GUIDANCE DOCUMENT ON GROUNDWATER SCHEME DEVELOPMENT

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Guidance Document on Groundwater Scheme Development

Report to the

Water Research Commission

by

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Photo credit: Dr Kevin Pietersen – Installed groundwater infrastructure, Bosbokduin, Hessequa Local Municipality.

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FGD	Focus group discussions
KII	Key informant interviews
O&M	Operation and maintenance of groundwater infrastructure
SADC	Southern African Development Community
SDG	Sustainable Development Goals
SDG 6	SDG of clean water for all

1. INTRODUCTION

1.1. Background

The Strategic Water Sector Cooperation between Denmark and South Africa is long-term bilateral cooperation contributing to the South African water sector by sharing practical experience and providing expert input into the South African municipal sphere gaps. The cooperation support intends to add long-term value to optimise groundwater utilisation. This project aims to facilitate the development of guidelines for groundwater schemes at the municipal level.

Typical groundwater schemes in South Africa comprise boreholes equipped with pumps or motorised wellfields operated by water agencies or local authorities. In some settings, the boreholes may form part of the water treatment and reticulation system (Figure 1).

Figure 1: Groundwater supply system (a) borehole equipped with submersible pump (b) raw water tank (c) water treatment (d) water storage tank.

The National Water Act of 1998 (RSA 1998) recognises the strategic importance of groundwater and deals with it as an integral part of the hydrological cycle. In practice, groundwater forms an essential part of any water management and supply programme, and municipalities developed many water supply schemes using groundwater as a resource. However, schemes fail due to a lack of knowledge and mismanagement, and the municipalities consider groundwater resources unsustainable. Limited access to groundwater resources in many parts of South Africa is due more to the infrastructure's functionality than the physical availability of groundwater resources (Cobbing et al., 2015; Dolo, 2019).

> Groundwater infrastructure can be considered critical infrastructure as it is socially, economically or operationally essential to the functioning society or community, both in normal circumstances and in the extreme circumstances of an emergency
>
> (Gallego-Lopez and Essex, 2016)

The non-functionality of groundwater supply schemes affects the achievement of the Sustainable Development Goal (SDG) of clean water for all (SDG 6). There is a need for SDG investment planning to move from concentrating on covering targets to focusing on quality infrastructure and proactive monitoring to reduce the future burden placed on communities (Truslove et al., 2019, 2020; Danert, 2022).

Achieving the SDG 6 goal of clean water for all requires considerable financial resources for expanding and modernising groundwater infrastructure and operation and maintenance (World Bank 2018). Compared with the resources available for determining primary groundwater availability, such as hydrogeological maps, there are few resources for institutionalising operation and maintenance procedures and few guidelines for the operation and maintenance (O&M) tasks themselves (Cobbing et al., 2015). Providing safe drinking water as set out in SDG 6.1, the emphasis cannot solely be on the source of water provision and the service level delivered to the household (Kalin et al., 2019).

There are many challenges to implementing groundwater infrastructure sustainability and resilience, ranging from inadequate funding to poor governance. Groundwater infrastructure can be considered critical infrastructure as it is socially, economically or operationally essential to the functioning society or community, both in normal circumstances and in the extreme circumstances of an emergency (Gallego-Lopez and Essex, 2016). Hence the need to develop guidelines for installing groundwater schemes.

> Why is groundwater important to water utilities?
> Wherever available, groundwater resources have significant advantages as a primary source of water utility supply since:
>
> - They provide a climate-resilient source of water supply because of the large natural storage of groundwater systems
> - They facilitate flexible stepwise water-supply development in response to growth in population and per capita water demand
>
> However, if groundwater resources are not managed adequately, they can be degraded by a number of processes, including:
>
> - Uncontrolled access by private borehole water users can degrade the aquifer system and diminish water utility revenue considerably
> - Gradual deterioration of groundwater quality due to inappropriate land use, industrial discharges to the ground, wastewater seepage from on-site sanitation and leaking sewers, and other sources
>
> (Foster and Gogu, 2022)

1.2. Aim and objectives

The project aims to facilitate the development of guidelines for groundwater schemes at the municipal level. The objectives are as follows:

a) Construct the resource development life cycle for groundwater scheme development at the municipal level

b) Customise a groundwater mapping methodology based on the Denmark approach

c) Assess conjunctive use of surface water and groundwater and its role in water security in installing groundwater schemes

d) Include groundwater monitoring network design incorporating quality and quantity in the guidelines for proactive mitigation of issues

e) Develop a framework approach for the final design, which includes aspects of wellfield/borehole development, bulk infrastructure, management plan, costing and training

f) Conduct a stakeholder engagement workshop

1.3. Resource development life cycle for a groundwater scheme

A safe groundwater drinking-water supply system is fundamental to public health and welfare in municipalities and includes:

- Water treatment facilities
- Treated water storage and distribution systems
- Source-water development and protection (which springs and groundwater)
- Water resource management
- Demand management
- Maintenance and rehabilitation of water storage infrastructure and reticulation networks

Some rural municipalities in South Africa often have tens or hundreds of settlements serviced by boreholes, each needing attention and support on-site. Frequently a discourse of shortage is put forward for water problems – shortage of water, a shortage of skills, a shortage of funds or spare parts. However, the main reason groundwater sources fail is mechanical breakdowns and other issues related to operation and maintenance (O&M), not the groundwater resource's failure (WRC 2015).

> The development of groundwater infrastructure is critical for job creation, economic growth, poverty reduction and improved livelihoods. Unfortunately, there has been chronic underfunding of infrastructure, resulting in an infrastructure gap. An important lever to close the infrastructure gap is to optimise existing assets through proper O&M.
>
> (SADC-GMI 2020)

To counteract groundwater infrastructure failures McConville and Mihelcic (2007) have put forward a life cycle approach that considers sustainability factors over the entire life of a product or process, from conception through use and disposal.

The life cycle of groundwater supply projects can be divided into six stages, as shown in Figure 2: (a) needs assessment, (b) legislative and permitting requirements, (c) groundwater exploration, (d) Drilling, pumping tests and borehole construction, (e) implementation and (f) O&M (after McConville and Mihelcic, 2007). This guidance document constructs the resource development life cycle for groundwater scheme development at the municipal level covering aspects related to planning phases, resource development, design and costing, implementation, and O&M of groundwater schemes.

Figure 2: The five life cycle stages of a water and sanitation development project. Solid arrows indicate the flow of the life cycle process. The dotted arrow indicates the potential for interaction between stages 2 and 3 (after McConville and Mihelcic, 2007)**.**

2. NEEDS ASSESSMENT

A needs assessment helps the practitioner identify, understand, and better address water supply challenges in an area. The needs assessment process requires the active and constructive commitment of all concerned stakeholders to examine, identify, and diagnose the challenges that require addressing for improvement. Methodologies to conduct a needs assessment include:

- **Background research**: This involves the analysis of secondary data comprising published and internet materials. The secondary data collected has been cleaned, analysed and collected for purposes other than the needs assessment, such as academic research.
- **Focus group discussions** (FGD): FGD is a qualitative need assessment method that explicitly uses group interaction to generate data, i.e. people are encouraged to talk to each other and ask questions, exchange experiences and comment on each others' points of view (Figure 3).

Figure 3: FGD with community members in a rural community, Limpopo Province

- **Household surveys**: Practitioners use household surveys to collect detailed and wide-ranging socio-demographic data about their water supply condition.

- **Site visits and observations**: Using this method, researchers observe a particular group in their environment and make recommendations regarding needs based on their observations (Figure 4). This method depends on the researcher's skills; it can be subjective and open to interpretation and may have ethical implications.

Figure 4: Site visit with community members to relay their experiences

- **Key informant interviews** (KII): Practitioners use structured or semi-structured KII to identify an individual or small group of individuals' needs. KII gathers qualitative data and is time-consuming and resource-intensive. The method depends on the interviewer's skills.
- **Questionnaires**: These are useful for collecting information from relatively large numbers of people. Questionnaires can be qualitative, i.e. ask open questions which can be responded to in a variety of different ways, easy to design but harder to analyse, or quantitative, i.e. use closed questions, i.e. questions that require yes/no answers, box-ticking or scale answers, more challenging to design but easier to analyse.

The needs assessments aim to help understand current levels of groundwater supply coverage, including the existing infrastructure and services, their condition, and what the government must do to meet the minimum standards set by policy or legislation.

3. LEGISLATIVE AND PERMITTING REQUIREMENTS

The Constitution of the Republic of South Africa Act 108 of 1996 states that everyone has a right to an environment that is not harmful to their health or well-being and to have the environment protected for the benefit of present and future generations through reasonable legislative and other measures (RSA 1996):

a) Prevent pollution and ecological degradation
b) Promote conservation
c) Secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development

South African water legislation considers groundwater a national resource requiring sustainable management. The Water Services Act 108 of 1997 and the National Water Act 36 of 1998 provide the framework for the delivery of water services while also providing a combination of legal obligations, rights, responsibilities and constraints for the sustainable development and management of water resources in South Africa. However, in terms of the Constitution, the executive power to deliver water and sanitation services falls under local government (LHR 2009).

The role of government is that:

- The national government must manage water resources through various water boards
- Municipalities are responsible for delivering water and sanitation services and must draw up plans for delivery. These plans must take into account effective delivery services to informal communities
- Our law recognises that due to a lack of resources government cannot provide these services to everybody immediately. However, the government must have a clear plan with timeframes and budgets to provide these services and increase access
- Government must do so without trade-offs of other basic rights

(HRC 2018)

3.1. Constitutional rights

The Constitution provides for three spheres of government and sets out the functions of these three distinctive, interdependent and interrelated spheres. The principles of cooperative governance provide that all interactions between the three spheres of government must play out in a coordinated and cooperative manner (LHR 2009).

Sections 24 and 27 of the Bill of Rights in the Constitution grant specific rights to access to sufficient water, an environment not harmful to health and well-being and the protection of the environment from degradation (LHR 2009). Section 27 guarantees the right of every person to have access to sufficient water and obliges the state to take "reasonable legislative and other measures, within its available resources, to achieve the progressive realisation" of this right.

> Section 10 of the Constitution affords everyone "inherent dignity and the right to have their dignity respected and protected". Section 24 lays down the right to a safe and healthy environment free from pollution and ecological degradation. Section 27(1)(b) entrenches the right of everyone to have access to water. It falls within a cluster of socio-economic rights providing for, among other things, health care services, including reproductive health care (section 27(1)(a)), sufficient food and water (section 27(1)(b) and social security and social assistance (section 27(1)(c))
>
> (De Visser et al., 2009)

3.2. National Water Act

The National Water Act reaffirms the role of the state by confirming in Section 3 that "as the public trustee of the nation's water resources, the National Government, acting through the Minister, must ensure that water is protected, used, developed, conserved, managed and controlled sustainably and equitably, for the benefit of all persons and in accordance with its constitutional mandate." The National Water Act provides the legal framework for managing water resources, which includes allocating water for beneficial use and redistributing water (LHR 2009). The National Water Act introduced the following measures necessary for groundwater resources (Pietersen, 2004):

- Formal recognition of the unity of the hydrologic cycle
- Provision for resource protection and sustainability through resource-directed measures and source-directed controls
- Confirmation of water as a national resource under national management
- Obligations to meet rights of neighbouring states concerning shared watercourses
- Decentralisation of water management within a national framework
- Limitation of rights into perpetuity through a system of water use licensing
- The requirement to allocate water specifically to achieve social and economic optimal water use
- The formal requirement for water conservation and demand management
- Economic pricing of water

3.2.1. Groundwater protection

Groundwater protection zoning requires minimising groundwater contamination potential by human activities on or below the land surface. The National Water Act requires the consideration of source-and resource-directed measures when issuing a water use licence. Source-directed controls are done by understanding the relationship between polluting activities (sources) and the impacts (i.e. quality effects) on the groundwater resource. Groundwater protection zoning can be a proactive step towards protecting critical water resources and can be implemented through various integrated regulatory actions (Nel et al., 2009). There are several zones typically delineated for groundwater protection (Figure 5):

- An **operational zone** immediately adjacent to the site of the borehole, well field or spring to prevent rapid ingress of contaminants or damage to the site (also referred to as the accident prevention zone)
- An **inner protection zone** based on the time expected to reduce pathogen presence to an acceptable level (often referred to as the microbial protection area)

- An **outer protection zone** is based on the time expected for dilution and effective attenuation of slowly degrading substances to an acceptable level. A further consideration in delineating this zone is sometimes also the time needed to identify and implement remedial intervention for persistent contaminants.
- A further, much larger zone sometimes covers the total capture area of a particular abstraction where all water eventually reaches the abstraction point. This is designed to avoid long-term degradation of quality.

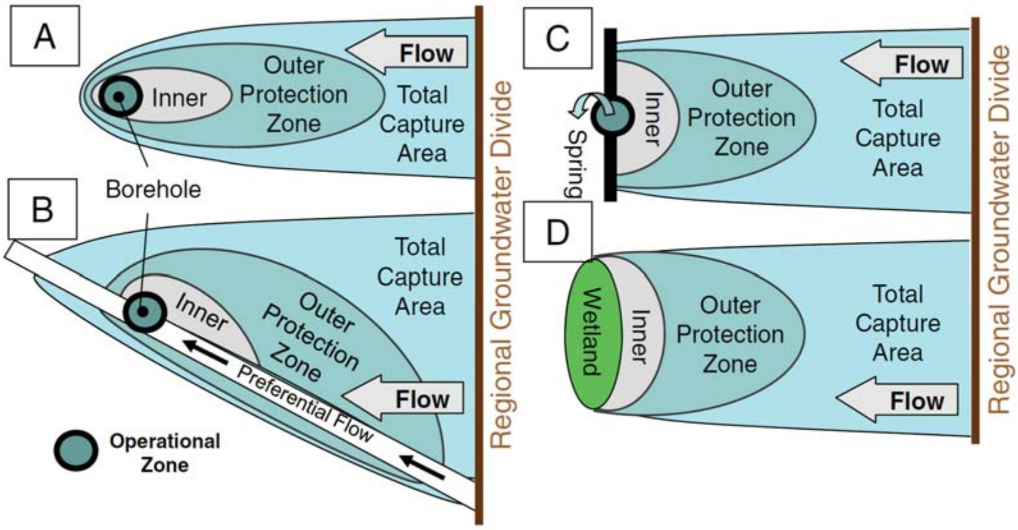

Figure 5: Different protection areas are delineated around (a) borehole in uniform flow field; (b) borehole near preferential flow path; (c) spring near geological control; (d) wetland or other ecosystems (Nel et al., 2009)

3.2.2. Water use authorisation

There are various water use authorisations for groundwater and surface water recognised and issued in South Africa under the National Water Act with emphasis on groundwater (Kotzé, 2015):

- **Existing Lawful Water Use**: This groundwater was abstracted after 1 October 1996 and before 1 October 1998.
- **General Authorisation**: Groundwater abstractions under General Authorisations are limited and are mainly for domestic watering, stock watering, non-commercial irrigation purposes, and small-

scale exploration purposes.

- **Groundwater Use Licensing**: Groundwater abstractions exceeding the General Authorisation limits as determined on quaternary drainage regions form part of groundwater use licenses. This includes, in certain circumstances, non-commercial irrigation where the General Authorisation is too limited due to the extent of the property, such as various smallholdings. Groundwater abstractions for bulk water supply, mine dewatering, and irrigation schemes are part of groundwater use licensing.
- **Controlled activities**: According to Section 37 of the National Water Act, the irrigation of any land with waste or water containing waste generated by a waterworks or any industry, activities that can modify the atmospheric precipitation, a power generation activity that alters the flow regime of a water resource, recharging an aquifer with waste or water containing waste, activities as declared under Section 38, are handled as controlled activities which must be authorised. Other examples of controlled activities are artificial recharge and hydraulic fracturing.

3.2.3. Groundwater monitoring

Monitoring is the building block in managing groundwater resources. The reader is referred to the monitoring guidelines.

3.3. Water Services Act

The Water Services Act is "the primary legal instrument relating to the accessibility and provision of water services (which include drinking water and sanitation services)". In terms of the Water Services Act, the responsibility for ensuring access to water services lies with water services authorities (municipalities). Water services authorities (through water services providers) must ensure access to both water supply and sanitation services (LHR 2009).

3.3.1. National standards for the provision of water services

The minimum standards and indicators for water services in South Africa relevant to groundwater are (DWAF 2001):

- The minimum standard for **basic sanitation** services is:
  (a) the provision of appropriate health and hygiene education
  (b) a toilet which is safe, reliable, environmentally sound, easy to keep clean, provides privacy and protection against the weather, well ventilated, keeps smells to a minimum and prevents the entry and exit of flies and other disease-carrying pests
- The minimum standard for **basic water supply** services is:
  (a) the provision of appropriate education in respect of effective water use
  (b) a minimum quantity of potable water of 25 litres per person per day or 6 kilolitres per household per month –
    (i) at a minimum flow rate of not less than 10 litres per minute
    (ii) within 200 metres of a household
    (iii) with effectiveness such that no consumer is without a supply for more than seven full days in any year
- A water services institution must take steps to ensure that where the water services usually provided by or on behalf of that **water services institution are interrupted** for a period of more than 24 hours for reasons other than those contemplated in section 4 of the Act; a consumer has access to alternative water services comprising:
  (a) at least 10 litres of potable water per person per day
  (b) sanitation services sufficient to protect
- Within two years of the promulgation of these Regulations, a water services authority must include a suitable programme for **sampling the quality of potable water** provided by it to consumers in its water services development plan.
- The **water quality sampling programme** contemplated in sub-regulation (1) must specify the points at which potable water provided to consumers will be sampled, the frequency of sampling and for which substances and determinants the water will be tested.
- A water services institution must compare the results obtained from the testing of the samples with **SANS 241: Specifications for Drinking Water or the South African Water Quality Guidelines** published by the Department of Water Affairs and

Forestry.

- Should the comparison of the results as contemplated in sub-regulation (3) indicate that the **water supplied poses a health risk**, the water services institution must inform the Director-General of the Department of Water Affairs and Forestry and the Head of the relevant Provincial Department of Health and, it must take steps to inform its consumers -
  (a) that the quality of the water that it supplies poses a health risk;
  (b) of the reasons for the health risk
  (c) of any precautions to be taken by the consumers
  (d) of the time frame, if any, within which it may be expected that water of a safe quality will be provided
- A water services institution must take **measures to prevent any** substance other than uncontaminated stormwater from entering -
  (a) any stormwater drain
  (b) any watercourse except in accordance with the provisions of the National Water Act.

3.3.2. Obligations of water services authorities to provide access to water services

Every water services authority has to prepare a water services development plan. Such development plans must be developed in consultation with consumers, who have a right to comment and to have their comments considered before the plan is adopted (LHR 2009).

3.3.3. Mandatory by-laws

Every water services authority must draft by-laws to provide water services (LHR 2009). Examples of bye-laws are given in

Table 1.

Table 1: Groundwater by-laws tools (Curran et al., 2009)

Groundwater data collection and mapping	• Identifies vulnerable areas for protection • Directs development to appropriate locations • Serves as a foundation for all other tools • Can be done on a broad scale to set the stage for a more detailed scale assessment later
Water management and well protection planning	• Establishes strategies within a designated planning area to safeguard all water resources and reduce conflict among water users, including well-protection planning • Focuses on water conservation & pollution prevention • Provides for broader consultation and continuous monitoring
Regional growth strategies	• Coordinates region-wide action among jurisdictions sharing one or more aquifers • Designates urban containment boundaries that direct development to appropriate locations • Includes regional commitments to groundwater protection and sustainability • Supports data collection and mapping
Official community planning	• Guides how and where new development occurs • Directs municipalities to undertake groundwater protection measures • Raises awareness within a community of groundwater issues and areas of concern • Establishes and contains the guidelines for development permit areas
Zoning for groundwater protection	• Regulates use and density of property development away from groundwater-limited or aquifer recharge areas • Can limit lot sizes to reduce density in groundwater-scarce areas • Can prohibit potentially polluting uses in areas where aquifers must be protected • Sets standards on aspects of development that will have an impact on the water resources on the site or in the area (e.g. setbacks from riparian areas) • Can encounter groundwater-sensitive development by clustering development through rezoning

	• Can leverage habitat protection or water-efficient amenities when rezoning
Aquifer protection development permit areas	• It can be used to accomplish similar goals as regulatory bylaws but limited to specific areas or types of ecosystems (may apply across several different zoning designations) • Prohibits site disturbance before development approval • It can allow local government to monitor ecosystem conditions as development progress and for a specific amount of time post-development • Allows local governments to collect security from permit-holders that can be used to complete permit requirements if the permit holder-does not comply
Aquifer protection development approval information areas	• Guides how and where new development occurs • Directs municipalities to undertake groundwater protection measures • Raises awareness within a community of groundwater issues and areas of concern • Establishes and contains the guidelines for development permit areas
Subdivision serving bylaws	• It can require that works mimic natural hydrology • Can set drainage and rainwater infiltration standards • Can require standardised minimum flow rates for providing sustained yield • Can require boreholes to be closed when the property is connected to a community water system • It can require bonding for future operations and maintenance of larger systems • Can take into account cumulative impacts of incremental development

4. GROUNDWATER EXPLORATION

Most South African aquifer systems occur in fractured geological environments. Hydrogeologists require a multi-disciplinary approach to improve the borehole success rate in these terrains, sustain groundwater resources sustainably, and meet water services standards. This approach must incorporate (Sami et al., 2002a):

a) An understanding of the structural geology and its influence on the occurrence of groundwater to identify target features
b) The identification of appropriate methods and interpretative techniques to delineate target features in the field
c) The use of simple yet effective groundwater resource evaluation methods

Sami et al. (2002) put forward the following guidelines for exploration in complex terrains:

- **Hydrocensus**: The objective of a hydrocensus is to hydrogeologically characterise a region in terms of the physical and economic feasibility of meeting water demands through groundwater by quantifying:

    - Expected borehole yields and their variability by geological domain
    - Historic drilling success rates and probabilities of exceeding specific yields
    - The proximity of boreholes to geological structures and their yield
    - Depth to water strikes
    - Static water levels
    - Groundwater chemistry
    - Potential hydrogeological targets

    The hydrogeologists conduct an hydrocensus by collecting data from the national groundwater databases, previous hydrogeological investigations and field surveys (Figure 6). The data is overlayed the data onto existing geological maps using a GIS. The specific processes are:

- Inputting hydrocensus data into a GIS database, such as ArcView, and creating layers for lithology, structures, yield, static water level, water strike depth and water quality
- Characterising domains by using domain boundary polygons to separate borehole data with similar hydrogeological attributes
- Determining the percentage of dry boreholes, and the variability in yield distribution of successful boreholes for each domain
- Determining the optimum drilling depth for each domain based on the depth below which few boreholes encounter water
- Identifying domains where poor water quality precludes water use by categorising median water quality
- Identifying geological indicators of potential geochemical hazards
- Performing a proximity analysis of yield versus distance from known structures to identify significant structures and the importance of structures on borehole success

Figure 6: Hydrogeologists measuring field parameters in the field

- **Tectonics and Geodynamics**: Geodynamic investigations require solving the tectonic history of the target area so that the hydrogeologists explain the mapped, identified, or presumed structures and lineaments in terms of historical and present-day geological strain. The objective is to define a chronologically expected pattern to explain observed faulting by strain analysis using a strain ellipse. This allows the identification of the potential rejuvenation of structures by subsequent tectonic events and the present strain on existing structures. Existing structures considered to be under extension present hydrogeological targets. The process involves investigations into:

    - Identification of geological domains based on lithology, geochronology and structural setting
    - Pre-depositional environment to identify aquifer boundaries and their nature (depositional-lithological versus post-depositional or tectonic)
    - Plate tectonics and its impact on geological strain in the region
    - Metamorphism and ductile deformation episodes and their expression in the lithologies
    - Intrusive and volcanic history
    - Recent tectonic history and processes
    - Mapping of faults and shears
    - Application of strain analysis based on historic strain and stress to derive a pattern of faulting, folding, thrusting and shearing
    - Verification of predicted faulting against observed fault pattern

- **Structural Analysis**: A structural analysis attempts to identify strain conditions in rocks by identifying compressional and tensional orientations by mapping the strike and dip of joints and plotting the data on stereonets. The objective is for hydrogeologists to identify the extensional orientation so that geological structures are aligned perpendicular to the extension (Box 1). These targets are then assumed open and therefore targeted as preferential targets. The investigations conducted include:

    - Identifying the age relationship of various formations present in the region

- Mapping of the strike and dip of joint sets in the various lithologies post-dating the study area, as identified at road cuttings and stream beds
- Plotting joint lineation and bedding data on stereonets
- Classification of joints by age relationship or by dip to categorise features by tectonic origin
- Derivation of compressional and extensional relationships by structural analysis

Box 1: Geomechanical modelling as a tool for groundwater exploration of fractured rock aquifers (Friese et al., 2006).

The authors applied a procedure to evaluate the potential relationship between known groundwater abstraction locations in fractured-rock environments and geomechanically-modelled sites of high dilatancy. The method (SMT method) relied on rock mechanic principles and stress-strain relationships to transform strain data, in the form of a solid geology map, to stress data. Results of the SMT analysis for the study area have revealed a strong correlation between known borehole positions and the proximity and alignment of these boreholes to two prominent fault/fracture zone systems. The approach can be applied to other areas where a reasonable understanding of the most recent history of brittle tectonics exists. The hydrogeologist can correlate the lineament directions with various brittle structures related to extension stresses through SMT and lineament analysis.

- **Remote Sensing**: The objective of using remote sensing methods is to identify structures that may be of hydrogeological significance, are not noticeable in the field or have not already been mapped. These can be identified by satellite images using variations in surface reflectance, aerial photos using variations in tone and contrast, or airborne geophysics (Box 2) based on variations in the rock's physical properties. Remote sensing investigations ideally require the following steps:

  - Selection of applicable digital features to highlight features of interest
  - Identification of lineaments and overlaying onto topographic and geological maps using a GIS
  - Preparation of strike-frequency rose diagrams to identify dominant orientations
  - Preparation of strike-total length plots to identify regional orientations and trends
  - Preparation of strike-maximum length plots to identify regional

structures

- Identification of target lineament orientations based on geodynamics and structural analysis. and lineament strike analysis

Box 2: Mapping groundwater resources – SkyTem (Møller et al., 2009)

Groundwater mapping in Denmark began in the 1990s because of the pressure on groundwater resources due to urban development and pollution from industrial and agricultural sources. The groundwater mapping included survey drillings, modelling based on existing knowledge and geophysical mapping with newly developed methods that made area coverage on a large scale possible. The most-used geophysical method in the groundwater mapping programme is the airborne transient electromagnetic method, or SkyTEM, used for mapping to a maximum depth of 250-300 m. The purpose of groundwater mapping is to provide a basis for targeted efforts to protect groundwater where it is most vulnerable. Groundwater mapping is carried out in areas with special drinking water interests, which comprise 40% of Denmark's area. Based on groundwater mapping, municipalities prepare action plans for groundwater protection. Action plans are prepared closely with stakeholders: waterworks, agriculture, etc.

- **Modelling:** Developing a groundwater model of an aquifer system enables the quantification of groundwater and evaluation of groundwater dynamics. This includes quantifying and evaluating groundwater inflow (recharge from rainfall and lateral inflow), groundwater flow through the aquifer and groundwater outflow (subsurface drainage, seepage, evapotranspiration and abstractions).

  The methodology includes (Thorn et al., 2022):

  - **Geological mapping**: In this step of the groundwater mapping, the aquifers and aquitards of the mapping area are defined and mapped out, accomplished in a three-step process:

    a) Development of a conceptual model
    b) Development of a 3D geological model
    c) Development of a 3D hydrostratigraphic model

    The **conceptual model** presents a summary of the contemporary understanding of the hydrogeological processes that control groundwater occurrence, movement and quality within a specific geological setting by interpreting all information obtained in the previous steps. Conceptual models range from a simple cross-section to clarify the geological to a detailed understanding of complex flow regimes that supports a full numerical water resources model.

The second step in the geological mapping procedure is developing a **3D geological model**. The model is configured using geological modelling software, such as Leapfrog or GeoScene3D. The geological model includes the modelling of the different formations and ages and considers the mapping area's depositional, structural and tectonic history.

The third step in the geological modelling process is developing a digital **3D hydrostratigraphic model**. The hydrostratigraphic model is based upon the digital 3D geological model, where the geological units are divided into aquifers and aquitards, depending on their hydrogeological properties.

- **Groundwater quality modelling**: The purpose of groundwater quality modelling is to describe the groundwater chemistry observed in the mapped aquifers, including the geochemical processes and conditions, and describe how this changes geographically.

  The primary processes that are typically analysed include:

  - Groundwater oxidation state, where oxidized groundwater indicates younger, more vulnerable aquifers, and strongly reduced groundwater indicates older, less vulnerable aquifers
  - Pyrite oxidation state, where groundwater that shows an influence of pyrite oxidation is younger and can indicate nitrate leaching from the surface
  - Sulphate reduction, where aquifers showing sulphate-reducing conditions have older groundwater, indicating a relatively well-protected aquifer
  - Ion exchange, particularly the ratio between sodium and chloride ions, which provides information on

whether the aquifer is undergoing seawater intrusion, freshening or mixing, as well as a relative age (high sodium to chloride ratio generally indicates old groundwater)

- **Groundwater modelling**: For each mapping area, a groundwater model is developed. The primary objective for the modelling is to:

  – Calculate the well field capture zones
  – Calculate wellhead protection zones
  – Simulate groundwater potential for each aquifer
  – Calculate groundwater recharge, both to the saturated zone and aquifer specific

  Activities for the construction of the steady-state model include:

  – Develop the finite difference mesh, including refinement around wellfields
  – Assign the model layer surfaces
  – Assign the model boundaries (perimeter boundaries and surface water features)
  – Assign groundwater recharge
  – Develop the hydraulic conductivity data for the model layers and assign them to the model layers
  – Prepare pumping borehole data and assign it to the model
  – Testing the model and making sure that the model runs properly

  Activities related to the calibration of the steady-state model include:

  – Construct a groundwater level contour map representing a steady-state or quasi-steady-state condition
  – Prepare the steady-state water level target for steady-

state model calibration

- Conduct sensitivity analysis to gain insight into model behaviour
- Develop a calibration strategy including:
  - Calibration targets: water level and baseflow data
  - List of adjusting parameters, and ranges
- Prepare the PEST (a model-independent parameter optimiser) data for steady-state model calibration
- Conduct the PEST run, review the results and re-run PEST iteratively until an acceptable match is achieved

Generally, dynamic models are preferred, but there can be local areas where there is insufficient data to develop a robust dynamic model, either in number of time series or geographical coverage.

- **Scenario analysis**: Once the model is validated, different scenarios are simulated. As a minimum, a scenario with the maximum allowed abstraction/pumping is run (called the permit scenario). Depending on the mapping area and the stakeholders involved, other scenarios can be run, including no abstraction or actual/historical abstraction rates. Additional scenarios to test the importance of non-calibrated input parameters, such as effective porosity, are also sometimes conducted.

- **Mapping (producing actual 2D maps):** The output of the above steps is maps that detail well field capture zones, wellhead protection zones, source protection areas, and vulnerability assessments.

- **Field Verification Investigations**: Field proofing investigations are required to identify the nature of target lineaments to determine their nature and origin and to pinpoint the lineaments in the field using observation or geophysics, with due consideration given to constraints on siting. The objective is to identify drilling sites with structural features of hydrogeological significance at locations where drilling and water abstraction are physically, economically, socially and legally acceptable.

A field survey is also required to evaluate the effect of constraints on target site selection. These constraints may include:

- Topographic and access constraints affecting drilling rig mobilisation
- Water demand location and topographical constraints on reticulation or distribution
- Quantitative water demand and its impact on target location in terms of large regional structures versus smaller local structures
- Access to properties and water rights
- Contamination potential and vulnerability
- Acceptance of drilling site by stakeholders
- Field investigations include:
- Observation of land use and geology to identify the nature of lineaments and ensure that they are structurally significant
- Observation and evaluation of constraints in terms of drilling rig accessibility, topographic constraints between source and demand location, distance from demand points, contamination
- Field geophysics to pinpoint the structure in the field at potential target points

Geophysical surveys used in groundwater mapping include (Thorn et al., 2022):

- Resistivity methods, such as aerial electromagnetics (AEM), transient electromagnetics (TEM), multi-electrode profiling (MEP), and single-point electrode profiling (Wenner and Schlumberger)
- Seismic surveys
- Magnetic resonance sounding (MRS)
- Borehole logging

Figure 7 summarises the groundwater exploration process developed by (Sami et al., 2002b; Thorn et al., 2022).

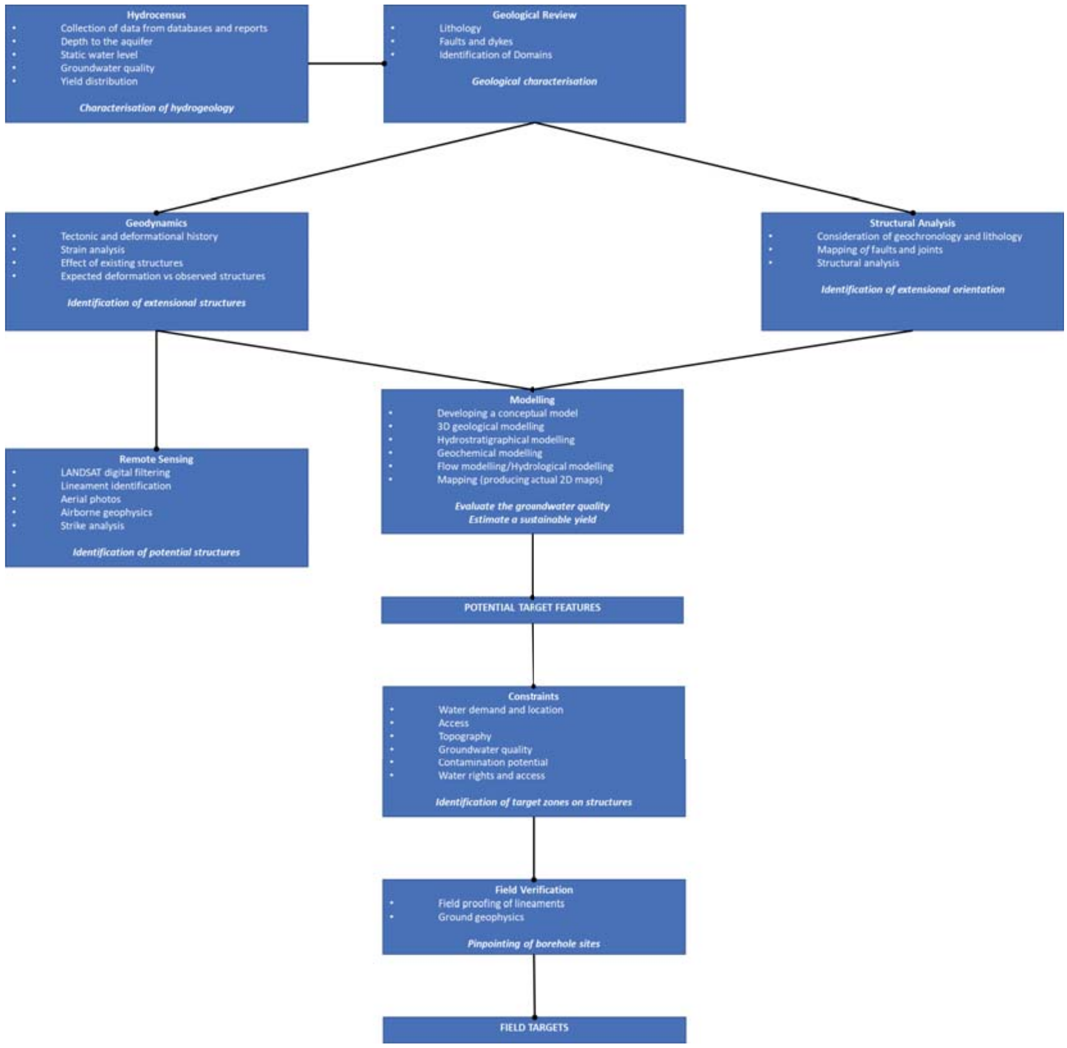

Figure 7: Flow chart of the groundwater exploration process (Sami et al., 2002b; Thorn et al., 2022)

5. BOREHOLE DRILLING, BOREHOLE CONSTRUCTION AND PUMPING TESTS

5.1. Borehole drilling

Poor borehole drilling impacts construction and O&M. Borehole drilling is a specialised area that requires specialised borehole drilling equipment and skilled personnel (Box 3). The technical specifications for borehole drilling need to be drawn up by qualified and experienced personnel who should plug all the possible loopholes that contractors could use to compromise quality works. Supervision of the drilling works requires equally qualified and experienced personnel (SADC-GMI 2020).

Box 3: Examples of good practices manuals for drilling (PRACTICA Foundation 2010; Danert 2015; UNICEF 2016)

Instruction handbook for manual drilling teams on hydrogeology for well drilling, well installation and well development: Available manuals in the series include:

- **JETTING** - This handbook describes the various jetting techniques used to drill wells in loose and soft soil formations. With this technique, wells are drilled for several hours rather than days.
- **PERCUSSION** - This handbook describes in detail the percussion technique. Although the technique is slower than other drilling techniques, it is the only manual drilling technique that can drill through consolidated rock layers
- **HAND AUGER** - This handbook describes the hand auger technique. This cheap and effective technique is suitable for sinking shallow wells in soft soils and is excellent for soil surveys. Many drilling teams have this technique in their toolkit to complement other drilling techniques.
- **SLUDGING** - This handbook describes the sludging technique and, in greater detail, the ROTA-sludge technique. It combines sludging and percussion and is particularly useful due to its versatile application for various soil formations.

The manual 'Understanding Groundwater & Wells in manual drilling' complements the four (4) technical training handbooks and highlights those essential subjects relevant to manual drilling, geohydrology, hygiene, well installation and well development in practice in simple and understandable language.

Manual Drilling Compendium 2015: This compendium draws together experiences of manual drilling from 36 countries. It synthesises otherwise highly fragmented information, much of which has never been published in academic or grey literature.

Manual Drilling Toolkit: This toolkit supports African countries wishing to embark on the professionalisation of manual drilling. The toolkit includes Technical Notes, Technical Manuals, Advocacy Materials, Mapping suitable areas for manual drilling, Case Studies, and Implementation and Training Manuals. This initiative aims at builds the capacity of the local private sector to respond to the ever-increasing demand for safe water in rural areas.

Rotary drilling techniques are primarily applied in South Africa as the method allows the construction of deeper boreholes (Figure 8). The drillers use circulating fluids to cool and lubricate the cutting tools and remove debris from the hole. The circulating fluids are compressed air, pumped water with additives and drilling muds or foams.

Figure 8: Down-the-hole hammer (DTH) rotary drilling rig

During the drilling process, the hydrogeologist obtains formation samples: the usual sampling interval is one meter (Figure 9).

Figure 9: Drilling cuttings laid out at 1 m intervals

5.2. Borehole construction, disinfection and site finishing

5.2.1. Borehole construction

There are various borehole construction methods for the various geological formations, e.g. crystalline and sedimentary consolidated formations.

The hydrogeologist designs the borehole construction to match the characteristics of the aquifer. Technical considerations include (SADC-GMI 2020):

a) **Borehole screens**: The hydrogeologist selects the borehole screens after conducting a sieve analysis of the aquifer material obtained during drilling or from prior knowledge of the aquifer. Types of screens include Johnson wire-wound screens, bridge, slotted polyvinyl chloride (PVC) or plastic casing, and mild steel casing. Johnson screens are expensive, and hydrogeologists use ordinary screens (mild perforated steel, PVC, or plastic casing). Hack saw cut slots are discouraged as they tend to clog more quickly, thus reducing the borehole yield.

b) **Placement of borehole screens**: The hydrogeologists place the screens against the aquifers (water-yielding formations). In confined aquifers (aquifers in which the water level rises above the aquifer), hydrogeologists screen 80-90% of the thickness of the aquifer and the best results are obtained by centring the screen section in the aquifer (Driscoll, 1986). For unconfined aquifers (aquifers in which the water level may be roughly the same level as the water strike), maximum yield is obtained by using the longest screen possible. Screen design is a critical factor for the efficiency of a successful borehole. The screen design must accommodate the varying physical and chemical characteristics of groundwater. Screens with the wrong slot size, low open area, slots not matching aquifer material and gravel/filter pack, or screens placed in the wrong locations can result in reduced borehole yields through clogging of the screens.

c) **Gravel/Filter Pack**: gravel pack helps in filtration, stabilising of the aquifer, preventing the collapse of the formation, which would lead to low abstraction volumes (low yields), minimising sand pumping, which would damage the pump, reducing the groundwater flow velocity to levels preventing screen encrustation or wear, and reduction in head losses. The width of the annular space and the type of material are also important considerations.

d) **Location of the pump in the borehole**: The pump should ideally not be placed within the borehole screens. It should instead be placed within a plain or unperforated casing, commonly referred to as a pumping chamber. Ideally, pumping should be carried out in confined aquifers at levels above the top of the aquifer to avoid agitating the filter pack and aquifer material.

During drilling, mud and borehole cuttings can plug the aquifer. The driller must thoroughly remove the material through the borehole development process.

5.2.2. Borehole disinfection

The purpose of disinfection is to cleanse the borehole of any bacteria, particularly coliform bacteria, introduced during the rehabilitation or testing operations. Disinfection can be accomplished by injecting chlorine (or chlorine-yielding compounds) into the borehole in quantities.

5.2.3. Site finishing

Upon completion of the rehabilitation and pumping test, all the debris from a construction, such as unsuitable or rejected materials, spillage and cuttings, shall be removed. The site of the work shall be cleaned of all rubbish, excess materials, false works, temporary structural installations and abandoned equipment. All resulting construction scars from these works shall be treated to blend with the contour and vegetation of the surroundings.

5.3. **Pumping tests** (Pietersen and Beekman, 2015)

The pumping test is one of the most valuable tools for evaluating groundwater resources. It is a method of assessing the performance of a borehole, the borehole yield, the zone of influence of the borehole and aquifer characteristics (i.e. the aquifer's ability to store and transmit water, aquifer extent, presence of boundary conditions and possible hydraulic connection to surface water).

> The pumping test can provide (van Tonder, et al., 2002):
> - Improved conceptual understanding of the aquifer system;
> - Quantification of the hydraulic characteristics and properties of the aquifer system; and
> - Assessment of both the sustainable yield and the condition or efficiency of the borehole.

A pumping test consists of pumping groundwater from a borehole, measuring water levels in the pumped borehole, and observing boreholes (if present) during and after pumping. The hydrogeologist uses the data to plot drawdown and recovery. How the water levels respond to the pumping is analysed to derive information about borehole efficiencies and the hydraulic parameters of the aquifer system. Thus, it becomes critical that hydrogeologists oversee pumping tests properly.

5.3.1. **Pre-Pumping test procedures**

Pumping tests of boreholes form an integral part of any groundwater development programme (Figure 10). Hydrogeologists carry out pumping tests to determine the hydraulic parameters of the aquifer (hydraulic conductivity, transmissivity, storativity and specific capacity), the long-term yield of the tested borehole and the correct size and type of pump to be installed. Data from properly conducted pumping tests are essential for groundwater management.

Figure 10: Installing a submersible pump in borehole 64 in the Nyamandhlovu area for pumping tests (photo credit Hans Beekman)

Pumping tests measure the water level decline in the pumped borehole and any observation/monitoring boreholes.

The hydrogeologists conduct three types of pumping tests:

a) Step drawdown test
b) Constant discharge tests
c) Recovery test

To ensure the hydrogeologist conducts proper pumping tests, it is important to state the objectives and understand the hydrogeology (conceptual model). The conceptualisation is important to determine the most appropriate pumping test method for determining the hydraulic parameters. Issues to consider upfront is (BC, n.d.):

- Depth of pump setting and type of pump
- Pumping duration
- Pumping rate
- Control and measurement of the pumping rate
- Frequency of measurement of the water levels in the pumped borehole
- Measuring water levels in neighbouring (observation) boreholes and streams
- Discharge of pumped water
- Collection of water samples for water quality analysis
- Special conditions to be aware of, e.g. aquifer boundary conditions.

If the pumping test involves pumping a large volume of water for a long duration (e.g. 24 to 72 hours), the hydrogeologist must notify the owners of neighbouring boreholes. The pumping of these neighbouring boreholes during the pumping test could affect the results. Preferably the hydrogeologists could use neighbouring boreholes as observation boreholes.

The pumping borehole should be selected so that aquifer boundaries do not prematurely influence the drawdown data before trends can be recognised.

The pump is usually placed above the borehole screen to maximise the drawdown for the pumping test. The pump intake should not be placed within the borehole screen as this may cause increased velocities resulting in sanding and potential casing deterioration, along with screen plugging. The pump is set at or just above the uppermost major water-bearing fracture for hard-rock boreholes. In this regard, the driller's borehole construction report provides guidance.

There are several factors to consider when determining the type of pump to use and the depth at which it should be set, including:

- Borehole diameter
- Desired pumping rate
- Total dynamic head including the pumping water level, the above ground head (if applicable) and all friction; losses in the casing, pipes, fittings
- Reliability of power source
- Horsepower requirements

Also, consider whether the pump is submersible and has variable speeds. Power needs to be continuously available to the pump during the test. If power is interrupted, it may be necessary to terminate the test, allow the borehole to recover and run a new test.

Most pump manufacturers provide performance curves for their pumps. This is a graphical representation of the pump performance characteristics. Selecting the correct pump for the various pumping tests requires discussion with the pumping test operators.

The pumping test's duration depends on the borehole's purpose, the type of aquifer and any potential boundary conditions. Aquifer types and potential boundary conditions obtained from:

- Borehole construction reports for the pumping borehole and any neighbouring borehole(s)
- Information on the aquifer and surface water bodies, such as lakes or rivers in the vicinity of the borehole
- Qualified borehole drillers and professional hydrogeologists

There are three main aquifer types: unconfined aquifers, confined aquifers and leaky aquifers (Figure 11).

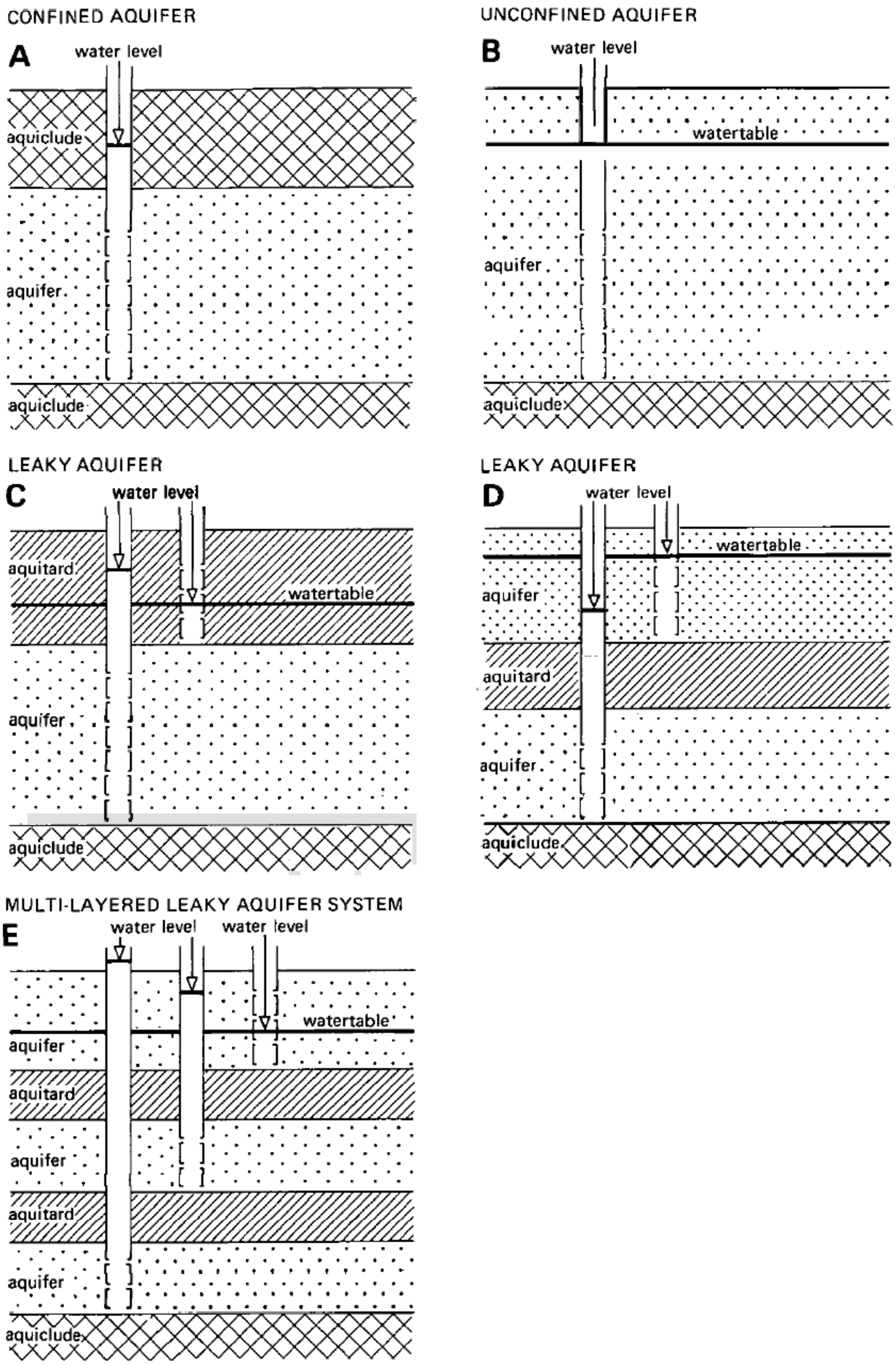

Figure 11: Different types of aquifers (Kruseman & de Ridder, 1990)

There are two types of aquifer boundaries: barrier and recharge boundaries. Barrier boundaries represent zones where there is no flow and consist of folds, faults, or relatively impervious deposits (aquicludes) such as shale or clay (Walton, 1962). Recharge boundaries represent zones along which there is limited or no drawdown, and they may consist of rivers, lakes, and other bodies of surface water hydraulically connected to aquifers (Walton, 1962).

Minimum durations of traditional (constant discharge) pumping tests are 24 to 72 hours unless stabilisation occurs – local by-laws, regulatory requirements or a qualified professional stipulate minimum pumping duration. Duration is generally longer, e.g. 72 hours, for production boreholes for urban water supply or hard rock boreholes due to uncertainties, and 48 hours for boreholes completed in unconfined aquifers due to the delayed release of water as the water level goes down or "delayed yield" effect.

Pumping tests must be conducted using specialised test equipment (Figure 12). The test unit must comprise a pump, preferably a positive displacement (PD) type pump element and a pump head driven by a motor fitted with an accelerator, gearbox and clutch.

Figure 12: Unimog with crane and trailer with pumping test equipment for Nyamandhlovu pumping tests (photo credit: Hans Beekman)

Water must be discharged away from the borehole to avoid recirculation, especially when aquifer conditions are unconfined to leaky.

Water should be discharged through a lined channel or a pipe (Figure 13). The discharge channel or pipe length depends on soil conditions, test duration, and yield.

Figure 13: Discharge of water (photo credit J Cobbing, SLR)

In practice, the discharge point has to be downstream of the borehole or at a down-gradient from the borehole. The pumping test operator measures discharge by the volumetric method, V-notch weir or flow meter:

- **The volumetric method** determines the time required to fill a container or drum of a known volume. All time readings must be made using a stopwatch. The volumetric method is especially recommended for low discharges.
- **V-notch Weir** is a rectangular weir of known dimensions installed in a horizontal position at the end of the discharge point of the borehole. The weir outlet is a rectangular plate with a 90^o constriction (notch) over which the water flows. The height of the water flowing over the notch is related to a particular discharge
- **Flow meter** is calibrated and of a similar diameter to the discharge pipe to which it is installed. The anticipated test yield must be compatible with the measuring range of the flow meter. An in-line flow meter (Figure 14) is the most accurate test yield method.

Figure 14: Taking readings from the in-line flow-meter (photo credit: Hans Beekman)

- Water level measurements must be taken within a piezometer (measuring) tube. A piezometer made of PVC tubing must be attached to the pump column and installed simultaneously with the pump (Figure 15).

Figure 15: Taking water level readings

The piezometer tube acts as a stilling well within the borehole, and water level readings are not affected by turbulence or cascading caused by pumping.

The water level must be read using an electrical dip meter with an accuracy of +/- 10 mm. Readings can also be taken using a pressure transducer and data logger.

Pumping tests must be carried out for the minimum duration specified by the hydrogeologists. If a mechanical breakdown or other reason prevents the test from being completed, the test must be repeated after allowing recovery of the water level to its original level.

The test must also be repeated if either an interruption of the test of more than 5% of the elapsed pumping time occurs or if the variation in discharge rate exceeds 5%.

The collection of accurate and reliable test data is essential.

The test data recorded must include the following basic information:

- the unique borehole number, 1:50 000 map sheet number, grid reference, preferably a GPS reading, and location of the tested borehole
- the depth to ground level
- the depth to water level before the start of testing
- the depth at which the test pump was installed
- the type, make, and model of the pump used
- the pumping rate, as measured at regular intervals during the test
- the water level in the borehole as measured according to a prescribed schedule both during and after pumping

Knowledge of groundwater chemistry and, where required, bacteriological quality is essential to determine its suitability for the intended use and overall groundwater resource management.

During the constant discharge test, temperature, electrical conductivity, pH and Alkalinity measurements should be taken using field kits, at the beginning, halfway through the test and a few minutes before the termination of the test. Other constituents can be measured using portable test kits as required.

Water samples (filtered and acidified for the metals/cations and unfiltered for anions) should be collected before the end of the pumping test. The sample must be submitted to a reputable laboratory to determine the suitability of the chemical constituents for the intended use.

5.3.2. Step drawdown test

Step drawdown tests are designed to establish the short-term relationship between yield and drawdown for the tested borehole. This test is carried out to determine the optimum yield for the constant discharge test. Under certain circumstances, such as screened and filter-packed boreholes, the data collected from this test determine the borehole efficiency.

The step drawdown test comprises four or five different discharge rates,

During each time step, the discharge is maintained constant, but it is increased at the beginning of each subsequent step. Measurements of the discharge and the drawdown are taken at specified intervals during the test.

There are many different ways to perform a step test, but the most common practice is as follows (ICRC, 2011):

- Start with a low pumping rate, and increase the rate with each successive step without switching off the pump between steps. The pumping/discharge rates can be determined as follows:
  - STEP 1: one-third of the expected yield
  - STEP 2: two-thirds of the expected yield;
  - STEP 3: equal to the expected yield; and
  - STEP 4: one-and-a-half times the expected yield
- All steps should be the same length, with somewhere between 60 and 120 minutes per step being standard.
- The pumping rate for the final step should be at or beyond the intended operational pumping rate when the borehole is fully commissioned. Of course, this depends on whether the pump being used for the step test is capable of that pumping rate

The equipment necessary for conducting a step test is as follows (ICRC, 2011):

- A motorised pump complete with a power supply, rising main, valves and discharge pipes is set up so that the discharge rate can be changed to achieve the rates required for the different steps. Most pumps work at a fixed speed, so this is usually achieved by 'throttling' the pump using a valve and progressively opening the valve to achieve successively greater discharge rates

- A stopwatch to measure the time of pumping and recovery
- A dipper to measure the water levels
- A method of measuring the pumping rate (bucket and stopwatch, flow gauge, etc.)
- A notebook, or a standard form with a clipboard, and a pencil, to record the test data
- Linear graph paper and ruler to plot the results or software.

Step tests are primarily designed to provide information about the borehole performance characteristics (the yield-drawdown relationship).

5.3.2.1. Step-test procedure

Assuming that all the equipment is ready and people have been assigned their tasks, the procedure for conducting a step test is as follows (ICRC, 2011):

a) Choose a suitable local datum (such as the top of the casing) from which all water-level readings will be taken, and measure the rest-water level. The water level must be at rest before the start of the test, so the test should not be conducted on a day when the borehole is being drilled or developed, or when the equipment is being tested.

b) Open the valve to the setting for the first step and switch the pump on, starting the stopwatch simultaneously.

c) Measure the water level in the borehole every 30 seconds for the first 2.5 minutes, then every minute until 10 minutes have elapsed, then again at 12 minutes and 15 minutes, then every 5 minutes until 30 minutes, then every ten minutes until the end of the step (the length of each step is 120 minutes. If you miss the planned time for a water-level reading, write down the time the reading was taken. Record all the readings on the standard step-test form).

d) Measure the pumping rate soon after the start of the step, and then at the same intervals as the water levels. If there is a noticeable change in the rate of increase of drawdown or the pump sounds different, then measure the pumping rate at those times. If the pumping rate changes significantly (say by more than 10%), then adjust the valve setting to maintain as steady a pumping rate as possible throughout the step. Be careful not to over-adjust and make the problem worse.

e) At the end of Step 1, open the valve further to the setting for Step 2, note the time (or restart the stopwatch) and repeat the procedures for measuring water levels and pumping rates (see above).

f) Repeat the procedure for subsequent steps, progressively increasing the pumping rate for each step.

g) At the end of the final step (probably Step 4 or 5), switch the pump off, note the time (or restart the stopwatch), and measure the water-level recovery at the same measurement intervals as for measuring the drawdown in each step. Continue for at least the length of a step, and ideally for much longer, until the water level approaches the pre-test level.

5.3.2.2. Analysis and interpretation

The step drawdown test provides information on borehole performance. The most frequently used method to determine aquifer losses and well losses is Hantush Bierschenk's method which is a modification of the Jacob method. See further explanation of the methods in (Kruseman & de Ridder, 1990).

The selection of the pumping rate for the constant discharge test is an outcome of the step test. The following rule of thumb may be helpful (WE Consult, n.d.):

The specific capacity is calculated by dividing the pumping rate over the drawdown. Several values for the drawdown after a fixed period at particular yields (the step drawdown test rates) are known from the step drawdown test. When plotted as specific capacity versus yield, the curve shows a distinct kink at the rate above which the aquifer is depleted, indicating the optimum, highest possible yield (Figure 16). The constant discharge test should then be performed at this rate (~18m^3/hr in the example in Figure 16) to certify the sustainability of this pumping rate. This rate is lower than the rate at which the test needed to be stopped and equal to or a bit higher than the highest rate at which the water level stabilised, without running the risk of the water level dropping to the level of the pump intake or reaching the screened sections of the permanent casing.'

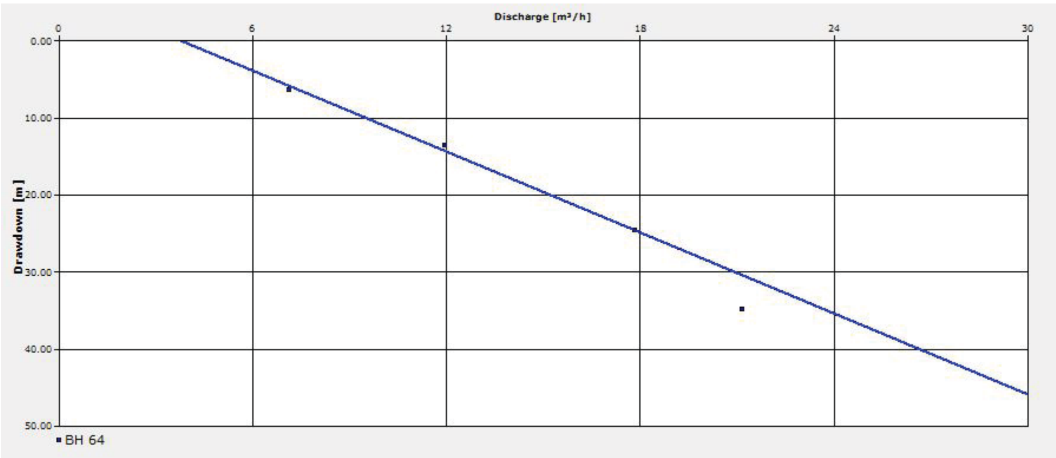

Figure 16: Specific capacity vs yield.

5.3.3. Constant Discharge test

A constant discharge test is performed to:-

- Gather basic hydraulic information
- Determine the long-term optimum production yield of the borehole

Pumping of the borehole is carried out at a constant discharge as determined from the step drawdown test for the duration of the test.

Measurements of both discharge and drawdown are taken at specified intervals.

5.3.3.1. *Equipment **and limitations***

The equipment necessary for conducting a constant-discharge test is as follows (ICRC, 2011):

- A motorised pump with power supply, rising main, valves and discharge pipes. Particular care needs to be taken with the discharge arrangements for constant-discharge tests, especially if the test lasts several days. Ensure that the water will not recirculate back into the borehole or create a nuisance by accumulating in or flowing to an inconvenient location. Discharging into a natural flow channel at some distance from the borehole is usually the best option.
- A stopwatch to measure the time of pumping and recovery
- A dipper to measure the water levels. If available, a pressure transducer with a built-in data logger is very valuable because it continues to collect data while the people responsible for manual dipping are resting.
- A method of measuring the pumping rate (bucket and stopwatch, flow gauge, or weir tank)
- A notebook, or a standard form with a clipboard, and a pencil, to record the test data
- Semi-log graph paper and a ruler to plot the results or software to assist in the preparation

The two main decisions to make with a constant-rate test are the pumping rate and the duration of the test.

5.3.3.2. *Pumping **rate***

Typically, the chosen pumping rate is equal to the intended operational pumping rate when the borehole is fully commissioned, although some hydrogeologists prefer to set the test pumping rate 25-50% higher than the intended operational pumping rate. Information from a step test is beneficial in deciding on this pumping rate (Figure 16). The chosen rate also depends on how the borehole will operate. Some boreholes are pumped at a high rate to fill up a storage tank or reservoir in a relatively short period, and then the water is used gradually (by gravity) from storage. The pumping rate for the test can either be the actual pumping rate when the pump is switched on or the average long-term pumping rate (including the non-pumping periods). If the focus of the test is on long-term sustainability, then it would be better to use the average pumping rate.

5.3.3.3. Length of test

Ideally, a constant-discharge test should be long enough for the water level to reach or approach equilibrium.

5.3.3.4. Pump performance

The discharge rate of a centrifugal pump depends on several factors, such as power and efficiency (ICRC, 2011); the most critical factor, however, is the total hydraulic head against which the pump works. The total head includes static head and friction losses in the pumping and discharge system. During a pumping test in a borehole, as the water level falls, the total head that the pump works against will increase, and the discharge rate will fall. This relationship is illustrated by pump-performance curves, which can be defined for each type of pump (and can usually be provided by the pump manufacturer). The practical relevance of undertaking pumping tests is that it can be challenging to maintain a constant discharge rate if the total head changes significantly, which is inevitably the case during most pumping tests, especially at the start of the test. Careful pump selection is the best solution so that the pump is not operating at the extremes of its performance.

Many aquifers behave differently in the wet and dry seasons; if possible, constant-rate tests should occur at the appropriate time of year. For example, if the borehole is intended as a water source for critical drought periods, it should be tested during the dry season; otherwise, a false impression will result in the aquifer's performance. Another good reason to conduct a test during a dry period is that groundwater levels may be influenced by recharge from heavy rainfall, which makes it more challenging to interpret the test results.

5.3.3.5. Constant-discharge test procedure

Assuming that all the equipment is ready and people have been assigned their tasks, the procedure for conducting a constant-discharge test is as follows (ICRC, 2011):

a) Choose a suitable local datum (such as the top of the casing) from which all water-level readings will be taken, and measure the rest-water level. The water level must be at rest before the start of the test, so the test should not be conducted on a day when the borehole is being drilled or developed, or when the step test is taking place.

b) Open the valve to the appropriate setting, switch the pump on, and start the stopwatch simultaneously. Do not keep changing the valve setting to achieve a particular pumping rate (a round number in litres per minute, for example). Instead, aim for an approximate rate and measure the actual rate below.

c) Measure the water level in the borehole according to the time intervals on the form. Record readings on the form.

d) Measure the pumping rate soon after the start of the test and at the intervals specified on the form. If there is a noticeable change in the rate of increase of drawdown, or if the pump sounds different, then measure the pumping rate at those times as a borehole. If the pumping rate changes significantly (say by more than 10%), then adjust the valve setting to maintain as steady a pumping rate as possible throughout the test but be careful not to over-adjust and make the problem worse.

e) At the end of the test, switch the pump off, note the time (or restart the stopwatch), and measure the water level recovery at the same measurement intervals for measuring the drawdown. Continue until the water level has recovered to the pre-test level or at least approaches that level. If there is a problem during the test, such as an interruption to the power supply or a pump failure, then use your judgement, depending on when the problem occurs and how long it is likely to last. For example, if something goes wrong in the first few minutes, wait for the water level to recover and start again. If the failure occurs well into the test and can be solved quickly, just restart the pump and carry on. If it takes a long time to solve, it may be better to allow full recovery of the water level and start again. For long, constant-rate tests, it is essential to ensure an adequate fuel supply to last the planned duration of the test.

5.3.3.6. Analysis and interpretation

Many methods (e.g., Theis, Cooper-Jacob) and computer software programs exist for interpreting pumping test data. The hydraulic properties computed by a particular method can only be considered correct if the assumptions included in the conceptual model on which the method is based are valid for the particular system being tested (OHIO EPA, 2006). See further explanation of the methods in (Kruseman & de Ridder, 1990).

5.3.3.7. Controlling the pumping rate (ICRC, 2011)

Control of the pumping rate during the test is vital as it allows for reliable drawdown data to be collected to determine the yield of the borehole and aquifer properties. Controlling the pumping rate by adjusting the pump speed is generally not satisfactory. It is better to use a gate valve to adjust the pumping rate to keep it constant. The discharge pipe and the valve should be sized so that the valve will be from ½ to ¾ open when pumping at the desired rate. The valve should be installed at a sufficient distance from the flow measurement device to avoid any impacts from turbulence. Measuring the discharge of pumped water accurately is also important, and standard methods of measuring discharge include using an orifice plate and manometer, an inline flow meter or observing the length of time taken for the pumped water to fill a container of known volume. The flow measurement device should be compatible with the expected pumping rate.

5.3.3.8. Observation boreholes

Whenever possible, observation boreholes should be monitored during the pumping test. It is important to accurately measure the distances between the pumping borehole and the observation boreholes.

5.3.4. Recovery test

The recovery test forms an essential part of the testing programme. It commences immediately after the constant discharge test is completed and involves recording the water level (residual drawdown) towards the original rest water level

The test must continue until the residual drawdown has recovered to the original water level.

Recovery tests are valuable for several reasons (ICRC, 2011):

- They provide a helpful check on the aquifer characteristics derived from pumping tests for minimal extra effort, extending the monitoring period after the pump has been switched off
- The start of the test is relatively 'clean.' In practice, the start of a constant-rate test, for example, rarely achieves a clean jump from no pumping to the chosen pumping rate. Switching a pump off is usually much more manageable than starting a pump, and

the jump from a constant pumping rate to no pumping can be achieved relatively cleanly

- Similarly, recovery smoothes out small changes in the pumping rate during the pumping phase, and there is no problem with well losses from the turbulent flow. When the recovery data are analysed, this results in more reliable estimates of aquifer properties.
- The water levels in the borehole are easier to measure accurately in the absence of turbulence caused by the pumping (especially in the early stages of the test, when water levels change quickly). Some people find it easier to take readings quickly with a dipper when the water level rises than when it falls
- Recovery tests represent a good option for testing operational boreholes that have already been pumping at a constant rate for extended periods. In these cases, the recovery test can be performed when the pumps are first switched off, followed by a constant discharge test when the pumps are switched back on again

5.3.4.1. Equipment and limitations

The equipment required for a recovery test is straightforward (if we ignore the fact that all the pumping equipment is still in place from the pumping period that immediately preceded the recovery test):

- A stopwatch to measure the time of recovery
- A dipper to measure the water levels (or a pressure transducer with a built-in data logger, if available)
- A notebook, or a standard form, and a pencil, to record the test data
- Semi-log graph paper and ruler to plot the results or software

Ideally, the duration of the recovery test should be as long as is necessary for the water to return to its original level, which, theoretically, would be as long as the duration of the pumping phase of the test programme. In practice, however, the recovery test is often shorter, partly because of cost (keeping equipment and personnel on-site). However, it should not be too short because, as described the constant-discharge test, the data from the early part of the test are affected by well storage. If the data from the constant-discharge test have been roughly plotted in the field on semi-log graph paper, this will give some idea of the length of time before the data become useful for calculating transmissivity (when they fall on a straight line). The pump should not be removed from the borehole while the recovery test is taking place because the sudden removal of the submerged volume of the pump and rising main will cause a sudden change in the water level in the borehole. For a similar reason, there must be a non-return valve (called a foot-valve in this context) at the base of the rising main. In the absence of a foot valve, when the pump is switched off, the contents of the rising main will flow back down into the borehole and cause a sudden change in the water level.

5.3.4.2. Recovery-test procedure

The procedure for undertaking a recovery test is as follows (ICRC, 2011):

- Switch the pump off and start the stopwatch at the same time
- Measure the water level in the borehole the same way as for the pumping test. Record all the readings on the standard form. Make sure the same datum is used for measuring water levels as for the pumping phase.

5.3.4.3. Analysis and interpretation

Recovery tests provide an independent check on the transmissivity and storativity determined from a pumping test. The Theis recovery method is widely used to analyse recovery tests (Kruseman & de Ridder, 1990).

6. IMPLEMENTATION

This phase consists of the installation of the groundwater infrastructure. In South Africa, there are numerous groundwater schemes and technologies (Table 2). The groundwater schemes range from simple spring protections to mechanised boreholes. Multi-borehole schemes with storage buffers and extensive reticulation serving large areas with complex O&M characteristics are at the upper level of complexity. In a few cases, groundwater use evolved as part of planned urban water-supply development, e.g. Atlantis. However, it has occurred more often in response to water shortage or service deficiency and through private initiatives, e.g. Lusaka, Dar-es-Salaam, Cape Town, Windhoek and Gaborone and probably elsewhere (SADC-GMI 2019a). Infrastructure that brings water to communities must always be kept functional. As stated above, it has become clear that limited accessibility to groundwater resources in most areas is more frequently a function of the functionality of the infrastructure than the physical availability of groundwater resources. Non-functionality of the infrastructure is also related to infrastructure vandalism (SADC-GMI 2020). The responsibility of the groundwater infrastructure lies with the Engineer.

Table 2: Types of groundwater schemes (SADC-GMI 2020)

Standalone scheme	• A spring, borehole or well equipped with a pump. Typically, many standalone schemes only have one water source without a backup in the case of failure
	  ◦ Rising main pipeline from the borehole to the storage reservoir
	  ◦ Water treatment and disinfection and disinfected water storage reservoir. Many schemes supply groundwater without treatment or disinfection
	• Distribution pipelines to communal tap stands or private connections

Group scheme	• More than one groundwater source (spring, borehole or well equipped with a pump) • Rising main pipeline from the borehole to a central storage reservoir • Water treatment and disinfection and disinfected water storage reservoir. Some schemes supply groundwater without treatment or disinfection • Distribution pipelines to reservoirs at the individual settlements that may be supplied by gravity or pumped

	• Distribution pipelines to communal tap stands or private connections
Regional scheme	• Multiple groundwater sources or wellfields • Raw water pipelines, pump stations and reservoirs • Water treatment and disinfection facilities • Treated water pipelines, pump stations and reservoirs • Reticulation networks
Private supply	Private supply schemes could range from a borehole or well with a hand pump in the yard to a sophisticated system integrated with a fully plumbed house or institution, including complex water treatment, storage, and a booster pump station.

Figure 17: Type of groundwater schemes (a) and (b) spring supplying a town; (c) handpump supplying a village; (d) and (e) cluster of boreholes forming part of a wellfield; and (f) deep well supplying an island community

Centrifugal and positive displacement rotor stator-type pumps are commonly used in South Africa.

6.1. Responsibility for operation and maintenance (SADC-GMI 2020)

Within South Africa, municipalities are the responsible institution for groundwater supply. Organisational responsibility for the water and sanitation O&M includes a range of functions and requires a multi-disciplinary team to staff the institution. The typical ambit of O&M functions is listed in Table 3

Table 3: Operation and maintenance functions

Management	**Mechanical and electrical**
Planning of activities	Inspections
Establish work procedures	servicing
Performance measurement	repairs
Corrective action	refurbishments
Quality management	replacements
Analysis of reports	**Networks**
Administration	Pipeline repairs
Finance	Unblocking sewers
Information technology	Pipe replacements
Stores	New connections
Human resources	Disconnections
Procurement	Structural repairs
Vehicles fleet management	**Treatment works**
Buildings	Produce potable water
Customer Service	Produce safe effluent
Meter reading	Sludge handling
Billing	**Tankering**
Receive revenue	Tank/pit emptying
Credit control	Sludge disposal
Unauthorised connections	Potable water delivery
Commercial	Fuel delivery
Administer contracts	**Engineering**
Administer new applications	Technical support
Address complaints	Water balance and UFW
Communication	Groundwater monitoring

Capital Works	Asset management
Service new areas	Operational data analysis
Pipe replacements	Technical analysis
Equipment replacement	Technical specification

Managing large complex regional water supply schemes requires sophisticated management and a skilled staff complement that can adequately fulfil all the physical and administrative functions required. Unfortunately, the skills and resources required are not always available to the responsible institutions.

The consequence of scheme failure is that the customers who can most afford to pay for the service tend to look for alternative arrangements like private boreholes. This reduces the income available to the operating institution making it more likely that the system will fail.

In dispersed rural communities, especially where there are many standalone schemes, individual handpumps, and spring protections, communities can plan an influential role in the scheme operation, doing essential maintenance and communicating and reporting to the responsible authority. In some cases, communities cover the cost of these services as their contribution to their water supply, while the local operation, maintenance and monitoring is remunerated by the responsible authority elsewhere.

The technical challenges of servicing schemes for dispersed rural communities are often exacerbated by the logistical challenges and the time required to travel on poor roads between the service centre and the village where the scheme is situated. Table 4 lists the technical issues experienced with the O&M of these schemes in schemes in two districts in the Eastern Cape of South Africa.[1]; access was a critical issue for all components.

[1] Gibson, J., 2011, Is it Worth Building Regional Schemes – Reflections from the Eastern Cape, South Africa, 6th Rural Water Supply Network Forum 2011 Uganda

Table 4: Challenges experienced in delivering operation and maintenance services in dispersed rural settlements

Scheme Element	Technical O&M Challenges
Treatment Works	Skilled operators required
	Sophisticated electronic controls
	Access roads
Pump Stations	Access roads
	Sophisticated electronic controls
	Mechanical-Electrical skills required
Reservoirs	Access roads
	Flow regulation
	Telemetry (radio network maintenance)
	Integrity of the tank stand
Pipelines	Large diameter
	Mechanised lifting required
	Access roads
Reticulation	Meter reading
	Leaks
	Billing
	Cost recovery
Boreholes	Access
	Power (diesel / electricity)
	Lack of standby

The maintenance of handpumps and smaller standalone schemes from boreholes and springs require less technical skilled input. The difficulties associated with access and the fact that the schemes are dispersed over large areas give rise to additional logistic challenges and associated costs for the type of schemes (Figure 18). The challenge of fuel supply and the servicing of diesel engines is one of the significant cost drivers.

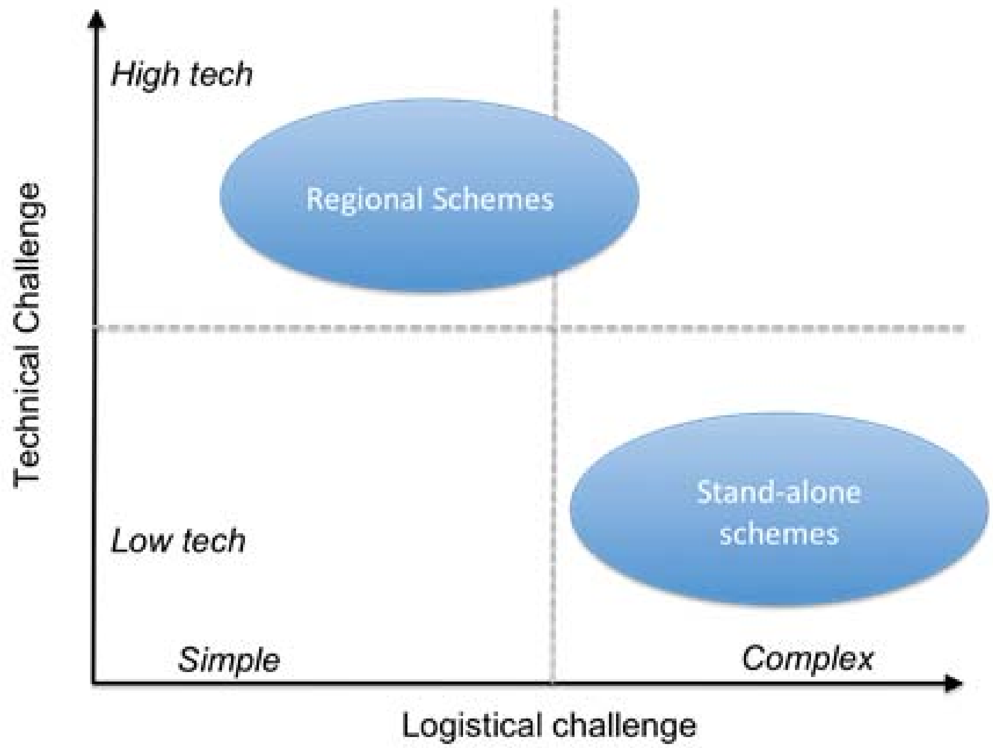

Figure 18: Big regional schemes substitute technical complexity for small schemes' logistical challenges.[2]

[2] ibid

7. OPERATION AND MAINTENANCE (SADC-GMI 2020)

There are many challenges to implementing infrastructure sustainability and resilience, ranging from inadequate funding to poor governance (Table 5). **Sustainability** is defined through the triple bottom line of environmental, social, and economic system considerations. **Resilience** is viewed as the ability of a system to prepare for threats, absorb impacts, recover, and adapt following persistent stress or a disruptive event (Marchese et al., 2018). **Sustainable infrastructure** refers to projects planned, designed, constructed, operated, and decommissioned to ensure economic, financial, social, environmental (including climate resilience), and institutional sustainability over the entire life cycle of the project (IDB 2018). Appropriate technology that fits the local context and environment underpins infrastructure sustainability.

Table 5: Common challenges to implementing resilient infrastructure solutions (Scheider-Roos n.d.)

Challenge/barrier	**Implication**
Inadequate funding	– The growing gap between existing and the required infrastructure – The increased cost of resilient infrastructure – Difficulty in structuring bankable projects – Difficulty attracting private finance – Basel III Regulatory Framework – further reduced funding

Challenge/barrier	Implication
Weak institutional capacity	– Centralised institutions unable to respond to O&M issues in a timely way – Poorly resourced institutions that are unable to function well – Lack of clarity of roles and responsibilities leads to a lack of accountability – Poor planning and coordination (unbudgeted expenditure, e.g., decommissioning) – Lack of quality standards or their enforcement – Flawed project analysis, selection & identification of needs – Lack of regional vulnerability assessment & high uncertainty in future conditions – Poor design leads to costly maintenance – Lack of oversight of O&M contractors
Weak legal framework	– Lack of legal instruments for setting operational standards and norms
Lack of security securing the infrastructure leading vandalism of the infrastructure	– Broken infrastructure leading to intermittent water supplies – Increased O&M costs perpetuate the vicious cycle of poverty
Corruption	– Procurement (inflated prices and poor quality products) – Lack of transparency (breeding more corruption) – Nepotism (unqualified staff who do not add value)
Political interference	– Directing institutional operations (procurement, resource allocation, etc.) – Nepotism
Lack or poor O&M	– Lack of O&M strategies and implementation
Lack of civil society and stakeholder's participation and coordination	– Lack of interest in infrastructure as the communities perceive it as 'theirs.' – Lack of women involvement (women are most affected by the unavailability of water resources) – Lack of sectoral coordination leads to players opting for their preferred way of doing things

Challenge/barrier	Implication
Inappropriate technology	– Difficult to maintain and repair – Lack of availability of spares – Too complex to be understood by local artisans (disincentive to the promotion of village-level O&M or VLOM)
Lack of M&E	– Lack of data and information for proper resource allocation and proper planning

For groundwater infrastructure to be sustainable and resilient, its lifespan must be ensured through proper O&M, as this is the main cause of infrastructure breakdown. This led to community dissatisfaction and continued poor governance of water infrastructure (Sohail et al., 2005). Figure 19 provides an overview of properties that make infrastructure resilient.

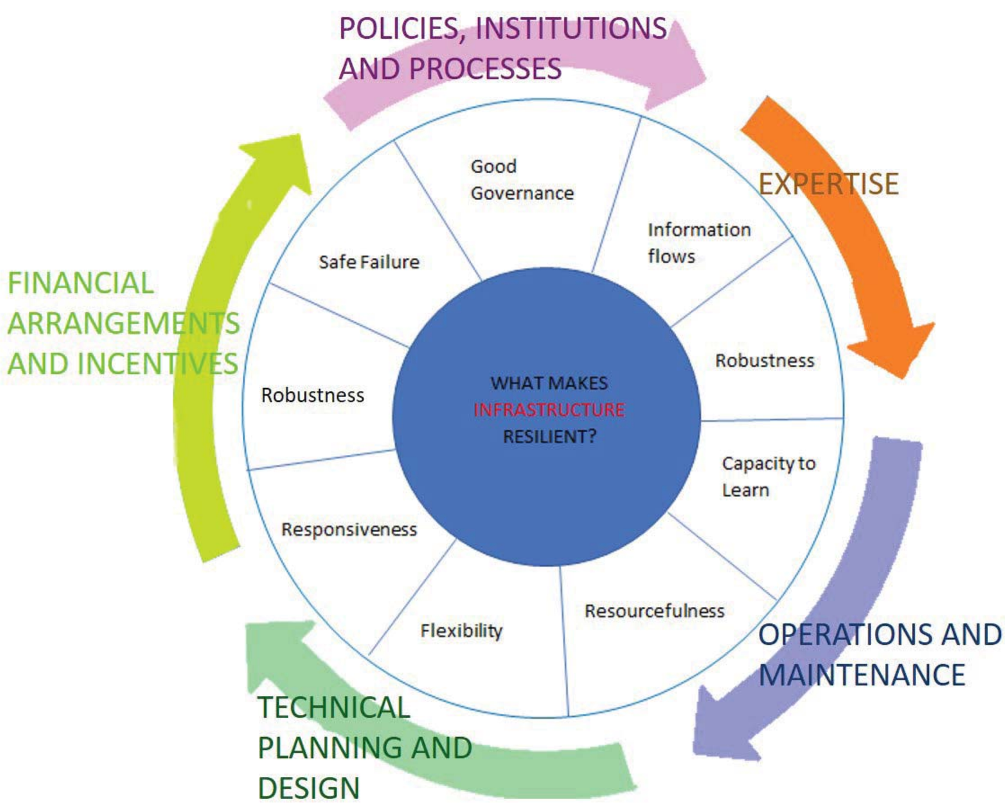

Figure 19: Infrastructure resilience properties (Gallego-Lopez and Essex, 2016)

7.1. Factors undermining groundwater infrastructure sustainability and resilience

The sustainability and resilience of services are commonly undermined by the following factors (Brikké and Bredero, 2003):

- The project was poorly conceived (e.g., a project that only increased the number of water points, or sanitation facilities, as a way of improving accessibility to these services, without considering the broader range of factors needed to sustain the benefits)
- There was minimal or no community involvement and participation in the project; hence, the communities did not have a sense of project ownership. Demand and community involvement (of both men and women) are critical to generating long-term community commitment to improved services and sustaining the services. Community involvement and participation also make the community members responsible for the choice of technology and make community members aware of the financial, managerial, and technical implications of their choice, including future O&M tasks associated with the technology
- The performance of the project facilities was either not assessed or was insufficiently monitored during the O&M phase of the project cycle (ineffective or non-existent O&M)

7.2. Other factors that undermine the sustainability

Several other factors could militate against sustainability, and these include:

7.2.1. Inappropriate system design and quality of infrastructure

No matter how good the management of a water supply facility is, if it is not technically well designed, it will operate inefficiently. Finding water supply schemes that have been badly designed, poorly constructed, and use inappropriate technologies is not uncommon. When a facility is improperly designed and constructed, even with the best will in the world, it will not perform satisfactorily.

A lack of communication between the system designer and the system operators also provides a further drawback. It is imperative that plant or equipment operators, whether in a rural area receiving a borehole or in an urban centre receiving complex water supply facilities, need to be familiar with, approve of, and comfortable with the technology. Training should be instituted where required, and refresher courses scheduled. In addition, there needs to be continuous information feedback from the operators to the designers pinpointing problems or challenges faced with the equipment, as this will provide for early remedial measures.

7.2.2. Political interference

Political interference has been identified as a serious contributory reason for the poor performance of water supply and sanitation agencies/institutions. This is most noticeable in countries where the government owns, operates, and maintains water supply facilities (Brikké and Bredero, 2003). Political interference manifests itself in several ways. In some instances, purely for political reasons, it is directed that water be provided free of charge or that the charges be set low to the extent of not even covering costs of O&M, let alone capital costs. The directive requesting water service institutions not to charge proper tariffs for water makes it difficult to run a self-financing viable system. In rare cases where governments fund O&M costs, when facing fiscal challenges, water supply facilities often become soft targets for budget cuts.

Political interference is also evident in several other ways, such as the choice of technologies. For one reason or another, government officials may support purchasing a technology or system that may not be the best or most appropriate selection for the scheme. Also, equipment suppliers and external support agencies frequently hinder the wise choice of technology by lobbying politicians or through restrictive policies of tied aid. It has also been established that the award of a contract for the provision of services such as drilling of boreholes may be influenced by politics resulting in the selection of a contractor who carries out substandard work, which ultimately negatively impacts O&M and, thus, the sustainability of water supply infrastructure.

A possible and workable alternative for better water supply systems is to devolve the responsibility of managing the systems from the government to autonomous agencies/institutions, which will manage the facilities under the government's technical, financial and administrative guidelines. This can limit the extent of political interference by governments and allow the facilities to be managed more efficiently.

7.2.3. Conflicts, social unrest, theft, and vandalism

Conflicts, social unrest, theft, and vandalism hinder the sustainability of groundwater infrastructure. In municipalities with civil unrest, investment in water infrastructure fell short, further aggravated by the destruction of infrastructure and consequently regress after supply (SADC-GMI 2019b). The acts of vandalism are widespread in both urban and rural settings and take several forms: they include water theft leading directly to a loss of revenue for the utility, and the vandalism and theft of valuable metal pipes, fittings and manhole covers, leading to an increase in the utility’s maintenance costs (WSUP, 2014). The implications are (WSUP, 2014):

- Increased O&M costs – from the need for repair or replacement of vandalised pipes, fixtures, and fittings
- Increased non-revenue water (NRW) – from water losses due to either water theft or leakage from the damaged network
- Reduced customer satisfaction – from more frequent service interruptions and rise in tariffs to cover increased costs, which may, in turn, lead to further dissatisfaction and lost revenue from customers’ refusal to pay

7.2.4. Borehole/well drilling technical specifications

Technical specifications include the work's nature and class, the materials to be used, and the workmanship itself. These are important for the execution of the work. A lack of proactive approaches toward major repairs and sub-standard borehole construction alongside ageing infrastructure contributes to the reduced functionality of decentralised supplies (Truslove et al., 2019). The cost and quality of the work depend much on the technical specifications; as such, they need to be clear and of high quality. As described in the previous chapter, failure to develop good borehole drilling and technical construction specifications results in poor workmanship, which would impact O&M.

7.3. Typical cost structure of groundwater schemes

Understanding the costs associated with groundwater development (drilling, equipment, O&M) is crucial. However, the cost depends on various factors such as site conditions, labour and capital costs, relative water scarcity, depth to the water table, and relative fuel prices (Custodio and Gurguí, 1989). Figure 20 summarises the costs associated with groundwater abstraction.

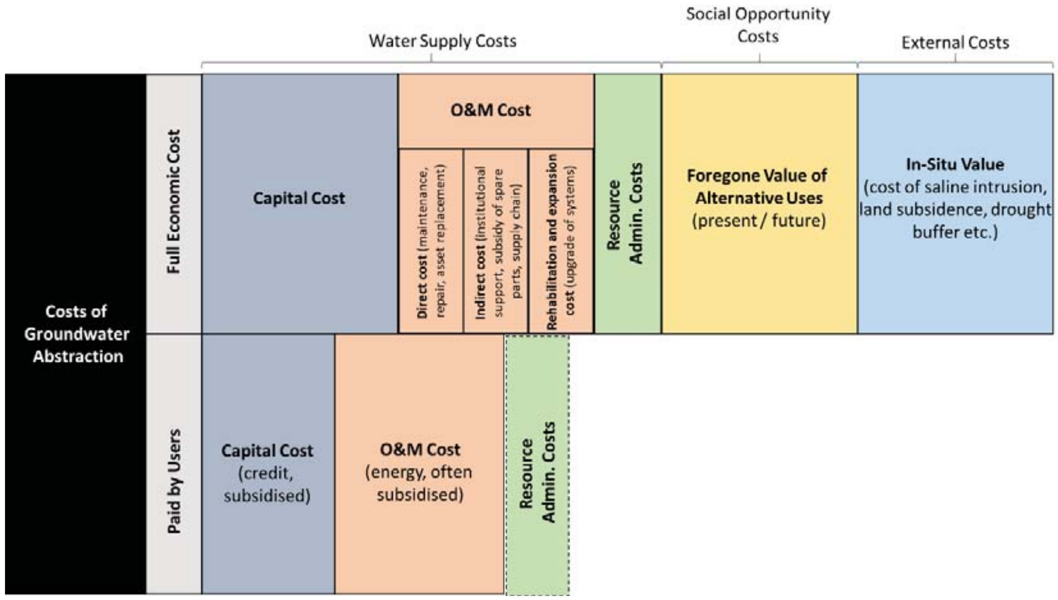

Figure 20: Costs associated with groundwater abstraction (Harvey, 2007; Smith et al., 2016)

Pumping groundwater requires energy, and potential energy sources include solar, diesel, and grid-connected. Energy costs can make up anything from 5% to 50% of the annual costs of running a groundwater scheme, depending on the energy source and extent of pumping required. Solar has minimal running costs, but the capital costs are high, as well as the susceptibility to vandalism and the reliance on sunlight. Diesel, while very common for small, rural schemes, is the most expensive to run and maintain, with grid-connected systems generally being 50% to 70% of the running cost of diesel systems. There are other benefits to grid-connected systems, such as the improved ability to automate electric motors, the potential to install a smaller capacity pump (since an electric pump can run continuously whereas a diesel pump generally operates for 8 hours a day), and the ability to install switches that require electricity such as no flow switches, cut off probes and pressure switches.

Solar and diesel pumping systems are preferred in rural regions that lack a grid connection, which is common in most rural parts of South Africa. While diesel and solar-powered pumps are popular, both have advantages and disadvantages Table 6.

Table 6: Advantages and disadvantages of solar- and diesel-powered pumps (Abu-Aligah, 2011).

Type of pump	Advantages	Disadvantages
Solar-powered	Unattended operations	High investment costs
	Low maintenance costs	Water storage required
	Long lifetime (low yearly costs)	Skilled technicians required for repairs
Diesel-powered	Fast and easy installation	Diesel is dependent on reliable supply and can be expensive
	Low investment costs	High maintenance costs
		Short life expectancy
		Noise and air pollution

Diesel and electricity-powered pumps are observed in other parts of the world, with the government playing a substantial role in subsidising such energy sources. The relative capital and running costs for different sources of pumping are given in Table 7.

Table 7: Capital and running costs of different power sources for pumping (Bruni and Spuhler, 2020)

		Human	Electricity			Diesel	Wind	Animal	Hydro
			Grid/ Mains	Solar	Diesel Generator				
Capital costs		*	****	*****	***	**	****	**	****
Running costs	Fuel	-	***	-	***	***	*	***	*
	Spares	*	*	*	***	****	*	*	*
	Maintenance	*	*	*	***	****	*	*	*
	Performance	*	***	***	***				

REFERENCES

Abu-Aligah M (2011) Design of Photovoltaic Water Pumping System and Compare it with Diesel Powered Pump

Brikké F, Bredero M (2003) Linking technology choice with operation and maintenance in the context of community water supply and sanitation

Bruni M, Spuhler D (2020) Mechanised Pumping. In: Sustainable Sanitation and Water management. https://sswm.info/sswm-university-course/module-4-sustainable-water-supply/further-resources-water-sources-hardware/mechanised-pumping. Accessed 29 Jul 2020

Cobbing JE, Eales K, Gibson J, et al. (2015) Operation and maintenance (O&M) and the perceived unreliability of domestic groundwater supplies in South Africa. South African Journal of Geology 118:17 LP – 32

Curran D, Geller D, Everdene B, et al. (2009) GROUNDWATER BYLAWS TOOLKIT 2009

Custodio E, Gurguí A (1989) Groundwater Economics, 1st edn. Elsevier Science

Danert K (2022) 'Stop the Rot Report II: Rapid corrosion of handpumps. Action research on handpump component quality and corrosion in sub-Saharan Africa. St Gallen

Danert K (2015) Manual Drilling Compendium 2015. St Gallen, Switzerland

de Visser J, Cottle E, Mettler J (2009) Realising the right of access to water: Pipe dream or watershed?

Dolo M (2019) Water supply challenges in urban and rural areas of Eastern Cape

Driscoll FG (1986) Groundwater and Wells, Second. Johnson Screens, St. Paul, Minnesota, USA

DWAF (2001) Regulations relating to the compulsory national standards and measures to conserve water. Republic of South Africa

Foster S, Gogu R (2022) Groundwater Assessment and Management for Sustainable Water-Supply and Coordinated Subsurface Drainage" A Guidebook for Water Utilities and Municipal Authorities. London

Friese A, Swartz H, Titus R, et al. (2006) Geomechanical modelling as a tool for groundwater exploration of fractured rock aquifers in the Namaqualand region, South Africa. Pretoria, South Africa

Gallego-Lopez C, Essex J (2016) Introducing infrastructure resilience

Harvey PA (2007) Cost determination and sustainable financing for rural water services in sub-Saharan Africa. Water Policy 9:373-391. https://doi.org/10.2166/wp.2007.012

HRC (2018) The Right to Water and Sanitation. Johannesburg

IDB (2018) What is Sustainable Infrastructure? A Framework to Guide Sustainability Across the Project Cycle

Kalin RM, Mwanamveka J, Coulson AB, et al. (2019) Stranded assets as a key concept to guide investment strategies for Sustainable Development Goal 6. Water (Switzerland) 11: https://doi.org/10.3390/w11040702

Kotzé YL (2015) A Framework for Groundwater Use Authorisations as Part of Groundwater Governance in Water Scarce Areas within South Africa. University of the Free State

LHR (2009) Water Supply and Sanitation in South Africa: Environmental Rights and Municipal Accountability. Pretoria

Marchese D, Reynolds E, Bates ME, et al. (2018) Resilience and sustainability: Similarities and differences in environmental management applications. Science of the Total Environment 613-614:1275-1283

McConville JR, Mihelcic JR (2007) Adapting life-cycle thinking tools to evaluate project sustainability in international water and sanitation development work. Environ Eng Sci 24:937-948. https://doi.org/10.1089/EES.2006.0225

Møller I, Søndergaard V, Jørgensen F (2009) Geophysical methods and data administration in Danish groundwater mapping. Geological Survey of Denmark and Greenland Bulletin 17:41-44

Nel J, Xu Y, Batelaan O, Brendonck L (2009) Benefit and Implementation of Groundwater Protection Zoning in South Africa. Water Resources Management 2009 23:14 23:2895-2911. https://doi.org/10.1007/S11269-009-9415-4

Pietersen K (2004) A decision-making framework for groundwater management in arid zones (with a case study in Namaqualand). University of the Western Cape

Pietersen K, Beekman H (2015) Guidelines and protocols for pumping test of the Nyamandhlovu Aquifer

PRACTICA Foundation (2010) Understanding groundwater & wells in manual drilling. Papendrecht, Netherlands

RSA (1998) National Water Act. South Africa

RSA (1996) Constitution of the Republic of South Africa

SADC-GMI (2020) Training manual for operation and maintenance of groundwater infrastructure in SADC. Bloemfontein, South Africa

SADC-GMI (2019a) Guidance Document: Operation and Maintenance of Groundwater Schemes. Bloemfontein, South Africa

SADC-GMI (2019b) Guidance document: Building Groundwater Resilience. Bloemfontein, South Africa

Sami K, Neuman I, Gqiba D, et al (2002a) Status groundwater exploration in geologically complex and problematic terrain – guidelines. Water Research Commission, Pretoria

Sami K, Neumann I, Gqiba D, et al. (2002b) Groundwater exploration in geologically complex and problematic terrain-case studies. Pretoria, South Africa

Scheider-Roos K Introduction to SuRE. https://unfccc.int/files/cooperation_and_support/financial_mechanism/standing_committee/application/pdf/session_9___schneider-roos-gib.pdf. Accessed 27 Mar 2020

Smith M, Cross K, Paden M, Laban P (2016) Spring – Managing groundwater sustainably. Gland, Switzerland

Sohail M, Cavill S, Cotton AP (2005) Sustainable Operation and Maintenance of Urban Infrastructure: Myth or Reality? J Urban Plan Dev 131:39-49. https://doi.org/10.1061/(ASCE)0733-9488(2005)131:1(39)

Thorn P, Vermaak N, Kotzé Y, Højberg L (2022) Groundwater mapping and assessment: A comparison of the Danish and South African approaches

Truslove JP, Coulson AB, Mbalame E, Kalin RM (2020) Barriers to handpump serviceability in Malawi: life-cycle costing for sustainable service delivery. Environ Sci (Camb) 6:2138-2152. https://doi.org/10.1039/D0EW00283F

Truslove JP, v. M. Miller A, Mannix N, et al (2019) Understanding the Functionality and Burden on Decentralised Rural Water Supply: Influence of Millennium Development Goal 7c Coverage Targets. Water (Basel) 11: https://doi.org/10.3390/w11030494

UNICEF (2016) Manual Drilling Toolkit. https://www.unicef.org/wash/3942_59785.html. Accessed 21 Jul 2020

World Bank (2018) Assessment of Groundwater Challenges & Opportunities in Support of Sustainable Development in Sub-Saharan Africa. Washington, DC

WRC (2015) Groundwater for domestic water supply – Insights from Research and Municipal Case Studies. Pretoria

WSUP (2014) Reducing vandalism of water and sanitation infrastructure: experience from Zambia’s Copperbelt