **Exact location of borehole** • **Lithology logs (normally per 1 metre of drilling depth) such as: type of formation, texture, colour, structure, state of weathering, etc.** • **Penetration rates per 1 metre of drilling depth** • **Depth of water strike,** • **Blow yield of each water strike and final at last,** • **Quality of water from each strike (Use pH and EC as indicators)**
5. Borehole construction	• **Actual borehole designs and dimensions** • **Borehole construction details – casing, well screen and gravel/ sand packed depth** • **Optional: Site description with photographs**
6. Development and completion	• Borehole completed, now waiting handover to the client/responsible authorities, • Record of groundwater level data after completion, • Record below yields and blow depths
7. Demobilisation	• The drilling site is now clean and restored to its former state and site ready for handover. • Start compiling the drilling report
8. Documentation and handing over	Submit the **drilling report** and hand over the borehole to the client. • The report should document the whole borehole installation processes, analyse borehole data obtained and develop an initial conceptual un derstanding of the aquifer where the borehole has been drilled. • Such initial conceptual understanding should include aspects such as lithological logs, location of main flow zones (water strikes), piezometric/hydraulic heads, aquifer structure and type

Text in **bold** indicate data which should be stored in databases or data archives. *See* Annex B.

Box 3.2 Potential issues in recording of borehole location

Borehole location/coordinates:

In the inventory of the current state of groundwater data collection and data management in SADC Member States (IGRAC and IGS, 2019b) and from experience in groundwater projects it was noted that proper recording of a unique borehole location is not obvious.

A common issue is that for old boreholes the location is often not exactly known. This can be because the borehole was drilled prior to the use of GPSs and a small-scale topographic map was used to plot the location, or multiple boreholes on a farm are all plotted at the same (random) location on the farm. There are also issues with the use of different map projections and coordinate systems in the past, and the locations of old boreholes not having been converted to the new system.

Less obvious issues also exist that a borehole may have multiple different coordinates, which creates confusion. For example, because coordinates were recorded at different times, with different equipment and accuracy (e.g. during drilling, during construction and during testing or surveying of the borehole). If such situation exists it is important to clean it up in the database and to decide on one (accurate) coordinate to describe the location of the borehole. This may require additional field work.

3.2.3 Borehole Testing

To test borehole performance, estimate sustainable yield and to estimate the aquifer hydraulic properties. Testing for borehole performance and estimation of sustainable yield is often called well-performance test or borehole testing, while tests to calculate physical or hydraulic properties of the aquifer/aquifer system tend to be referred to as pumping tests. Many different methods are available depending on the specific purpose of the test, the availability of suitable observation boreholes in the radius of influence of the pumped borehole and the conceptual understanding of the aquifer or aquifer system. Table 3.3 provides an overview of the main steps and expected outcomes from borehole testing.

Appendix C provides a more complete overview in describing considerations and steps in borehole testing and setting up pumping tests.

The following data from borehole testing should be stored in (national) databases at the groundwater departments or other relevant authorities:

- Location of pumping test (pumped borehole and observation boreholes if any);
- Date of pumping test;
- Type of pumping test;
- Duration of pumping test;
- Time-variant data:
  - Pumping rate against time
  - For each borehole: Drawdown and/or recovery against time

Report on results from analysis of the borehole/ pumping test, including (as appropriate):

- Well performance characteristics - Specific capacity and well efficiency;
- Sustainable/Safe/Reliable yield; and
- Physical/hydraulic characteristics of the aquifer/aquifer system: hydraulic conductivity or transmissivity, specific storage or storativity, specific yield, hydraulic resistance.

Table 3.3 A summary of the main steps and expectations of aquifer pumping tests

Step	Purpose	Key data to be collected	Estimated parameters
Planning	To enable preparation of the constant rate discharge test	• Site location, • Date, • Depth of water strikes, • Aquifer lithology, • Blow yields, • Refer to drilling report	Not applicable
Borehole fluid electrical conductivity (FEC) profiling	Locate water strikes and groundwater flow zones	• Borehole FEC profile	• Depth of water strikes and groundwater flow zones
Calibration test	Select appropriate CRD	• Time and ground water levels (draw down), • Step discharge rates.	• Appropriate CRD
Step-drawdown test	Assess well efficiency characteristics	• Time and ground water levels (draw down), • Step discharge rates.	• Well efficiency, • Hydraulic properties
Constant rate drawdown (CRD) test	Estimate borehole sustainable/reliable yield, Estimate aquifer hydraulic and storage properties	• Time and ground water water levels (drawdown), • Average CRD	• Sustainable/reliable yield • Hydraulic properties of the aquifer\aqu. tard
Recovery test	Estimate aquifer hydraulic and storage properties Evaluate the % of recovery	• Residual time, • Residual ground water levels	• Hydraulic properties • Evaluate the % of recovery

3.3 Strategies to Encourage Stakeholder Participation in Obtaining Essential Data

The previous sections described the essential data that should be collected from borehole siting, drilling and testing, for storage in groundwater databases or data archives. The challenge in maintaining up-to-date databases and data archives is to ensure that the correct data are properly recorded in the field and that the data are submitted to the section responsible for the management of the databases and data archives (*See* also Chapter 5 on quality control). For this process to be successful it is crucial to know the stakeholders involved and to create incentives for them to collect and submit the correct data. Stakeholders involved in the different stages can be:

- Government officials (from water department, geological survey);
- Officials from other public or semi-public organisations (such as water utility companies);
- Consultants (hydrogeological and/or geophysical, borehole drilling companies); and
- Borehole owners which can be the government itself, semi-public/parastatal organisations, private companies or individual private well owners.

It is important to find ways to continuously engage and encourage permanent participation of stakeholders in collecting essential data from borehole drilling, siting and testing and to provide the data to the relevant government department for storage in data archives or databases. Different strategies are required given the variety of stakeholders. Strategies can involve creating a stimulating environment (for example by making it easier to collect and submit the data) and can include legal or regulatory instruments to ensure that the data are collected and submitted.

3.3.1 Promoting Groundwater Data Collection

There are various strategies for groundwater departments to encourage stakeholders in all sectors (public, semi-public and private) to collect essential data and submit it for storage in data archives or databases. These include:

- **Simplifying recording and submitting of data**
  This can be done by clearly specifying the minimum list of data and the require data formats. Clear and easy to use field forms can guide and simplify data collection. Modern tools such as mobile phone applications can make it even easier to record the data accurately (by making use of digital field forms that can include simple checks and predefined options) and which can also facilitate submitting the data (e.g. by exporting data files that can be shared via e-mail, or more advanced by submitting data directly to the database).
- **Train stakeholders**
  For many of the stakeholders involved, collection and in particular submitting data for archi ving purpose is not a top priority. Some may also not be aware which data need to be collected. To raise awareness on the importance of these data and to capacitate stakeholders in collecting the right data, groundwater departments can organise workshops/provide clear instructions on data collection and data submission, not only for the field technicians in their own departments but also for other stakeholders such as drilling companies and consultatancies.
- **Provide stakeholders access to the data**
  SADC-GMI (2018) states that the issue of public access to groundwater data held by the state is poorly articulated at the policy level. This should be addressed. If stakeholders can easily make use of the data and information in national databases for their own purposes, then they may become more inclined to contribute to these databases by providing data from their own borehole siting, drilling and testing activities.
- **Address issues related to sensitive data**
  It has to be clear to stakeholders which of the data they are requested to provide will be used, by whom and for what purpose. If not, stakeholders may be reluctant to submit data.
- **Raise awareness on the benefits of the data**
  Analysis and interpretation of groundwater data in SADC region is very limited (IGRAC, 2019b). It is important for groundwater departments to develop informative products, based on the data from national archives / databases, to showcase the importance of those data to the general public and in particular to the groundwater professionals such as drillers and consultants. This can for example be maps of aquifer productivity, conceptual models of the aquifer systems, etc. but also through regular reporting on the management of national groundwater resources. The value for individual private borehole owners to submit data could be to get free advice about the state of their borehole in terms of yield and quality (borehole health check’).

3.3.2 Legal and/or Regulatory Instruments

Government through the relevant groundwater departments is the custodian of all groundwater resources, and legal enforceable instruments are part of the strategies to ensure that essential data are collected and submitted to government. Enforceable legal instruments can be applied to the main stakeholders in the following considerations:

- **Registration or licensing of borehole drilling and groundwater use**
  All borehole owners, through compulsory registration or licensing of boreholes and/or of groundwater use with conditions on data submission, can be obliged to collect and submit data on siting, drilling and testing. For specific sectors such as waste facilities (e.g. landfills, mine dumps, etc.) the collection and submission of essential groundwater data can also be arranged through the operation licenses.
- **Professional licensing and/or registration**
  For drillers and consultants, the condition to adequately record and promptly submit essential data can be made part of their operating license and/or professional registration.
- **Contractual agreements**
  Tender documents for groundwater resources related work for the (semi-)public sector should include conditions to collect and submit essential data.

Successful implementation of legal and regulatory instruments requires not only that these instruments are developed as needed, but above all requires enforcement out in the field. Regulations to protect groundwater resources are often not in place and where these are in place, often no enforcement or sanction of unlawful activities takes place (SADC-GMI, 2018). It is necessary to develop capacity to enforce groundwater regulations (not only in relation to groundwater data collection, but more importantly on groundwater use and groundwater quality protection). Depending on the organisational structure of government it may be most efficient to develop this capacity within the broader sector of environmental law enforcement, rather than specifically for groundwater.

3.4 Main Messages

- **Data from borehole siting, drilling and testing are essential to develop conceptual understandings of aquifer systems and to sustainably manage groundwater abstractions;**
- **Data from drilling and borehole construction are virtually lost if they are not properly recorded during the drilling and construction phase. It is therefore crucial to put procedures in place for all stakeholders to properly record those essential data and submit them for storage in data archives or databases; and**
- **Groundwater departments need to initiate activities to stimulate or even oblige stakeholders to submit the essential data from drilling, testing and siting of boreholes. Enforcement of groundwater regulations requires capacity building in the field of environmental law enforcement.**

4 ORGANISATIONAL AND PLANNING ASPECTS OF GROUNDWATER MONITORING

4.1 Introduction

Groundwater monitoring is the continuous measurement of variables such as groundwater levels, quality or abstraction to assess the status and trends. Whereas collection of data from borehole siting, drilling and testing (dealt with in chapter 3) is performed on an ad-hoc basis, collection of groundwater monitoring data is continuous, hence long term appropriate planning and organisation is required.

This chapter focuses on the organisational and planning aspects of developing and implementing groundwater monitoring programmes. The chapter starts with a discussion of monitoring objectives and scale of monitoring programmes. Thereafter organisational and planning aspects of developing and implementing a monitoring programme are discussed. This provides guidance for setting up groundwater monitoring programmes with clear objectives and realistic ambitions (in terms of costs for equipment, logistics and personnel) that can be maintained for long periods of time. The chapter does not cover hydrogeological considerations for designing groundwater networks, groundwater monitoring protocols and procedure as there are already ample guidelines, textbooks and scientific papers available on these topics. The chapter concludes with a discussion on an alternative way to collect data through community-based groundwater monitoring.

Throughout this chapter, the authors made extensive use of the Guideline on Groundwater Monitoring for General Reference Purposes (IGRAC, 2008), which is highly recommended for further reading when developing a groundwater monitoring programme.

4.2 Objectives and Scales of Groundwater Monitoring

Different questions or monitoring objectives require different data and therefore different monitoring programmes (parameters to be monitored, 3-D spatial distribution or network of observation points, and frequency of observation). The absence of clear monitoring objectives will lead to inefficient monitoring programmes. Many shortcomings in groundwater monitoring can be explained by the absence of clear monitoring objectives, in SADC and in other regions of the world (Tuinhof, et al. 2006). Clearly defining the objectives for groundwater monitoring is the first step. It is necessary to define the questions you want to answer using the monitoring data (Box 4.1).

Measurement of groundwater levels

Examples include:
- What is the general trend in groundwater resources availability in an aquifer or area (general reference monitoring)?
- Is there any leakage of contaminants from an industrial site (pollution containment monitor ing)?
- What is the long term expected quality of groundwater abstracted in the wellfield for public water supply (protection monitoring)? and
- What is the safe pumping regime in the wellfield for public water supply (protection monitoring)?

These different questions/monitoring objectives determine which parameters are needed from which locations and at which frequency. Table 4.1 presents an overview of monitoring programmes categorised by monitoring objective and scale, and in relation to the stages of groundwater development and management.

Measuring of water levels is part of groundwater monitoring

Table 4.1 Classification of groundwater monitoring networks based on the monitoring objectives

Stage of groundwater development & management	Main category		Monitoring objective/function(s)		Scale**	Well locations
Reconnaissance of the groundwater system	Primary networks: Resource monitoring*	Impromptu monitoring	Characterise the groundwater system (quantity and quality) Estimate potential for groundwater development		Regional***	Use of existing observation points
Early stage of groundwater exploration and development	Primary networks: Resource monitoring*	Basic - General reference monitoring	Identify trends in time in groundwater storage Identify trends in time in groundwater quality Study and predict regional impacts from groundwater abstractions	Determine (positive) effects of groundwater management interventions	Regional***	Improved network of observation points (existing and new)
Stage of intensive groundwater exploitation and management	Primary networks: Resource monitoring*	Primary – Reference monitoring	Evaluation of general groundwater behaviour: • trends resulting from land-use change, groundwater use and climatic variation • processes such as recharge, flow and diffuse contamination		Regional	Optimised network in uniform areas with respect to hydrogeology and land use, and away from direct influence of pumping
	Secondary networks	Protection monitoring or Compliance monitoring	Protection of: • strategic groundwater resource • wellfields/springheads for public water supply • urban infrastructure from land subsidence • archaeological sites against rising water table • groundwater-dependent ecosystems against potential impacts (e.g. of abstraction, pollution, changes in land-use)		Local Regional in some cases (e.g. strategic groundwater resource in regional aquifer)	Around areas/facilities/features requiring protection
	Secondary networks	Pollution containment monitoring or Compliance monitoring	Early warning information of groundwater impacts from: • intensive agricultural land use • industrial sites with groundwater pollution hazards • solid waste landfills and water treatment plants • quarries and mines, • etc.		Local	Immediately down and up-hydraulic gradient from hazard
	Temporary networks	Project monitoring (temporary!)	Specific, often temporary monitoring to study a specific phenomenon, such as: • specific research (state of contamination) • effect of an intervention (e.g. remedial measure)		Local (mostly)	Defined by phenomenon to be studied

* In the transition from Impromptu – Basic – Primary monitoring the objectives / functions accumulate. i.e. a properly designed primary reference monitoring network still also fulfils the objectives from the Impromptu and Basic monitoring. This is indicated in the table by the dashed line.

** Regional / Local. Regional can be sub-national (e.g. regional aquifer), national, supra national (e.g. transboundary aquifer, SADC-region)

*** Some local scale monitoring (secondary, tertiary or quaternary) may already exist, also in these earlier stages.

Source: Modified from IGRAC (2008) and Tuinhof, et al. (2006).

Monitoring objectives can evolve (as shown in the Table 4.1), from unplanned reference monitoring by simply using data from existing boreholes and with no prior definition of monitoring objectives and/or monitoring network, to well-designed primary reference networks, supplemented by secondary and tertiary monitoring networks. Secondary and tertiary monitoring networks will generally require a denser distribution of data points, possibly higher monitoring frequency. In terms of groundwater quality measurements may require more parameters to be analysed.

While it is clear that different monitoring objectives require different monitoring programmes it is essential to realise that one monitoring site (borehole) can be part of multiple monitoring programmes. As an example, Figure 4.1 illustrates how some observation points (and the data collected from those points) may contribute to different monitoring programmes. For example, a point can serve in the local protection monitoring, national general reference monitoring and in the international network, but not all points from the local protection monitoring are used to answer questions related to the large international network.

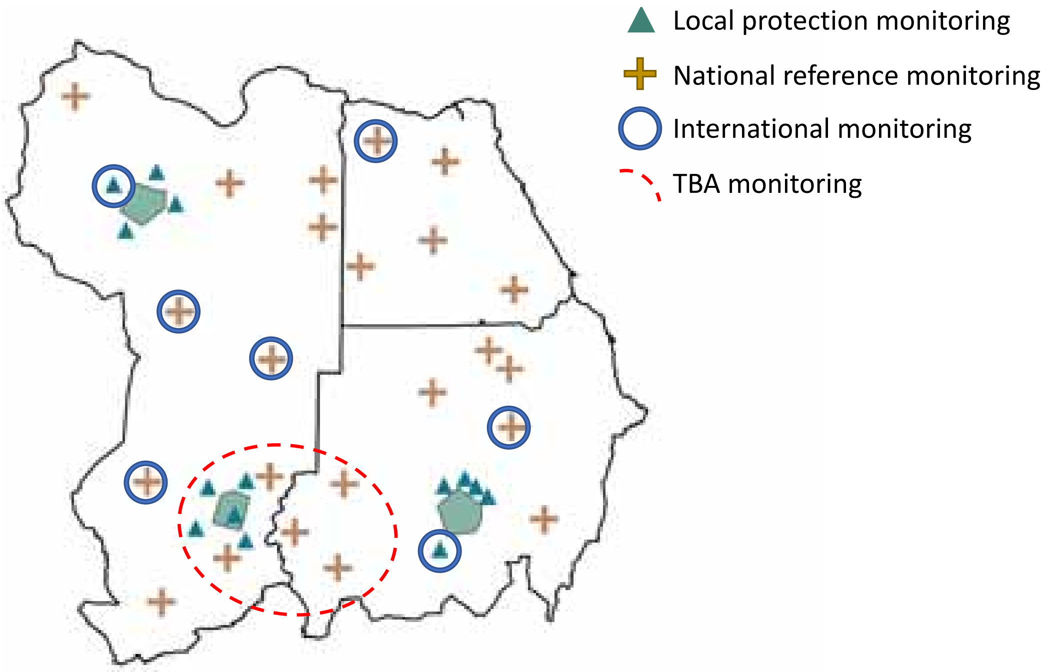


Figure 4.1 Synergies between different monitoring programmes

Another example would be in a groundwater quality monitoring programme where a selection of monitoring points is sampled annually to monitor trends in time, while a larger number of points may be used for five-yearly reports on the spatial distribution of water quality (IGRAC, 2008).

Effective use of data from a single monitoring site for different monitoring programmes requires cooperation between organisations involved in monitoring at different scales and this process benefits from well-structured and widely accessible national groundwater databases (chapter 6). Transboundary monitoring programmes usually make use of data collected in national or local programmes. In the Unites States of America, a National Groundwater Monitoring Network was created on the basis of existing Federal, multistate, State, Tribal, and local monitoring programmes (Box 4.2). This is also the strategy that was recommended to develop a SADC-wide monitoring programme (Wellfield Consulting Services, British Geological Survey, 2011a; Wellfield Consulting Services, British Geological Survey 2011b; Wellfield Consulting Services, British Geological Survey and 2011c).

Box 4.1 Examples of groundwater monitoring objectives

Data needs related to groundwater status and development:

- Sustainable management of groundwater abstractions;
- Determining the best locations for groundwater abstraction;
- Studying the effects of climate change on groundwater resources; and
- Informing managers or the general public periodically on the actual status of groundwater.

Data needs related to protection of groundwater systems and the environment:

- Protection of groundwater systems from over-exploitation;
- Protection of nature conservation areas from declining groundwater tables;
- Protection of aquifers from contamination from 'point sources' such as mines, or waste disposal sites;
- Control of saline water intrusion or up-coning in aquifers; and
- Protection of aquifers from contamination by diffuse sources of pollution; and control of land subsidence caused by groundwater abstraction.

Modified from: IGRAC (2018) Guideline on Groundwater Monitoring for General Reference Purposes

Box 4.2 United States National Groundwater Monitoring Network – Inspiration for a SADC-wide groundwater monitoring network

The United States the Subcommittee on Groundwater (SOGW), http://acwi.gov/sogw/pubs/tr/index.html), together with its working groups, includes more than 70 people representing the private sector and 54 different organisations, including nongovernmental organisations, State and local agencies, Federal agencies, and academia. The SOGW was comissioned by the Federal Advisory Committee on Water Information (ACWI) to develop a framework that establishes and encourages implementation of a long-term groundwater quantity and quality monitoring network. This Framework led to the creation of a National Groundwater Monitoring Network (NGWMN), providing data and information necessary for the planning, management, and development of groundwater resources in a sustainable manner (i.e. to meet current and future water needs and ecosystem requirements). Data from the NGWMN are shared via a dedicated portal: https://cida.usgs.gov/ngwmn/

The NGWMN is envisioned as a voluntary, cooperative, integrated system of data collection, management, and reporting that will provide the data needed to help address present and future ground-water management questions. Thus, the NGWMN may be thought of as an aggregation of wells selected from existing Federal, multistate, State, Tribal, and local ground-water monitoring networks completed in selected aquifers across the Nation. It takes advantage of, but also seeks to enhance, the existing monitoring efforts.

The NGWMN will provide data that can be used to assess baseline conditions and long-term trends in water levels and water quality in important aquifers on a national, multistate, and regional scale.

Source: SOGW (2013)

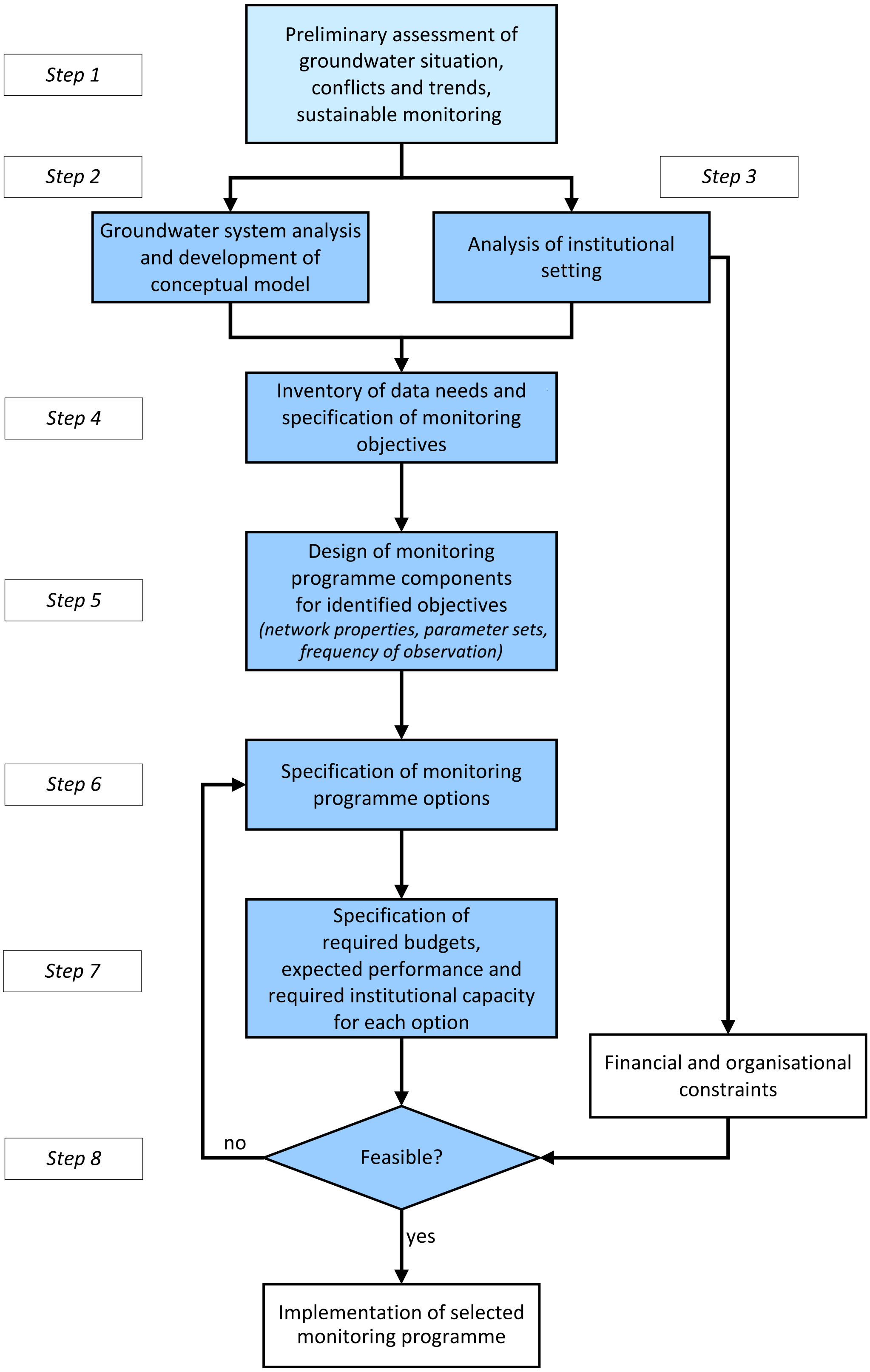
4.3 Developing a Monitoring Programme

IGRAC (2008) present the designing and the implementation of a groundwater monitoring programme as a stepwise process, as shown in Figure 4.2 with further details in Box 4.3. The steps aim to ensure that monitoring programmes are developed in such a way that they provide the right data to the users (institutions and persons involved in groundwater assessment, development, management and protection or other groundwater-data dependent activities) within the available budget, capacity and institutional arrangements.

It is beyond the scope of this Framework to discuss all aspects in detail. For this the reader is referred to IGRAC (2008).

The following sections highlight the most relevant aspects categorised in three steps: the preliminary assessment (step 1), the design of a monitoring programme (steps 2 – 7) and implementation and maintenance (steps 7 – 8).

Drilling data are crucial in understanding groundwater systems



Source: IGRAC (2008)

See Box 4.3 for explanation

Figure 4.2 Scheme for design of a groundwater monitoring programme

Box 4.3 Description of different steps in developing a groundwater monitoring programme

Step 1: Preliminary assessment of the groundwater situation, the problems and trends as well as the size of a sustainable groundwater monitoring programme

This step is to assist in evaluating whether or not systematic groundwater monitoring is desirable in an area and what the objectives and scope of the monitoring programme(s) should be, considering the given budgetary and organisational conditions. The activities described are aimed at providing the components for a 'quick scan' of the groundwater situation, the actual problems and a list of key issues for monitoring.

Step 2: Analysis of the groundwater system and development of a conceptual model

This step involves analysis of the groundwater system (aquifer and flow systems) and development of a conceptual model on the basis of available hydrogeological and hydrological information. The conceptual model, in turn, forms the technical framework for the groundwater monitoring network design. Groundwater quality is also analysed in relation to the groundwater flow systems defined.

Step 3: Analysis of the institutional setting

This step concerns an inventory of the institutions involved in groundwater exploitation, management and protection as well as analysis of their roles, mandates, tasks and related budgets and manpower. Evaluating these conditions should lead to a better idea of the scope and limitations related to extending or improving groundwater monitoring.

Step 4: Inventory of data needs and specification of monitoring objectives

The inventory of data needs includes listing the users of groundwater data and assessing their data needs. Monitoring objectives may include provision of data for assessment, development, use, management and protection of groundwater resources.

Step 5: Design of groundwater monitoring programme components for identified objectives

This step concerns analysis of the monitoring objectives and translation into components of the monitoring programme. Each monitoring objective leads to a monitoring component with its own specific requirements (area to be covered, preferential network set-up, parameters needed, frequency of sampling, etc.). By bringing the components together in a scheme, the various functions and needs of the monitoring programme will become clear. Because of the complexity of situations, a modular structure of the monitoring programme is recommended.

Step 6: Specification of monitoring programme options

Feasibility of a monitoring programme depends among other things on the budgets and institutional capacity available. It is good practice to consider a limited number of possible monitoring programme options, for instance with increasing level of complexity. Options may differ with respect to the scope of the programme, the area covered or the properties involved (e.g. network density, frequency of observation, etc.). Specification of the options to be considered should be done in consultation with representatives of the institution responsible for groundwater management and monitoring. The details of the programmes considered should be clearly specified in maps and/or tables.

Source: IGRAC (2008)

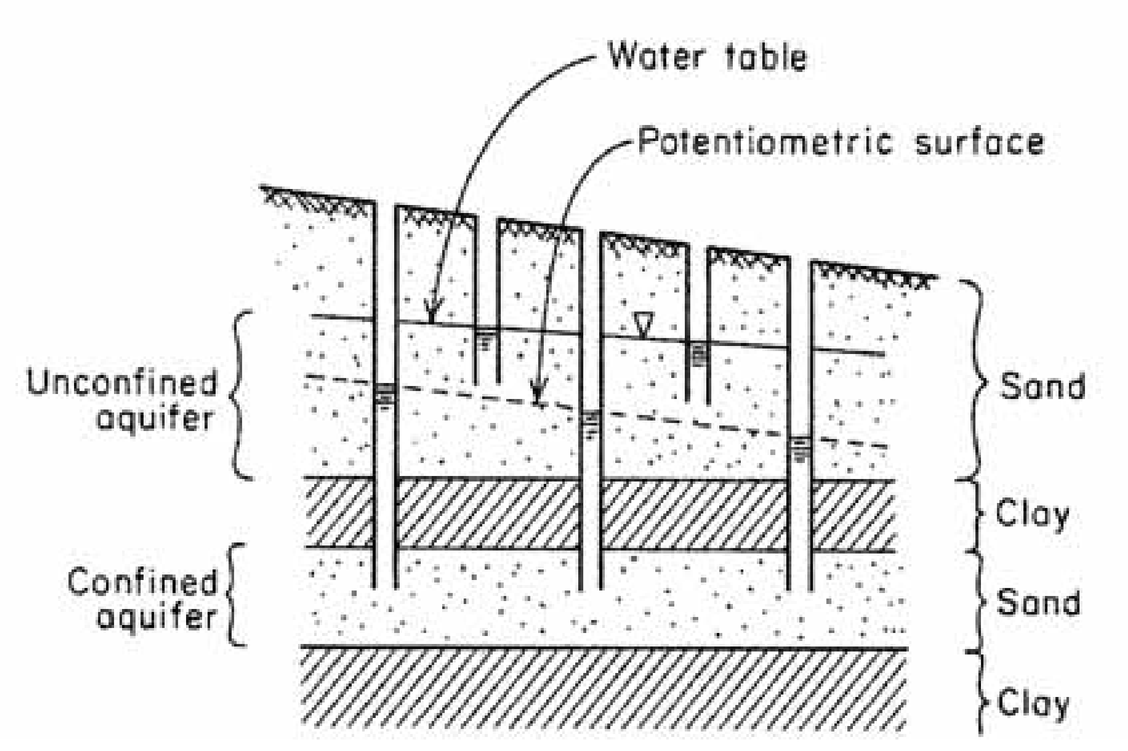
See Figure 4.2 for schematic overview

4.3.1 Preliminary Assessment

Except maybe for impromptu monitoring (Table 4.1), minimum information on the hydrogeological context is required before a monitoring programme can be developed. The purpose of this preliminary assessment phase is to create an overview of all relevant aspects defining the need, objectives and priorities for the monitoring programme. This phase involves:

- Defining key issues that require monitoring;
- Defining a suitable/manageable scale for monitoring (the area to be monitored);
- General characterisation of the target area in terms of climate, hydrological, topographical and socio-economic relevant features;
- Hydrogeological characterisation of the area; and
- Specifying key issues that can be analysed through monitoring (IGRAC 2018).

The hydrogeological characterisation involves conceptualising the groundwater system. It is essential to have some idea of what the water bearing formations (i.e. aquifers) are, where they are located, what the general direction of flow is in the different aquifers, including the location of recharge and discharge zones and what use is being made of groundwater. Preliminary information on the hydrogeological context is acquired from data from borehole siting, drilling and testing and from related datasets, like geological, soil and land use maps, meteorological data and topography (*See* also Chapter 2). Aquifers are 3-dimensional bodies and, as such, a good understanding of groundwater resources is only possible if this 3-dimensional component is taken into consideration. This aspect is often not sufficiently taken into consideration resulting in data from different aquifers being treated as if they represent one aquifer, while they are quite distinctly different systems (*See* Figure 4.3).



Source: Freeze and Cheery (1979)

Figure 4.3 Groundwater level profiles in two overlying aquifers

The last step in the preliminary assessment is equally important to the general and hydrogeological characterisation but it is often overlooked by hydrogeologists. In order to design a monitoring programme that can be implemented and sustained over long periods of time, it is essential that right from the start the available budget and human capacity is taken into consideration. This has to match with costs and required capacity for design and implementation, as well as for network maintenance, data collection, data management and analysis (*See* also section 4.3.3 and Chapter 9).

4.3.2 Design of a Monitoring Programme

Once the monitoring objectives, the data needs and the scale of the monitoring programme have been defined through preliminary assessment, the design of the monitoring programme can start. This involves defining:

- What data to collect;
- At which locations (3-D distribution);
- How often;
- For how long;
- How to organise this; and
- How to pay for this?

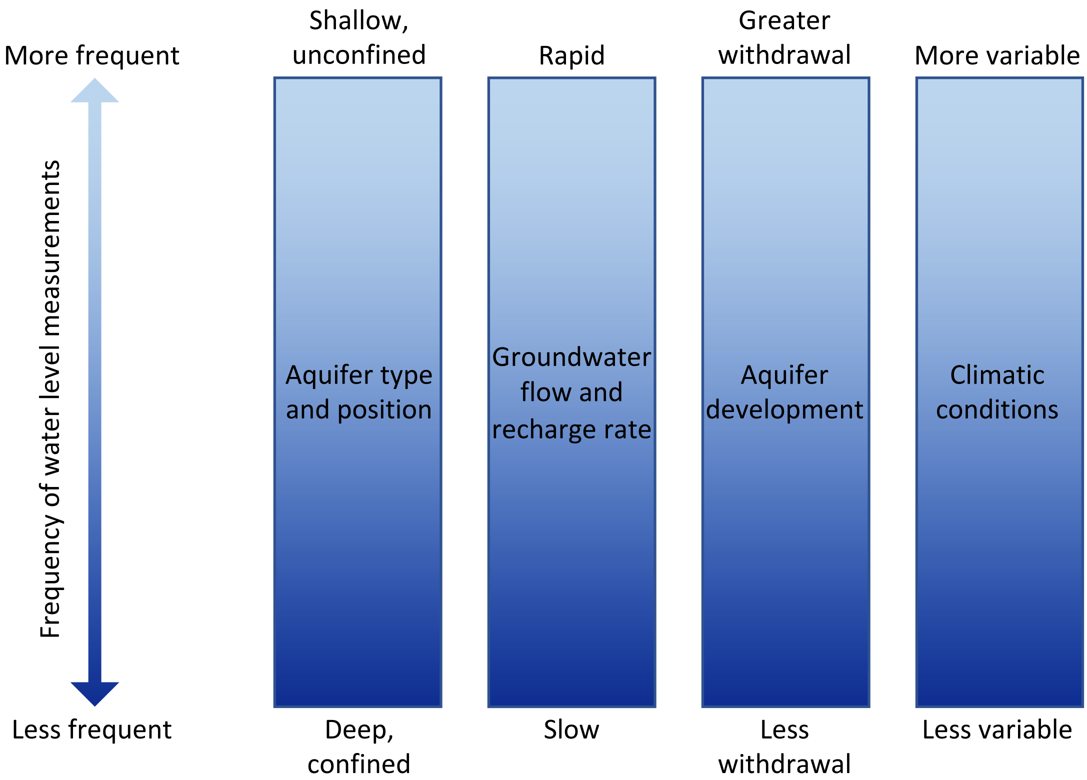
As explained in the introduction, it is beyond the scope of this Framework to provide technical details, guidelines or comprehensive design criteria for groundwater monitoring networks. There are ample of guidelines and manuals available (*See* also Annex E) and the final choice depends on the monitoring objectives in combination with the characteristics of the monitoring area and the available budget. As an example, Table 4.2 provides an indication of the different data needs for different monitoring objectives, while Figure 4.4 provides an impression of factors to consider when determining the frequency of monitoring groundwater levels. 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 hydro-chemical processes in the aquifer, and the process or expected contaminant to be monitored.

Table 4.2 Example of data needs from different data sources for specified objectives

Monitoring objectives	Groundwater observation wells			Groundwater pumping wells			Springs			Surface water observation points		
	Levels	discharge	quality	levels	discharge	quality	levels	discharge	quality	levels	discharge	quality
Groundwater development												
GW system characterisation	xx	n.a.		x			x			x		
GW potential for development (quantity and quality)	xx	n.a.	xx		xx	xx		xx	xx		xx	xx
Best locations for well fields	xx		xx			xx			x			(x)
Control and protection												
Trends of over-exploitation	xx	n.a.		x	xx			xx			xx	
Nature conservation	xx	n.a.			xx		x	xx			xx	
Saline water intrusion	x	n.a.	xx*		xx	xx*				x	x	(x)
Land subsidence	x	n.a.			xx							
Contamination of aquifers		n.a.	xx			xx			xx			xx

x = desirable data; xx = necessary data; xx* = mainly Chloride; n.a. = not applicable.

Source: IGRAC (2008)



Source: Taylor and Alley (2001) cited in SOGW (2013)

Figure 4.4 Factors to consider when determining the frequency of groundwater level monitoring

During the assessment of groundwater data collection and data management practices in the region (IGRAC, 2019b) it was apparent that in many, if not all, Member States the budget and capacity for groundwater is limited, such that it is not possible to only rely on dedicated groundwater observation points (i.e. boreholes that are constructed specifically for groundwater monitoring and are not in use for groundwater abstraction). Budget to drill and construct dedicated observation wells is limited and there are several examples from different Member States where boreholes originally used for groundwater monitoring are being equipped with pumps to supply water. This situation means that in many cases it is necessary to rely on other sites to obtain groundwater monitoring data. This can be boreholes equipped with motor pumps or hand-pumps, hand dug wells or springs.

In many cases these sites can be used for various groundwater monitoring purposes, as long as the limitations are known, and special procedures may need to be observed. For example, when using a borehole equipped with a pump it is necessary to ensure that the pump is switched off and sufficient time is allowed for the groundwater level to recover to the static water level (assuming that the borehole is used to monitor the general groundwater level in the area). The recovery time after pumping will vary depending on the abstraction rate and aquifer characteristics. Boreholes in unconfined aquifers will take longer to recover than those in confined aquifers, and full recovery make take a very long time. A good rule of thumb is to ensure that recovery is at least 95 percent of the drawdown observed immediately after pumping.

Other limitations with production boreholes are that there may be no access-point for a groundwater dipper or that the dipper can get tangled around the pump or lifting pipe. This is something to be considered in the design and construction of pumping boreholes to equip them with a separate access pipe, sufficiently deep below the pump installation depth, allowing for manual groundwater level measurements and/or installation of a data logger.

In most cases it is still possible to collect samples for groundwater quality analyses from any type of borehole, hand-dug well or spring as long appropriate guidelines are followed to ensure that an aquifer representative sample is collected. For example, some large-diameter hand-dug wells can be open and without sanitary seals. This means that the groundwater in the well is particularly vulnerable to direct contamination from above and the chemical composition of the water in the well may be affected by exposure to the atmosphere. As a hand-dug well cannot be purged like is common practice with boreholes, this may affect the sample.

As noted before, aquifers are 3-dimensional and multi-layer systems tend to have different characteristics such as groundwater composition and differences in piezometric head (*See* Figure 4.3). For monitoring purposes, it is essential to know what you are measuring (e.g. from which depth the groundwater in the well originates). If constructed properly, boreholes drilled specifically for groundwater monitoring purposes will only have well screens at individual aquifer layers, and in case of a multi-layer system the different layers will be sealed off with well plugs / packers, so that the groundwater level or a sample can be taken from a specific aquifer. Boreholes drilled for groundwater abstraction often penetrate multiple water bearing layers. This means that a sample taken from such a borehole, will be a mixed sample and the measurement of the groundwater level in such a borehole will be mostly be representative of the water bearing layer with the highest piezometric head. This factor limits the use of production boreholes for groundwater monitoring purposes in individual aquifer layers.

Groundwater abstraction must also be monitored. It is an important input parameter for groundwater models, but is also provides unique and crucial insights into the use of groundwater including the socio-economic importance of groundwater use. Exact monitoring of abstraction volumes from hand-pumps and hand-dug wells is difficult, but can be estimated. Monitoring of abstraction volumes from boreholes equipped with motor pumps can very easily and effectively be done through the installation and regular recording of water meters. This should be common practice and needs to be encouraged and enforced throughout the region to gain a better understanding of groundwater use and for compliance monitoring purposes.

Use of data loggers

Groundwater monitoring can be done manually or with automatic data loggers. Automatic data loggers can be used to measure groundwater levels, groundwater quality parameters like Total Dissolved Solids, Electrical Conductivity, temperature and pH, as well as groundwater abstraction and spring discharge.

The main advantages of automatic data loggers are that:

- Data can be collected without the need to visit the monitoring site for each measurement. This means that it is possible to monitor at higher frequencies than what may be practically, or budgetary feasible through manual observations. And data are collected at exact intervals which can have benefits as well; and
- Data can be collected at very high frequency, which in many cases will not be needed for groundwater monitoring, but it is extremely useful for pumping tests or to observe ground water dynamic response to the pumping regime for example in a wellfield.

Data loggers however, cannot fully replace the need to visit monitoring sites at a regular basis. The measurements need to be calibrated with manual measures, and this needs to be repeated at regular intervals (at least once a year, but preferably more often) to be able to correct for drift of the sensor; measurements need to be downloaded for storage in the databases; and to check if equipment is still functioning properly (vandalism, failing battery). How often sites equipped with data loggers are visited depends on many factors again, but preferably it is done at least two to four times a year to prevent data gaps, should equipment malfunction.

Automated data loggers in combination with telemetry can be used to transmit data directly to a database, without the need for human intervention. A major advantage of telemetry is to get access to real-time data. This means equipment malfunction can be detected early. Without telemetry, a malfunction of a data logger may only be detected after several months resulting in data loss over the same period of time, while in the case of telemetry it is possible to solve the issue immediately and prevent loss of data. Like normal data loggers, the sites still not to be visited at a regular basis to replace batteries and to perform manual measurements for re-calibration. Site visits can be less frequent though, which can be particularly useful for remote sites. These sites need an access to telemetry networks (e.g. GSM - Global System for Mobile Communications).

Costs for data loggers and telemetry devices are higher than costs for manual equipment. Whether the additional investments are justifiable or even cost-effective in the long run depends on many factors such as availability of staff, salaries of staff, remoteness of the monitoring sites and frequency of monitoring.

4.3.3 Implementing and Maintaining Long-Term Monitoring Programme

To ensure that the monitoring programme is implemented and can be maintained for a long time, it is essential to assess the feasibility of a monitoring programme prior to implementing. Feasibility entails two main aspects, the budget and the human capacity:

1. **Budget:**

   Implementation and maintenance costs should not exceed the available budget. Available budget should cover initial investment to establish the monitoring network, but (annual) budget should also be secured to cover costs associated to conduct the monitoring over long periods of time. Costs that should be considered include those related to:

   - **Establishing monitoring points (incidental or non-recurring expenses**) e.g. drilling of monitoring boreholes, measures to protect boreholes against vandalism, purchasing data loggers and/or dip meters, sampling pumps, etc. In some cases, maybe lab instruments, or even vehicles;
   - **Logistics (recurring expenses)** e.g. Costs for running vehicles;
   - **Laboratory costs (recurring expenses);** Lab analysis;
   - **Consumables (recurring expenses)** e.g. sampling bottles, litmus paper, batteries for equipment;
   - **Personnel (recurring expenses)** e.g. costs of staff doing the monitoring, data entry, data quality control, and drivers.
   - **Maintenance (recurring expenses);**
     Maintenance costs include the repair or the replacement of damaged and vandalised boreholes and equipment, cleaning of boreholes; and
   - **Additional costs (incidental)**
     Training of staff.

   If the proposed monitoring programme exceeds available budget (for initial investment and/or long-term budget for recurring costs), the costs will need to be reduced. This will usually mean that the network needs to be redesigned with fewer monitoring points, less frequent observations (in case of manual monitoring and groundwater sampling), or in the case of groundwater quality monitoring the parameters to be monitored can also be narrowed down. Redesigning the network may mean that the original monitoring objective has to be re-assessed and possibly adjusted to a less ambitious objective. IGRAC (2008) give some examples on how to prioritise monitoring efforts, for example by following a risk-based approach and prioritising groundwater quality monitoring activities on those (areas of) aquifers that are most vulnerable to pollution (derive information from mapping of aquifer vulnerability to pollution), or by reducing ambitions for instance by monitoring pilot areas that are considered to be representative for a larger region, or by lowering the monitoring frequency.

Determining if a monitoring programme can realistically be implemented and maintained for long periods of time is a crucial step towards successful monitoring. There are ample examples, also in SADC region, where a monitoring programme was implemented in a project with sufficient funding for the establishment of the network, but there were not sufficient resources to maintain the monitoring programme, resulting in haphazard data collection and ultimately in data sets of poor quality.

2. **Human capacity:**
   Implementing and maintaining a monitoring programme requires staff with the right training and skills, like hydrogeologists, field technicians, drivers and lab technicians. Human capacity gaps can be to some extent filled in through external contracting (e.g. lab analysis, or even sampling for water quality analysis), but it is important to also invest in capacity-building of regular staff. Most importantly, this will be the (regular) training of field technicians, to ensure that they are able to collect high quality data. Similar to the budget,it is important to evaluate, prior to implementation of a monitoring programme, if the required capacity is available.

In addition to budget and human capacity, there are other important organisational aspects that may need to be considered. For instance, access to monitoring points must be guaranteed, which means that monitoring point are as much as possible located in places that are accessible and on public land. When monitoring points are located on private property, the long-term right of access has to be secured.

4.4 Evaluating Existing Monitoring Programmes

From time to time monitoring programmes should be reviewed to verify if monitoring objectives are met. If this is not the case, the monitoring programme (i.e. network of observation points, frequency of observation, quality of data collected, etc.) should be reviewed and redesigned / adjusted in order to achieve objectives. If this is not possible (e.g. for budgetary reasons) than the monitoring objective should be reviewed.

Evaluation of the programme may also indicate that the objectives are being met, but that the monitoring programme can be optimised (either by dropping monitoring locations or reducing frequency of observation). Table 4.3 and Table 4.4 provide some guidance on optimising the number of wells and the monitoring frequency for monitoring programmes on groundwater quality.

Credit: IGRAC

Using advanced tools for groundwater investigations

Table 4.3 Considerations to retain or remove a well from a groundwater quality monitoring network

Reasons for retaining a well in monitoring network	Reasons for removing a well from monitoring network
Well is needed to further characterize the site or monitor changes in contaminant concentrations through time	Well provides spatially redundant information with a neighbouring well (e.g., same constituents, and/or short distance between wells)
Well is important for defining the lateral or vertical extent of contaminants	Well has been dry for more than two years*
Well is needed to monitor water quality at a compliance or receptor exposure point (e.g., water supply well)	Contaminant concentrations are consistently below laboratory detection limits or clean-up goals
Well is important for defining background water quality	Well is completed in same water-bearing zone as nearby well(s)

*Periodic water-level monitoring should be performed in dry wells to confirm that the upper boundary of the saturated zone remains below the well screen. If the well becomes re-wetted, then its inclusion in the monitoring programme should be evaluated.

Source: US EPA (2007)

Table 4.4 Considerations for changing the groundwater sampling frequency

Reasons for increasing sampling frequency	Reasons for decreasing sampling frequency
Groundwater velocity is high	Groundwater velocity is low
Change in contaminant concentration would significantly alter a decision or course of action	Change in contaminant concentration would not significantly alter a decision or course of action
Well is necessary to monitor source area or operating remedial system	Well is distal from source area and remedial system
Cannot predict if concentrations will change significantly over time, or recent significant increasing trend in contaminant concentrations at a monitoring location resulting in concentrations approaching or exceeding a clean-up goal, possibly indicating plume expansion	Concentrations are not expected to change significantly over time, or contaminant levels have been below groundwater clean-up objectives for some prescribed period of time

Source: US EPA (2007)

4.5 Community-Based Groundwater Monitoring

Most of the basic groundwater monitoring data are not very complicated to collect, and it can be done by non-professionals with inexpensive equipment, if sufficiently capacitated. Involving non-professionals in groundwater monitoring has two main advantages:

- **Decrease costs:** In general, there will be savings on logistics if local people are engaged in monitoring activities, which can be considerable for remote regions with limited or poor road access. Communities may engage on a voluntary basis. If not, the wages or compensations allowed to non-professionals will be lower than the wages of regular staff; and
- **Awareness-raising**: Engaging communities in groundwater monitoring can develop a sense of ownership and responsibility for groundwater resources (Tordiffe et al. 2010; Walker etal. 2016). It can also assist in decreasing vandalism of monitoring boreholes, an issue reported in almost all SADC member states. Awareness raising will likely facilitate the adoption of good practices of groundwater use and protection. For this reason, many community-based projects go beyond the collection of data and also involve the communities in decision making and management.

The disadvantage can be that quality of data are less reliable but, when collected in large amounts, they provide statistically significant insight on groundwater resources (Walker et al.

2016). Just like with professional field technicians, adequate training in quality assurance and quality control procedures can help in collecting reliable data.

Community-based groundwater data collection can be facilitated through the use of mobile phone apps. They can make it fun to collect data, they can prevent mistakes in the recording and transferring of data, and can allow for quick transfer of data from the field to the database. A selection of potentially useful apps is provided in Annex D. With the expansion of information and communication technologies (ICT) and the increasing access to internet and telephone networks in SADC, involving communities in groundwater data collection could unlock a large amount of data across SADC and increase awareness among the population.

The main challenge to set up a successful community-based project is to identify the right candidates. Candidates must have access to a groundwater monitoring point and to a communication network. Kongo et al. (2010) and Ministério da Energia e Águas (2014) recommend using existing governance structures in the communities and deal with formal or informal leaders.

After screening the potential candidates, it is crucial to find incentives that will ensure a long-term commitment. Incentives can be financial or in-kind compensations (e.g. mobile phones, bicycles or t-shirts, which are useful for performing the project tasks), but an interest in the project objectives is reportedly the best incentive (SADC, 2011; Roy et al. 2012). Schools, for instance, are recognised to be particularly good candidates, because environmental monitoring and awareness raising on environmental issues are in line with education programmes (Roy et al. 2012). Likewise, it is assumed that community-based projects have higher chances of success if they visibly improve living conditions of the communities. Therefore, community-based groundwater data collection may be better suited for local monitoring, not for regional primary monitoring (even though regional authorities could promote several local community-based monitoring projects).

For the same reason, it may be advisable to combine groundwater monitoring with surface water monitoring, if communities also rely on surface water (Kongo et al. 2010). The importance of incentives suggests that when designing community-based projects, groundwater departments should identify how groundwater monitoring can contribute to the communities, before identifying how communities can contribute to groundwater monitoring.

To keep candidates enthusiastic and active during the project, it is important to provide feedback to them in the form of data and information, or include them in the management of groundwater. Dedicated websites and apps can be used to organise the exchange of data and information and maintain a strong tie between the project partners. In-field trainings should be organised regularly to capacitate the partners before and during the project (Kongo et al. 2010, SADC 2011).

Investing in capacity-building and incentivising candidates will increase the chances of success of community-based projects and encourage awareness-raising on sustainability issues related to groundwater.

4.6 Main Messages

- **Monitoring of groundwater levels, quality and abstraction is essential to understand trends in resource development and to define effective management interventions; Regular and consistent monitoring of groundwater abstraction is limited in SADC region, and must be improved;**
- **Different monitoring objectives normally require different monitoring networks, but single points can potentially serve multiple networks;**
- **Cost-effective monitoring requires the right choices on methods (manual, data**

loggers), regular maintenance and re-evaluation & optimisation of the networks;

- **Monitoring never stops and requires continuous budget and capacity;**
- **Groundwater monitoring is not just a technical exercise, it requires organisation and planning at various levels throughout organisations including budgets for incidental investments and recurring costs for data collection and maintenance;**
- **Community based groundwater data collection can be a cost-effective measure, in addition to conventional groundwater data collection, with the added benefit that it can trigger community participation in groundwater management; and**
- **Equipping all pumped boreholes with an access tube to measure groundwater levels, greatly facilitates groundwater data collection in a country.**

5 DATA QUALITY ASSURANCE AND QUALITY CONTROL

5.1 Introduction

Quality assurance (QA) is a set of operating principles, procedures and actions ensuring that reliable data is collected. Quality control (QC) is a set of procedures and actions intended to ensure that groundwater data meet the requirements. Quality assurance aims to prevent errors from happening during the data collection process, while quality control aims to identify (and where possible correct) errors in the collected data afterwards. In the context of groundwater data, the principle of quality assurance relates mostly to the data collection process out in the field (and for groundwater analysis also in the lab), while quality control will mostly take place in the office prior to accepting data for final inclusion in the database.

5.2 General Measures to Reduce Errors and Improve Consistent Data Collection

There are several reference books, guidelines and technical manuals available that provide guidance on procedures to improve data collection and enhance quality of groundwater data (for a selection *See* Table 5.1 and Annex E). In terms of planning and organisation it is important to look beyond such guidelines and to consider which actors (stakeholders) can influence the quality of groundwater data, and what instruments are available to them to collect reliable data.

Training on data collection procedures helps to improve quality of groundwater data

This section highlights general measures to reduce data collection errors and enhance quality of data. These measures apply throughout the different phases of groundwater data collection and for different purposes. Using this Framework as a basis, Member States are encouraged to develop the specific procedures for quality control and assurances.

Table 5.1 Examples of guidelines on groundwater data collection

Data collection work phases	Examples of guidelines
Borehole sitting/survey	• Guidelines for the Groundwater Development in the SADC Region (SADC, 2001)
Borehole drilling and installation	• Code of Practice for Cost Effective Boreholes (Rural Water Supply Network, 2010); • Groundwater Protection Regulation Handbook (British Columbia Water Associ ation, 2017) • Professional Water Well Drilling (UNICEF and Skat Foundation, 2016) • Short Course: Drilling Supervision. Cost-Effective Boreholes (Adekile and Danert, 2014)
Borehole testing	• Analysis and evaluation of pumping test data (Kruseman and de Ridder, 1994) • Guidelines for the Groundwater Development in the SADC Region (SADC, 2001) • Manual on Pumping Test, Analysis in fractured – Rock Aquifers (van Tonder et al. 2001a) • Estimation of the sustainable yields of boreholes in fractured rock formations (van Tonder et al. 2001b)
Groundwater levels	• Groundwater Level and Well Depth Measurement: Operating Procedure (US EPA, 2016a)
Groundwater sampling	• Groundwater Sampling and Analysis – A Field Guide (Sundaram et al. 2009) • Groundwater Sampling Guidelines (EPA Australia, 2000) • Technical Guidance Manual for Ground Water Investigations – Chapter:10 Ground Water Sampling (Ohio Environmental Protection Agency, 2012) • Quick Guide to Drinking Water Sample Collection (US EPA, 2016b) • Groundwater Sampling Manual (Water Research Commission (WRC), 2017)
Groundwater abstractions	• Measuring the taking of water (Department of Water- Western Australia, 2016)

There are different measures available to reduce errors and improve consistency in data collection. They include the following:

- **Training and capacity development**
  - Staff involved in coordination, supervision and/or interpretation: One can only distinguish if data collected make sense if one understands its hydrogeological meaning. It is therefore important that those tasked with quality control of the data and information have enough (academic) background in groundwater science. Ad-hoc additional professional training through short courses and workshops may be required to improve skill and knowledge in specific fields and to keep up with new developments.
  - Field technicians: It is important to have well trained and informed technicians involved in the collection of groundwater data; typically, field technicians are trained on the job. Also, for technicians it is important to provide refresher courses to improve skill and knowledge in specific fields and to keep up with new developments. A more structural approach to building capacity for field technicians is through certification based on vocational training programmes. Vocational training for groundwater technicians is not widely available. Development of such programmes could be taken at the regional SADC-wide level.
  - External parties (drillers, consultants, lab services): Adhering to minimum professional standards is the responsibility of the professionals themselves. Groundwater departments can however, contribute through organising short courses, training workshops or demonstrations for private sector parties, to improve skills and to promote new technology and methods. Formal certification of professionals is another instrument to improve quality assurance.

- **Guidelines for data collection**
  - Professionals involved in groundwater data collection should make use of available guidelines and manuals. It should be the responsibility of the groundwater departments to develop, adopt and implement specific country-wide guidelines for data collection for different types of groundwater data presented in this Framework. *See* Table 5.1 for examples.

- **Data collection forms/field-forms**
  - Develop and/or adopt data collection field-forms/templates, to be used by field tecnicians for collecting different types of data. Adequate examples of such forms are widely available, like in SADC (2001): Guidelines for the Groundwater Development in the SADC Region.
  - These forms help to ensure systematic and consistent collection of data irrespective of who is collecting the data and when.
  - The major challenge with data collection forms / templates is to implement the consist ent and continuous use of these forms. This should be the responsibility of staff in coor dinating and supervising positions.
- **Use mobile application for data recording in the field**
  - The use of mobile phone applications (apps) for data recording/capturing in the field can be useful addition or even an efficient alternative to using field-forms.
  - Apps can assist in preventing simple mistakes by making use of built-in logical data checks and by eliminating data entry errors resulting from unclear data forms, etc.
  - Apps can reduce costs and time by immediately recording data in electronic format, thereby shortening the process of first recording data on paper and then transferring the data to electronic databases in the office at a later stage.
  - Time saving also allows for quicker interventions.
  - Examples of mobile phone applications are given in (*See* Annex D).
- **Equipment calibration, test and use**
  - Equipment needs to always be calibrated and used according to the manufacturer's specifications and guidelines.
  - Equipment needs to be checked periodically in line with manufacturer's specifications and guidelines.
- **Automated data collection techniques**
  - While automated data collection techniques, such as the use of automated groundwater level recorders with data loggers, offer many advantages, it is important to obtain some manual reference measurements in case the technology fails.
  - In some cases, automated data collection devices have a lower accuracy of measurement than manual devices. For example, accuracy of water level loggers tends to be a pecentage of the full range of measurement. This means that a logger with a range of 100 m of groundwater level variation may have an accuracy of +/- 5 cm, while a carefully done manual measurement of a groundwater level with a dipper can reach an accuracy of +/- 0,5 mm. Depending on the situation a manual measurement may be preferred, while in other situations the use of data loggers may be preferred (e.g. in a pumping test when many consecutive measurements are to be taken at short intervals).
- **Define target/acceptable data quality and corrective measures**
  - Although this is not common practice in hydrogeology, accepted data quality should be defined in advance as part of the data quality objectives, in line with the purpose of collecting the data. Once data are collected, their quality should be assessed against these standards. For example, the range of Ion Balance Error (IBE) which will be acceptable

for groundwater quality monitoring should be defined when developing a sampling program. While there are guidelines in literature, it is important for those involved in data collection to define what quality would be acceptable.

Table 5.2 lists the different actors involved in different processes related to groundwater data collection, what responsibilities these actors have in relation to quality control and assurance, and the measures available to assist them in performing these tasks. The specialised and academically trained staff (in table categorised as 'supervisors') have a central role in managing all quality control and assurance processes and in capacitating the other actors involved.

Table 5.2 Roles of actors involved in groundwater data collection processes

	Borehole installation			Monitoring		
	Siting	**Drilling**	**Testing**	**Levels**	**Quality**	**Abstraction**
Field Technicians	• Use of field forms; • Use of mobile phone apps; • On the job training; • Vocational training.					
Drillers		• Use of field forms; • Use of mobile phone apps; • Registration; • Certification.				
Supervisors*	• Academic training; • Specific professional training as required; • Develop and implement use of field forms + procedures; • Initiate development / implementation of mobile phone apps; • Conduct on the job training; • Provide regular "on-site" supervision; • Check and sign-off collected data; • Develop routine checks for application prior to accepting data to database; • Assure inclusion of relevant QA/QC procedures in tendering mechanisms					
Office Staff	• Perform data quality checks using checklists and simple (visualisations) tools prior to accepting data for inclusion in final databases**					
Laboratory staff					• Standard routines; • Basic checks of results (e.g. ion balance error); • Certification.	
Data users	• Analysis and interpretation are the best data quality check. Procedures should be in place for users to provide feedback to database manager to flag data as 'suspicious'.					

* Supervisor: Geophysicist/Geologist/Hydrogeologist. This can be both office staff in a coordinating role as well as staff supervising field activities.

** Ideally the database is set up in such a way that data are entered in the database and that there is a functionality to first label data as 'temporary/un-checked' and after quality checks have been performed as 'final/quality checked/approved'.

Important quality assurances measures for groundwater level measurement are emphasised in Box 5.1, because it is the most basic parameter measured in groundwater.

5.3 Office Quality Control and Quality Assurances

Data collected in the field must be entered into a database, and routes followed are:

1. The field technician enters the field data on an electronic device in the field (mobile applications). The application will upload the data directly into the database – eliminating the chance of typing errors;
2. The field technician enters the data on field forms and once in the office transfers the data to the database. Data need to be typed again but by the same person who entered it on the

field form; and
3. The field technician enters the data on field forms and hands the form over to a dedicated data entry person in the office. Data need to be typed by a different person adding to the possibility of making mistakes (difficulties in understanding hand-writing, nor knowledge of situation in the field, etc).

When data are entered into the database, the data should be checked for logical errors. Examples are measured water level that are deeper than the actual borehole, or pH values entered are higher than 14. Other potential errors are large differences in measured values compared to the values or trends of the data already in the database (statistical or visual filtering on outliers).

The ultimate check on the validity of the measured data are the use of the data during analysis and interpretation. This can only be performed after the data are entered into the database. The database must therefore have the capability to flag individual records as suspicious.

Box 5.1 Basic quality assurances for groundwater level measurements

Some of the important routine measures of quality assurances during measurements of groundwater level are:

- Always measure groundwater levels in relation to the established/agreed reference point. The reference point of measurement must also be captured on the field form and in the database.
- Special care should be taken to allow the water level to equilibrate after removing the borehole sealing caps. Time required to equilibrate will depend of site-specific hydrogeological characteristics, thus it is not possible to set any guideline. However, taking several repeated readings and comparing them might give an indication.
- When possible at one site/borehole, the same model of water level measuring instrument should be used for all measurements.
- Groundwater level changes observed through monitoring must be carefully evaluated to determine the cause because there can be a variety of causes. There must be some explainable cause of any changes in groundwater levels, otherwise it can be regarded as measurement error.
- To help understand the meaning of the measured groundwater levels, information on borehole construction, aquifer types and water strikes should be available/accessible.
- Decontaminate the water level measuring device before moving to the next borehole. For sites not known or suspected to be contaminated, simply wash the devices with deionised or tape water. For contaminated and polluted sites, specific decontamination procedures may be required, and preparations be made prior to field visit.
- Calibrate, test and use data loggers according to the manufacturer's instructions and specifications.
- When water level data loggers are deployed for continuous groundwater monitoring, it is important to take manual reference-level readings at set intervals during their deployment. This serves as the basis/datum for evaluating the measured changes and correcting for any drift in the sensors of the data loggers.

Suspicious data can originate from data entry mistakes, data transfer mistakes or problems in field when the measurements were taken. When data are flagged as suspicious, the process on how the data was obtained must be traced back and rectified as needed, if possible. If all the correct procedures were followed and no discrepancies were found, data must be flagged as 'approved' or 'final' in the database.

To implement this form of quality control on groundwater data requires staff members in coordinating and supervising positions to develop and implement such checks, including adding this as required functionality to groundwater databases.

Figure 5.1 provides a flow diagram depicting data flow from field collection to final database storage, with various quality control and assurance processes.

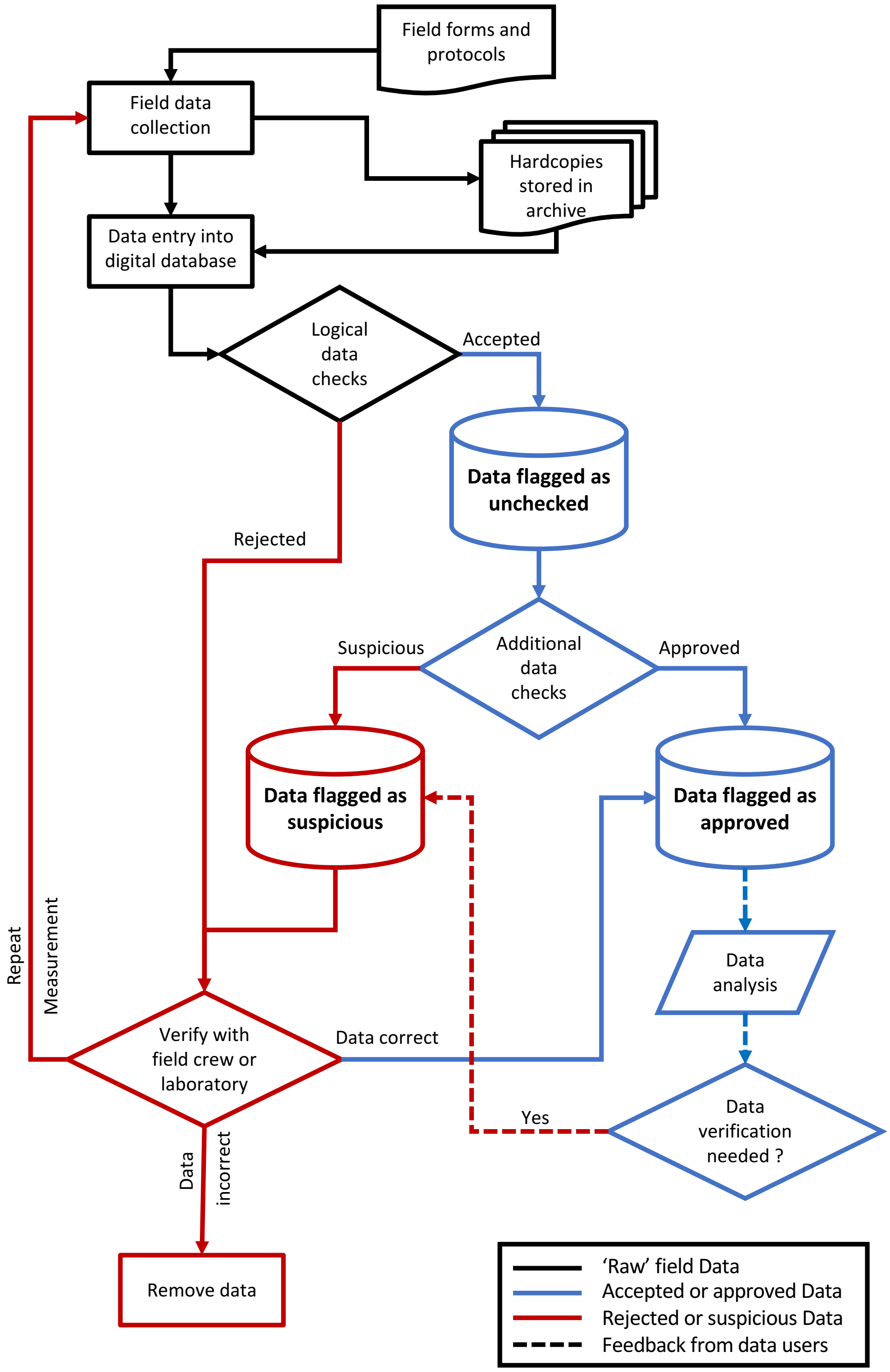


Figure 5.1 Flowchart of quality checks in data management process

5.4 Main Messages

- **Certification of professionals involved in groundwater data collection (such as drillers, hydrogeology and geophysical consultants, laboratory services) will assist in improving the quality of the collected groundwater data;**

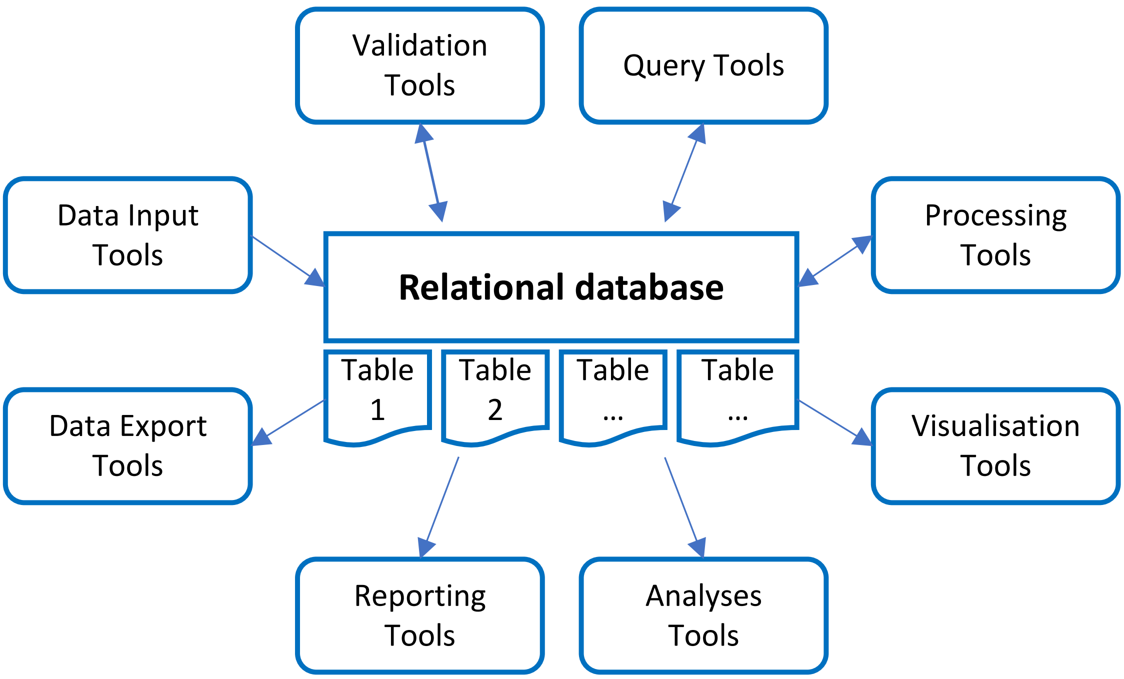
- **Development of vocational training programmes for groundwater technicians (or more broadly environmental monitoring technicians) is instrumental in improving the quality and efficiency of groundwater data collection;**
- **Collecting good quality data in the field is aided by adhering to guidelines and suffcient training of field technicians;**
- **Using modern technologies such as digital field forms in mobile phone applications can make the groundwater data collection process more efficient and can reduce errors;**
- **Using automated devices for data collection such as data loggers can improve effeciency but does not necessarily result in more accurate data;**
- **Before data are stored as final data in databases, routine checks must be done to verify the quality of the data.**

6 DATA STORAGE

6.1 Introduction

All essential groundwater data that are collected (*See* chapters 3 and 4) must be stored in a central place to build a historical record and allow the data to be used at a later stage (for example for trend analysis). Data can be stored in hardcopy in a filing room or archive. In this 'digital era' softcopies of data must also be kept on a computer or central server. Hardcopies can be scanned and stored to replace the filing room. But for processing and analysis, field data must be entered into a computer system in formats that can be processed and in a logical structure. The FAIR acronym captures the need for data to be Findable, Accessible, Interoperable, and Reusable (Wilkinson et al. 2016). This requires the use of a database.

There are different types of databases and they vary from simple spreadsheets to elaborate desktop programmes and server-based databases. Figure 6.1 shows a typical groundwater data management system. In a basic setup, different tools can consist of different software packages with import and export functionalities enabling interoperability. In an advanced setup all essential tools will be integrated into one user-interface (one software package), although even the most advanced solutions still require additional tools for specific purposes (e.g. analysis through groundwater flow modelling).



Source: Fitch et.al. (2016)

Figure 6.1 Conceptual model of groundwater data management system

The most basic requirement for any database software is functionality to:

- Enter new data (data entry tool);
- Store multiple data types in a structured manner (data stored in linked tables); and
- Export data in more widely compatible formats (data export tools).

Database systems (be it one integrated software package or a combination of different software tools) used to store groundwater data at the national level will also require functionality to ensure data security (e.g. back-up tools), and check data quality (validation tools).

As the number of people using the database expands and the amount of data increases, there is need for additional functionality allowing for multi-user options, with different user authorisations facilitating more advanced data quality control, data security, queries, and reporting tools.

In this chapter the most relevant database concepts are discussed, followed by a discussion of the advantages and limitations of the three categories of software solutions.

6.2 Database Concepts and Important Functionalities

6.2.1 Data Structure

A logical structure of a database is crucial for different users to be able to work with the database and to ensure data consistency. A database is a collection of tables storing different types of information. The central table will be the one defining the name of the monitoring points (site identification name / number) together with a position (coordinates) and additional basic descriptive parameters (*See* Box 6.1). Other tables are used to store specific types of data such as time-series data of water levels, water quality and water abstraction, and other data such as borehole lithological logs, borehole construction data, down-the-hole borehole geophysics, pumping test data, and together with quality control labels.

The tables are connected via specific fields (identifiers). In a simple but robust set-up the tables are linked using the site identifier (e.g. borehole number, or SiteName in Figure 6.2) that needs to be entered for each dataset/table.

Duplication of data in different tables must be avoided, as this poses a risk in terms of data consistency. For example, higher accuracy borehole coordinates and elevation obtained from surveying are meant to replace those obtained from a simple hand-held GPS, but are only updated in one table, and the less accurate duplicate data in other tables are forgotten to be updated. This will lead to confusion. Only the identifiers used to link tables must be duplicated (*See* Figure 6.3).

6.2.2 User Interface

The user interface is the part of the software with which the user directly interacts. User interfaces are designed to simplify the use of different tools (*See* Figure 6.2) through menus and buttons. The advantage is that users do not need to know the underlying low-level database commands or coding of routines, and it is also possible to shield unauthorised users from using certain functionality that could damage the database. Developing an adequate user-interface requires a thorough understanding of the data related workflow (*See* for example Figure 5.1 on flow chart for quality checks), the different users, their needs and their technical capacity in terms of using the software.

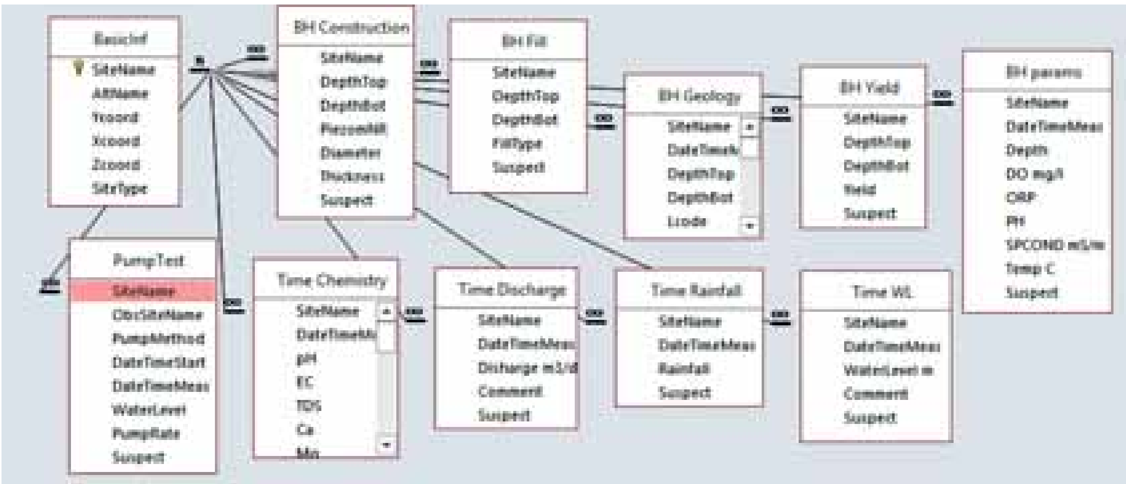


Figure 6.2 Example of database structure in MS Access with relationships between different tables in a groundwater database.

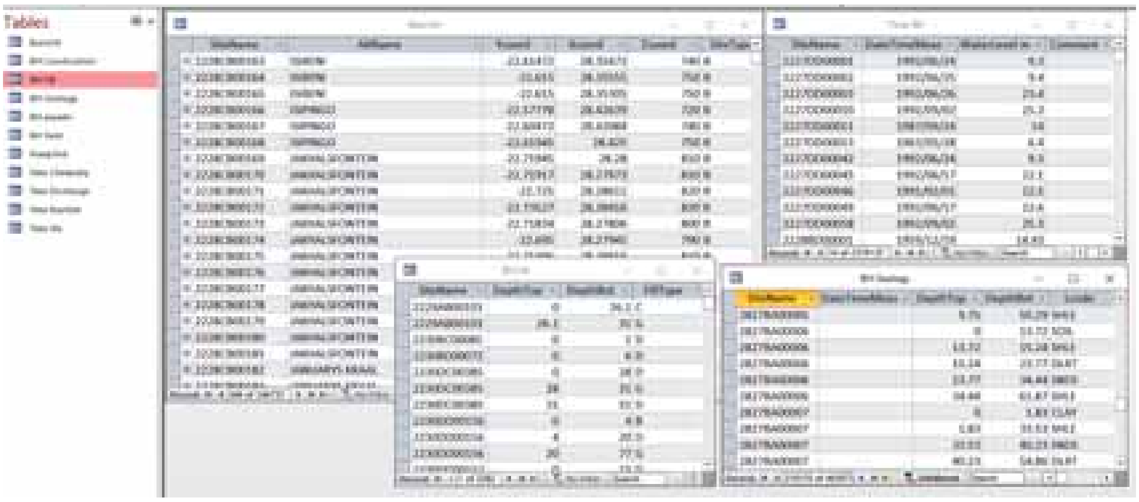


Figure 6.3 Example of a database in MS Access, showing different tables with some of the data. The tables are linked through the identifier 'SiteName'

6.2.3 Multi-user Options

A single user environment can be sufficient in a setup for a relatively small group of professionals involved in data management, who are all based in one office and with a limited amount of data. Comprehensive national groundwater databases, with different parameters, will generally have a larger user group, with multiple users entering data into the system while other users, possibly from other locations (e.g. regional offices, or parastatals with direct database access) may interrogate and extract data from the database at the same time. This setting requires multi-user options with different user authorisations and access levels.

Box 6.1 Minimum requirements to properly establish a site (borehole) in the database

Borehole location and 'administrative data':

To properly establish a site (borehole) properly on a database, each site requires the following essential data:

- Name/Borehole identifier: This must be a unique identifier based on a national naming/numbering convention for boreholes. In practice, it is very useful if the database allows for additional altenative numberings; for example, those used in projects, regionally or from the borehole siting stage.
- Coordinates: X and Y (or longitude and latitude) are crucial, but in groundwater also the elevation (Z-value) of the ground surface and reference point for groundwater level measurements (generally top of casing) is important.
  Different projected coordinate systems are being used throughout the region and sometimes also within countries. For example, South Africa uses a Transverse Mercator (TM) projection for 1:50 000 maps, while an Albers Equal Area projection is used for small scale 1:250 000 maps, both with the Hartebeeshoek (WGS84) datum. Namibia also uses TM projection but with the Schwarzeck datum, while Botswana uses UTM with zone 35S datum. If projection and datum are not known substantial inconsistencies can arise. For example: a change of datum from Cape Datum (officially used in South Africa before 1992) to Hartebeeshoek datum (used after 1992) without proper conversion resulted in changes of coordinates of more than 400 meters at places. It is therefore crucial to record projection and datum in the database.
- Ideally the Method used to establish the coordinate (Map with scale and year of publishing, Handheld GPS, Differential GPS, traditionally surveyed) with an indication of the coordinate accuracy is also recorded.

Any other information describing the monitoring point and is surroundings.

- Type: the type of monitoring point must be recorded (Borehole, hand dug well, spring, river, dam, etc)
- Site Status: Status of the monitoring point (In-use, Abandoned, Destroyed, unknown)
- Purpose: Main purpose of the water access point (Monitoring, Drinking water supply, Irrigation, Stock Watering, Industrial use, etc)
- Owner: Information regarding the owner of the site (Name of Owner; Contact details) is important.For example, to ask access permission for monitoring, or to request information related to licensing conditions.
- Topographic Setting: groundwater relevant observations such as Alluvial pan, Dry river bed, hillside.

6.2.4 Quality Control and Data Security

Collection of groundwater data are expensive and sometimes impossible to repeat (e.g. historical groundwater level records or lithological logs from drilling). It is therefore crucial that the collected data are quality checked and protected against loss or alterations by users.

Quality control

Throughout the process of data collection different quality assurance and quality control steps are required, some of which can be integrated into the database solution (*See* Figure 5.1). One step is data validation using logical checks. For example, to refuse negative values in the borehole depth field, groundwater levels above the top of the casing or pH values outside the 0 – 14 range. Other functionality can allow for flagging of unchecked, suspicious and checked data or even record a full audit trail (*See* below).

User roles

To avoid errors, a database should only be operated by authorised (and adequately trained) staff. Different database users tend to have different roles and responsibilities: e.g. data entry, quality control, database management/administrator, data users. Ideally different authorisations (access levels) can be assigned to these different users.

Back-ups

All databases must be backed up on a regular basis to reduce risks of data loss in case of a calamity such as hard disk failure, fire or flooding. For large databases that are used intensively, backups should be made daily, while for smaller and less intensively used databases a backup can be made after entering new data (although the risk with ad-hoc back-ups is that they tend to be forgotten). Back-ups should be stored off-site (in another location), or at least on a different computer. By simple copying of the master file, only the latest version of the file can be restored. If restoring of different versions is a requirement, software capable of incremental backups and restores must be installed.

Audit trail, commit and rollback

To allow for data quality control procedure within a database, it is useful if an 'audit trail' of crucial database operations can be kept. This means that if some value is changed a copy of the original value is stored as well as the date, time and the user who changed it. Such log is useful to check procedures, trace and correct possible errors. Database transactions such as 'commit', and 'rollback' (generally managed via the user interface) are useful to protect the database from mistakes and to facilitate data quality control procedures. Changes made to a database by adding, changing or deleting data will only be made permanent after a 'commit transaction' has been issued and when something unforeseen happens all changes can be reversed by issuing a 'rollback'.

6.3 Spreadsheet Database Option

Spreadsheet software such as Microsoft Excel, Google Docs Spreadsheets, Apache OpenOffice Calc, Libre Office Calc, can be used to set up a simple database to store groundwater data. Apart from being a low-cost or free option, it is also an easy option as most groundwater professionals know how to work with spreadsheets.

Data structure: Spreadsheet programmes allow using multiple worksheets in one file. Different worksheets can store data related to one specific parameter thereby mimicking the tables from a database. Different spreadsheet columns will act as the different fields of each table, while the rows act as the records. The advantage is that the data structure can be set-up by any person with basic excel skills and basic understanding of relational databases.

User interface: As most groundwater professionals are able to use spreadsheet software, it will not be necessary to set-up a user interface 'on top of' a spreadsheet database. It is however, possible to develop for example data input forms, reporting templates and macros for certain routines.

Quality control and data security: Spreadsheets also allow for basic data validation when entering new data. Spreadsheets can also be used to create graphs (e.g. for visual quality checks) and perform computational, statistical and more advanced logical evaluations (for data quality checks and/or for data analysis).

6.3.1 Limitations of Spreadsheet-based Databases

- **Not designed as a database**: Spreadsheet software is not specifically developed to be used as a relational database. Focus is much more on performing calculations on multiple data and to visualise data, for example in graphs. This means that it is not the most robust database solution in particular if the number of users increase and the need for integrated data tools increases. For example, it is very easy to move data around a spreadsheet, and there is a risk that users change the data structure according to their own specific (short-term) needs thereby corrupt the database structure. Many users typically 'squeeze' all data of one borehole into one worksheet, thereby mimicking a report with different data for one site (borehole) rather than mimicking a relational database where data are grouped per category. If the relational database structure is not maintained, data ends up being copied to multiple places which makes it harder (or near impossible) to manage the database and to maintain data integrity. Also, users can easily use an extra worksheet for some 'quick temporary' data or processing, ultimately resulting in messy spreadsheets and nobody knowing any longer what where the original raw data from the field.
- **Limited capacity:** The amount of data that can be stored in a spreadsheet is limited, athough for counties with smaller data sets this may in practice not be the limiting factor. Depending on the complexity of the database a spreadsheet may become slow in processing data when the amount of a data increases.
- **Limited tools:** It is possible to programme simple tools such as data entry forms and to generate reports from spreadsheets, but in practice user functionality of a spreadsheet database is limited as compared to advanced databases.
- **Single user:** A spreadsheet is a single user option, as only one user can edit the spreadsheet at any given moment. Multiple users can work on multiple copies of the database concurrently but when all the users start making changes it becomes very hard and time consuming to incorporate the changes into one (master) database. Using a spreadsheet in combination with a cloud service like MS One-drive, Google Drive and Dropbox, means that the data files can be edited directly in the cloud removing the risk of losing data by faulty hardware or hardware theft whilst also allowing for some basic form of multi-user access.
- **Basic backup:** Spreadsheets only have the most basic automated back-up functionality zby saving only the most recent previous version of the file. For more advanced automated backing up of the database additional software tools will be required, or back-ups have to be made manually. Manual backups are very unreliable as it is easily forgotten. When working with single file databases a backup can be performed just by copying the file to another computer or external hard drive or to a cloud service. It is possible to use free cloud services, as long as the datasets are not too large, but this is not preferred as these free services can be cancelled at any time.

6.4 Relational Database – Desktop Option

If the shortcomings of using a spreadsheet outweigh the benefits, dedicated desktop database options can be considered. There are many cost-effective desktop options, such as Microsoft Access, OpenOffice Base, LibreOffice Base and more, some of these even being free of charge.

Database structure: The main advantages of dedicated database packages are that they have standard capability to link data records, which allows for more functionality and flexibility when it comes to performing queries and generating reports. The relational database needs to be set-up before it can be used (unlike a spreadsheet where you can modify the structure at any time). Different tables need to be defined, as well as each field (column) in the table and the relationship between the different tables. All fields must be pre-defined by data type (Text, Number, Date, etc).

User interface: The advantage of this set-up is that it is more robust (the database structure cannot be corrupted by a standard user) and more advanced validation rules are possible. Functionality to search and query data will be more advanced and more user friendly than with spreadsheets. Relational databases also have the capability to create index files. These index files allow for fast searches and queries, which is particularly relevant for large data sets.

Multi-user options: Desktop options are capable of multi-user access (advantage over spreadsheets), but the number of concurrent users is limited as are the different user authorisations that can be defined.

Quality control and data security: Dedicated database software generally supports important functionality assisting in the data entry and data quality control process. For example: Changes made to a database by adding, changing or deleting data will only be made permanent after a 'commit transaction' has been issued, when something unforeseen happens all changes can be reversed by issuing a 'rollback'. Desktop versions store the whole database in one file making it relatively straightforward to back-up to an external hard drive or into the cloud, or even share the complete database, much alike a spreadsheet. For more advanced backup option dedicated software will be required.

Training of young groundwater professionals from SADC Member States on data collection during the project workshop.

6.4.1 Limitations of Desktop Based Database Solutions

- **Specialist database knowledge required:**
  Desktop database options can be operated without a specially developed user interface, but knowledge about databases is required to do so. To make the database more accessible

to a wider user-group, a user interface needs to be developed (to hide all low-level commands from the end user). Developing a good user interface requires specialist knowledge as well as a good understanding of the workflow and technical capacity of staff involved.

- **Multi-user options** although possible are still limited as compared to server-based database systems. To allow remote access to the database server-based solutions are needed.

6.5 Relational Database – Server-based Option

The major advantages of server-based options over desktop options are:

- The enormous data storage capacity;
- Advanced options for multi-user access with different authorisation levels; and
- Possibilities for remote access.

These are all three relevant functionalities for a comprehensive national groundwater database that will normally have many different users, possibly at different locations. Several server-based options are available such as MS SQL-Server or Oracle database.

Server-based options are superior (or at least equal) to the other database options. Server-based options tend to be custom made which also allows for the implementation of advanced user interfaces with integration of many different data tools.

6.5.1 Limitations of Server-based Database Solutions

Server based solutions or 'databases engines' are extremely powerful but require staff with specialised training in database management. The database administrator is responsible, together with the developers, for the running of the user interface.

In addition to the database engine, a database structure is needed and a (custom made) front-end / user interface to make the database usable for those entering and retrieving the data. Developing a custom user interface can be lengthy and costly process and requiring a thorough understanding of the datasets, the data related workflow, the different users, their needs and their technical capacity in terms of using the software. Where the spreadsheet and desktop versions can be operated without a user interface this is impossible for with server-based database.

When running the database on a server, a safe enclosure is needed to protect it. This can be an air-conditioned room with fire retardant materials, an automatic fire extinguishing system, an uninterruptable power supply, etc. The price for server-based groundwater database together with all infrastructure is considerable. An alternative is to use a hosting service. Many of these services offer virtual servers that can be used to run a database. In these cases, the hosting organisation takes care of all the infrastructure (hardware), but not of the user interface.

Table 6.1: Overview of database functionalities and organisational requirements for different database options

Database Type	Spreadsheet database	Desktop relational database	Server based database
Maximum number concurrent users	1	255 (theoretically, MS Access)	32676 (MS SQL-Server)
Maximum database size	2 GB (MS Excel)	2 GB (MS Access)	524272 TB
Primary database model	Flat	Relational	Relational
Query/filtering functionality	Basic	Advanced	Advanced
Indexing of data	No	Yes	Yes
Logical checks on data entry	Basic	Advanced	Advanced
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 in the cloud.	External hard-drive or in the 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 authorisation levels can be set	Advanced management of user roles and authorisation levels possible (and required)
User interface	Generally, not required but possible (e.g. data input forms)	Not required, but practical; relatively easy to develop	Required and custom-made
Integration of various tools (processing, analysis, visualisation, reporting)	Basic	Moderate (self-made/ 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 of relational database concepts and (optional) programming in Visual Basic.	• 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 and concepts of relational 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 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)

6.6 Main Messages

- **Data need to be stored in a structured way, in digital formats that can be easily processed to enable efficient and cost-effective access, retrieval and processing for future studies;**
- **The choice of database software should be based on the (expected) amount of data to be stored as well as available human capacity and skills to manage the data;• Advanced server-based database solutions provide the most robust solutions but come at a high cost: Setting up and maintaining advanced server-based database solutions requires substantial initial investment but also has recurring costs for specialist capacity to maintain the database and data servers, in addition to the costs related to the standard updating of the data in the database;**
- **For countries with a limited amount of groundwater data, limited resources and human capacity, well designed spreadsheets can be an adequate and highly cost-effective alternative to advanced databases desktop or server-based database solutions. If the data are well-structured, migrating the data to more advanced database systems at a later stage when needed, is relatively straightforward; and**
- **Member States need to develop a national naming convention for groundwater sites and standardised unique naming of all database parameters.**

7 DATA SHARING AND ACCESS

7.1 Introduction

The Global Diagnostic on Groundwater Governance (FAO, 2016a) emphasised that effective groundwater management requires the active participation of all stakeholders. To actively and responsibly engage in groundwater management, stakeholders need to be aware of the state of groundwater and sustainability challenges, e.g. in relation with groundwater use and pollution. Groundwater departments must actively share reliable and up-to-date data and information on groundwater to stakeholders and give them access to data and information on their request.

7.2 The Importance of Sharing Data and Information

The need for sharing data and information has long been recognised at regional and global levels. (*See* Box 7.1).

Box 7.1 Global recognition of the importance of stakeholders' access to environmental data and information.

Principle 10 of the 1992 United Nations' Rio Convention states that 'each individual shall have appropriate access to information concerning the environment that is held by public authorities, including information on hazardous materials and activities in their communities' and that 'States shall facilitate and encourage public awareness and participation by making information widely available."*See* https://www.un.org/documents/ga/conf151/aconf15126-1annex1.htm

In Europe this has led to the adoption of the Aarhus convention in 1988 by UNECE (entered into force in 2001, *See* http://ec.europa.eu/environment/aarhus/index.htm) and the INSPIRE Directive in 2007 by the European Union (*See* https://inspire.ec.europa.eu/inspire-directive/2).

The Aarhus convention states that: 'In order to contribute to the protection of the right of every person of present and future generations to live in an environment adequate to his or her health and well-being, each party shall guarantee the rights of access to information, public participation in decision-making, and access to justice in environmental matters in accordance with the provisions of this Convention.'

The INSPIRE directive aims to 'create a European Union spatial data infrastructure for the purposes of EU environmental policies and policies or activities which may have an impact on the environment. This European Spatial Data Infrastructure will enable the sharing of environmental spatial information among public sector organisations, facilitate public access to spatial information across Europe and assist in policy-making across boundaries". The Directive came into force in 2007 and will be implemented in various stages, with full implementation required by 2021.

In parallel, EU has created the Water Information System for Europe (WISE, *See* https://water.europa.eu/freshwater) in 2007, a web-based platform for sharing water information and data. According to the Water Framework Directive (*See* http://ec.europa.eu/environment/water/water-framework/index_en.html), EU Member States must report on water resources. The water data provided by the Member States are compiled and shared in WISE.

The European experience shows so far that data sharing within and between countries can be achieved if legally enforced and if the organisations are given sufficient time to implement it, step bystep.

At SADC level, the importance of data sharing is recognised in the SADC Regional Water Policy (SADC, 2005), which states that:

i) Member States shall timeously share relevant available information and data regarding the hydrological, hydro-geological, water quality, meteorological and environmental condition of shared watercourses;

ii) Member States shall ensure that members of the public in the region have access to relevant and understandable information regarding water resources impacting on their health or safety and on economic interests; and

iii) SADC, (Shared Water Course Institutions) SWCIs as well as Member States shall establish mechanisms for regular interpretation and dissemination of essential information on water resources so that the public is regularly informed.

Implementation of the SADC Regional Water Policy by Member States is gaining traction. Sharing of information (in the form of reports via websites) is now common practice in most Member States, although the amount of information generated based on groundwater data remains limited (IGRAC and IGS, 2019b). Providing access to and active sharing of groundwater data are generally less developed in the Member States (IGRAC and IGS, 2109b). Yet, data sharing is crucial because data are objective and independent of the context, unlike information (Van der Gun 2018, Box 7.2). A notable exception is South Africa's National Groundwater Archive which provides access to groundwater data online.

Box 7.2 Data vs information

The terms 'data' and 'information' are often used as synonyms. In this Framework we consider 'data' as raw, unprocessed data stored in groundwater databases, while 'information' is the message resulting from data analysis (*See* figures a and b below). The need to share 'information' is generally well understood in the Member States, although it is not always efficiently implemented. The need to share 'data' is less accepted. Yet, data sharing is crucial because data are objective and independent of the context, unlike information (Van der Gun 2018). Data can be used and reused to produce information at various levels and for different purposes.

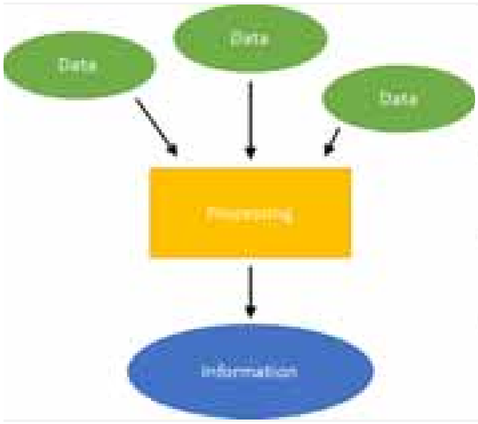


Fig. a: Information is created from data chain

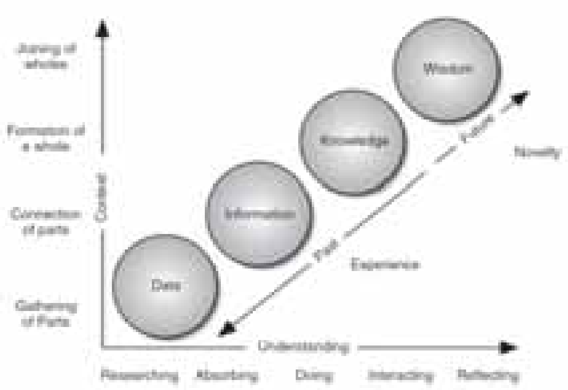


Fig. b: The DIKW hierarchy depicted as a linear (Clark, 2004 in van der Gun, 2018).

There are several levels at which groundwater data and information sharing must be organised:

- **Between organisations collecting groundwater-related data**
  Groundwater assessment requires data of different types that are collected by various stake holders (*See* Chapter 2 and Table 2.1 on data for transboundary aquifer assessment). Each Member State usually has one main organisation in charge of groundwater data collection and data management, like a groundwater department, typically within the ministry of water. Additional groundwater and groundwater-related data can be collected by other stake

holders, such as water utility companies, other departments within the water ministry, other ministries, provincial/district level, municipalities, universities and non-governmental organ isations. It is important that groundwater departments actively cooperate with other data-holders to get access to all the necessary data and information needed for integrated assessment of groundwater resources and development of suitable interventions.

- **At transboundary level**
  The joint assessment and management of transboundary aquifers (TBA) require that countries exchange data and information on these resources. Sharing data between different countries implies an additional challenge of harmonising the data, because different countries usually store data in different formats. Pioneering work in data sharing and harmonisa tion in SADC TBAs has been done for the Stampriet aquifer, shared by Botswana, Namibia and South Africa (GGRETA project), and the Ramotswa aquifer, shared by Botswana and South Africa (RAMOTSWA project). Lake and River Basin Organisations (L/RBOs) also play a role in sharing transboundary data, and there is increasing awareness of the need to incorporate groundwater data in the systems managed by L/RBOs in view of integrated water resource management and conjunctive use of groundwater and surface water.
- **At regional level**
  In addition to TBA specific or L/RBO cooperation, there is an increasing demand for data for regional studies, in particular in a region like SADC with very active cooperation at the regional level. For example to assess impacts of climate change on groundwater, as climate change does not stop at national borders. Regional policies should be guided by regional information (e.g. indicators, reports), based among others on datasets provided by Member States. Additionally, there is added benefit in sharing data and information as Member States can learn from each other. Many Member States share the same groundwater issues (e.g. declining water levels, contamination, sea water intrusion) and can benefit from the experiences in other countries. Exchanging knowledge also implies the exchange of information and data.
- **With general public and civil society**
  Groundwater users are the main beneficiaries of groundwater data collection and data management. These stakeholders can be individuals or groups with similar interests. It is crucial for groundwater stakeholders to be well informed on groundwater issues, based on transparent access to data and information. Groundwater data collection and data management programmes are generally financed through tax revenues. Therefore it can be argued that tax payers also own the data collected in the activities they subsidise. It is all the more true when people contribute to the collection of groundwater data, like drillers or communities engaged in community-based monitoring. Providing access to data may also be an incentive for potential data providers to contribute to groundwater data collection as they can use the data to their own benefit as well.

7.3 Smart Sharing of Data

Having the data properly stored in a centralised database (*See* chapter 6) is the first condition enabling efficient access to data. This section explores different ways to improve data sharing.

7.3.1 Open Data

Figure 7.1 provides an overview of different access levels to data. The easiest and most efficient way to share data is by making them accessible to anybody, irrespectively of who makes the request and for what purpose. Such data are called ‘open data’. In most SADC Member States, access to groundwater data is somehow restricted, either explicitly (e.g. data are available upon request, possibly against a nominal fee) or implicitly (i.e. the organisation doesn't have an online repository supporting efficient sharing of data). An example of open data is the South Africa's National Groundwater Archive.

Protected data tend to be less efficient than open data. Both parties (those requesting data and those providing data) must invest time and money each time data are needed or even worse: data which cost a lot to collect is not at all being used. Investing in a culture and in IT infrastructure which allows for open data policies and access of data without intervention by the data owner, is ultimately a cost-efficient way to sharing data.

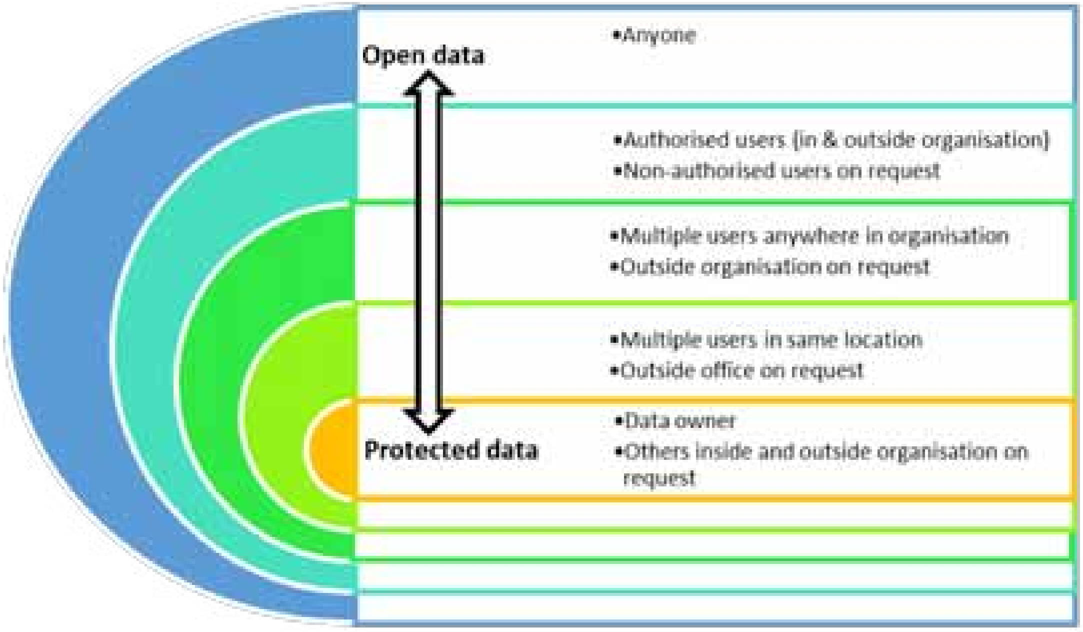


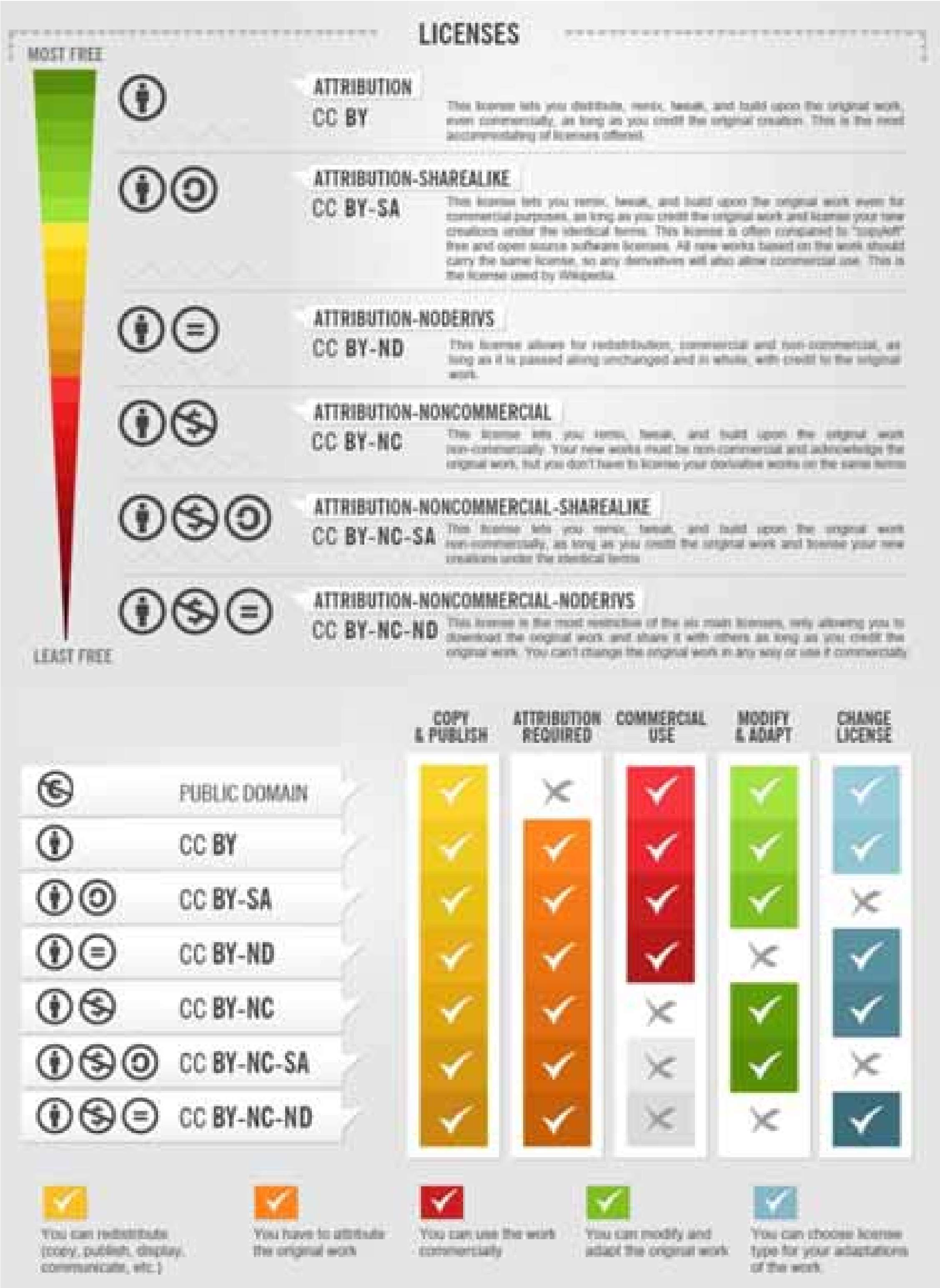
Figure 7.1 Different levels of access to data, with circles representing stakeholder groups that have easy access

To solve matters of ownership and copyrights, open data can be licensed (Bureau of Meteorology, 2017). Readily available licenses like Creative Commons licenses are available to specify different options in terms of attribution (providing credits to the original data owner), if the data can be used in re-processed form or not, for commercial and/or non-commercial use. Figure 7.2 provides an overview of currently available Creative Common licensing types.

7.3.2 Metadata

When sharing data, it is very important to share all relevant metadata, i.e. 'data about the data'. Metadata must explain what the data actually are. For instance, groundwater levels can be expressed as absolute elevations or depths, different units can be used to express groundwater data, different coordinate systems are used across SADC. Metadata should also provide relevant information like the method used to collect the data, the date of collection, the details of the data owner, the purpose of the data, etc. The relevance of metadata increases when sharing data at the transboundary or international levels, because the chances are higher that different methods and conventions are used.

To use data efficiently, it is crucial to provide (and therefore store in groundwater databases) all relevant meta-data. This should be organised at the national level, but harmonisation could be brought to the SADC level through a dedicated working group under existing structures, to facilitate the exchange of data among countries.



Source: https://foter.com/blog/how-to-attribute-creative-commons-photos/

Figure 7.2 Overview of main Creative Common Licenses

7.3.3 *Open Geospatial Consortium Standards and Interoperability*

There are many software applications and file formats for handling tabular or geospatial data. Not all software applications can read all file formats. This causes issues in terms of interoperability, as data files received from another organisation using other applications and formats may be impossible to use.

The Open Geospatial Consortium (OGC) was created to address interoperability issues with geospatial data applications and formats. Since 1994, OGC aims at developing and implementing standards and protocols for formatting and exchanging geospatial data, to ensure interoperability between geospatial data systems and users. Over 500 organisations dealing with geospatial data, coming from different sectors (e.g. commercial, governmental, non-profit, research) and from different countries are actively involved.

For instance, the Web Map Service (WMS) is an OGC protocol for sharing geo-referenced images over the internet, like a map of monitoring boreholes. WMS also supports the visualisation of data associated to features in the images, like groundwater monitoring data associated to boreholes on a map. To be able to share data via WMS, organisations must have their geospatial data stored in a GIS database on a map server allowing internet access (Figure 7.3).

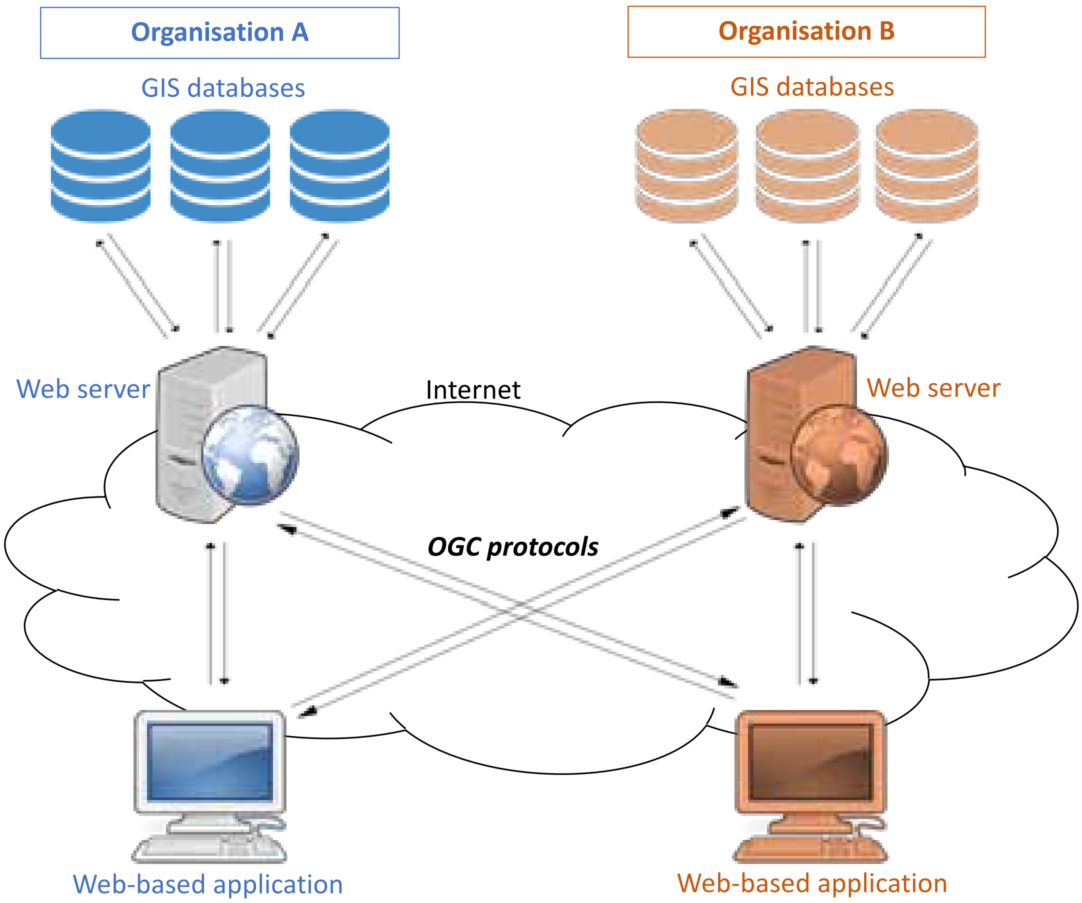


Figure 7.3 Schematic overview of data exchange between two organisations using OGC standards and protocols

Data shared via WMS can be visualised in any web browser in basic format. The data become more useful when viewed in dedicated web-based GIS applications that support data from multiple servers and allow for user interactions, such as zooming and access to the feature table. There are free software applications available for GIS databases, map servers and web-based GIS applications that can be used to set up a Spatial Data Infrastructure (SDI) (*See* Box 7.3).

Box 7.3 Overview of freely available software for storing, online sharing and visualising of geospatial data

Sharing geospatial data on the Internet using Open Geospatial Consortium (OGC) standards requires different software components: a GIS database, a map server and a web-based user application Commercially licensed solutions are available, but there are also several free and very adequate software programmes available, which will reduce costs for developing and maintaining a (SDI). For example:

- GIS database: PostGIS (https://postgis.net/)
- Map server: GeoServer (http://geoserver.org/), MapServer (https://www.mapserver.org/)
- Web-based applications: OpenLayers (https://openlayers.org/)

Free software like GeoNode (http://geonode.org/) and GeoNetwork (https://geonetwork-opensource.org/) integrate the three components in one package and provide an easy-to-use interface.

All these applications are also open-source.

To implement web services for geospatial data, a reasonably reliable internet connection is required, as well as investments to set up and maintain the hardware (server) and software components and costs for (specialised) personnel.

OGC has developed several other services, in addition to WMS, that operate in a similar fashion and which can be useful for groundwater data. A complete list of OGC services can be found on OGC's website: http://www.opengeospatial.org/.

OGC data sharing services are supported by dedicated XML-based informatic languages, such as the Geographic Mark-up Language (GML). In development is the Groundwater Mark-up Language (GWML) , which aims at supporting the exchange of all groundwater data types, i.e. not only maps but also borehole lithological logs, borehole construction data, geophysical exploration data, hydrogeological models and groundwater monitoring data.

With OGC protocols and standards, geospatial data can be accessed anywhere, provided there is Internet, and with a wide range of applications. They offer flexibility in user access and authorisations. Different data sharing protocols can be chosen, supporting different actions with the data, e.g. visualisation, download, edit. Organisations can lock the data with an access key (password) and share the key with selected organisations, thereby controlling who can access the data. From the data users' perspective, data are accessible anytime without needing to store and manage them, which would require extra time and money. Data storage and management remain under the responsibility of the data owning organisation. Data users do not need to keep local copies of data, they always have access to the most up-to-date data directly from data owners.

Advantages of data sharing protocols are obvious and some organisations in SADC are already sharing groundwater data using OGC services, like SADC-GMI (http://www.gip.sadc-gmi.org/), ORASECOM (http://gis.orasecom.org/), and the water departments of Botswana and South Africa to share data on the Ramotswa transboundary aquifer (http://www.ramotswa.un-igrac.org/) (Figure 7.4).

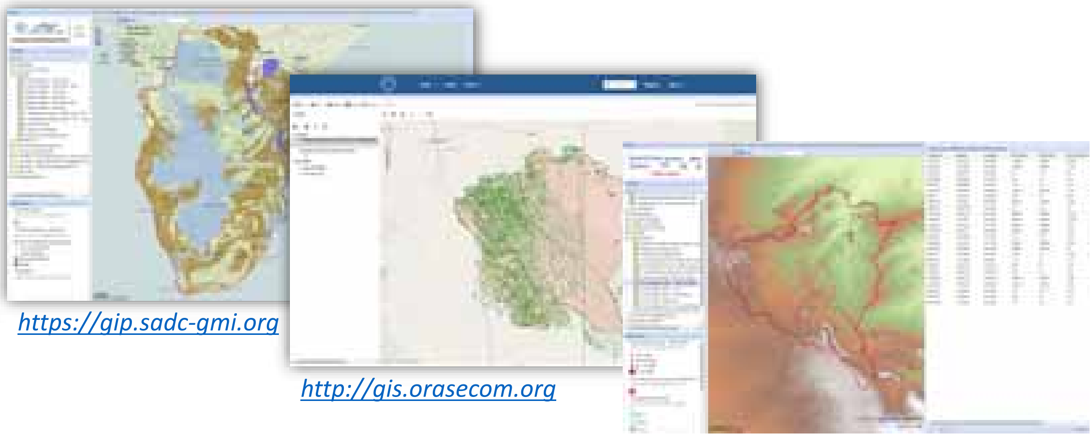


Figure 7.4 Examples of groundwater data sharing applications in SADC.

7.4 Main Messages

- **Awareness and stakeholder involvement in groundwater management require that stakeholders have access to data and information on groundwater, which is the responsibility of the groundwater departments;**
- **Data sharing will enable informed decisions in the management of transboundary aquifers;**
- **Groundwater departments must actively cooperate with other data owners or custodians to get access to all necessary data and information needed for integrated assessment of groundwater resources and development of suitable interventions in their country;**
- **Developments in ICT offer promising solutions for data sharing, like open data standards that allow for seamless access to data from other organisations whilst eliminating the need to manage the data in multiple organisations; and**
- **Protocols need to be developed and implemented at national and SADC levels for the technical and practical issues related to data sharing, including issues such as standardised formats and minimum required meta-data. Ideally this is done through working groups under existing structures.**

8 TRANSLATING DATA INTO INFORMATION

8.1 Introduction

The purpose of groundwater data is to produce information supporting the management of groundwater and related fields. This chapter addresses what sort of information can be processed out of groundwater data, what it takes to turn data into information and how information can be shared with targeted stakeholders. Shortcomings in groundwater data collection and data management might be identified when processing data into information: this chapter discusses how data processing should guide the improvement or the further development of groundwater data collection and data management programmes.

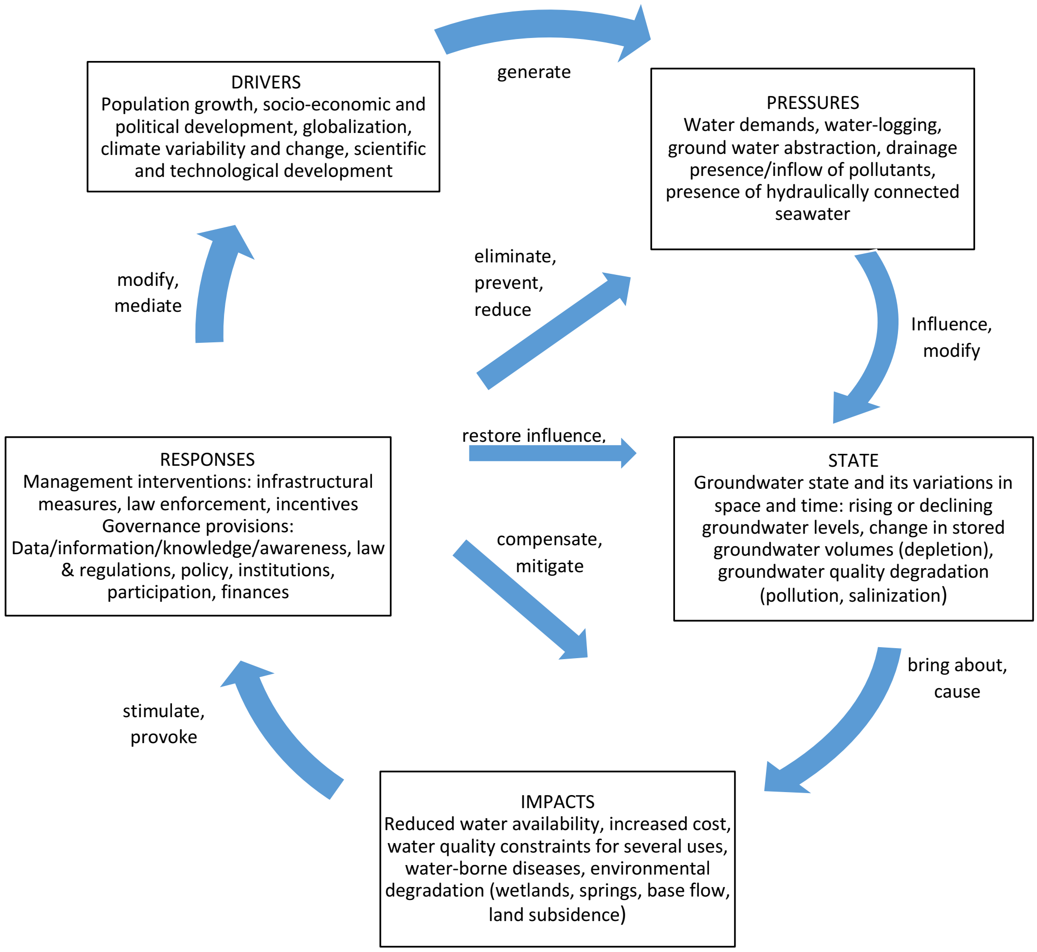
8.2 What is Relevant Groundwater Information?

The previous chapter highlighted the need to share groundwater data and information to all stakeholders. Groundwater stakeholders include hydrogeologists, social scientists, lawyers, planners, groundwater managers, politicians and other decision-makers, water-using industries, households, environmentalists and the general public (van der Gun 2018). It is important to realise that different stakeholders have different needs in groundwater information and a different level of understanding of groundwater. For example, a private well-owner is likely to be interested in the quality of the water from his own borehole but may be less interested in the over-all state of groundwater resources in a larger region or aquifer. He or she may also not understand detailed results from laboratory analysis, but will simply want to know if the water quality is sufficient for their purpose (e.g. domestic water, watering cattle, and irrigating crops). A drilling company will need more detailed information than the well owner, for example maps indicating aquifer productivity, depth of the aquifer layers and general groundwater in a region.

Groundwater monitoring provides decision makers with relevant information

Policy makers will be interested in the status and trends of groundwater resources so as to make policy responses to the challenges faced. For example ‘groundwater levels are declining in region x’, ‘arsenic contamination occurs in region y’, ‘seawater intrusion is progressing in the city of… ’. Such information however, is insufficient to develop adequate interventions. To achieve sustainable management of groundwater resources, it is critical to understand the mechanisms influencing the status and trends of groundwater resources, as well as the impacts that changes in groundwater have on society and the environment. Therefore, more elaborate information is required such as 'groundwater levels are declining in region x as a result of climate change and this may cause shallow hand-dug wells to dry out', 'arsenic contamination in region y is of natural origin and is an immediate threat to the health of the rural communities who depend on these wells for domestic water", 'seawater intrusion is progressing in the city of .... because of over-pumping in the municipal wellfield and is endangering public water supply'.

The Drivers, Pressures, State, Impact and Response (DPSIR) framework[5] adapted to groundwater resources management (van der Gun 2018, Figure 8.1), provides a useful framework to analyse drivers and pressures that can affect the state of groundwater, the impacts this has and what could be appropriate responses to improve the state of the groundwater resources and to compensate or mitigate negative impacts. Groundwater data collection programmes may produce data for assessing Pressures (e.g. groundwater abstraction monitoring), State (through groundwater level monitoring and groundwater quality monitoring) and Impacts (e.g. springs monitoring). Typical groundwater data, however, will not be sufficient to analyse the full DPSIR suite, and other data need to be sourced from other organisations (*See* also chapter 2).



Source: van der Gun (2018)

Figure 8.1 The DPSIR framework of analysis, tailored to groundwater resources management

[5] Developed by the European Environment Agency, the DPSIR (for Drivers, Pressures, State, Impact and Response) is a causal framework for analysing the relations between society and the environment, i.e. how the society impacts the environment and vice-versa. European Environment Agency (EEA), 1999 Environmental indicators: Typology and overview (available from https://www.eea.europa.eu/publications/TEC25). The DSPSIR is an extension of the original PSR model developed by OECD, 1991 Environmental indicators. A preliminary set. Paris, France.

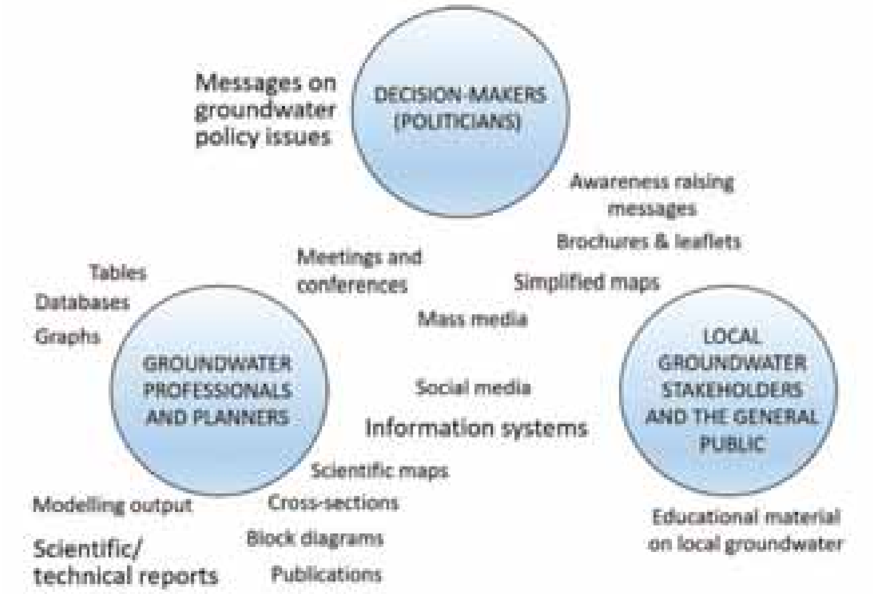
8.3 Organising Data Analysis and Interpretation

Surface water and groundwater behave differently, and therefore require different and specialised tools, methods and knowledge to analyse them. Groundwater data analyses require staff with a background in hydrogeology (preferably a higher academic degree). Specific issues require staff specialised in different fields of hydrogeology, like hydro-geochemistry or groundwater flow modelling. As data and information from other disciplines are required to assess and manage groundwater resources, other specialists should also be involved in analysis, with backgrounds in hydrology, engineering, agriculture, land-use management or economy, depending on the issues at hand. Large groundwater departments may have some of this specialist knowledge available within the ministry, but usually this requires cooperation with other departments and ministries or hiring external consultants.

Besides scientific skills and expertise, hydrogeological analysis mostly require dedicated software programmes, such as interpretation of pumping tests or geophysical surveys, interpretation of hydro-chemistry data, GIS analysis and groundwater flow modelling. Access to software should not be a problem because many are available for free. Adequate training of staff in the use of these software tools is more challenging. In addition to the skills developed in academic training, groundwater departments can also organise in-house trainings. Careful selection of software programmes will also assist in reducing training and interoperability issues. The most comprehensive or expensive software is not always the best. For a groundwater department with a relatively small team working with limited data and staff having to work on different tasks, a different software solution may be required than for a large department with a lot of dedicated staff, managing large amounts of data.

8.4 Targeting the Right Audience

Once appropriate information is produced, groundwater departments must find a way to reach targeted stakeholders with that information. In Figure 8.2, Van der Gun (2018) regroups stakeholders in three categories: decision-makers, groundwater professionals and planners, and local groundwater stakeholders such as farmers or private well owners and the general public, and presents different formats for information sharing to best serve different stakeholders.



Source: van der Gun (2018)

Figure 8.2 Selected forms of presenting groundwater data and information for targeted users

8.5 Reassessing and Improving Data Collection and Data Management

It is very likely that gaps or shortcomings in the data collection and data management programme will be identified when interpreting the data. Additional data may be needed which require updating parts of the programme. It is also possible that more data are collected than necessary, which is not cost-efficient. Here also, the programme could be revised and optimised. It is important that the staff engaged in interpretation of groundwater data provides feedback to those in charge of groundwater data collection, to make this process more efficient.

Producing relevant information provides justification to decision-makers to increase budgets for groundwater data collection and data management. Decision-makers will be more easily convinced to invest more in groundwater data collection and data management programmes if they *See* the outcomes of their investments as is shown in the cartoon in Figure 8.3. Therefore, even organisations that suffer from serious budget shortages should try their best to turn data into information and share it around.

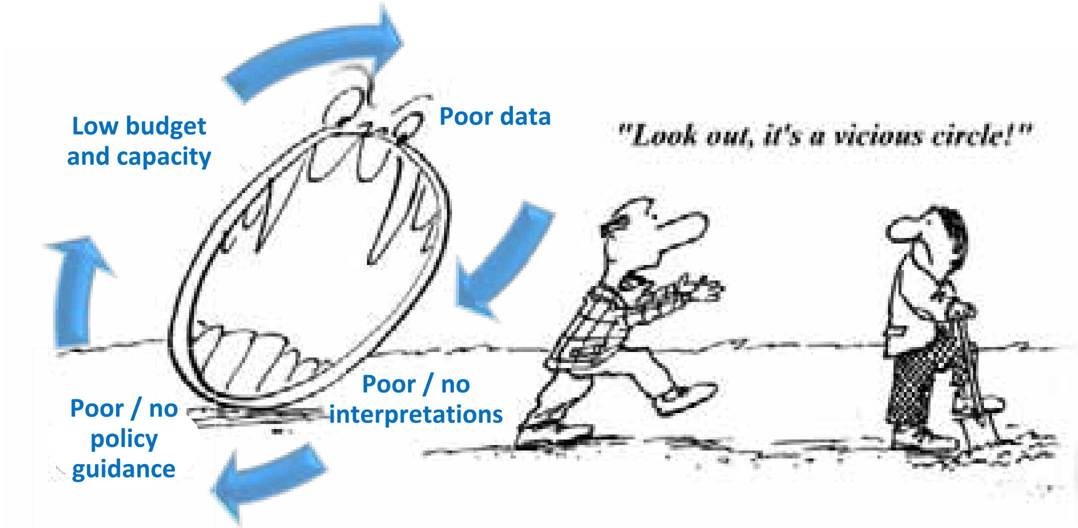


Figure 8.3 Vicious circle in groundwater data collection and data management

8.6 Main Messages

- **Data needs to be turned into information to communicate key messages to stakeholders and to developed fact-based interventions**
- **Different stakeholders require information to be presented differently;**
- **Data needs to be turned into information to demonstrate the usefulness of data to the stakeholders engaged in groundwater data collection; and**
- **Data analysis and interpretation assists in identifying data gaps and data quality issues that may lead to reassessment of data needs and data collection procedures.**

9 BUDGET PLANNING

9.1 Introduction

Many components of data collection and data management described in the SADC Framework for Groundwater Data Collection and Data Management can be done within the departments responsible for groundwater data collection and data management. In cases of lack of capacity, external professional experts can be engaged. It is therefore important to take into account the various costs associated with data collection and data management activities. This chapter provides an overview of cost components associated with data collection and data management activities. It does not provide cost for each activity, as this varies per SADC Member State, and also depends on scale of project, geography, topography and hydrogeological setting. The last section of the chapter provides suggestions for financing groundwater data collection and data management.

Credit: SADC- GMI

Costs related to data collection and management should be factored in during the planning process

9.2 Borehole Siting, Drilling and Testing

9.2.1 Borehole Siting

Borehole siting is done through surface geophysical survey. Siting of private boreholes for domestic purposes may however, be done based on a visual site inspection. Depending on the setup, the costs for siting can be fixed per single or multiple boreholes. In case of multiple boreholes, a larger geophysical survey may be executed at once. The costs vary with the geophysical method and scale of the survey. Typically, a surface magnetic survey with a magnetometer will be cheaper than resistivity tomography or an electromagnetic survey. While the use of multiple methods as complementary techniques is encouraged to improve understanding of the subsurface thereby increasing chances of success, it also comes at an extra cost.

Major cost components are labour, logistics related to field work, as well as costs for data analyses which will depend on scale of survey and methods used. Costs for equipment can include purchase, rentals or depreciation. Major costs for geophysical survey for siting a borehole drilling target are listed in Table 9.1. During planning, these costs should all be fixed components.

Table 9.1 Major aspects to consider when costing for geophysical survey for borehole siting

Activities	Typical costing unit
Desktop study	• Professional fees (per hour or per day) • Costs for data acquisition (maps, pre-existing data/studies)
Site visit/walk/planning	• Professional fees (per hour or per day)
Field geophysical survey	• Cost per borehole/Costs per unit length of survey/Costs per project (depending on setup) • Equipment costs (usually per day)
Logistics (costs for vehicle, fuel, field allowances.) for site visit and field survey	• Costs per kilometre • Costs per staff member per day
Data analysis, reporting and data handover*	• Professional fees (per hour or per day) • Costs for printing or consumables

* Data handover is crucial for building up a groundwater database, and it should be specifically requested (and budgeted) for to receive all relevant data (*See* chapter 3) in formats that can be processed.

9.2.2 Borehole Drilling

Borehole drilling encompasses actual drilling, borehole construction and development. Costs related to equipping a borehole with a pump is excluded as that is beyond the scope of this Framework. Table 9.2 provides an overview of the typical costs. Fixed costs are agreed before drilling, while variable costs are finalised after the drilling.

Table 9.2 Major aspects to consider when costing for drilling a borehole

Activity	Costing unit	Type of cost
Site establishment	Per site/borehole	Fixed
Drilling	Per metre of drilling	Variable
Reaming	Per metre of drilling	Variable
Solid casing	Per metre	Variable
Screened casing	Per metre	Variable
Gravel/sand pack	Per kilogramme	Variable
Developing	Per hour of development	Variable
Sanitary/bentonite seal	Per metre	Fixed
Borehole pad	Per borehole	Fixed
Professional data collection (Borehole lithological logging, intermittent yield measurements, final as built borehole designs, field water quality monitoring, water level monitoring during drilling)	Per metre or professional fee (per hour or day)	Variable
Field equipment (water level meters, V-notches, field water quality meters, hand lenses)	Per equipment	Fixed
Logistics (costs for vehicle, fuel, field allowances etc.)	Per kilometre travelled Per staff member per day	Fixed
Data analysis, reporting and data handover*	Professional fee/hour	Fixed

* Data handover is crucial for building up a groundwater database, and it should be specifically requested (and budgeted) for to receive all relevant data (*See* Chapter 3) in formats that can be processed.

9.2.3 Borehole Testing

Borehole testing refers to tests for borehole yield estimation, borehole performance assessment and estimation of aquifer parameters. Main costs to be taken into account are associated with site establishment and the testing hours. For Step drawdown test and Constant rate discharge test the type of cost are regarded as fixed or variable as this could vary from one supplier to the other. For example, some have standard fixed prices for 24-hour or 72-hour test. It is more important for the responsible department to understand the goal of the tests and the required duration so that they negotiate with the supplier. Table 9.3 shows major aspects to consider when costing for borehole testing.

Table 9.3 Major aspects to consider when costing for borehole testing

Activity	Costing unit	Type of cost
Site establishment	Per site/borehole	Fixed
Step drawdown test	Per unit or per hour and the pumping rate)	Fixed or variable
Constant rate discharge test	Per unit or per hour and the pumping rate)	Fixed or variable
Data collection- supervision (water levels, quality monitoring, yields, installation)	Professional fees (per hour or per day)	Variable
Logistics (costs for vehicle, fuel, field allowances etc.)	Per kilometre travelled Per staff member per day	Fixed
Data analysis, reporting and data handover*	Professional fee/hour	Fixed

* Data handover is crucial for building up a groundwater database, and it should be specifically requested (and budgeted) for to receive all relevant data (*See* Chapter 3) in formats that can be processed.

9.3 Groundwater Monitoring

Section 4.3.3 referred to some of the costing aspects related to developing a groundwater monitoring programme. These can be divided into the following cost components:

1) Designing the network (once-off investment);
2) Establishing the network (once-off investment);
3) Monitoring and maintenance (annually recurring costs); and
4) Evaluating networks (periodic investment, e.g. every 5 years)

IGRAC (2008) provides detailed overviews of the different cost components related to developing and implementing a groundwater monitoring programme (*See* IGRAC 2008, sections 3.6, chapter 8 and Annex F). This section provides a summary of the cost components.

Table 9.4 provides an example with three options of costs for establishing a monitoring network using existing boreholes, new boreholes, discharge measuring stations and recorders. In addition to the costs listed in the table, the once off investment for monitoring equipment should also be included (water level dippers, data loggers, EC-meters, sampling pumps, etc).

Groundwater monitoring should be done using the right tools

Table 9.4 Example of table for calculation of investments for different monitoring programme options

	Unit cost	Option 1		Option 2		Option 3	
		Number	Total cost	Number	Total cost	Number	Total cost
Upgrading existing wells		n1		n2		n3	
Cleaning, testing, small repairs, sample taps	x		x		x		x
Site protection (concrete base, cap, aprons, etc.)	x		x		x		x
Administrative costs	x		x		x		x
Installation of new wells		m1		m2		m3	
Drilling – depth class 1	x		x		x		x
Drilling – depth class 2	x		x		x		x
Well installation – depth class1	x		x		x		x
Well installation – depth class2	x		x		x		x
Cleaning and development	x		x		x		x
Site protection (concrete base, cap, aprons, etc.)	x		x		x		x
Administrative costs	x		x		x		x
Discharge measurement stations (only if relevant)		p1		p2		p3	
Installation	x		x		x		x
Site protection	x		x		x		x
Administrative costs	x		x		x		x
Recorders (only if relevant)	x	q1	x	q2	x	q3	x
Total investments			X		Y		Z

n, m, p and q: numbers of units involved

Source: IGRAC, (2008)

The annual costs for monitoring and maintenance (Table 9.5) can be split into costs for:

- Equipment (including replacement and maintenance;
- Measurements (including salaries, travelling expenses; and
- Data management (including salaries, office costs.

Annual costs for equipment replacement can be calculated by dividing the investments for replacement by the expected lifespan. For a well-protected monitoring borehole, the life time may vary between 25 and 50 years, while for most monitoring equipment the lifespan will be shorter and more in the range of 2 – 10 years.

Considerations on costing of measurements (groundwater sampling, groundwater level measurements and abstraction monitoring) are provided in the sections hereafter.

Table 9.5 Example of table for calculation of yearly costs of different monitoring programme option

	Unit cost	Option 1		Option 2		Option 3	
		Number	Total cost	Number	Total cost	Number	Total cost
Annual costs of replacement and repairs							
Monitoring wells	x	m1	x	m2	x	m3	x
Discharge measuring stations (if relevant)	x	n1	x	n2	x	n3	x
Measuring equipment (tapes, recorders, etc.)	x	p1	x	p2	x	p3	x
Other							
Annual costs of data collection and analysis							
Groundwater level measurements *	x	q1	x	q2	x	q3	x
Groundwater quality sampling *	x	r1	x	r2	x	r3	x
Laboratory analysis *	x	s1	x	s2	x	s3	x
Discharge measurements *	x	t1	x	t2	x	t3	x
Annual costs of data management							
Groundwater level measurements	x	u1	x	u2	x	u3	x
Groundwater quality sampling	x	v1	x	v2	x	v3	x
Laboratory analysis	x	w1	x	w2	x	w3	x
Annual office costs			x		x		x
Total annual costs			X		Y		Z

* The unit costs should include the frequency of observation, the costs of travelling, etc.

Source: IGRAC (2008)

9.3.1 Groundwater Sampling

The main cost associated with groundwater sampling are those related to logistics (travel to the field), staff time and laboratory cost. If samples are collected through purging, then pumping cost also need to be considered the staff time are going to increase. It is therefore important for groundwater departments to determine the appropriate ways for collecting representative samples as this will have huge implications on sampling and costs.

Laboratory analysis cost varies depending on the type and the parameters analysed. For example, the cost for analysing organic chemistry parameters and inorganic chemistry parameters will be different.

Table 9.6 Major aspects to consider when costing for groundwater sampling

Activity	Costing unit	Type of cost
Logistics (costs for vehicle, fuel, field allowances etc.)	Per kilometre travelled Per staff member per day	Fixed
Field collection of samples, incl. purging	Professional fee/hour	Variable or fixed
Equipment	Per item (replacement) costs, Per item maintenance and repair costs	Variable
Consumables (sampling bottles, field test kits, etc)	Per item (costs may be covered under either items)	Fixed
Delivery of samples to laboratory	Per distance	Fixed
Laboratory analysis	Per sample/type of analysis and or parameter	Fixed
Data analysis, reporting and data handover*	Professional fee/hour	Fixed

* Data handover is crucial for building up a groundwater database, and it should be specifically requested (and budgeted) for to receive all relevant data (*See* chapter 3) in processable format.

It is therefore important for departments to establish parameters which are vital for their monitoring programme as this has cost implications. Some of these aspects have been discussed in chapter 4. Table 9.6 shows major aspects to consider when costing for groundwater sampling.

9.3.2 Groundwater Level Monitoring

Groundwater level measurements can be measured manually or through partly or fully automated systems. In section 4.3.2 Design of a monitoring programme advantages of data loggers and data transfer via telemetry are discussed. The choice on the use manual groundwater dippers or data loggers possibly in combination with telemetry is not simply a financial one, as was discussed in Chapter 4. Whichever the choice, there is always a need for site visits to calibrate the data loggers based on manual measurements, to check on equipment, replace batteries and possibly to download the data from the data loggers.

Table 9.7 Major aspects to consider when costing for groundwater level monitoring

Activity	Costing unit	Type of cost
Logistics (costs for vehicle, fuel, field allowances etc.)	Per kilometre travelled Per staff member per day	Fixed
Equipment: • Manual dippers • Tape measure • Data loggers • Telemetric data transmitters • Handheld GPS, etc.	Per item (replacement) costs, Per item maintenance and repair costs	Variable
Field collection of measurements	Professional fee (per hour or day)	Fixed
Data analysis, reporting and data handover*	Professional fee (per hour or day)	Fixed

* Data handover is crucial for building up a groundwater database, and it should be specifically requested (and budgeted) for to receive all relevant data (see chapter 3) in formats that can be processed.

9.3.3 Groundwater Use Monitoring

Groundwater use monitoring is essential as it allows amount abstracted over time to be determined. Groundwater use is determined on the basis of abstracted volumes. In general, groundwater abstraction volumes can be determined through direct measurements or estimated through indirect approaches. However, direct measurements is the only accurate way for regulatory purposes.

There are two major approaches for installing water meters:

1) Installation of a water metre is a condition under the water use license. Borehole owners (or holder of the water use license) are obliged to install an approved water metre device at all borehole outlets for measuring the volume of groundwater pumped. Costs for purchasing, installation and maintenance are for the borehole owner; and
2) Installation of water meters is stimulated by the responsible departments, either by subsiding the costs or to take care of the installation of the water meters. In that case it is important to make clear and unambiguous agreements on maintenance and ownership.

The following table provides a summary of the aspects to consider when costing for groundwater use monitoring.

Table 9.8 Major aspects to consider when costing for groundwater use monitoring

Activity	Cost responsibility	Costing unit	Type of cost
Purchase of water meter device	Groundwater user*	Per device	Fixed
Installation	Groundwater user*	Per installed device	Fixed
Maintenance of the device	Groundwater user*	Per device	Variable
Installation verification	Department	Per site and distance travelled (costs for logistics and man-hours)	Fixed
Submission of data	Groundwater user	Per data set	Fixed
Inspection	Department	Per site and distance travelled (costs for logistics and man-hours)	Variable

* Depending on set-up this can also be the responsibility of the department

9.4 Data Management

Data management entails all data handling processes after the data are received from field technicians or laboratory. Costs for data management depend on the expected size of data sets and requirements of the department. Costs are related to staff costs, hardware and software. Staff costs are related to responsibilities such as:

- Liaising with data providers (providing borehole identification numbers, receiving data, feed back after quality control, etc);
- Data entry;
- Data quality checks;
- Database administration and management; and
- IT support.

As explained in Chapter 6, data may be stored in spreadsheets or in a comprehensive multi-user-access server-based databases. In a simple set-up, with limited amounts of data, where spreadsheets are used, or single file desktop database solutions, the databases can very easily be stored either on a network drive, and backups can be made in the cloud keeping the cost down to a contract with a cloud storage service (*See* Table 9.9).

Table 9.9 Cost incurred using a single file data storage option

Item/Activity	Cost responsibility	Costing unit	Type of cost
Software for data storage (spreadsheets)	Department	Per device	Fixed per year, or once depending on licence*
Data backup in the cloud	Department	Per subscription or contract	Fixed per year

* Free when using freeware such as OpenCalc

Larger, server-based databases are preferably stored locally on servers and data storage banks at the department. It requires computer hardware and dedicated infrastructure such as climate-controlled housing with an uninterruptable power supply (UPS) and emergency power supply when the national grid fails. To reduce the possible loss of data, back-ups must be performed on a daily basis and stored off-site. Larger databases also need a front-end, or user interface, to allow data operators to interact with the database. User interfaces are almost always custom made and need dedicated personnel to develop and maintain. When developing web-based access for users outside the organisation, firewalls and other security measures must be in place to protect the stored data (Table 9.10).

Table 9.10 Cost incurred using a SQL-server data storage option

Item/activity	Cost responsibility	Costing unit	Type of cost
Storage facility (server room)	Department	Once off	Fixed
Hardware (server)	Department	Per Item	Fixed
Data storage banks	Department	Per Item	Fixed
Uninterrupted Power Supply	Department	Per Item	Fixed
Fire extinguisher system	Department	Per Item	Fixed
Emergency Power Supply (Generator)	Department	Per Item + running cost /hour	Fixed
High-speed network connections	Department	Per network speed and bandwidth	Fixed
Backup facility (off-site)	Department	Per subscription or contract	Fixed
Database software	Department	Per number of seats (users)	Fixed
Database administration	Department	Professional fee/hour	Fixed
Database front-end development	Department	Professional fee/hour	Fixed
Hardware (workstations)	Department	Per Item	Fixed

Please note that most of the items need annual maintenance which needs to be budgeted for

9.5 Fundraising Initiatives

Groundwater data collection and data management are ongoing exercises with considerable associated costs that require sustainable funding plans to keep running. In many countries there is a need for redirecting finances, bringing public financing in line with policy priorities (for instance recovering costs of management interventions), and for developing new financial incentives to encourage private commitment to sustainable groundwater management. Given the value of groundwater for the economy and society, sufficient and regular financing for the basic functions of groundwater governance should be secured, including monitoring, administration, regulation, capacity building and innovation (van der Gun and Custidio, 2018).

In this section, we highlight some of the options available for groundwater departments to fund groundwater data collection and data management activities.

- **National budget**
  Groundwater data related activities can be funded through the regular budget allocations for the responsible department and ministry. The risk of this financing mechanism is that budget for groundwater data activities need to be secured in each budgeting cycle and risk being cut when there are other priorities, while groundwater data collection activities are long-term ongoing activities requiring long-term budget.
- **Dedicated groundwater tax**
  An alternative way to fund groundwater data activities is through a dedicated groundwater tax. In Netherlands for example, national water act permits the Provincial Governments who have an important role in strategic groundwater management and monitoring of groundwater resources to issue a groundwater use tax. The National Water Act (Netherlands Government, 2009) dictates that revenues from groundwater tax is available to that particular province and can only be used to cover costs associated with:
  - Measures directly related to preventing negative effects of groundwater abstraction and infiltration of water into aquifers (this includes research necessary for policy development, and groundwater monitoring);
  - The keeping of a register of all groundwater abstractions and infiltrations; and
  - Financial compensations related to damages resulting from licensed groundwater abstraction.

  The direct benefit of such a dedicate tax with limited spending opportunities is that budget for specific groundwater related activities is secured. Additional benefit is that the institute responsible for groundwater management is the one who can set the tax level (price per m3 groundwater abstracted) and that tax revenue increases as groundwater abstractions (and required management activities increase).

The success of such a tax comes with proper law enforcement, including a functioning system of registration of groundwater abstractions and regular (annual or quarterly) reporting on groundwater use.

- **Cost recovery fees**
  Alternative to taxing based on groundwater use, it is also possible to generate income based on cost recovery fees. This can be fees for registration and licensing of the drilling of boreholes and/or for groundwater abstraction. A fee on cost recovery basis can also be charge for providing data from the groundwater databases.
- **Conditions of licensing**
  Through licensing conditions, the holders of a drilling permit or a groundwater abstraction permit can be made responsible for collecting and providing data to the responsible department. This does not generate any budget but, if enforced, it is a way to ensure that stakeholders also contribute to the collection of relevant data at their own expenses.
- **External funding**
  It is not uncommon in the SADC region for activities related to groundwater data collection and data management to have been / being funded through international donor organisations. To initiate new activities and to cover the costs for the initial investments, this may be a suitable source of funding. But experience has shown that once the initial investment is made and the project budgets have been depleted, there is often insufficient budget for the continued data collection activities. Therefore, and to avoid lost investments, it is of paramount importance for any externally funded groundwater data collection and management programme to secure continued funding for management and maintenance through national resources.

9.6 Main Messages

- **Groundwater departments must understand the various cost involved in data collection and data management activities.**
- **Funding for groundwater data collection and data management activities can be sourced in different ways. External funding may be suitable for initial investments, but budget for continued management and maintenance should come as much as possible from national financial resources.**

10 National and Transboundary Institutional Aspects

10.1 Introduction

The involvement of several organisations in groundwater data collection and data management calls for a clear definition of responsibilities, to make sure that all aspects are taken care of and to minimise overlaps and duplication of efforts. The chapter discusses institutional aspects of groundwater data collection and data management at national and transboundary level.

10.2 Division of Roles at National Level

It is necessary to have a clear picture of the stakeholders engaged in groundwater data collection and data management within each Member State to understand who is doing what. There can be several stakeholders, such as national departments (sometimes in different ministries), water user organisations, water utility companies and NGOs, acting at national, province, district or municipality levels. A clear distribution of roles is needed to efficiently collect and manage groundwater data. A screening of the stakeholders engaged in groundwater data collection and data management will identify if all activities are duly assigned and enable an efficient management of all groundwater resources. It will also identify any overlap in stakeholders' activities.

There may be discrepancies between what stakeholders are supposed to do, according to their mandates, and what they actually do in practice. Based on this recommended screening, Member States may assign or re-assign the responsibility of groundwater data collection and data management to the relevant stakeholders. Responsibilities should be written in the mandates of organisations and in official policy documents.


Credit: SADC GMI

Groundwater experts from SADC at a SADC-GMI workshop on management of transboundary aquifers

As part of the project Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States a complete screening of the institutions engaged in groundwater management was done for the entire SADC region and for the following SADC Member State: Angola, Botswana, eSwatini, Lesotho, Malawi, Mozambique, Namibia, Seychelles, South Africa, Tanzania, Zambia and Zimbabwe (SADC Groundwater Management Institute, 2019).

IGRAC (2008) provides a list of how groundwater monitoring responsibilities are usually divided:

- **Primary – reference monitoring**
  'Responsibility for baseline groundwater monitoring may lie at national, state, district or municipality level. However, in case of monitoring of water quality of drinking water sources (tap water, bottled water/drinks, milk) responsibility usually is with those companies providing them. Often water utility companies also have monitoring wells in the up-gradient

catchment area of abstraction wells in order to be able to avert provision of polluted water resources and are obliged to submit their monitoring data to institutions which have the duty to supervise them.'

- **Protection and compliance monitoring**
  'Concerning monitoring of waste disposal sites, effluents and leakages from sewer lines and sewage treatment plants, mines, tailing dams, refineries, storage and processing facilities for chemical and hazardous substances, etc., the responsibility may be either at national/state level (and be paid for by the operator) or may lie with the operator itself who then has the duty to furnish the data.'
- **Pollution containment monitoring**
  'Monitoring of spills is commonly ordered (and conducted) by a governmental institution and must be paid for by the polluter (if the polluter-pays-principle is in place). In cases where contamination is widespread and cannot be attributed to a single source, such as agriculture, industry, urbanisation, traffic or contaminated surface water sources, monitoring will have to be conducted and paid for by the government. Monitoring of saltwater intrusion may be part of government's responsibility or, if it can be attributed to the over-abstraction by single users, be in the liability of these users.'

As part of groundwater monitoring, the collection of borehole siting, drilling and testing data must also be clearly assigned. As Chapter 3 highlighted, the collection of data can be challenging because they are not measured directly by the groundwater departments. It is necessary that the departments have the (legal) means to enforce the collection of data from all stakeholders.

Groundwater management activities (i.e. data storage, data sharing, and data interpretation) must also be explicitly assigned. It must be clear where the data must be stored, who can access the data, how, and for what purpose. These questions can be sorted out easily (e.g. all data are in a single database and available in 'open access') or require more complicated arrangements and protocols.

IGRAC (2008) makes some recommendations to assign the responsibilities of groundwater data collection and data management. It suggests that groundwater monitoring be organised at the same level where groundwater is managed and protected. If groundwater resources and groundwater related sectors such as land-use and environment are managed at the national level, groundwater data collection and data management should be organised at the national level. Some tasks can be delegated, but responsibilities and associated budgets should be at that level.

Groundwater management is effectively carried out following hydrogeological units (i.e. aquifers) or surface water catchment units, not administrative borders. With that in mind, it is better to also organise the collection and the management of groundwater data following hydrogeological units or surface water catchment units.

Organisations in charge of groundwater data collection and data management must be provided enough authority to collect data from other stakeholders. As already emphasised in Chapter 7, the sharing of groundwater data between stakeholders should be legally enforced, and not depend on the goodwill of individuals. This should be the entire process of groundwater data collection and data management.

10.3 Transboundary and International Arrangements

The management of transboundary aquifers requires that sharing countries have a common understanding of the shared groundwater resources. This requires some form of joint assessment and a dedicated transboundary programme of groundwater data collection and data management. Such programme can be implemented in a 3-steps process.

1) The first step is to gather the data already available in the countries, harmonise the data and merge them into common datasets (IGRAC, UNESCO-IHP, 2015). Common datasets can then be interpreted and produce a first assessment of transboundary aquifers resources. This will be a one-off exercise, providing insight on the groundwater system (e.g.hydrogeological, environmental and socio-economic setting) as well as the status and trends of groundwater resources at that moment. This is not yet a programme of transboundary data collection and data management, as data are not continuously updated and processed. Such a programme is required to define adequate management strategies.
2) In a second phase, the countries should organise the regular update of transboundary datasets with data being collected on either side of the border (i.e. borehole siting, drilling and testing data and monitoring data). Chapter 7 provides guidance on how to organise the sharing of data between countries. Harmonising the data before every update of the transboundary dataset might become a burden. Instead, it is recommended that countries harmonise the way they collect and store groundwater data, so that the data being collected are formatted in the same way and can directly enter the transboundary dataset. Agreeing on standards for groundwater data collection and data management might be challenging but it will greatly facilitate the update of transboundary datasets and transboundary cooperation. Regularly updated transboundary datasets should be processed into relevant information and ultimately into adequate management strategies (Chapter 8). During this process, data gaps might be highlighted, such as insufficient monitoring points, monitoring frequency or monitored parameters.
3) In a last phase, the countries could engage in the further development of their transboundary monitoring programme, with for example the increase in monitoring frequency or the creation of new monitoring boreholes. It requires additional budgets and capacity from the countries and a joint effort in designing a monitoring programme that matches the objectives (and doesn't 'simply' reuse data being collected for other monitoring programmes).

AFD (2011) and UNECE Task Force on Monitoring and Assessment (2000) propose a methodological approach to achieve such a joint programme of groundwater data collection and data management. As at national level, transboundary data collection and data management require a clear assignment of responsibilities, between the countries and within the countries. Long-term transboundary cooperation requires some degree of formalisation. This can be a memorandum of understanding, a joint action plan or a treaty, specifying the objectives and the activities to be carried out over the transboundary aquifer. Such agreements are promoted through international initiatives such as the Resolution on the Law of Transboundary Aquifers adopted by the General Assembly of the United Nations (United Nations, 2008) and the SADC Regional Water Policy (SADC, 2005).

Usually, agreements of this kind are signed at national level. As such, national groundwater departments will usually be the main stakeholders in transboundary programmes, coordinating the efforts between stakeholders in their own country (IGRAC, UNESCO-IHP 2015). They usually provide staff and budget to the joint body, the working group in charge of transboundary aquifer activities (including the programme of groundwater data collection and data management). For the success of transboundary programmes, it is important that national groundwater departments have sufficient capacity. Groundwater data collection and data management should be well organised within the countries. If other stakeholders are collecting groundwater data in the transboundary aquifer, they should be associated in the programme as well.

Transboundary or international organisations might also support transboundary programmes of groundwater data collection and data management. Transboundary lake and river basin organisations (L/RBOs), initially created for managing surface water resources, are increasingly integrating groundwater resources. From this perspective, it is a logical strategy to integrate transboundary groundwater data collection and data management in well-established L/RBOs, as was decided for example for the Stampriet Transboundary Aquifer System in the Orange-Senqu River Basin (Box 7.1). A SADC-wide institution such as the SADC Groundwater Management Institute (SADC-GMI) can also be instrumental in setting up and supporting transboundary programmes of groundwater data collection and data management. The mandate of SADC-GMI includes transboundary aquifers, as well as data and information management for the SADC region. SADC-GMI does not aim to collect data in the field but could support the countries and the L/RBOs with capacity in establishing and managing transboundary datasets and information systems. *See* also Section 7.4 OGC standards and interoperability for potentials models to manage flow of information between different organisations.

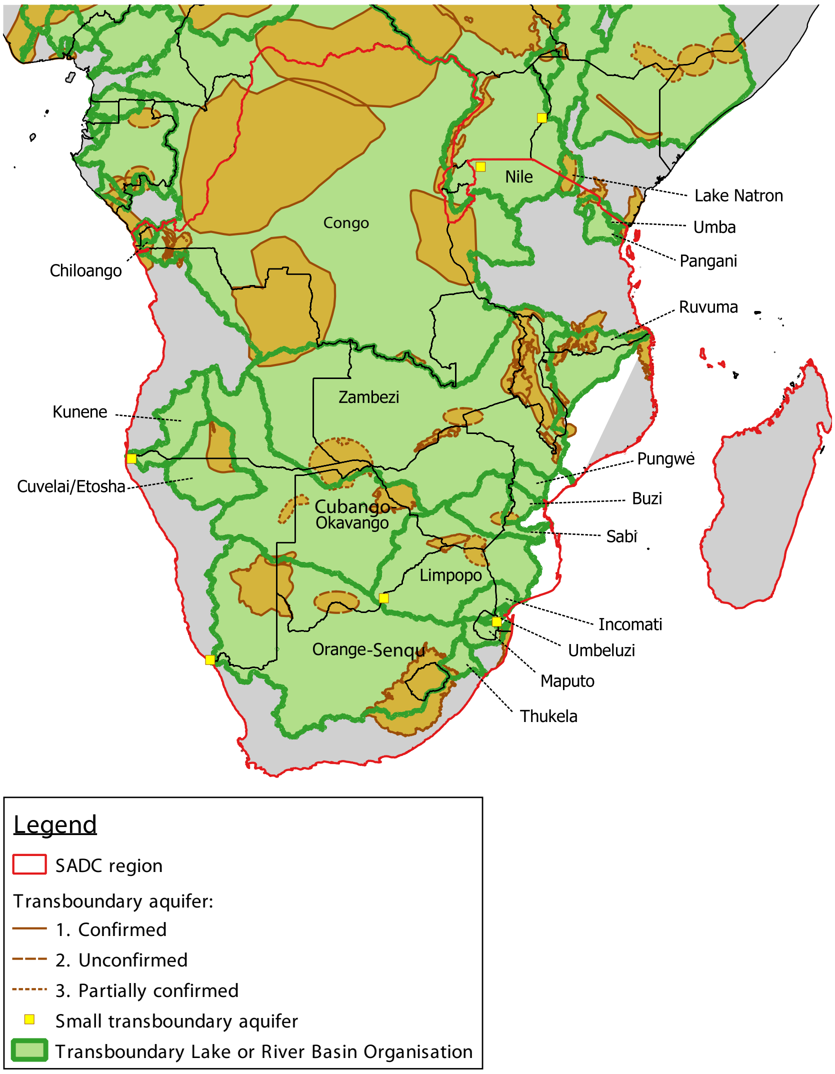


Figure 10:1 Map of international river basins and transboundary aquifers in SADC region

Box 10.1 An example of transboundary cooperation in SADC: the Stampriet Transboundary Aquifer System (STAS)

The Stampriet Transboundary Aquifer System (STAS) stretches across Botswana, Namibia and South Africa. It lies entirely within the Orange-Senqu River Basin. Since 2013, efforts have been made to assess the STAS and coordinate its management, with the support of the Groundwater Resources Governance in Transboundary Aquifers (GGRETA) project led by UNESCO-IHP and funded by the Swiss Agency for Development and Cooperation (SDC). It is an inspiring case-study for the assessment and the management of transboundary aquifers in SADC.

In the 1st phase of the project (2013-2015), a general assessment of the STAS was made, based on the compilation, harmonisation and reinterpretation of data from the three countries, coordinated by the Department of Water Affairs of Botswana, the Department of Water Affairs and Forestry of Namibia, and the Department of Water and Sanitation of South Africa. The assessment provided significant insight on the hydrogeology of the STAS and identified where management actions should be taken (mostly in protecting aquifers from contamination). Importantly, the 1st assessment highlighted that completing the picture of the status and trends of groundwater and defining adequate management strategies were hampered by the lack of sufficient monitoring data.

To organise the monitoring and the management of the STAS, a Multi-Country Cooperation Mechanism (MCCM) was established in the 2nd phase of the GGRETA project (2016-2018). The STAS MCCM was nested within the Orange-Senqu River Commission (ORASECOM), and more specifically within its Ground Water Hydrology Committee (GWHC). The GWHC advises ORASECOM on groundwater-related matters, including data collection and management and transboundary aquifers. Within the GWHC, the STAS MCCM aims at institutionalising the cooperation over the STAS and sustaining it after the span of the GGRETA project.

Next, the MCCM should address:

- The need for protocols and standards, so that data collected by the three countries are in the same format and can be merged easily into the transboundary database;
- The need for regular updates of the transboundary database with data from the countries. This should be done manually, until the national databases support the automatic exchange of data; and
- The need for additional monitoring data in some parts of the STAS.

Source: UNESCO-IHP, ORASECOM (2018)

10.4 Main Messages

- **The involvement of multiple organisations and stakeholders in groundwater data collection and data management asks for a clear division of roles and responsibilities;**
- **Transboundary programmes of groundwater data collection and data management should be implemented gradually, starting with an initial assessment based on gathering, harmonising and combining existing datasets from the countries, before moving on to joint monitoring;**
- **Transboundary programmes can depend on national representative organisations (e.g. ministries), who need to coordinate collection of data in their own country and the creation of transboundary datasets;**
- **National organisations engaged in transboundary programmes must have sufficient capacity. Budgetary and organisational issues at the national level are likely to replicate at the transboundary level; and**
- **Even though data may be collected through national organisations, transboundary and international institutions such as Lake and River Basin Organisations (L/RBOs) or the SADC Groundwater Management Institute (SADC-GMI) are well positioned to provide support to or even lead transboundary programmes of groundwater data collection and data management.**

REFERENCES

Adekile, D., Danert, K. (2014) Short Course: Drilling Supervision. Cost-Effective Boreholes. Skat Foundation. Available from: http://www.rural-water-supply.net/en/resources/details/570

Agence Française de Développement-AFD (2011) Towards *a Joint Management of Transboundary Aquifer Systems.* AFD Research Department

Bergkamp, G., Cross, C. (2006) *Groundwater and Ecosystem Services: Towards their Sustainable Use*. Proceedings from: International Symposium on Groundwater Sustainability

British Columbia Water Association (2017) Groundwater Protection Regulation Handbook Version 1. British Columbia. Available from: https://www.bcgwa.org/wp-content/uploads/2017-GWPR-Handbook_BCGWA_v1.pdf

Bureau of Meteorology (2017) Good Practice Guidelines for Water Data Management Policy: *World Water Data Initiative*. Bureau of Meteorology, Melbourne. Available from: http://www.bom.gov.au/water/about/publications/document/Good-Practice-Guidelines-for-Water-Data-Management-Policy.pdf

Department of Water - Western Australia (2016) Measuring the Taking of Water. Department of Water. Western Australia. Available from: https://www.water.wa.gov.au/__data/assets/pdf_file/0005/8186/109923.pdf

EPA Australia (2000) Groundwater Sampling Guidelines. Southbank Victoria. Available from: https://www.epa.vic.gov.au/~/media/Publications/669.pdf

FAO (2016a) Global Diagnostic on Groundwater Governance. FAO, Rome. http://www.fao.org/3/a-i5706e.pdf Available from: http://www.groundwatergovernance.org/

FAO (2016b) Shared Global Vision for Groundwater Governance 2030. FAO, Rome. http://www.fao.org/3/a-i5508e.pdf Available from: http://www.groundwatergovernance.org/

FAO (2016c) Global Framework for Action. FAO, Rome. http://www.fao.org/3/a-i5705e.pdf Available from: http://www.groundwatergovernance.org/

Fitch. P., Brodaric, B., Stenson, M., Booth, N. (2016) Integrated Groundwater Data Management. In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo JD., Ross A.(eds) Integrated Groundwater Management. Springer, Cham. Available from: https://doi.org/10.1007/978-3-319-23576-9_26

IGRAC (2008) Guideline on Groundwater Monitoring for General Reference Purposes. IGRAC report. International Working Group I. Utrecht 2006; revised 2008. Available from: https://www.un-igrac.org/sites/default/files/resources/files/WG1-7-Guideline-v12-03-08.pdf

IGRAC, UNESCO-IHP (2015) Guidelines for Multidisciplinary Assessment of Transboundary Aquifers. pp. 96. IGRAC, Delft. Available from: https://www.un-igrac.org/sites/default/files/resources/files/Guidelines%20for%20TBA%20Assessment%2020150901.pdf

IGRAC and IGS (2019a) Report on Activities. Capacity Building for Groundwater Data Collection and Management in SADC Member States (SADC-GWdataCoM project), CS2017/05. SADC Groundwater Management Institute, Bloemfontein

IGRAC and IGS (2019b) State of Groundwater Data Collection and Management in the SADC Member States. Capacity Building for Groundwater Data Collection and Management in SADC Member States (SADC-GWdataCoM project), CS2017/05.SADC Groundwater Management Institute, Bloemfontein

IPCC (2014) Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part B: Regional Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, New York

Jousma, G., Roelofsen, F.J. (2003) Inventory of Existing Guidelines and Protocols for Groundwater Assessment and Monitoring. Report nr. GP 2003-1. IGRAC, Utrecht, 2003. Available from: https://www.un-igrac.org/sites/default/files/resources/files/Rapport%204%20-%20Inventory.pdf

Kongo, V.M., Kosgei, J. R., Jewitt, G. P. W. and Lorentz, S. A. (2010) Establishment of a Catchment Monitoring Network through a Participatory Approach in a Rural Community in South Africa. Hydrology and Earth System Sciences 14, 2507–2525

Kovalevsky, V.S., Kruseman, G.P., Rushton, K.R., (Eds) (2004) Groundwater Studies - An international guide for hydrogeological investigations. IHP-VI, Series on Groundwater No.3. UNESCO-IHP, Paris, 2004. Pp 423. ISBN: 92-9220-005-4. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000134432

Kruseman, G.P., de Ridder, N.A. (1994) Analysis and Evaluation of Pumping Test Data. 2nd Edition. International Institute for Land Reclamation and Improvement, Wageningen.
Ministério da Energia e Águas – Angola (2014) Modelo de Gestão Comunitária de Água. Direcção Nacional de Abastecimento de Água e Saneamento. (Model for Community Water Management. National Directorate of Water Supply and Sanitation)

Moleme M.F. and Gomo M (2019). Evolution of Fluid Electrical Conductivity Profiles Associated with a Saline Contaminant Plume in a Horizontal Single-Plane Fractured-Rock Aquifer System. Natural Resources Research, 28(1): 79-90. https://doi.org/10.1007/s11053-018-9372-9

Netherlands Government (2009) Wet van, houdende Regels Met Betrekking tot het Beheer en Gebruik van Watersystemen (Waterwet). National Water Act, 2009

Ohio Environmental Protection Agency (2012) Technical Guidance Manual for Ground Water Investigations – Chapter: 10 Ground Water Sampling. Division of Drinking and Ground Waters, Columbus, Ohio. Available from: https://www.epa.state.oh.us/portals/28/documents/TGM-10.pdf

Roy, H.E., Pocock, M.J.O., Preston, C.D., Roy, D.B., Savage, J., Tweddle, J.C. and Robinson, L.D. (2012) Understanding Citizen Science & Environmental Monitoring. Final Report on behalf of UK-EOF. NERC Centre for Ecology & Hydrology and Natural History Museum.

Rural Water Supply Network (2010) Code of Practice for Cost Effective Boreholes. Available from: https://www.unicef.org/wash/files/Code_of_Practice_FINAL.pdf

SADC (2016a) SADC Selected Economic and Social Indicators. SADC, Gaborone

SADC (2016b) Regional Strategic Action Plan on Integrated Water Resources Development and Management – Phase IV (2016-2020). SADC Secretariat, Gaborone

SADC (2011) Development and Testing of Groundwater Drought Management Strategies in the Limpopo Basin Pilot Areas, Final Report.

SADC (2006) Regional Water Strategy. Southern African Development Community, Infrastructure and Services Directorate. SADC Secretariat, Gaborone

SADC (2005) Regional Water Policy. Southern African Development Community, Infrastructure and Services Directorate. SADC Secretariat, Gaborone

SADC (2001) Guidelines for the Groundwater Development in the SADC Region. Development of a Code of Good Practice for Groundwater Development in the SADC Region. Report prepared by Groundwater Consultants, Maseru, Lesotho. Prepared for: Southern African Development Community (SADC), Water Sector Coordination Unit (WSCU). Available from:
http://www.dwa.gov.za/Groundwater/Documents/Guidelines%20for%20the%20groundwater%20development%20in%20the%20SADC%20region%20-%20Report%20No%202%20(Final).pdf

SADC (2000) Revised Protocol on Shared Watercourses in the Southern African Development

Region. SADC, Gaborone
SADC Groundwater Management Institute (2019) Policy, Legal and Institutional Development for Groundwater Management in the SADC Member States (GMI-PLI). Regional Gap Analysis and Action Plan report. SADC GMI, Bloemfontein
Subcommittee on Ground Water (2013) A National Framework for Ground-water Monitoring in the United States. The Subcommittee on Ground Water of the Advisory Committee on Water Information, United States. First release – June 2009, Revised – July 2013. Available from: http://acwi.gov/sogw/pubs/tr/index.html
Sundaram, B., Feitz, A., Caritat, P., de Plazinska, A., Brodie, R., Coram, J., Ransley, T. (2009) Groundwater Sampling and Analysis – A Field Guide. Geoscience Australia. Available from: https://d28rz98at9flks.cloudfront.net/68901/Rec2009_027.pdf
Tordiffe, E.A.W. (2010) Groundwater Monitoring in the Orange-Fish River Basin, Namibia: Recommendations towards Establishing a Monitoring System. Report produced by GeoHydro Consultants Namibia and Karst Hydrogeological Consultants Namibia for the Ephemeral River Basins in Southern Africa (ERB) Project, Desert Research Foundation of Namibia (DRFN), Windhoek
Tuinhof, A., Foster, S., Kemper, K., Garduño, H., Nanni, M. (2006) Groundwater Monitoring Requirements for Managing Aquifer Response and Quality Threats. GW-MATE Briefing note series. Note 9. The World Bank, Washington. Pp10. Available from: https://www.un-igrac.org/sites/default/files/resources/files/GWMATE%20briefing%20notes%20-%20Monitoring%20Requirements.pdf
UNECE Task Force on Monitoring and Assessment (2000) Guidelines on Monitoring and Assessment of Transboundary Groundwater, Lelystad. Available from: http://www.unece.org/index.php?id=12609
UNESCO-IHP, ORASECOM (2018) Operationalization of the Stampriet Transboundary Aquifer System (STAS) Multi-Country Cooperation Mechanism (MCCM) https://groundwaterportal.net/sites/default/files/TORs_UNESCO_ORASECOM_Final.pdf
UN General Assembly (2008) Resolution on the Law of Transboundary Aquifers Adopted by the General Assembly of the United Nations (11 December 2008, A/Res/63/124)
UNICEF, Skat Foundation (2016) Professional Water Well Drilling: A UNICEF Guidance Note, Cost Effective Boreholes Partnership of the Rural Water Supply Network by UNICEF and Skat Foundation. Available from: www.unicef.org and www.rural-water-supply.net
United States Environmental Protection Agency-US EPA (2016a) Groundwater Level and Well Depth Measurement: Operating Procedure. Athens, Georgia. Available from: https://www.epa.gov/quality/groundwater-level-and-well-depth-measurement
United States Environmental Protection Agency-US EPA (2016b) Quick Guide to Drinking Water Sample Collection. Region 8 Laboratory Golden, CO 80403. Available from: https://www.epa.gov/sites/production/files/201511/documents/drinking_water_sample_collection.pdf
United States Environmental Protection Agency-US EPA (2007) Long-Term Groundwater Monitoring Optimization Clare Water Supply Superfund Site Permeable Reactive Barrier and Soil Remedy Areas Clare, Michigan. EPA 542-R-07-010. Available from: https://frtr.gov/pdf/PRB%20and%20Soil%20Remedy%20Areas%20Final%20Report.pdf
Van der Gun, J. (2018) Data, Information, Knowledge and Diagnostics on Groundwater. In Advances in Groundwater Governance, Karen G. Villholth, Elena Lopez-Gunn, Kirstin Conti, Alberto Garrido, Jac Van Der Guned(eds). CRC Press, Leiden
Van der Gun, J., Custidio, E. (2018) Governing Extractable Subsurface Resources and Subsurface Space. In Advances in Groundwater Governance, Karen G. Villholth, Elena Lopez-Gunn, Kirstin Conti, Alberto Garrido, Jac Van Der Gun(eds). CRC Press, Leiden

van Tonder, G., Bardenhagen, I., Riemann, K., van Bosch, J., Dzanga, P., Xu, Y. (2001a) Manual on Pumping Test, Analysis in fractured – Rock Aquifers. Water Research Commission (WRC), South Africa. WRC Report No III6/1/02, ISBN No 1 86845 861 X. Available from: http://scholar.ufs.ac.za:8080/xmlui/handle/11660/7423

van Tonder, G.J., Botha, J.F., Chiang, W.-H., Kunstmann, H., Xu, Y. (2001b) Estimation of the Sustainable Yields of Boreholes in Fractured Rock Formations. Journal of Hydrology, 241:70-90. Available from: https://www.sciencedirect.com/science/article/pii/S0022169400003693

Walker, D., Forsythe, N., Parkin, G., Gowing, J. (2016) Filling the Observational Void: Scientific Value and Quantitative Validation of Hydrometeorological Data from a Community-Based Monitoring Programme. Journal of Hydrology 538, 713-725

Water Research Commission-WRC (2017) Groundwater Sampling Manual. WRC Report No. TT 733/17, ISBN 978-1-4312-0926-2. Pretoria. Available from: http://www.wrc.org.za/wp-content/uploads/mdocs/TT%20733-17.pdf

Wellfield Consulting Services, British Geological Survey (2011a) Groundwater Monitoring Guidelines. Final report October 2011. Groundwater and Drought Management in the Southern African Development Community (SADC). Component 2: Regional Groundwater Drought Management Support. Contract 003D: Regional Groundwater Monitoring Network, Gaborone

Wellfield Consulting Services, British Geological Survey (2011b) Groundwater Monitoring Pilot Study. Final report October 2011. Groundwater and Drought Management in the Southern African Development Community (SADC). Component 2: Regional Groundwater Drought Management Support. Contract 003D: Regional Groundwater Monitoring Network, Gaborone

Wellfield Consulting Services, British Geological Survey (2011c) Transboundary Aquifers in SADC. Review and Classification with respect to Regional Groundwater Monitoring. Final report September 2011. Groundwater and Drought Management in the Southern African Development Community (SADC). Component 2: Regional Groundwater Drought Management Support. Contract 003D: Regional Groundwater Monitoring Network, Gaborone

Wilkinson, M.D. et al. (2016) The FAIR Guiding Principles for Scientific Data Management and Stewardship. Scientific Data. doi:10.1038/sdata.2016.18

World Bank (2017) Hidden and Forgotten: Managing Groundwater in Southern Africa. Available from: http://www.worldbank.org/en/news/feature/2017/06/07/hidden-and-forgotten-managing-groundwater-in-southern-africa

ANNEXES

Annex A Borehole Siting Procedures

Table A1 Summary of the main activities that should be undertaken during activity of borehole siting / survey and the expected outcomes

Activity	Objectives	What to do?	Equipment	Key data and information to be collected
1. Desktop study	• Develop a preliminary conceptual understanding of the hydrogeology of the area	• Search for relevant reported groundwater studies • Search for geological and hydrogeological maps in relation to the area of interest • Review and synthesis the information	• Internet, archives, library • Aerial and satellite imagery • Geological Maps + studies • Hydrogeological maps + studies	Have a general understanding of: • Records of existing boreholes, e.g. location of boreholes in a specific radius of influence from the area of interest (e.g. 2 km radius), water strikes, lithology, yields and groundwater levels, • Geological controls of groundwater occurrence • Types of typical aquifer occurring at regional scale and at local scales if there are any
2. Hydro-census and site walk	• Identify and understand groundwater use activities within the radius of influence if the area of interest • Confirmation of information gathered in step 1	• Conduct a field visit and collect existing borehole data; coordinates of boreholes, elevation, depth, yield, uses and quality (General water quality indicators: pH and Electrical conductivity), • Conduct a walk over the site where the borehole is to be placed.	• Global Positioning System (GPS) • Dip meter • pH and EC meters • Site Map	• Borehole location data (x, y, z) • Borehole use data • Records of yields for boreholes installed with water meters • Have an initial idea about layout of traverses for the geophysical survey
3. Interim report	• Plan for field geophysical survey	• Analyse information from activity 1 to 2 and write an interim report as the basis to plan for field geophysical survey planning	• No special equipment required.	• Decide/recommend on the type of equipment suited for field geophysical survey based on the understanding of site conditions, • Design the traverses' layout on the map for the geophysical
4. Field geophysical survey	• Locate the suitable drilling target using an appropriate geophysical method (s) and equipment recommended in interim report (Activity 4)	• Conduct the geophysical survey, • Record the geophysical parameters of investigation, • Record the coordinates of the start and end points of traverses, • Mark positions of potential interest as you survey (refined during data analysis)	• GPS, • Camera, • Geophysical equipment, • Materials for marking.	• Data of the investigated geophysical parameters, • Coordinates of start and end points of traverses, • Identified potential drilling sites

Activity	Objectives	What to do?	Equipment	Key data and information to be collected
5. Borehole siting report	• Give a detailed description of the borehole siting work and the main findings (Activity 1-5)	• Process and interpret the field geophysical survey data to identify the drilling target	• Knowledge and software/tool for processing and analysing data	• Data and analysis to motivate the selected target • Coordinates of selected drilling target(s), • Description of the drilling target, e.g. geological features being targeted like fault, fractures and etc., • Estimated depth of water strikes and overall drilling depth, • Provisional basic well design can be part of this phase • Report inclusive of all activities (1-5).

Safety and security measures must be put in place for every field visit according to the national standards, guidelines and professional ethics.

Annex B Borehole Drilling Procedures and Supervision

Table B1 below gives a summary of the main phases of borehole drilling supervision, responsibilities and the key data to be collected during the different phases. For the process of drilling

Table B1 Summary of the main steps of borehole installation, supervision and drilling responsibilities and other attributes

Borehole drilling supervision phases	Driller's Responsibility	Supervisor's Responsibility	Key data to be collected phase
1. Sourcing for the appropriate driller	• Respond to request by the client	• Request for a first quotation from at least 3 drilling contractors for the task at hand, • Use the assessment and check in step two and select the most cost effective and capable driller.	• Initial quotation for services of the drilling contractor for drilling, construction, development and completion
2. Pre-mobilisation	• Raise specific questions about scope of work and contract requirements, • Submit samples of materials	• Discuss about borehole design (use as a guide but can be modified during the drilling), • Check the quality and specifications casings and screens, • Check the quality and specifications of gravel/sand pack material + packers (if applicable), • Assess the overall capacity of the drillers.	• Most cost effective and capable driller selected for appointment • Indication of satisfaction with the quality of material and also capacity of the driller, if not: • Make recommendations to driller for improvements, • If not satisfied with material, communicate with driller and if possible, procure appropriate materials separately.
3. Mobilisation	• Submit program of work, • Avail equipment and materials for readiness inspection by drilling supervisor, • Move equipment to site and materials to the site.	• Check the readiness of the driller; • Approve drilling equipment and material, • Liaise/inform community leaders about the date of the drilling a week or two prior to drilling. • Guide the driller to the site (Now days GPS is used for direction)	• The community leaders are aware about the presence of the drilling team and have given their consent, • The driller has arrived on the site and ready for the drilling,
4. Drilling	• Position and operate the rig, • Drill, construct, develop and complete the borehole according to specifications in the drilling contract, • Collect drilling chip samples to a safe place for logging, and • Conduct blow yield test for each water strike	• Monitor the drilling right set up, ensure it is oriented according project specifications, • Monitor the drilling process, • Measure groundwater quality after water strikes (EC and pH can provide a general indicator) + record blow yields.	• Date of drilling • Exact location of borehole • Lithology logs (normally per 1 meter of drilling depth) such as: type of formation, texture, colour, structure, state of weathering, etc. • Penetration rates per 1 meter of drilling depth • indicators)
5. Borehole construction	According to the supervisor's specifications: • Gravel/sand pack the borehole • Install casing and screen • Etc.	• Instruct casing and screening depth as informed by observations made during in step 4 • Ensure gravel pack is properly placed around the borehole at the desired depths	• Actual borehole designs and dimensions • Borehole construction details – screen and gravel/sand packed depth • Optional: Site description with photographs
6. Development and completion	According to the supervisor's specifications: • Develop the borehole, • Construct sanitary seal and pad, • Disinfect the hole if it is needed.	Ensure that the: • Borehole is sufficiently developed i.e. water is clear, • Sanitary seal and pad properly constructed according to design specifications and to suit site conditions • Borehole is sufficiently disinfected. • Measure the groundwater level after completion	• Borehole completed, now waiting handover to the client/responsible authorities, • Record of groundwater level data after completion, • Record below yields and blow depths

it is important to distinguish between the driller's responsibilities from those of the drilling supervisor. This section is prepared mainly using the materials from the Rural Water Supply Network (2010), Adekile and Danert (2014), and UNICEF and Skat Foundation (2016).

Borehole drilling supervision phases	Driller's Responsibility	Supervisor's Responsibility	Key data to be collected phase
7. Demobilisation	• Remove all equipment and rubbish from site	• Ensure the drilling site is properly cleaned and restored to its former state	• The drilling site is now clean and restored to its former state and site ready for handover. • Start compiling the drilling report
8. Documentation and handing over	Submit all records to the drilling supervisor/client	• Report and handover the borehole to the client	Submit drilling report and hand over borehole to the client. • The report should document the whole borehole (s) installation processes analyse borehole data obtained in step 9 (drilling) to 11 (development & completion) and develop an initial conceptual understanding of the aquifer where the borehole has been drilled. • Such initial conceptual understanding should include aspects such lithology logs, location of main flow zones (water strikes), piezometric/hydraulic heads[1], aquifer structure and type

[1] To determine accurate piezometric/hydraulic, use borehole elevation (meters above mean sea level) determined using differential GPS.

Annex C Borehole Testing

Introduction

Pumping tests are conducted to test borehole performance, estimate sustainable yield and/or to estimate the aquifer hydraulic properties. Testing for borehole performance and estimation of sustainable yield is often called well-performance test or borehole testing, while tests to estimate physical/hydraulic properties of the aquifer/aquifer system tend to be referred to as (aquifer) pumping tests. Many different methods are available depending on the specific purpose of the test, the availability of suitable observation boreholes in the radius of influence of the pumped borehole, the conceptual understanding of the aquifer/aquifer system, etc. Due to the influence of heterogeneities, aquifers/aquifer systems respond non-uniquely to stress applied during the aquifer tests thus it is not possible to provide a single recipe on how the data should be collected and analysed. The expert involved in the test is fully responsible for the way in which the test is conducted and analysed (van Tonder et al. 2001a).

For detailed information on conducting aquifer pumping tests, data analysis and interpretation both SADC (2001) and Kruseman and de Ridder (1994) provide comprehensive guidance.

Borehole Yield Test

Anyone owning a borehole is interested to know the maximum discharge rate at which they can abstract groundwater for their specific purpose and in such a way that they can be assured of continuously getting water from their borehole for a specified period of time. Borehole yield is sometimes referred as the safe yield (Kalf and Woolley, 2005), reliable yield (Misstear and Beeson 2000; Hammond 2018) or sustainable yield (van Tonder et al. 2001b). In this Framework, the term sustainable yield will be used, but in practice these terms are interchangeable.

For estimating the sustainable yield of a single borehole, measurements are typically made in the pumping borehole. It is not mandatory to make use of additional observation wells, but if there are any observation boreholes or production boreholes (pump switched of and after sufficient recovery) in the locality of the test borehole, measurements can made be in those to assess the well inference effect. A flow diagram showing the main steps of aquifer pumping tests to estimate the sustainable yield of a single borehole is presented in Figure C1.

For a wellfield, the water balance approach is appropriate to determine sustainable pumping yields, and this can be applied through numerical groundwater flow modelling.

The duration of a Constant Rate Discharge (CRD) pumping test to estimate sustainable yield will vary depending on envisioned purpose of the borehole. Water needs for large scale (e.g. village, town, institutes and etc.) might require testing duration for 24 to 72 hours, while for a household borehole it could be just 3 to 8 hours. The CRD duration will thus vary depending on the anticipated use of the borehole. The emphasis should therefore be on operation-based management of borehole yield. This implies that regular monitoring of the groundwater levels should be done during the life time operations of the borehole such that the yield can be adjusted according to demands and to the aquifer's response.

Aquifer Parameters – Aquifer Pumping Test

Aquifer physical characteristics such as hydraulic conductivity and storage characteristics provide important information to understand aquifer characteristics and groundwater dynamics, and they are important input for numerical groundwater flow models which are used for scenario analysis/prediction purposes. The aquifer properties vary depending on the aquifer type (Table C1). Relevant aquifer hydraulic characteristics can be estimated from pumping tests. Kruseman & de Ridder (1994) describe the basic principle of pumping tests: "If we pump water from a well and measure the discharge of the well and the drawdown in the well and in piezometers at known

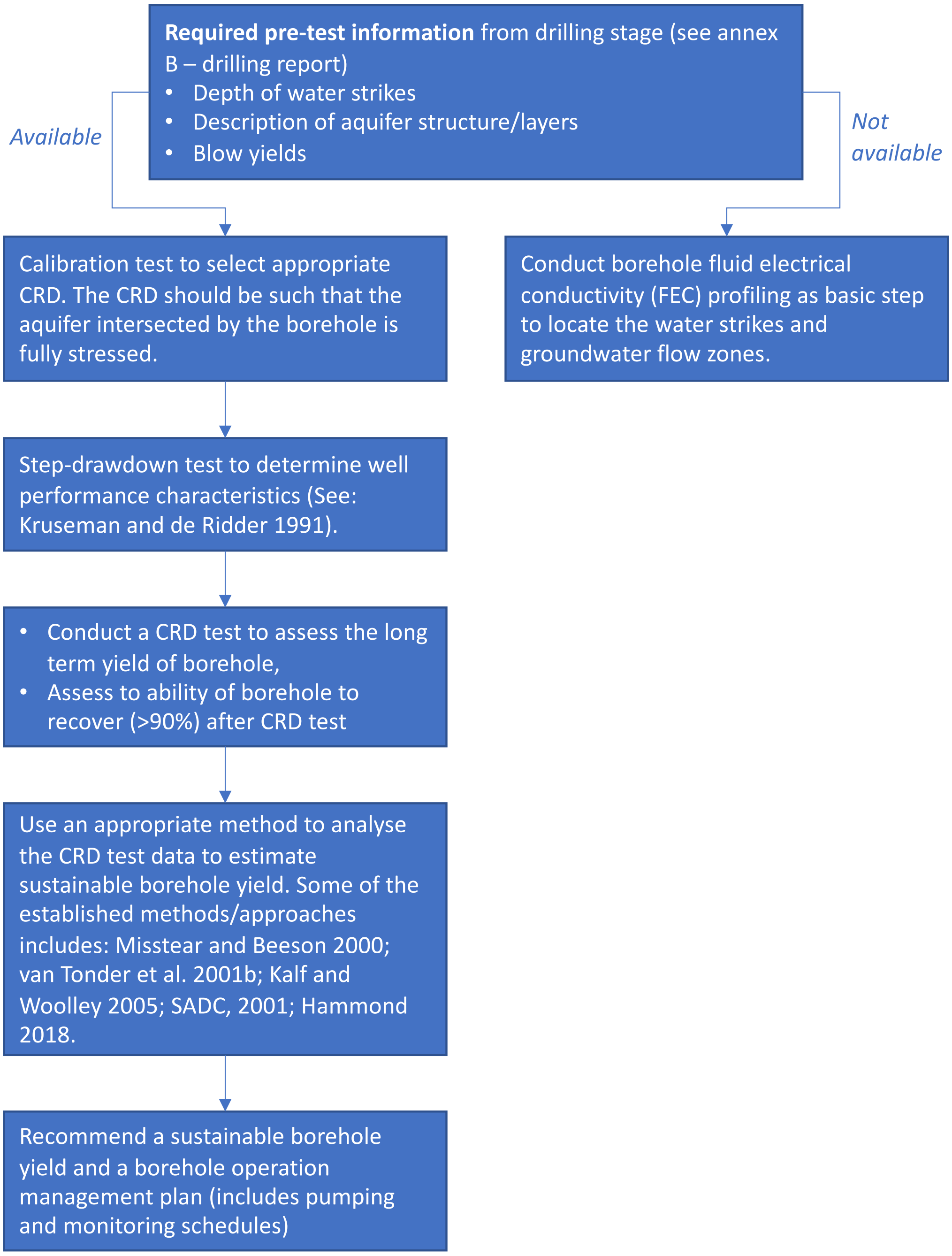


Figure C1: Flow diagram showing general steps of aquifer pumping tests to estimate the sustainable yield of a single borehole

distance from the well, we can substitute these measurements into an appropriate well-flow equation to calculate the hydraulic characteristics of the aquifer". Kruseman & de Ridder (1994) also state that drawdown data from the pumped well itself or from one piezometer often permit the calculation of aquifer hydraulic characteristics, it is nevertheless always best to have as many piezometers as conditions permit. The advantage of having more than one piezometer is that the drawdowns measured in them can be analysed in two ways: by the time-drawdown relationship and by the distance-drawdown relationship. The results of such analysis will be more accurate and will be representative of a larger volume of the aquifer.

Table C1 A summary hydraulic and parameters of aquifers which can be estimated from the analysis of the pumping test data

Aquifer type	Storage properties	Hydraulic properties
Unconfined	Storativity (S) Specific yield (S_y)	Horizontal hydraulic conductivity (Kh) Vertical hydraulic conductivity (Kv)
Leaky aquifer	Storativity (S)	Horizontal hydraulic conductivity (Kh) Transmissivity (T) Leakage factor (L)
Confined	Storativity (S)	Horizontal hydraulic conductivity (Kh) – generally denoted as K Transmissivity (T)
Confining layers/aquitards		Vertical hydraulic conductivity (Kv) / Hydraulic resistance (c)

Main steps and expectations of aquifer pumping tests

A summary of the main steps and expectations of aquifer pumping tests is presented in Table C2. The pumping tests start with planning on the basis of the drilling report. If the drilling report or borehole information is unavailable, then fluid electrical conductivity (FEC) borehole profiling can be used as a basic tool to locate water trikes and or groundwater flow zones. These zones are important because they typically represent the high transmissive and groundwater bearing zones of the aquifer which should be stressed during testing. It is ideal to place the testing pump below these zones to ensure that they can be stressed, and the water does not fall below the pumps during the test. Moleme and Gomo (2019) provide an example on the application of FEC borehole profiling to identify groundwater flow zones in typical fractured-rock aquifers.

Table C2: A summary of the main steps and expectations of aquifer pumping tests

Step	Purpose	Key data to be collected	Estimated parameters
Planning	To enable preparation of the constant rate discharge test	• Site location, • Date, • Depth of water strikes, • Aquifer lithology, • Blow yields, • Refer to drilling report	Not applicable
Borehole fluid electrical conductivity (FEC) profiling	Locate water strikes and groundwater flow zones	• Borehole FEC profile	• Depth of water strikes and groundwater flow zones
Calibration test	Select appropriate CRD	• Time and groundwater levels (drawdown), • Step discharge rates.	• Appropriate CRD
Step-drawdown test	Assess well efficiency characteristics	• Time and groundwater levels (drawdown), • Step discharge rates.	• Well efficiency, • Hydraulic properties
Constant rate drawdown (CRD) test	Estimate borehole sustainable/reliable yield, Estimate aquifer hydraulic and storage properties	• Time and groundwater water levels (drawdown), • Average CRD	• Sustainable/safe/reliable yield • Hydraulic properties of the aquifer \ aquitard
Recovery test	Estimate aquifer hydraulic and storage properties Evaluate the % of recovery	• Residual time, • Residual groundwater levels	• Hydraulic properties • Evaluate the % of recovery

Calibration test is done to help choosing an appropriate discharge rate for the aquifer pumping test. The appropriateness of the discharge rate will vary depending on the purpose of the aquifer pumping tests (Figure C1 and Figure C2). In practice, efficient calibrations tests require previous experience, field observation and some qualitative assessment.

Step-drawdown test is done mainly to assess the well efficiency characteristics. This is important because the well loss component of well efficiency is factored during the estimation of borehole sustainable yield estimation (Hammond 2018). Estimation of aquifer transmissivity and horizontal hydraulic conductivity can be made from step-drawdown test data (Kruseman and de Ridder 1994).

Step tests are typically followed by **constant rate discharge (CRD) test**, where the borehole is pumped at a constant rate throughout the duration of the test. Driscoll (1986) suggested CRD pumping test duration of 24 hours for confined aquifer and 72 hours for unconfined aquifer. Depending on the hydrogeological characteristics longer duration tests may still provide more data to better analyse effects of hydraulic boundaries in the aquifer and flow regimes in multi-layer systems, but in reality, the costs of extended tests will often be the limiting factor.

Recovery test involves measuring the recovery residual water levels with time after switching of the pump. Analysis of recovery data often provides an independent check of the pumping test data because it happens naturally. Traditionally, only hydraulic properties could be estimated from the recovery data but approaches have now been developed to estimate storage capacity from the recovery data (Ballukraya and Sharma 1991; Singh 2006 and Çimen 2015). Figure C2 shows a flow diagram illustrating the general steps of aquifer pumping tests to estimate aquifer parameters.

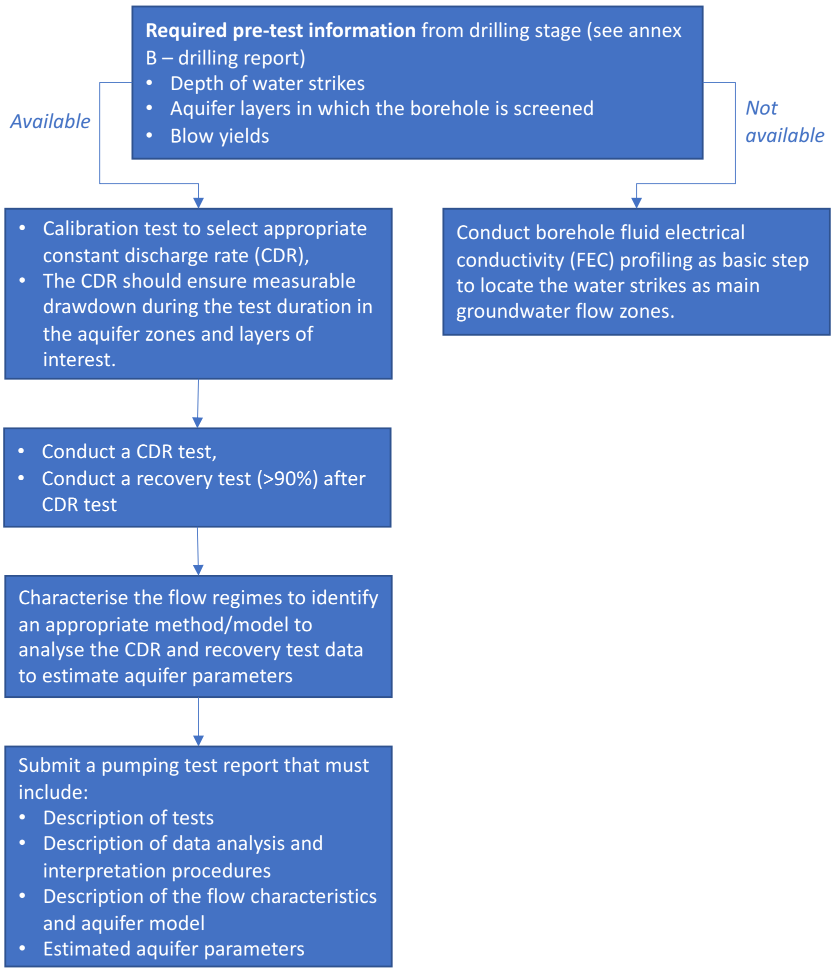


Figure C2 Flow diagram showing general steps of aquifer pumping tests to aquifer parameters

Annex D Mobile Phone Applications for Groundwater Data Collection

Table D1 Description of mobile phone apps relevant for groundwater data collection

<table>
<tr><th>App</th><th>Website</th><th>Freeware/ Paid license</th></tr>
<tr><td>AKVO Flow</td><td>https://akvo.org/products/akvoflow/#overview
http://flowsupport.akvo.org/container/show/akvo-flow-app</td><td>Paid</td></tr>
<tr><td colspan="3">App to collect, manage, analyse and display geographically-referenced monitoring and evaluation data through the use of mobile phones and internet connectivity. It offers fast data collection, survey flexibility and analytical tools.</td></tr>
<tr><td>Collector</td><td>https://www.esri.com/en-us/arcgis/products/collector-for-arcgis/resources</td><td>Paid</td></tr>
<tr><td colspan="3">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.</td></tr>
<tr><td>CrowdWater</td><td>https://www.crowdwater.ch/en/welcome-to-crowdwater/</td><td>Free</td></tr>
<tr><td colspan="3">App for collecting hydrological data. Data collected are: water level & streamflow, soil moisture and flow condition of a temporary stream.</td></tr>
<tr><td>FieldLogger</td><td>http://www.artesia-water.nl/software/fieldlogger/</td><td>Free</td></tr>
<tr><td colspan="3">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.</td></tr>
<tr><td>GeoPaparazzi</td><td>https://www.osgeo.org/projects/geopaparazzi/</td><td>Free</td></tr>
<tr><td colspan="3">App for qualitative field surveys. Features include: georeferenced notes, georeferenced and oriented pictures, form-based data survey, easy export of collected data, a map view for navigation with support for raster tiles and vector data.</td></tr>
<tr><td>GGMN App</td><td>https://play.google.com/store/apps/details?id=com.vesselstech.ggmn&hl=en</td><td>Free</td></tr>
<tr><td colspan="3">App to geo-reference and 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.</td></tr>
<tr><td>Go-Canvas</td><td>https://www.gocanvas.com/</td><td>Paid</td></tr>
<tr><td colspan="3">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 (determine site).</td></tr>
<tr><td>Go Groundwater</td><td>https://en.eijkelkamp.com/products/sensors-monitoring/go-groundwater-app-and-dongle.html</td><td>Paid</td></tr>
<tr><td colspan="3">App to configure and read out Divers (van Essen company data loggers) wirelessly with a smartphone via a Bluetooth dongle. Requires permanent installation of a Bluetooth dongle (IP67) in the monitoring well.</td></tr>
<tr><td>GW-Mobil</td><td>https://www.ribeka.com/en/products/gw-mobil/</td><td>Paid</td></tr>
<tr><td colspan="3">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.</td></tr>
<tr><td>LithoHero</td><td>http://lithohero.com/</td><td>Free</td></tr>
<tr><td colspan="3">Application to collect, record, and display sedimentological and stratigraphic data during fieldwork. The application can be used to describe outcrops or cores.</td></tr>
<tr><td>mWater</td><td>https://www.mwater.co/</td><td>Free / Paid</td></tr>
<tr><td colspan="3">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.</td></tr>
</table>

Mobile Water Management (MWM)	https://www.mobilewatermanagement.nl/ https://play.google.com/store/apps/details?id=com.mobilewatermanagement.sensor&hl=en	Free / Paid
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.		
MyWell	https://vesselstech.com/mywell.html	Free
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.		
Qfield	https://www.qfield.org//	Free
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.		

Note: This overview is not comprehensive and merely tends to illustrate the potential and availability of apps, without intending to recommend or promote a specific tool/app.

Annex E Recommended Reading

SADC Policies and Strategies

SADC (2005). **Regional Water Policy.**
The Regional Water Policy for the SADC region aims at providing a framework for sustainable, integrated and coordinated development, utilisation, protection and control of national and transboundary water resources in the SADC region, for the promotion of socio-economic development and regional integration and improvement of the quality of life of all people in the region.

Guidelines and Manuals

Water Research Commission (2017). **Groundwater Sampling Manua**l. Water Research Commission, Pretoria, South Africa. WRC Report No. TT 733/17, ISBN 978-1-4312-0926-2. Available from: http://www.wrc.org.za/wp-content/uploads/mdocs/TT%20733-17.pdf
The Groundwater Sampling Manual provides guidance on consistent groundwater sampling techniques that will ensure that all groundwater quality data collected is representative of in-situ groundwater quality at the time of sampling. Using these guidelines will reduce sampling errors thereby improving the quality of the data. Groundwater quality data collected according to these described techniques can then reliably be used to evaluate hydrogeochemical conditions and groundwater quality.

IGRAC (2008) **Guideline on Groundwater monitoring for general reference purposes.** IGRAC report. International Working Group I. Utrecht 2006; revised 2008. Pp165.Availavble from: https://www.un-igrac.org/sites/default/files/resources/files/WG1-7-Guideline-v12-03-08.pdf
The report provides extensive guidelines for developing and implementing efficient and realistic groundwater monitoring programmes. The guidelines cover aspects of designing groundwater monitoring networks in accordance with specific monitoring objectives. Additionally, and this makes these guidelines stand out from other guidelines on groundwater monitoring, the report also deals with practical, institutional, organisational and financial aspects of groundwater monitoring. This provides users of these guidelines the tools to design efficient monitoring networks which are realistic to implement and maintain.

Kovalevsky, V.S., Kruseman, G.P., Rushton, K.R., (Eds) (2004) **Groundwater Studies - An international guide for hydrogeological investigations**. IHP-VI, Series on Groundwater No.3. UNESCO-IHP, Paris, 2004. Pp 423. ISBN: 92-9220-005-4. Available from: https://unesdoc.unesco.org/ark:/48223/pf0000134432
Extensive guidelines/textbook (423 pages) covering all aspects of hydrogeological investigations. The book starts with comprehensive introductions to many hydrogeological principles the book and also covers aspects of groundwater data collection with practical information on available methods and equipment. Additionally the book also describes different hydrogeological investigation methods, aspects of data processing and of groundwater management. Specific descriptions of different hydrogeological settings (Hard rocks, carbonate rocks and volcanic rocks) complete the book.

SADC (2001). **Guidelines for the Groundwater Development in the SADC Region**. Development of a code of good practice for groundwater development in the SADC region. Report prepared by Groundwater Consultants, Maseru, Lesotho. Prepared for: Southern African Development Community Water Sector Coordination Unit (SADC WSCU). Funded by the government of France. Available from: http://www.dwa.gov.za/groundwater/Documents/Guidelines%20for%20the%20groundwater%20development%20in%20the%20SADC%20region%20%20Report%20No%202%20(Final).pdf
The report provides extensive guidelines (including some field forms/templates) on the following: • Desk study and reconnaissance survey for groundwater development; • Borehole siting; • Borehole drilling and construction; • Borehole development; • Groundwater sampling; • Pumping test of boreholes; • Recommendations on Production pumping; • Guidelines on hand dug wells and springs; and • Guidelines on reporting.

UNECE Task Force on Monitoring and Assessment (2000). **Guidelines on Monitoring and Assessment of Transboundary Groundwater.** Lelystad. Available from: https://www.unece.org/fileadmin/DAM/env/documents/2018/WAT/05May_28-30_IWRM_WGMA/Transboudary_Groundwaters.pdf
The character of these Guidelines is strategic rather than technical. They are intended to assist ECE governments and joint bodies in developing harmonised rules for the setting up and operation of systems for transboundary groundwater monitoring and assessment. The target group comprises decision makers and planners in ministries, organisations and institutions responsible for environmental, water or hydrogeological issues and all those who are also responsible for managing transboundary groundwaters. The Guidelines also aim to provide advice to those who are responsible for or involved in the development of sustainable water management schemes

Frameworks

SOGW (Subcommittee on Ground Water) (2013). **A National Framework for Groundwater Monitoring in the United States**. The Subcommittee on Ground Water of the Advisory Committee on Water Information, United States. First release – June 2009, Revised – July 2013 Available from: http://acwi.gov/sogw/pubs/tr/index.html
In 2007, the Subcommittee on Ground Water (SOGW) was commissioned by the Federal Advisory Committee on Water Information (ACWI) to develop a framework that establishes and encourages implementation of a long-term national ground-water quantity and quality monitoring network. The proposed National Ground-Water Monitoring Network (NGWMN) is envisioned as a voluntary, integrated system of data collection, management, and reporting that could provide the data needed to help address present and future ground-water management questions raised by Congress, Federal State, and Tribal agencies and the public.

FAO (2016). **Global Diagnostic on Groundwater Governance**. FAO, Rome (Italy). Available from: http://www.groundwatergovernance.org
This publication is one of the products of the Project 'Groundwater Governance — A Global Framework for Action' implemented during the period April 2011 – June 2016. It presents the state of groundwater governance across the world and how it differs from 'ideal conditions'. It builds on the several project activities, which included the draft of twelve Thematic Papers, describing the state-of-the-art as perceived by selected professionals, and several Case Studies, together summarised in a Synthesis Report. Five Regional Consultation Meetings were conducted in different parts of the world, with the aim to collect as much information as possible on groundwater governance in different regions and countries, and to capture the related perceptions and opinions of the more than five hundred participants. On top of this, five regional diagnostic reports on groundwater were prepared by knowledgeable professionals from each of these regions.

Data Management

Fitch P., Brodaric B., Stenson M., Booth N. (2016). **Integrated Groundwater Data Management.** In: Jakeman A.J., Barreteau O., Hunt R.J., Rinaudo JD., Ross A. (eds) (2016) Integrated Groundwater Management. Springer, Cham. DOI: https://doi.org/10.1007/978-3-319-23576-9_26
Overview paper describing various aspects related to data management, including data management models, aspects of quality assurance and quality control, data licensing and interoperability

EPA Australia (2000). **Groundwater Sampling Guidelines**. Southbank Victoria, Australia. Available from: https://www.epa.vic.gov.au/~/media/Publications/669.pdf
These Good Practice Guidelines for Water Data Management Policy have been prepared to assist officers responsible for formulating and implementing government strategy to improve water information, with the aim of advancing water policy, planning, management and operations. The guidelines describe the various high value uses of water data and identify seven elements to good practice in water data management. These include (1) identifying the priority water management objectives, (2) strengthening water data institutions, (3) establishing sustainable water data monitoring systems, (4) adopting water data standards, (5) embracing an open data approach to water data access and licensing, (6) implementing effective water data information systems and (7) employing water data quality management processes.

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