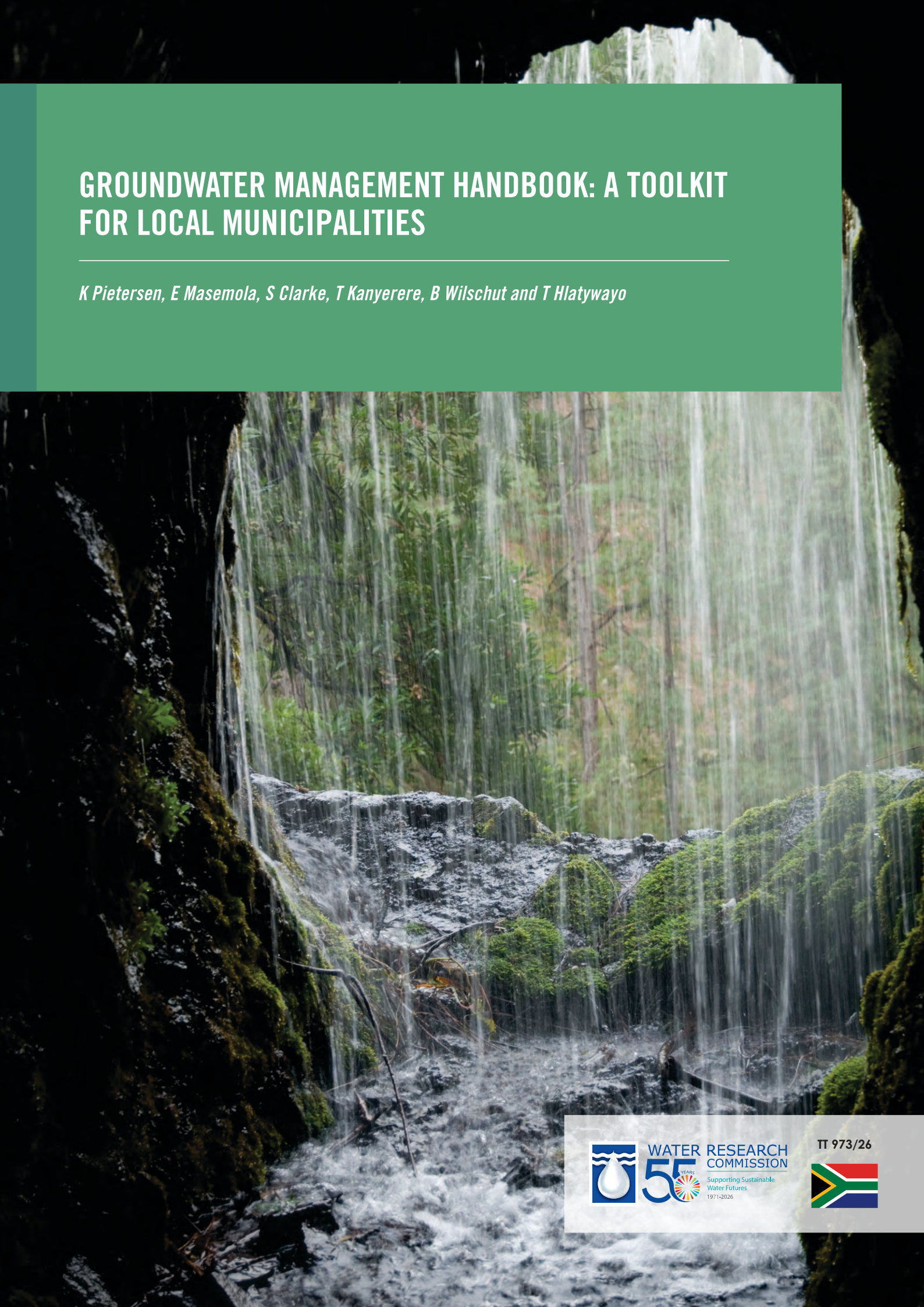
GROUNDWATER MANAGEMENT HANDBOOK: A TOOLKIT FOR LOCAL MUNICIPALITIES

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GROUNDWATER MANAGEMENT HANDBOOK: A TOOLKIT FOR LOCAL MUNICIPALITIES

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EXECUTIVE SUMMARY

Groundwater is a critical component of South Africa's water security, particularly for rural settlements, small towns, drought-prone municipalities and areas where surface-water schemes are costly, unreliable or unavailable. Despite this importance, groundwater is still too often treated as an emergency or secondary source rather than as a strategic municipal asset. This has contributed to underinvestment in hydrogeological skills, monitoring, data management, operation and maintenance, aquifer protection and long-term planning. The **Groundwater Management Handbook** responds to this challenge by providing municipalities with a practical toolkit to plan, develop, operate, protect, and govern groundwater resources in a more coordinated and sustainable way.

The handbook is intended primarily for Local and District Municipalities, including Water Services Authorities and Water Services Providers that currently use groundwater, intend to expand groundwater use, or are considering groundwater development for the first time. It is also relevant to municipal managers, councillors, planners, engineers, operators, hydrogeologists, environmental officials, finance officials and catchment-management actors who influence how groundwater is planned, funded, regulated and maintained. It translates national policy, legislation, research, and good practice into actions that can be implemented through municipal planning systems, budgets, bylaws, infrastructure programmes, monitoring systems, and operational procedures.

The handbook's central message is that groundwater reliability must be deliberately managed. Sustainable groundwater supply depends on sound governance, professional hydrogeological assessment, realistic yield determination, disciplined abstraction control, routine monitoring, proactive operation and maintenance, water-quality protection and clear institutional accountability. Municipal groundwater failures often stem not from the absence of groundwater, but from weak planning, inadequate data, poor infrastructure maintenance, limited technical capacity, fragmented mandates, insufficient budgets, and delayed responses to emerging risks.

The handbook is structured as a modular guide that moves from groundwater fundamentals to municipal governance, operational management, individual-user responsibilities, hydrostratigraphic context and practical case studies. It explains how groundwater occurs, moves and is replenished; why aquifer type, geology, recharge and water quality

determine development potential; and why groundwater must be managed as part of the broader hydrological cycle. It also highlights groundwater's role in water security, drought resilience, climate adaptation, rural development, agriculture, ecosystem support, and diversified municipal water supply.

At the strategic governance level, the handbook shows how municipalities can integrate groundwater into Integrated Development Plans, Water Services Development Plans, spatial development frameworks, land-use controls, bylaws, risk registers, performance systems and Medium-Term Revenue and Expenditure Framework allocations. This integration is essential because groundwater decisions affect, and are affected by, sanitation, stormwater, solid waste, housing, agriculture, mining, forestry, environmental management, infrastructure planning and disaster-risk reduction. Groundwater should therefore be planned and funded as part of the formal municipal water portfolio, not added reactively during droughts or service failures.

The handbook gives particular attention to the governance risks that undermine groundwater-dependent services. These include contamination from land use and infrastructure failures, drought and other extreme climatic events, low or declining yields, over-abstraction, unregistered private boreholes, weak monitoring networks, insufficient hydrogeological expertise, fragmented cross-sector decision-making, vandalism, infrastructure failure and persistent funding gaps. In each case, the handbook links the risk to practical management responses, institutional dependencies and enabling actions such as bylaw reform, source protection, monitoring networks, data platforms, standard operating procedures, asset rehabilitation, stakeholder forums and dedicated municipal capacity.

At the operational level, the handbook provides practical guidance for groundwater scheme development, testing, abstraction management, operation and maintenance, treatment, infrastructure protection and troubleshooting. It emphasises that borehole and wellfield performance must be based on hydrogeological investigation, pumping tests, sustainable yield assessment, water-level and water-quality monitoring, equipment standardisation and routine maintenance. It also provides guidance for responding to common operational problems such as borehole clogging, declining yields, pump failure, saline intrusion, nitrate contamination, vandalism and poor water quality.

Because South Africa's aquifers differ greatly by geology, climate, recharge and structural setting, the handbook also provides a hydrostratigraphic overview of the country's major aquifer systems. This context helps municipalities understand why groundwater development must be based on local evidence rather than generic assumptions. Fractured aquifers, karst systems, intergranular aquifers and double-porosity systems each require appropriate conceptual models, investigation methods, monitoring designs and management rules. Understanding these differences reduces the risk of failed boreholes, unrealistic yield expectations, over-abstraction and long-term resource degradation.

The handbook recognises that municipalities cannot manage groundwater alone. Private users, farmers, businesses, schools, clinics, industries, developers, catchment institutions, national departments, water user associations and communities all influence aquifer sustainability. For this reason, the handbook reinforces the principle that groundwater is a shared public resource. Responsible abstraction, pollution prevention, registration, monitoring, data sharing, and stewardship are necessary to protect both private supplies and municipal systems and to reduce conflict when boreholes dry up or water quality deteriorates.

The case studies included in the handbook illustrate both the opportunities and risks of municipal groundwater use. Examples from different hydrogeological and institutional settings show that groundwater can support reliable supply where it is properly investigated, protected, monitored and operated. They also show that schemes can fail when borehole interference, over-abstraction, poor water quality, weak maintenance, vandalism, inadequate treatment, insufficient data, or unclear institutional arrangements go unaddressed. These lessons reinforce the handbook's practical orientation: groundwater success depends on the connection between sound science, competent operations and accountable governance.

Overall, the handbook supports a shift from fragmented and reactive groundwater development to proactive, institutionalised groundwater management. It provides municipalities with the concepts, governance tools, operational guidance and practical checklists needed to make groundwater visible in planning, budgeting, regulation, monitoring and service-delivery accountability. By strengthening municipal capacity, improving data-driven decision-making, protecting aquifers and embedding groundwater in integrated water resource planning, the handbook aims to help municipalities secure more reliable, equitable and climate-resilient

water services. Its broader purpose is to ensure that groundwater is recognised, protected and managed as a strategic local and national asset for long-term water security in South Africa.

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ACRONYMS & ABBREVIATIONS

Acronym	Meaning
AMD	Acid mine drainage
AWRMS	Atlantis Water Resource Management Scheme
BB	Bangweulu Block
BOD	Biological oxygen demand
CC	Congo Craton
CMA/CMAs	Catchment Management Agency/Agencies
CPD	Continuous Professional Development
DALRRD	Department of Agriculture, Land Reform and Rural Development
DFFE	Department of Forestry, Fisheries and the Environment
DMRE	Department of Mineral Resources and Energy
DO	Dissolved oxygen
DRASTIC	Depth to water, Recharge, Aquifer media, Soil media, Topography, Impact of the vadose zone, and hydraulic Conductivity
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
EAO	East African Orogeny
EC	Electrical conductivity
e-WULA	Electronic Water Use License Application
GIS	Geographic information system
GLDAS	Global Land Data Assimilation System
GRACE	Gravity Recovery and Climate Experiment
GSM	Global System for Mobile Communications

GW	Groundwater
IB	Irumide Belt
IDP/IDPs	Integrated Development Plan(s)
IUCN	International Union for Conservation of Nature
IWRM	Integrated Water Resources Management
KB	Kibaran Belt
KC	Kaapvaal Craton
KPI/KPIs	Key performance indicator(s)
KS	Kheis Belt
LA	Lufilian Arc
MAR	Managed aquifer recharge
MB	Mozambique Belt
MODFLOW	Modular Three-Dimensional Finite-Difference Groundwater Flow Model
MOU/MoU/MOUs	Memorandum/memoranda of understanding
MSDF	Municipal Spatial Development Framework
MTREF	Medium-Term Revenue and Expenditure Framework
NASA	National Aeronautics and Space Administration
NB	Natal Province
NGO/NGOs	Nongovernmental organisation(s)
NORAD	Norwegian Agency for Development Cooperation
NWA	National Water Act
NWRS/NWRS-3	National Water Resource Strategy/Third Edition
O&M	Operation and maintenance
ORP	Oxidation-reduction potential

PI	Protective cover and infiltration conditions
PVC	Polyvinyl chloride
QA/QC	Quality assurance/quality control
QGIS	QGIS geographic information system software
RDM	Resource-Directed Measures
RSA	Republic of South Africa
SABS	South African Bureau of Standards
SACNASP	South African Council for Natural Scientific Professions
SADC	Southern African Development Community
SADC-GMI	Southern African Development Community Groundwater Management Institute
SANS	South African National Standard(s)
SB	Saldanian Belt
SDBIP	Service Delivery and Budget Implementation Plan
SMS	Short message service
SOP/SOPs	Standard operating procedure(s)
SVF	Saturated volume fluctuation
SWL	Static water level
SWSA	Strategic Water Source Area
TC	Tanzania Craton
TDEM	Time-domain electromagnetic method
TDS	Total dissolved solids
TMG	Table Mountain Group
UPVC	Unplasticised polyvinyl chloride
WASH	Water, sanitation and hygiene

WCB	West Congolian Belt
WHO	World Health Organisation
WRC	Water Research Commission
WSA/WSAs	Water Services Authority/Authorities
WSDP/WSDPs	Water Services Development Plan(s)
WSP/WSPs	Water Services Provider(s)
WSUD	Water Sensitive Urban Design
ZC	Zimbabwe Craton

1. BACKGROUND

1.1. PURPOSE OF THE HANDBOOK

The purpose of this **Groundwater Handbook** is to strengthen municipalities' capacity to plan, develop, and manage groundwater resources effectively (Box 1). It is designed as a practical toolkit that guides practitioners at different management levels to relevant methods, resources and support materials.

Box 1: Sustainable and climate-resilient development must address groundwater management [1].

Sustainable groundwater management supports climate-resilient water supplies to help meet goals for food security, energy development, and access to drinking water. It supplies water for sustainable cities and industrialisation. Achieving sustainable groundwater management demands coordination with surface water management for conjunctive use and collaboration among local groundwater users, technical specialists, and policymakers. Each has a role, at the local, basin, national, or international level, in implementing multi-actor, collaborative, and participatory strategies to catalyse sustainable groundwater management.

The Water Research Commission (WRC) has long invested in groundwater guidance documents, governance initiatives, and training manuals. **The handbook aims to provide a standardised resource for managing groundwater schemes across South Africa by consolidating this body of knowledge into a single comprehensive reference**.

Given the numerous challenges facing sustainable groundwater infrastructure, including inadequate funding, poor governance, and limited data availability, the handbook also helps municipalities source and organise **information on common issues in municipal groundwater use.**

1.2. TARGET AUDIENCE AND STRUCTURE

The WRC has supported the development of groundwater guidance documents, groundwater governance projects, and groundwater training manuals. This project provided an opportunity to compile this knowledge into a comprehensive groundwater management handbook, offering municipalities complete technical guidance and educational materials for sustainable groundwater management. The objective is to structure the handbook to facilitate data sourcing based on common issues encountered

by the municipal domestic sector. Numerous challenges hinder the implementation of sustainable groundwater infrastructure, including insufficient funding, vandalism (Figure 1), and poor governance. The handbook aims to catalogue best practices, illustrated through case studies, to enhance groundwater management. The process of preparing the handbook involved three phases: (i) document review, (ii) engagement with key organisations, and (iii) analysis and reporting. Consequently, this handbook is intended for local municipalities that are:

a) Using groundwater

b) Planning on expanding their groundwater use

c) Developing groundwater resources for the first time.

It is structured as a toolkit that directs practitioners to additional resources.



Figure 1: Example of vandalised groundwater supply infrastructure

1.3. STRUCTURE OF THE HANDBOOK

The handbook is organised into six parts (Figure 2). Section A provides fundamental information about groundwater. Sections B through E address

various management levels for municipal groundwater planning, development, and management, as well as supplementary sources for more detailed intervention strategies. Section F presents foundational information on South African hydrostratigraphy, and Section G presents case studies on groundwater schemes.

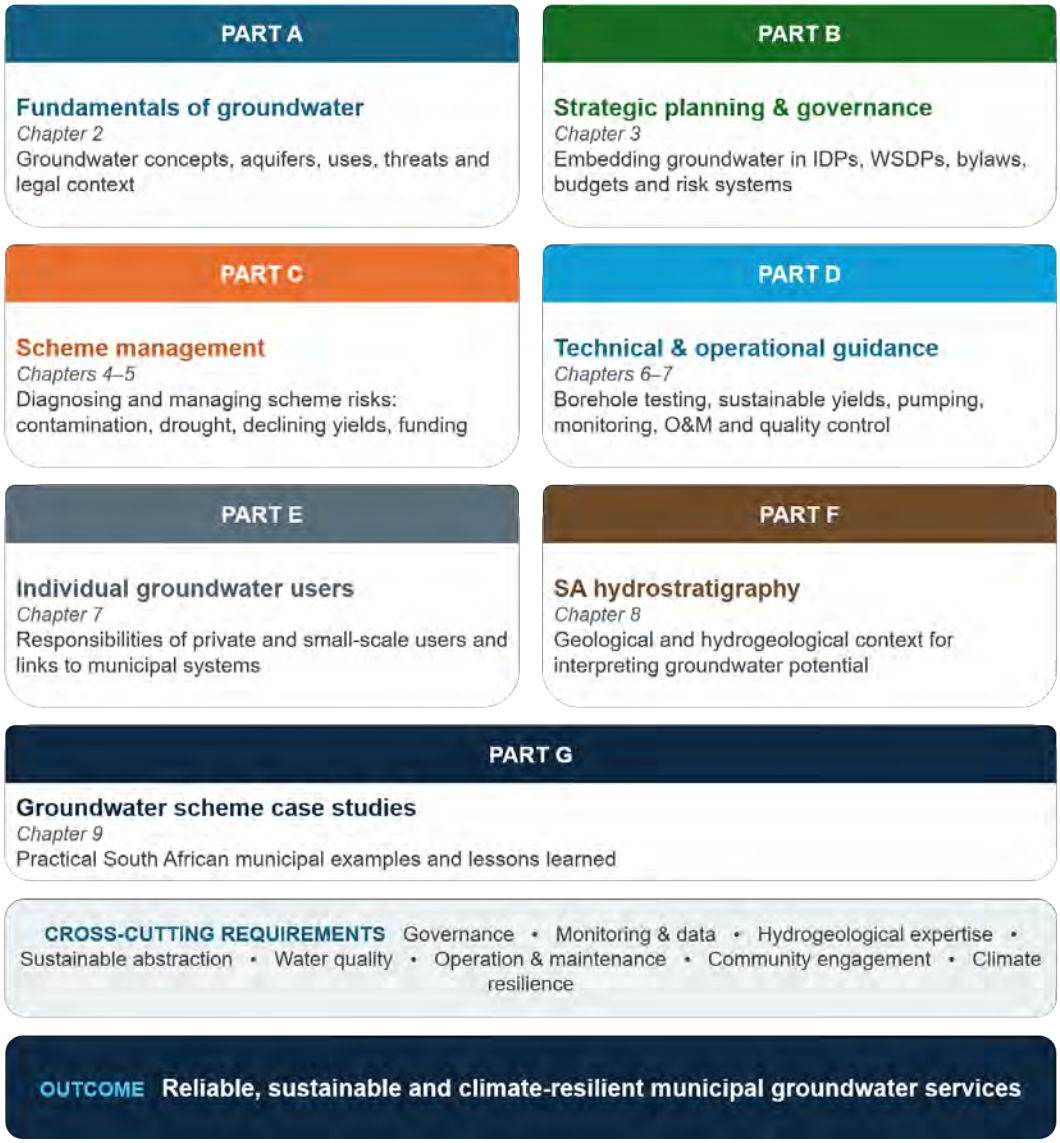


Figure 2: **Structure of the Groundwater Management Handbook — progressing from groundwater fundamentals and municipal governance to operational tools, hydrogeological context and practical case studies.**

Part A provides the essential understanding of groundwater, which is crucial for planning and management as detailed in Chapter 2. It explains what groundwater is, how it moves, its importance to South Africa's water security, and the threats that endanger its sustainability. Chapter 2

highlights groundwater's potential to boost economic growth, social development, and water security when managed properly. Despite supporting millions, especially in rural areas and towns, groundwater has often been underestimated and poorly managed compared to surface water. The chapter emphasises groundwater's untapped potential, the need to invest in infrastructure, skills, and institutions, and the promotion of conjunctive use to strengthen drought resilience and climate adaptation.

This handbook is structured as a guidebook to help municipalities find the information they need. It starts with the basics of groundwater, then shows how to plan for it, manage it, protect it, and learn from real examples. The main message is that groundwater can provide reliable water for communities, but only if it is properly planned, looked after, and included in everyday municipal decision-making.

Chapter 2 explores municipal groundwater use and related management challenges. Many municipalities rely on groundwater as a primary or supplementary source, yet its role remains insufficiently integrated into planning and regulation frameworks. This chapter discusses legal frameworks, responsibilities, water-use authorisations, and development plans. It illustrates various municipal schemes, from simple boreholes to complex wellfield systems, and case studies suggest that issues often arise from poor governance, infrastructure shortcomings, and inadequate monitoring and maintenance rather than water scarcity. **Part A underscores the vital role of municipalities in ensuring groundwater sustainability, highlighting the need for stronger capacity, clearer regulations, and better planning and maintenance to deliver reliable, safe groundwater services.**

Part B outlines the strategic and institutional foundations essential for sustainably managing municipal groundwater resources. It primarily targets municipal managers, councillors, planners, and catchment managers, emphasising the importance of integrating groundwater into formal planning, governance, budgeting, and decision-making frameworks, rather than perceiving it as a temporary or emergency water source. In Part B, the chapter aims to: (i) translate national policy and legislation into actionable initiatives at the municipal level, (ii) facilitate informed decision-making and prioritisation of budgets, and (iii) reinforce governance systems to ensure the proactive and sustainable management of groundwater resources. Throughout all risk themes, Chapter 4 consistently underscores enabling factors, including:

- Appointment of hydrogeologists within municipalities

- Formal platforms for stakeholder engagement
- Robust monitoring and data management systems
- Integration of groundwater into municipal performance, budgeting, and risk frameworks

Part B indicates that sustainable groundwater utilisation is chiefly a matter of governance and strategic planning. Municipalities that demonstrate excellence are those that:

- Incorporate groundwater into formal planning and budgeting
- Harmonise policies and bylaws across sectors
- Invest in institutional capacity, monitoring, and data
- Regard groundwater as a strategic, shared public resource, not an emergency fallback

Many groundwater scheme failures stem from governance, planning, funding, and maintenance weaknesses, not simply a lack of groundwater.
Sustainable groundwater supply depends on proper hydrogeological assessment, monitoring, data management, abstraction control and routine operation and maintenance.

Part C provides pragmatic and operational guidance for the formulation, diagnosis, implementation, and management of municipal groundwater schemes. It translates policy and strategy into practical tools, standard operating procedures (SOPs), and decision frameworks that municipalities can employ in the field to ensure the sustainable utilisation of groundwater resources. Part C is directed towards water resource planners, groundwater scheme engineers, and municipal technical staff, with the objectives to:

- Prevent and diagnose low or declining borehole yields
- Manage over-abstraction
- Address operation and maintenance (O&M) failures
- Protect groundwater from pollution, vandalism, and saline intrusion

Part C further frames groundwater management as a technical, operational, and institutional responsibility, not solely an emergency measure. The sustainability of municipal groundwater supply is contingent upon:

- Sound testing and diagnostics
- Proactive operation and maintenance (O&M) of groundwater infrastructure
- Strong abstraction control
- Infrastructure and aquifer protection
- Continuous monitoring

Part D offers practical, on-site guidance on establishing, operating, and maintaining groundwater supply schemes. It is intended for borehole practitioners, municipal technicians, operators, and engineers, providing strategic guidance by emphasising daily technical decisions and operational controls. This section translates groundwater policy and planning into SOPs that adhere to SANS 10299. The primary objective is to ensure that groundwater schemes:

- Deliver reliable water supplies
- Operate within sustainable yield limits
- Are protected from avoidable failures caused by poor testing, over-abstraction, and weak O&M

Municipalities need to integrate groundwater into IDPs, WSDPs, budgets, bylaws, spatial planning and performance systems.
Municipalities need stronger technical capacity, including hydrogeological expertise, operator training and standard operating procedures.

Part D emphasises that technical competence, consistent monitoring, and disciplined operations are essential for sustainable groundwater management schemes:

- Base pumping on tested sustainable yields
- Detect problems early through monitoring
- Maintain infrastructure proactively
- Integrate water quality, abstraction, and O&M into daily operations

Groundwater reliability, the part concludes, is engineered and managed—not accidental.

Part E focuses on individual groundwater users, defined primarily as Schedule 1 users under South African water law. These include households, smallholdings, farms, schools, clinics, and businesses that abstract groundwater for domestic, small-scale agricultural, or non-commercial purposes. Part E aims to help individual users understand groundwater behaviour, comply with municipal and legal requirements, and manage their boreholes to avoid negative impacts on neighbours, ecosystems, and municipal water systems. Its purpose is to ensure that individual users: (i) recognise that groundwater is a shared resource, and (ii) manage abstraction responsibly to avoid conflict, over-abstraction, and pollution.

Part F highlights the geological, hydrological, and climatic factors that influence the occurrence, movement, storage, and quality of groundwater in

South Africa. By defining the main aquifer types and hydrostratigraphic regions, the chapter provides the fundamental concepts needed for effective groundwater planning and management. South Africa's groundwater resources vary greatly and are mainly governed by geology. Most aquifers are fractured or karstic, with limited primary porosity, low and often sporadic recharge, and significant spatial heterogeneity. Consequently, groundwater yields, sustainability, and vulnerability to contamination can vary considerably over short distances. Understanding these traits is vital, as incorrect assumptions about aquifer behaviour can lead to failed boreholes, declining yields, deteriorating water quality, and long-term resource degradation. This emphasises the importance of developing detailed conceptual site models, supported by suitable geological, geophysical, hydraulic, and water-quality data, as the foundation for all groundwater decision-making.

Part G provides the hydrogeological foundation needed to interpret groundwater potential, limitations, and risks across South Africa's main aquifer systems. It explains how geology, aquifer type, recharge conditions, structural controls, and water quality influence the availability and sustainability of groundwater resources. By linking national hydrostratigraphic context to municipal planning and scheme operation, the chapter helps practitioners understand why groundwater development must be based on local aquifer behaviour rather than generic assumptions, and why conceptual site models, monitoring data, and professional interpretation are essential for reliable groundwater decision-making.

PART A

2. BASICS OF GROUNDWATER

To understand groundwater, it is important to understand the area's geology, geomorphology and climate. The geological layers that underlie a site strongly influence groundwater storage and flow. The rock formations may be horizontal, inclined, folded, and even intersected by vertical layers. These dynamics affect how water flows through the rocks.

The Department of Water and Sanitation (DWS) has developed an online groundwater dictionary. The dictionary defines all the groundwater terms; some of the most common ones are repeated in Box 2.

Box 2: Groundwater dictionary [2]

Groundwater	Water is found in the saturated zone below the water table.
Aquifer	A geological formation which has structures or textures that hold water or permit appreciable water movement through them.
Water table	The upper surface of the saturated zone of an unconfined aquifer at which pore pressure is equal to that of the atmosphere.
Saturated zone	The subsurface zone below the water table where interstices are filled with water under pressure greater than that of the atmosphere.

The Water Research Commission (WRC) has produced a publication, *Groundwater: The myths, the truths and the basics*, which addresses questions such as:

- How does groundwater move?
- Is groundwater really safe to drink?
- How can groundwater be polluted?
- Can a borehole really dry up?
- Can my neighbour's groundwater use affect my groundwater source?
- How do we find groundwater?
- Where is groundwater used in South Africa?

Hydrogeologists develop **conceptual site models** (Box 3) to identify rock formations and their defining characteristics, thereby determining whether they can be classified as aquifers, aquicludes, or aquitards. An **aquiclude** is a geologic material, stratum, or formation that contains water (i.e., has

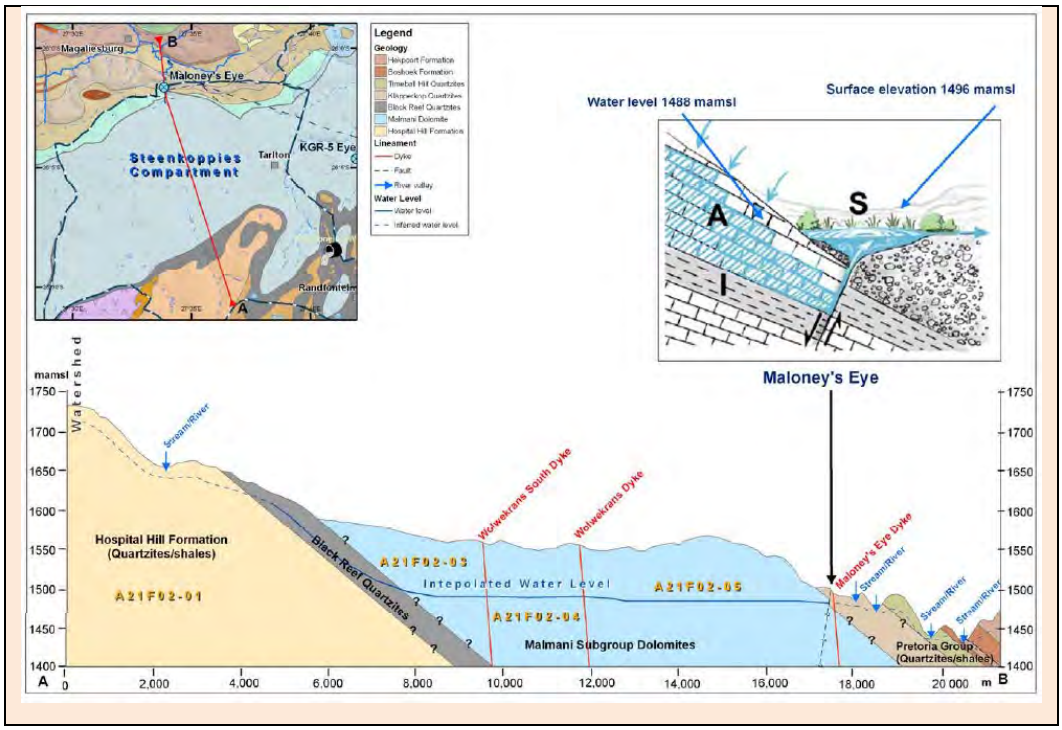
porosity) but does not transmit it (i.e., has zero or negligible permeability). **An aquitard** is a geologic material, stratum, or formation of low permeability (a confining unit) that transmits significant amounts of water only at a regional scale or over geologic time [3]. Box 4 illustrates an example of Maloney's Eye conceptual model, based on a south-north cross-section.

Box 3: Conceptual site model

A **conceptual site model** summarises the key characteristics of subsurface geological layers in an area. It is used to determine the aquifer's position, the presence of overlying confining units, and the likely mechanisms of groundwater storage and flow. The conceptual site model provides an initial indication of aquifer type, potential yield, and accessibility, and establishes a working hypothesis by outlining the relationships between contamination source areas, transport pathways, and potential receptors.

Box 4: An example of Maloney's Eye conceptual model [4]

An example of **Maloney's Eye conceptual model**, based on a south-north cross-section, is illustrated [4]. The Steenkoppies dolomitic compartment is directly adjacent to the Cradle of Humankind World Heritage Site, which forms part of the Zwartkrans dolomitic compartment. Understanding the Zwartkrans compartmentalised karst aquifer has become crucial since the first mine water started to decant in August 2002. Similarly, the Steenkoppies compartment has garnered significant attention since the naturally discharging spring, known as “Maloney’s Eye,” reached its lowest recorded flow. To aid visualisation, a section was drawn from south to north crossing the Steenkoppies dolomite compartment. Maloney’s Eye is located at the intersection of the Maloney’s Eye dyke and the east-west striking fault zone. Based on the digital elevation model, the Eye's surface discharge site lies above the groundwater level of the dolomite drainage area. The Eye is situated within the shales and quartzites of the Rooihoogte/Timeball Hill Formations; thus, its existence could be attributed to a low-permeability dyke and the fault zone crossing, which serve as the main water conduit from the dolomite into the shales and quartzites. The spring's recharge area likely includes the quartzites and shales of the Witwatersrand Group, extending farther south than the Steenkoppies dolomites. Significant inflows from other sources, such as effluent return flows and surface drainage from Brandvlei, form the allogenic recharge component of the Steenkoppies compartment. Within this compartment, the Wolwekrans dyke and the Wolwekrans south dyke show minimal differences in water elevation. Based on high transmissivities identified through pumping tests and gravity lows, these dykes are expected to be impermeable. Consequently, large-scale abstractions within the groundwater unit will also affect Maloney’s Eye discharge, given the flat hydraulic gradient and the interdependence among groundwater units.



Aquifers may be classified according to their hydraulic conditions. **Unconfined aquifers** are open to the ground surface and atmosphere and are characterised by a water table (phreatic surface). **Confined aquifers** consist of permeable layers bounded by low-permeability strata; they are fully saturated and pressurised, with hydraulic head indicated by a piezometric level. **Semi-confined aquifers** exchange water with adjacent aquifers through intervening aquitards. **Perched aquifers** are isolated groundwater bodies that occur above an aquiclude or aquitard, with unsaturated conditions beneath them.

You must understand groundwater before you can manage it. Geology, aquifer type, recharge, storage, flow paths and local conditions determine whether groundwater can be used sustainably.

Once underground, water moves at rates ranging from a few metres per day to a few centimetres per century. Compare this with the streamflow velocity measured in metres per second. It can take a few days or tens of thousands of years for groundwater to discharge to the surface as springs, via evapotranspiration, as baseflow to rivers, or artificially via boreholes [5].

The difference between an appropriate or efficient borehole yield and an aquifer's sustainable yield can cause considerable confusion. The yield of a borehole is similar to how much water can flow through a dam outlet. The larger the dam outlet, the greater the flow. However, the outlet's size tells you nothing about the dam's sustainable yield. That depends on the dam's

storage capacity and the streamflow to the dam. The yield of a borehole is determined by the size of the openings within a few metres of the borehole. The more openings there are, and the larger they are, the higher the borehole yield will be. Whether this yield is sustainable depends on the size of the underground storage system from which the borehole draws water, how much rainfall replenishes it, and who else is pumping water from the system [5].

In South Africa, fractured aquifers are the most common. Intergranular aquifers are restricted to coastal areas and river alluvium. Karst aquifers are found in the dolomitic areas (Figure 3).

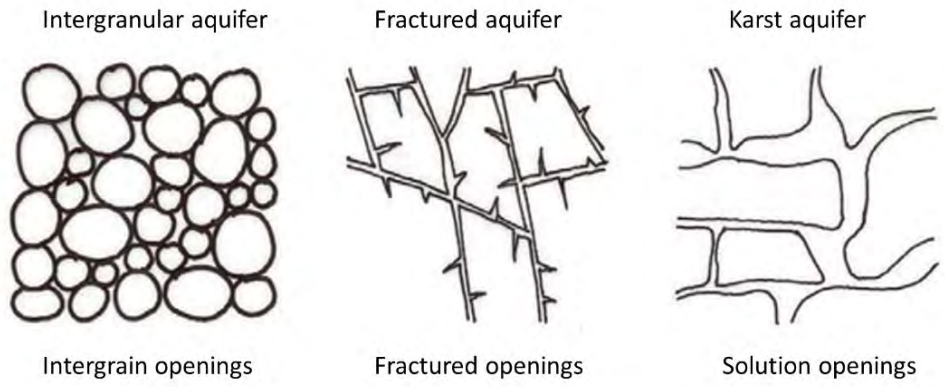


Figure 3: **Types of aquifers** **[6]**

Intergranular aquifers, also known as unconsolidated or primary aquifers, store groundwater within the pore spaces between individual particles of gravel, sand, and silt. The ability of these aquifers to yield water largely depends on the size and connectivity of their pore spaces, which allow groundwater to move and be extracted.

In highly fractured rocks, groundwater can be stored and transmitted through networks of cracks and fissures, forming **fractured aquifers**. The effectiveness of these aquifers depends on the rock's hydraulic conductivity, meaning that sufficient permeability is required for water to move through the fractured system and be accessible for abstraction.

Karst aquifers develop within water-bearing layers of soluble rocks, such as limestone and dolomite. In these systems, groundwater flow concentrates along fractures, fissures, conduits, and other interconnected openings enlarged by chemical dissolution. This process occurs when slightly acidic water reacts with the rock, gradually dissolving it and creating extensive underground drainage networks that characterise karst terrain.

Some aquifers exhibit both **intergranular and fractured characteristics,** also known as **double-porosity aquifers**. Pores and fractures allow both diffuse and conduit flow, increasing storage and productivity. Double-porosity aquifers exhibit a unique hydraulic response that distinguishes them from simple intergranular or fractured aquifers.

Since groundwater is invisible to the naked eye, it is easy to assume that everything underground is fine. "**Out of sight, out of mind**" or the "**invisible resource**" are phrases used to describe this attitude towards groundwater. The threats to groundwater, such as over-abstraction and pollution, can be just as unseen as the groundwater itself. Therefore, understanding and addressing these threats are especially important. [5].

a) **Over-abstraction:** The most obvious outcome of over-abstraction is the depletion of groundwater reserves and the drying up of boreholes. However, even before reaching this point, groundwater reserves exploited at unsustainable rates may cause problems such as:

- Borehole yields are reduced as water levels fall, increasing the cost of pumping and the cost of water
- Shallower boreholes supplying other people, often the economically disadvantaged people, dry up
- Land subsidence
- Intrusion of seawater into coastal groundwater reserves
- Fresher water is replaced by saline water from deep underground
- Ecosystems dependent on being fed by groundwater are damaged or destroyed
- A perception that groundwater per se is inherently unreliable and is the cause of the problems, rather than over-abstraction

In many cases, the damage from over-abstraction is irreversible.

b) **Pollution:** Groundwater is generally better protected from pollution than surface water. The filtering effect of groundwater flow, combined with the long time it spends underground, usually keeps groundwater free of disease-causing microorganisms. However, once groundwater becomes polluted, it is much harder to clean up than surface water. A river can cleanse itself, but an aquifer largely cannot, and human remediation efforts are often costly, ineffective, and sometimes impossible.

Pollution comes from two main categories of sources: point sources and diffuse, or non-point, **sources**. Examples of point sources include landfills, leaking petrol storage tanks, leaking septic tanks, and accidental spills. Infiltration from farmland treated with pesticides and fertilisers is an example of a non-point source. Municipal landfills and industrial disposal sites are among the more significant point sources.

Groundwater often spreads the effects of dumps and spills far beyond the site of their original contamination.

Whether over-abstraction or pollution is the cause, the problem is often similar: severe damage that is difficult or impossible to repair. The motto "prevention is better than cure" applies especially to groundwater. There are no "quick fixes."

2.1. UNLOCKING THE POTENTIAL OF GROUNDWATER

Enhanced and sustained investment, economic growth, and poverty alleviation in South Africa depend on the effective utilisation of all available water resources. Groundwater is recognised as a significant resource under the National Water Act, but has been neglected in management, and its value has been underestimated (Box 5). To use groundwater as a key resource, it will require increased initial investment in infrastructure, institutions, and capacity to ensure water security.

Box 5: From private water to public water

Since the democratisation of the country in 1994, groundwater's role in South Africa has undergone a **major change from an undervalued resource** with a 'private water legal status' to a source of domestic water and general livelihood as public water to more than 50% of communities in thousands of villages and small towns countrywide as part of the national drive to meet basic water needs [7].

2.2. INVESTING IN GROUNDWATER RESOURCES

A substantial amount of groundwater remains unused. The available yield of groundwater resources for development in South Africa is 7,500 million cubic metres per year (m^3/a), accounting for physical constraints on extraction, potability, and maximum permissible drawdown. Current usage ranges between 3,000 and 4,000 million m^3/a. Therefore, there is significant potential to greatly increase groundwater supplies in South Africa. Currently, only about 50% of available groundwater resources are utilised.

An additional 3,000 m³/a of groundwater resources could be developed [7].

Groundwater is a strategic water resource, not a backup option. It supports rural communities, towns, agriculture, ecosystems and urban water supply, and should be planned and managed as part of South Africa's long-term water security.

Groundwater supplies meet the needs of rural communities. Since 1994, most rural areas have depended on groundwater resources. More than 80% of rural communities in KwaZulu-Natal and the Northwest Province get their water from groundwater sources, and over 50% of rural communities in the Eastern Cape Province do the same. This access to groundwater is a crucial factor supporting sustainable livelihoods in many of these communities. Groundwater has significant potential to serve even more communities in areas where large bulk water infrastructure is lacking and arid conditions dominate.

Groundwater is not solely used for rural water supply. While its importance for rural areas is recognised, its role in urban water supply cannot be overlooked. For instance, the City of Tshwane sources a substantial portion of its water from boreholes and springs (Figure 4), which is mixed with surface water in the bulk distribution system. Over 60% of the water in the Capricorn District Municipality comes from groundwater resources. The City of Cape Town is planning to develop future water supplies from the Cape Flats and Table Mountain Group Aquifer systems. Major aquifers and potential drilling areas near the Nelson Mandela Municipality have also been identified, with groundwater capable of supplying approximately 20% of the municipality's current needs. Large towns such as De Aar and Mahikeng depend entirely on groundwater resources.



Figure 4: **City of Tshwane fountains were the only water source from 1855 until 1935, and today provide 10 % of the city's water supply (photograph courtesy of Jeff Davies)**

The combined use of surface and groundwater enhances overall water security. Developing and managing water resources to ensure water security remains central to pursuing growth, sustainable development, and poverty reduction. Conjunctive use of surface and groundwater resources involves the coordinated operation of a groundwater basin and a surface-water system to increase total water supplies and improve water-supply reliability. This approach is based on the principle that utilising surface water when it is abundant, recharging aquifers, and conserving groundwater supplies during wet years will ensure water availability for pumping in dry years.

Artificial Recharge involves moving surface water underground for storage in an aquifer during wet years (Figure 5). The DWS Artificial Recharge Strategy acknowledges that underground water storage is an efficient method because it is not susceptible to evaporation losses and remains relatively safe from contamination. The Strategy highlights regions suitable for artificial recharge. The total excess water that can be stored in this way is estimated at 7,944 million cubic metres [8].



Figure 5: **The City of Windhoek uses large-scale water banking to augment the town's water supply [9]**

Groundwater is important for food security. A key component of South African agricultural policy is increasing the incomes of the poorest groups in society by expanding opportunities for small- to medium-scale farmers. Most of these farmers depend entirely on groundwater for domestic and agricultural use. Examples of this include:

- Polokwane farming community
- Bainsvlei irrigation systems just outside Bloemfontein
- Bapsfontein/Delmas irrigation farmers' abstraction from the dolomites

Groundwater plays a vital role in the environment. Many ecosystem services are directly connected to groundwater storage, recharge, and discharge. However, the interdependencies between these services and groundwater are often unrecognised and undervalued in decision-making and in the management of water resources and river basins. Typically, groundwater is viewed as outside the scope of the ecological reserve[1], except where its discharge supports surface water bodies. This overlooks an important shortcoming in current legislation, as groundwater provides

[1] The ecological reserve relates to the water required to protect and sustain the aquatic ecosystems to secure ecologically sustainable development and water use. https://wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/WaterWheel_2008_01_Kidz%20p%2028-29.pdf

many ecological functions. Wetlands often act as zones where groundwater discharges. For instance, Lake Sibaya in KwaZulu-Natal relies on nearby aquifers (Figure 6). Additionally, groundwater may be crucial in maintaining habitats for freshwater organisms in Lake St Lucia during periods of high salinity. It supplies baseflow to rivers, helping them during low-flow periods. A clear example of a riverine ecosystem sustained by groundwater discharge is the Sabie-Sand River system.



Figure 6: **The southern basin of Lake Sibaya (photograph courtesy of Sue Van Rensburg) [10]**

2.3. GROUNDWATER RESOURCES THREATS

Pollution is threatening groundwater resources. South Africa's groundwater supplies are increasingly threatened with contamination by various sources. For example:

- The coal mining industry in South Africa is a mature industry with a large number of closed collieries. Although many of these collieries closed some time ago, no rehabilitation or remediation has occurred. Groundwater pollution includes acidification and increased concentrations of pollutants such as sulphates and heavy metals.
- Over the past decade or so, many gold mines in the Gauteng region have closed, and dewatering operations have ceased. In abandoned mining areas, the subsequent rise in water table has led to significant groundwater pollution from acid mine drainage (AMD). AMD results from the oxidation of metal sulfides and is characterised by elevated heavy metal concentrations, high sulfate concentrations, increased electrical conductivity, and lower water

pH in the mining area. It can also lead to radioactive material pollution.

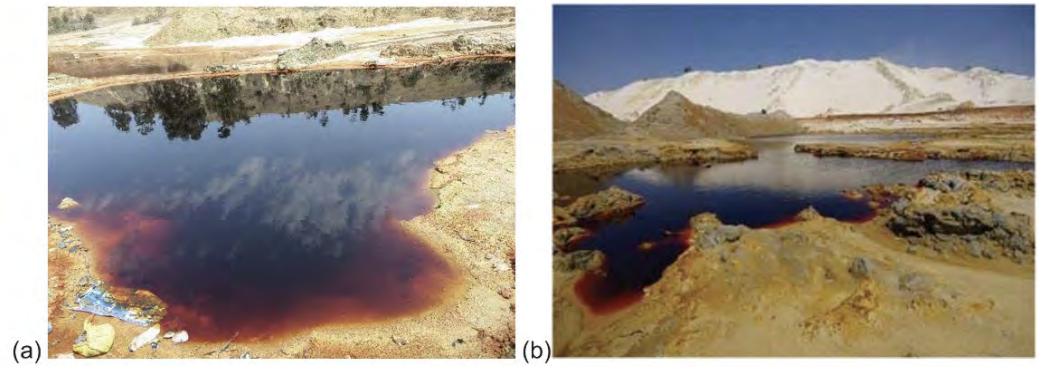


Figure 7: **AMD formed on the tailing dumps in the (a) Central Rand basin, (b) West Rand basin of the Witwatersrand goldfields. The deep red colouration shows the presence of a high Fe^{3+} concentration [11]**

- In urban areas, the indiscriminate use of chemicals and the generation of wastes at both the domestic and industrial levels tend to concentrate potential sources of contamination. In this regard, organic contaminants are a high-priority class of contaminants with inadequate controls or regulation. Most aquifer systems in South Africa's urban areas have been degraded to some extent.
- Agriculture is the biggest user of groundwater and also contributes to diffuse contamination. Nitrate is the most common agricultural contaminant, and pesticides and herbicides may pose problems in some areas. Groundwater salinity has also increased in irrigated areas, such as the Vaalharts Irrigation Scheme and the Great Fish and Sundays River Basin.

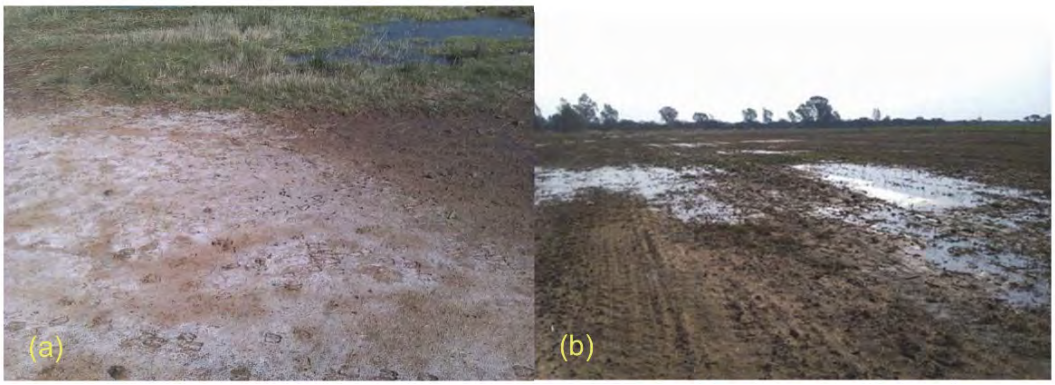


Figure 8: **Areas visited at Vaalharts showing (a) salt accumulation and (b) waterlogging [12]**

Over-abstraction of groundwater resources in some regions is causing declining water levels. The Dendron aquifer is a classic example of groundwater over-abstraction in South Africa. Water levels have dropped more than 50 metres in the last 30 years. In the Tosca Molopo area, abstraction from high-yielding deep boreholes has led to regional declines of 10 to 20 m and locally up to 60 m in water levels due to intensive irrigation. The lack of management of groundwater management is also evident in community water supplies, where, in some cases, groundwater is developed unsustainably. This leads to resource failure and puts communities at risk.

The impact of climate change on groundwater resources is unknown. Although predicting climate change impacts is complex, uncertainties in our predictions are gradually diminishing as international Global Climate Models continue to improve, and suitable techniques for downscaling these predictions from global to regional and catchment scales are being developed and refined. Predictions for southern Africa include rising temperatures and potential evaporation (evapotranspiration) rates, shifts in precipitation patterns, more frequent flooding and droughts, and, in coastal areas, sea-level rise. The implications for groundwater are unknown but may be considerable.

Groundwater capacity is lacking. Hydrogeology lacks technical capacity. This skills shortage is more pronounced in the public sector because the private sector attracts most of the available talent. The Ground Water Division of the Geological Society of South Africa can develop a sector-wide programme to leverage capacity and support the implementation of the Water for Growth and Development Strategy.

2.4. PROMOTING GROUNDWATER USE

Integration of groundwater into the National Water Resources Strategy (NWRS) (Box 6). The role groundwater plays in maintaining important surface water systems, riparian and other vegetation, and vital ecosystems is increasingly recognised, as is the fact that groundwater and surface water are intimately linked and form part of the same hydrological cycle. Aquifers can buffer surface-water variability and drought cycles because of their large storage capacity and long-time scales.

Box 6: NWRS and groundwater

The National Water Resource Strategy Third Edition (NWRS-3) acknowledges/recognises the integral role of groundwater in integrated water resources management in South Africa for the sustainable use and management of the country's water resources. As the country transitions towards a more Integrated Water Resource Management phase, groundwater must be recognised as a valuable resource by both land-use planners and municipalities [13].

Groundwater cannot be managed in isolation. The integration of all water resources needs to be considered in assessment and planning at the national and local scales. The National Water Act (NWA, Act 36 of 1998) and the National Water Resource Strategy (NWRS, DWAF 2004), which emerged from the National Water Policy of 1997, treat groundwater as part of an integrated water resource. Despite the policy drivers, South Africa is struggling to move towards integrated water resource management. Groundwater is a long-neglected resource, and elevating it to partnership status with surface water requires firm action to be meaningful. Unfortunately, groundwater is sometimes considered a problem rather than a valuable resource. **Management strategies will be needed to address the unique characteristics and roles of groundwater while preserving the concept of a common resource, in the context of both continuity within the hydrological cycle and national ownership of the resource.**

The DWs have led a strategic groundwater-focused intervention to inform the revision of the National Water Resources Strategy [7]. This strategic intervention is intended to guide not only policy-makers and regulators, but also the many user and service sectors, including the research and information sectors. The aims are:

- **Groundwater as a resource must be given its rightful status alongside surface water, helping to meet the growing water demand as a recognised strategic resource within an integrated water resource management approach**
- **The knowledge and use of groundwater must be increased, along with the capacity to ensure sustainable management**
- **Proactive groundwater management programmes must be developed and implemented at required water resource management levels, focusing on both quantity and quality aspects**

Critical interventions include:

- Exploiting groundwater resources will require investment in groundwater infrastructure to be established.
- At the same time, the water resource management institutions need to incorporate groundwater in planning, assessment and management.;
- Even though great strides have been made in the knowledge and understanding of South Africa's groundwater resources and groundwater potential, there are still many areas in which knowledge is deficient, e.g, quantification of surface-groundwater interdependencies; social, economic and ecological roles of groundwater; impacts of climate change on estimation of groundwater recharge; etc. The adequacy of current research in providing essential knowledge should be continuously assessed to intensify and/or refocus research investments.
- Skills and capacity need to be maintained and, in certain groundwater areas, expanded considerably. Urgent attention is needed to retain skills and capacity, especially in the public sector.

2.5. GROUNDWATER USE IN SOUTH AFRICAN MUNICIPALITIES

The current reliable yield of surface water at an acceptable assurance of supply is approximately 10,200 million cubic metres per annum (m^3/a) nationally, with the combined storage capacity of large dams being about 31,000 million m^3. Of the approximately 5,000 registered dams, the majority (3,832) are small (less than 12 m) and serve farms and municipalities. These smaller dams play a vital role in local water security and climate resilience. South Africa remains heavily reliant on surface water, and where additional water exists, such as in the uThukela, Mzimvubu, and Pongola basins, it is often located in areas far from existing demand centres. **Therefore, it is essential for South Africa to focus its water resource planning on improving integrated water resource management to ensure ongoing water security** (Box 7) [13].

Box 7: Diversifying the water supply mix

To balance supply and demand, South Africa must shift from the current water mix, which is dominated by surface water with some groundwater and return flows, to one that includes increased groundwater use, stormwater harvesting and reuse, desalination, and treated acid mine drainage (AMD).

Action emanating from the NWRS-3 relating to groundwater includes [13]:

- District and Local municipalities must appoint hydrogeologists to manage their aquifers, if necessary, in terms of appropriate regulation
- Review of municipal by-laws to ensure protection and sustainable management and use of groundwater
- Continuous review of groundwater tender documents to achieve continuity in approach and information from source development to O&M
- Undertake a councillor induction programme to inform and capacitate on the benefits of groundwater and the role it can play in water and sanitation service delivery
- Initiate formal training courses for groundwater personnel at the local level, from pump operators to technicians and managers
- Develop groundwater in a conjunctive manner with other local resources (such as surface resources, reuse, desalination and rainwater harvesting
- Apply operation and maintenance of groundwater infrastructure by the local municipality (WSA or WSP) and the conservation and protection of their groundwater sources to achieve sustainable water service provision, from local groundwater resources

Rising water demand and extreme climate conditions have forced municipalities to consider multiple water sources (Box 8). **However, the important role of groundwater as a buffer against water deficits and as a means of ensuring basic water services for many is poorly integrated into policy and institutional frameworks. Despite this, groundwater supplies at least 78.5% of communities in South Africa, equating to an estimated 34.1 million people.**

Box 8: The importance of groundwater to water utilities

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 [14]

2.6. LEGAL FRAMEWORK FOR GROUNDWATER MANAGEMENT

The **National Water Act of 1998** [15]and associated regulations recognise the strategic importance of groundwater and treat it as an integral part of the hydrological cycle. In practice, groundwater is an essential component of water management and supply programmes, and municipalities have developed many water supply schemes that utilise groundwater. However, schemes often fail due to insufficient knowledge and mismanagement, leading municipalities to deem groundwater resources unsustainable**. Limited access to groundwater in many parts of South Africa is more about infrastructure issues than the physical availability of groundwater resources** ([16], [17]).

Box 9: The National Water Act and groundwater

The National Water Act, which emerged from the National Water Policy of 1997, has become the cornerstone of groundwater governance in South Africa and is based on three pillars: social equity, economic efficiency, and environmental sustainability. The fundamental principles and objectives of South Africa's water law, with implications for groundwater, are that:

- All water resources are common to all (water considered as a public asset), and are subject to national control (trusteeship vested in the state)
- All water has a consistent status in law, irrespective of where (and where in the water cycle, including groundwater) it occurs
- Groundwater is an integral part of the water resource and must be managed as such (supporting the principles of IWRM: groundwater should not be seen in isolation).

The DWS gazetted **draft regulations on groundwater resource protection** and sustainable management, inviting public comment. Developed under the 1998 National Water Act, the proposed new

regulations focus on: (i) identifying and controlling certain activities related to the drilling and management of boreholes and aquifers; (ii) setting the necessary general and specific requirements, practices and standards; (iii) improving groundwater resource data and information management by providing for: groundwater user geosite registration, driller and pump installer registration, (iv) the creation of a system for capturing: borehole drilling and geosite information, as well as geohydrological information and reports, and (v) streamlining the South African National Standards for groundwater management, drilling and pump testing.

The **Water Services Act 108 of 1997** and the National Water Act 36 of 1998 provide the framework for delivering water services and set out 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 [18].

Box 10: The role of government in water supply and sanitation

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
- South African law recognises that, due to a lack of resources, the 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 [19]

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 [20]:

- **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 property's extent, such as on various smallholdings. Groundwater abstractions for bulk water supply, mine dewatering, and irrigation schemes fall under 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.

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)”. Under the Water Services Act, water services authorities (municipalities) are responsible for ensuring access to water services. Water services authorities (through water services providers) must ensure access to both water supply and sanitation services ([18], (Box 11).

The minimum standards and indicators for water services in South Africa relevant to groundwater are [21]:

- 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.

Box 11: High Court ruling secures water rights for Klipgat C community [22]

The Court order declared the Madibeng Local Municipality's failure to provide a basic water supply to the residents of Klipgat C unconstitutional and in contravention of the Water Services Act 108 of 1997 and its regulations.

The order compels the Madibeng Local Municipality (the Municipality), or, if it is under administration, the MEC of Local Government and Human Settlements, to take immediate and concrete steps to ensure that the Klipgat C community in the North West Province receives a permanent, sufficient, safe, and accessible water supply. Provide a permanent water supply to the Klipgat C community. This victory is the culmination of years of advocacy and litigation to secure the residents of Klipgat C's constitutional right to access sufficient, safe, and reliable water.

Background

The residents of Klipgat C have endured severe hardship for over a decade, surviving on irregular, insufficient water deliveries, often forced to walk long distances to collect water from unsafe sources. Vulnerable groups, including the elderly, children, and persons with disabilities, have been disproportionately affected, with many using their social grants to buy water or pay others to fetch it. The lack of water has undermined basic hygiene, health, dignity, and children's ability to study and thrive.

Despite previous court orders and repeated interventions by the South African Human Rights Commission, the Municipality failed to comply with its constitutional and statutory obligations. Infrastructure installed in parts of Klipgat C remained unused due to the absence of a connection to bulk water supply.

The Court's order

The Pretoria High Court has declared the Municipality's failure to provide basic water supply to Klipgat C as unconstitutional and in contravention of the Water Services Act, 1997, and relevant regulations. The order directs the Municipality, or the MEC for Local Government and Human Settlement if the Municipality is under administration, to:

- Install a permanent water supply system that provides at least 25 litres of water per person per day or 6 kilolitres per household per month, with water sources located within 200 metres of every household.
- Ensure the water supplied is safe for human consumption, in accordance with national standards.

- Increase interim water deliveries to Klipgat C to three times a week and disinfect water trucks and tanks monthly, until the permanent system is operational.
- File detailed implementation plans and progress reports with the court within 60 days of the order. The plan must include proposed timelines, procurement processes, the officials responsible, and the connection date for the permanent system.
- File quarterly progress reports with the Court and Applicant explaining the steps taken and progress achieved in implementing the order.

If the Municipality fails to comply and is not under provincial administration, the Minister of Water and Sanitation must invoke sections 63(4)–(7) of the Water Services Act to intervene and assume the necessary functions to secure compliance. Should the Municipality already be under administration and the MEC fails to act, the Minister is likewise compelled to intervene. Should the Municipality or MEC fail to comply, the Minister of Water and Sanitation is empowered to intervene and assume responsibility for implementation.

Constitutional and human rights significance

This order reaffirms the fundamental right of access to sufficient water, as enshrined in section 27 of the Constitution, and the interconnected rights to dignity, equality, health, and the best interests of children. The court recognised the severe and ongoing violation of these rights and the urgent need for effective remedies.

The order sets a precedent for holding municipalities and other organs of state accountable for service-delivery failures and ensuring that vulnerable communities are not left behind. It also underscores the importance of judicial oversight and structural interdicts in vindicating constitutional rights.

This Water Services Act legally recognises boreholes and wells as official water services infrastructure. It means that any groundwater abstraction point operated by a municipality or provider must comply with the Act's standards and regulations. Water supply services involve extracting groundwater from an aquifer, treating it if necessary, and distributing it to consumers. Similarly, sanitation services are vital for protecting groundwater, as poor sanitation facilities (e.g., leaking pit latrines) can contaminate groundwater. The Water Services Act regulates groundwater, not by controlling the volume of water extracted (which is covered by the National Water Act), but by overseeing infrastructure and the quality of services provided to the public.

Every water services authority has to prepare a **water services development plan (WSDP)**. 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 [18].

Every water services authority must draft bylaws to provide water services [18]. Examples of by-laws are given in Table 1.

Table 1: Groundwater by-laws tools [23]

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 on 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 guidelines for development permit areas
Zoning for groundwater protection	• Regulates the 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 is 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 progresses 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 on 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 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 a 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 consider cumulative impacts of incremental development

The Local Government: Municipal Systems Act (Act 3 of 2000) outlines the key processes for planning, managing performance, mobilising resources, and engaging partnerships that municipalities can utilise to ensure service delivery. The **Integrated Development Plan** (IDP) is the primary tool for achieving this, acting as a five-year strategic plan that guides all municipal planning, budgeting, and development. The IDP must include a WSDP, which serves as the municipality's detailed roadmap for providing universal, affordable, and sustainable access to water and sanitation services within its area. A municipality may choose to supply water directly (through an internal mechanism) or enter into a Municipal Service Partnership with an external provider, such as a water board or a private company. This process often involves a formal assessment, sometimes called a **Section 78 process**, to determine the most suitable

delivery model. Among the 257 municipalities in South Africa, a review of the municipal IDPS revealed that at least 137 municipalities are using or planning to use groundwater (Table 2).

Table 2: Number of municipalities that use or plan on using groundwater based on their IDP

Province	Number of Municipalities
Eastern Cape	18
Free State	17
Gauteng	11
Kwa Zulu Natal	16
Limpopo	9
Mpumalanga	19
North-West	9
Northern Cape	16
Western Cape	22
Total	**137**

The **Natural Scientific Professions Act, 2003** (Act No. 27 of 2003), is the primary legislation establishing and governing the South African Council for Natural Scientific Professions (SACNASP) and the registration of natural scientists in South Africa. SACNASP is the legally mandated body that registers and regulates the professional practice of groundwater scientists. The Natural Scientific Professions Act requires natural scientists practising in a consulting capacity to be registered with SACNASP. SACNASP also requires registered professionals to maintain and update their skills through Continuous Professional Development (CPD). Registered persons are obliged by their Code of Conduct to practice strictly within their area of competence and to maintain and enhance this competence throughout their careers.

2.7. OVERVIEW OF GROUNDWATER SCHEMES IN SOUTH AFRICAN MUNICIPALITIES

While the national government, through DWS, is accountable for groundwater resource management, municipalities are the critical players on the ground. The municipalities are grappling with failing infrastructure, a surge in unregulated private drilling, and the complex task of crafting bye-laws that are both effective and legally sound. Their success in navigating these challenges is essential for South Africa's water security.

In South Africa, there are numerous groundwater schemes and technologies (Table 3). The groundwater schemes range from relatively simple spring protections and hand-dug wells equipped with ropes and buckets to more sophisticated handpumps and mechanised boreholes. Multi-borehole schemes with storage buffers and extensive reticulation serving large areas, characterised by complex operational and maintenance requirements, are at the upper end of the complexity spectrum. In a few cases, groundwater use evolved as part of planned urban water-supply development, e.g. Atlantis. The infrastructure that brings water to communities must always be kept functional. It has become clear that limited groundwater access in most areas is more often a function of infrastructure than of groundwater availability. Non-functionality of the infrastructure is also related to infrastructure vandalism [24].

Table 3: Types of groundwater schemes [24]

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 a 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 a 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.

2.8. GROUNDWATER SCHEMES

Chapter 8 illustrates the diversity of municipal groundwater schemes in South Africa and the different management lessons they provide. The Mogwadi and Mahikeng examples show how productive aquifers can become stressed where abstraction, especially for irrigation and municipal supply, exceeds recharge and where governance, monitoring, and enforcement are weak. Garies demonstrates the importance of water quality management in arid basement aquifers, where sufficient groundwater may be available but salinity requires treatment before use. Albertinia highlights the value of combining springs and production boreholes, while also showing how poor wellfield layout, borehole interference, over-abstraction, and infrastructure constraints can reduce scheme performance. Atlantis provides a contrasting example of planned groundwater management through managed aquifer recharge, wastewater reuse, stormwater capture, aquifer protection, and wellfield operation as part of an integrated municipal water system. Beaufort West shows the vulnerability of fractured Karoo aquifers to drought, over-abstraction, infrastructure failure, water losses, water-quality variability, and vandalism.

Taken together, these case studies show that groundwater scheme reliability depends on more than the presence of groundwater. Sustainable

performance requires appropriate hydrogeological investigation, realistic yield estimates, well-designed borehole and wellfield layouts, reliable infrastructure, treatment where water quality is unsuitable, continuous monitoring of water levels and chemistry, and clear institutional arrangements for operation, maintenance, abstraction control, and aquifer protection. The examples also show that municipalities should incorporate groundwater into water supply planning as a strategic resource, rather than treating it as an emergency or temporary source.

2.9. THREATS TO MUNICIPAL GROUNDWATER DEVELOPMENT AND MANAGEMENT

The types of challenges municipalities face vary with individuals' unique experiences, knowledge, roles, and responsibilities, as well as landscape characteristics and socio-economic and socio-political contexts. Commonly cited challenges include:

- **Lack of education and awareness** – groundwater education is needed for significant groundwater users like farmers and municipalities to mitigate issues such as over-abstractions, poor borehole siting, and lack of monitoring and borehole registration.
- **Stakeholder perceptions** – persistent views that groundwater supply is an interim solution to mitigate drought impacts, despite the potential to be incorporated into water supply resilience planning.
- **Funding for groundwater development** – groundwater development and management have declined due to a greater focus on data collection and less on integration into existing municipal management systems and infrastructure. Schemes are implemented without adequate resource planning, thereby compromising the sustainability of operations and maintenance.
- **Water accounting tools** – tools used to account for groundwater use and impacts have limited capacity to reflect the systems that are being modelled accurately. Often, incorrect assumptions are made, leading to an underestimation of the implications.
- **Policy, legal, and institutional challenges** – institutional changes, policy shifts, and a lack of necessary drilling regulations have not supported the advancement of groundwater, although municipalities rely on groundwater. Current decentralised groundwater development makes it harder to enforce regulations,

and poor integration of the resource into resilience planning worsens the challenge.

- **Typical groundwater inquiries** – in general, groundwater users appear to be concerned about aquifer water quality and quantities, managing the resources sustainably, and matters related to regulatory compliance.

Additionally, there are shared perceived threats to groundwater use across South Africa's municipalities, with the most common cross-cutting threat identified by the IDPs presented in Figure 9.



Figure 9: **Cross-cutting threats to groundwater resources captured in municipal IDPs**

Steps remain to create an enabling environment for the sustainable protection and development of groundwater resources. Although groundwater use is widespread, relevant policies, regulations, and institutional structures and systems still do not adequately reflect the critical role of groundwater resources. For municipalities currently using, or planning to expand, groundwater use, an enabling environment must be established through reviewed policies, strategic plans, and frameworks. Alongside the threats identified in their Integrated Development Plans, municipalities also recognised several opportunities they can pursue to strengthen and optimise groundwater use, which include:

- Appointment of hydrogeologists in municipalities to guide project scopes and strengthen technical capacity.
- Implementation of monitoring programmes to support informed groundwater management.
- Introduction of groundwater-specific regulations, along with strengthened education and awareness initiatives.
- Expansion or rehabilitation of boreholes to improve groundwater availability (refurbish, re-equip, or expand use).
- Aquifer protection and recharge planning, including recharge-zone protection, catchment strategies and SWSA recognition.
- Strengthened partnerships and integrated planning through stakeholder collaboration and coordinated feasibility efforts.
- Support for agriculture and rural resilience through targeted programmes for farmers, schools and health facilities.
- Use of monitoring tools such as telemetry and water meters.
- Water conservation and demand management measures, including drip irrigation approaches.
- Implementation of managed aquifer recharge and conjunctive use strategies.
- Adoption of alternative energy solutions such as solar power for groundwater operations.
- Treatment and water quality improvement interventions, including rehabilitation of polluted aquifers.

PART B

3. STRATEGIC GROUNDWATER RESOURCE PLANNING, DEVELOPMENT AND GOVERNANCE

Groundwater is already an important part of water supply for many South African municipalities, but it is often not managed with the same level of strategic attention as surface water, bulk infrastructure or conventional municipal services. When municipalities treat groundwater only as an emergency source, they risk underinvesting in the planning, monitoring, technical capacity, and operation and maintenance systems needed to keep schemes reliable. This chapter therefore focuses on the governance decisions that determine whether groundwater becomes a sustainable municipal asset or remains a vulnerable and poorly understood source of supply.

Strategic groundwater management requires municipalities to connect technical groundwater information with policy, budgeting, land-use planning, infrastructure investment, water services planning and service delivery accountability. Decisions about borehole siting, abstraction, aquifer protection, water quality, drought response and infrastructure maintenance cannot be made in isolation from Integrated Development Plans (IDPs), Water Services Development Plans (WSDPs), spatial planning frameworks, bylaws, risk registers and performance systems. The chapter explains how these municipal instruments can make groundwater visible in everyday planning and decision-making.

The emphasis throughout this chapter is practical: municipalities need clear roles, adequate budgets, enforceable bylaws, reliable data, hydrogeological expertise, stakeholder engagement and routine monitoring to manage groundwater proactively. By strengthening these governance foundations, municipalities can reduce the risks of contamination, over-abstraction, drought vulnerability, vandalism, infrastructure failure and scheme collapse, while improving the reliability and resilience of local water services.

3.1. TARGET AUDIENCE

Part B is intended for municipal decision-makers and governance actors who influence how groundwater is planned, funded, regulated and

monitored. This includes Municipal Managers, Councillors, Water Services Authority and Water Services Provider managers, catchment managers, municipal planners, environmental managers, infrastructure and engineering managers, finance and budgeting officials, and officials responsible for IDPs, WSDPs, bylaws, land-use planning, risk management and service delivery performance. The chapter is also relevant to senior technical staff and hydrogeological advisers who support strategic decision-making, because it explains how to translate groundwater considerations into municipal policies, programmes, budgets, governance systems and accountability arrangements.

3.2. PURPOSE

Chapter 3 aims to help municipalities move from recognising groundwater as a water source to managing it as a strategic municipal asset. It provides guidance for informed decision-making, translating national policy and legislation into municipal programmes, governance systems, bylaws, planning instruments and operational responsibilities. The chapter supports municipalities in setting strategic direction, prioritising budgets, defining institutional roles, strengthening accountability, and integrating groundwater into IDPs, WSDPs, spatial plans, risk registers, performance systems, and service delivery planning. It emphasises that sustainable groundwater management depends on coordinated governance, reliable data, hydrogeological expertise, stakeholder engagement and proactive investment, rather than ad hoc or emergency responses.

3.3. QUESTIONS FOR CONSIDERATION

The following questions are intended to help municipalities assess how visible, coordinated and practical groundwater management is within their current planning and governance systems. They provide a starting point for identifying gaps in policy, bylaws, institutional capacity, data, monitoring and cross-departmental coordination. By working through these questions, municipalities can clarify whether they treat groundwater as a strategic water-supply resource and whether the necessary controls, responsibilities, and support systems are in place to manage it sustainably.

- Is the municipality using or planning on using groundwater in the future?
- Does the municipality have bylaws for groundwater protection, development and management?

- Do related policies and by-laws, e.g., for stormwater management, sanitation services and spatial planning, support or conflict with groundwater resource protection and development?
- Does the municipality have the necessary knowledge, skills and capacity to support groundwater schemes within its jurisdiction?

All District Municipalities and some Local Municipalities are designated as Water Services Authorities (WSAs). These WSAs oversee water supply and sanitation responsibilities and are authorised to sign contracts with Water Service Providers (WSPs). Each WSA must develop a Water Services Development Plan (WSDP) to ensure efficient, affordable, and sustainable access to water. Consequently, both Districts and Local Municipalities must prepare Integrated Development Plans (IDPs) and WSDPs. However, Local Municipalities not designated as WSAs must develop Water Sector Plans within their IDPs.

The WSDPs offer only general comments on groundwater quantity and accessibility in the respective areas. They do not detail the potential availability or the technical difficulties involved in accessing the resource. They make little mention of groundwater quality. Additionally, groundwater monitoring requires urgent improvement.

Figure 10 presents a structured framework for integrating groundwater management into municipal planning and policy development. It outlines eight strategic focus areas, each with specific action items to ensure groundwater considerations are effectively incorporated into local government operations. This framework serves as a governance roadmap to help municipalities – whether cities or towns – transition from neglecting groundwater resources to actively managing them as a vital strategic asset for water security.

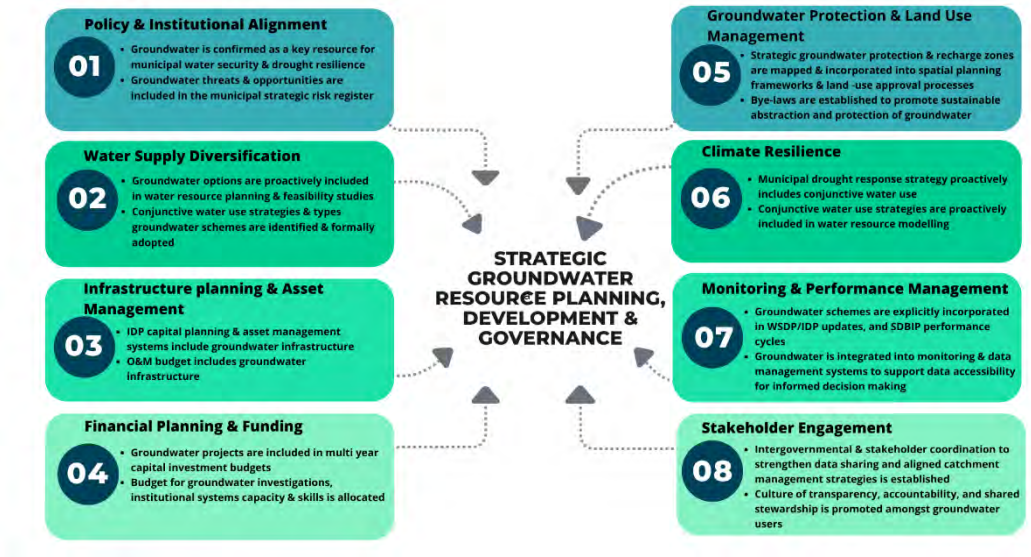


Figure 10: Strategic groundwater resource planning, development, and governance

3.4. GROUNDWATER INCLUSION IN WSDPS

Water Services Development Plans (WSDPs) are the main municipal instrument for translating groundwater requirements into practical service-delivery commitments. If groundwater is not clearly reflected in the WSDP, it remains vulnerable to fragmented planning, underfunding, weak monitoring and unclear accountability. This section sets out how municipalities can use the WSDP to recognise groundwater as part of the formal water supply mix, define the infrastructure and institutional arrangements needed to manage it, and align groundwater planning with broader water services, land-use, environmental and financial planning processes.

When groundwater is absent from, or only weakly described in, the WSDP, these planning commitments become difficult to achieve. The main threats arise when groundwater is treated as a secondary or emergency source rather than as a planned component of municipal water services. Poor WSDP integration can result in groundwater schemes being developed or expanded without reliable aquifer assessments, sustainable yield estimates, water quality information, abstraction controls, treatment requirements, lifecycle costing or long-term O&M arrangements. This creates a risk of maladaptation, where groundwater is relied on during drought or service failure without the governance, finance, monitoring and technical support needed to keep the source reliable.

These planning weaknesses are often compounded by infrastructure-related threats. Boreholes, pumps, pipelines, electrical equipment, telemetry, treatment units and reservoirs can fail because of vandalism, theft, poor asset management, delayed maintenance or lack of operator capacity. Weak WSDPs may also conceal risks such as dependence on single boreholes, absence of backup supply, incomplete asset registers, inadequate monitoring networks, unclear asset ownership, and insufficient protection of wellfields and recharge areas from pollution or incompatible land uses.

For this reason, the WSDP should be treated as the cornerstone of municipal water services planning for groundwater-dependent systems. It is a legally required plan that translates the objectives of the Municipal Systems Act and the Water Services Act into a practical, community-informed programme for providing reliable, affordable and sustainable water and sanitation services. For municipalities that use or intend to use groundwater, the WSDP should define groundwater's current and future role, the infrastructure needed to secure supply, the monitoring and protection measures required to manage risk, and the budget and institutional responsibilities needed for implementation.

The strategic intent follows directly from this role: groundwater must be planned, funded, operated and protected as part of the municipal water supply system, rather than treated as an informal contingency option. A groundwater-responsive WSDP should link national legislative requirements to local service-delivery priorities, identify the communities and systems that depend on groundwater, define the technical and financial support required, and make groundwater visible in municipal budgets, risk management, infrastructure planning, and performance reporting.

In practical terms, a WSDP that incorporates groundwater must go beyond merely listing boreholes. It should explain how groundwater contributes to the water balance, which aquifers or wellfields are used, how abstraction will be managed, what water quality risks exist, what monitoring is required, and how infrastructure will be operated, maintained, and protected. This requires integrated management, cross-sector collaboration and dedicated investment in data, technical capacity and routine O&M.

The following elements therefore provide a practical checklist for what a comprehensive groundwater-responsive WSDP should include:

- **Current and future consumer profile**: Identify communities currently reliant on groundwater (municipal boreholes or private

supplies) and project future demand that may require groundwater development

- **Type of services provided**: Detail the role of groundwater in the overall water supply mix, including the proportion of supply from aquifers, borehole locations, and yields
- **Infrastructure requirements**: Inventory existing boreholes, pumps, and treatment systems. Identify needs for new boreholes, rehabilitation of old ones, and infrastructure for conjunctive use (integrating groundwater with surface water) [35]
- **Water balance**: Analyse the sustainable yield of aquifers versus current abstraction rates. This requires sufficient monitoring networks to track groundwater levels and quality over time [35]
- **Environmental overview**: Assess the risk of groundwater pollution from sources like poorly managed sanitation, solid waste disposal, and stormwater runoff. Identify recharge areas and wetlands that need protection.
- **Gap analysis and strategies**: Identify challenges such as a lack of monitoring data, skills shortages, or institutional fragmentation that hinder effective groundwater management

Once these elements are included, the next step is to ensure that they are managed across municipal functions rather than within the water services department alone. To address this, municipalities need to practise integrated water resource management (IWRM), which involves coordinated development and management of water, land and related resources. In the context of groundwater, this means:

- **Cross-directorate collaboration**: Water service officials must interact with those responsible for land use planning, environmental management, and solid waste to ensure that development decisions do not compromise groundwater quality or recharge.
- **Protecting the resource**: The WSDP should include strategies to protect groundwater sources, such as controlling pollution from greywater, managing stormwater to prevent contamination, and preserving wetlands and open spaces that act as natural soakaways for aquifer recharge.
- **Aligning boundaries**: Municipal boundaries rarely align with hydrological (catchment) boundaries. IWRM requires municipalities to collaborate with neighbouring authorities and Catchment Management Agencies to effectively manage shared groundwater resources.

This integrated approach also creates the basis for conjunctive use where municipalities rely on both surface water and groundwater. Instead of managing these sources separately, the goal should be to operate them as a single water supply system. This approach offers significant advantages:

- **Increased resilience**: Groundwater can act as a buffer during droughts when surface water sources (dams, rivers) are depleted.
- **Enhanced total yield**: Optimal integration can result in a total system yield that is higher than the sum of each source managed separately. However, research confirms that planned conjunctive use has not yet been successfully implemented in many South African municipalities because of the governance and capacity challenges noted above.

To move from intention to implementation, municipalities need a simple institutional framework that embeds groundwater and IWRM requirements into WSDP preparation, review and reporting. This framework rests on three essential pillars [35]:

- **Leadership and clear structures**: Establishing clear roles and responsibilities within the municipality for groundwater management and ensuring strong leadership to drive integration.
- **Formal stakeholder engagement**: Creating structured platforms for engaging with internal departments, external stakeholders (like water users and Catchment Management Agencies), and the community.
- **Sufficient monitoring networks**: Investing in the infrastructure and skills needed to monitor groundwater levels and quality, providing the data that underpins sound decision-making and stakeholder trust.

3.5. GROUNDWATER CONTAMINATION, LAND USE AND PLANNING PRESSURES

Land-use decisions and basic service infrastructure can either protect groundwater or create long-term contamination risks. Municipalities therefore need to treat groundwater quality as a planning, services and governance issue, not only as a technical water-quality concern. This section focuses on the pressures created by sanitation, wastewater, solid waste, stormwater, industrial and mining activities, recharge-area disturbance, and spatial development decisions, and explains how

municipal policies, bylaws, land-use controls, monitoring systems, and service-delivery planning should address these risks.

The main threats arise from pollution pathways that allow contaminants to move from the land surface or shallow subsurface into aquifers. These include leaking sewers, poorly maintained wastewater systems, pit latrines, septic tanks, waste disposal sites, cemeteries, contaminated stormwater, agricultural chemicals, industrial sites, mining areas, fuel storage facilities and accidental spills. Recharge areas, wetlands, wellfields and highly permeable or fractured zones are especially vulnerable because contaminants can reach groundwater more quickly or affect strategically important water sources.

These risks intensify where spatial planning, sanitation design, stormwater management, waste licensing, environmental approvals, and groundwater protection are handled separately. Development pressure for housing, industry, agriculture or infrastructure can place polluting activities too close to boreholes, recharge zones or vulnerable aquifers if groundwater is not screened early in the approval process. Once groundwater is polluted, remediation is difficult, expensive and often only partially effective. Preventing contamination through land-use planning and service-infrastructure controls is therefore far more effective than attempting to rehabilitate an aquifer after damage has occurred.

3.5.1. Aligning policies, legislation and strategies

To respond to these risks, municipalities first need to align the policies, bylaws, strategies and planning instruments that shape land-use and service-delivery decisions. The strategic intent is to proactively protect the municipality's strategic aquifers, recharge zones, and groundwater-dependent supply areas so preventable pollution does not undermine water security. This requires embedding groundwater protection in planning, development approvals, sanitation design, stormwater management, waste management, infrastructure maintenance, and compliance systems. The emphasis should be on prevention, early detection, and enforceable mitigation measures, because rehabilitating contaminated aquifers is costly and technically difficult, and the damage may persist for decades.

This policy alignment is necessary because municipalities must balance land development, housing delivery, sanitation access, economic activity and environmental protection while safeguarding strategic groundwater sources. These trade-offs are unavoidable, but they become risky when groundwater is considered too late in planning or authorisation processes.

If strategic aquifers identified in the IDP, WSDP or MSDF are not linked to enforceable land-use controls, service-design standards and compliance monitoring, municipal water resilience and long-term water security can be compromised.

For this reason, groundwater protection should be translated into clear priorities that can be reflected across bylaws, policies, spatial plans, water services plans and municipal risk systems:

- Groundwater is embedded in the municipal water security risk management system and internal controls that navigate trade-offs between development and protection of key aquifers through aligned municipal bylaws, policies and strategies with a clear link to the SDBIP performance cycles.
- Early identification of critical groundwater zones is institutionalised within spatial development application workflows, so potential pollution and land use pressures are screened before approvals through (e.g., adoption of groundwater protection zones/recharge areas as a formal planning layer in the MSDF).
- Where national regulations are insufficient, best practice frameworks are adopted at the municipal level (e.g., protection zones guideline, sanitation services protocols, stormwater and waste practices) and made binding via policy and standards.

3.5.2. Integrate groundwater protection to promote basic services and a healthy environment

Once the policy and planning framework is aligned, the next step is to embed groundwater protection in the practical systems through which municipalities provide basic services and manage a healthy environment. Sanitation, wastewater, stormwater, solid waste, roads, housing and industrial development can all create pathways for contamination if they are poorly located, designed or maintained. A healthy environment and reliable groundwater supply therefore depend on service-delivery standards that recognise local hydrogeological conditions, protect recharge areas and wellfields, and prevent pollutants from entering vulnerable aquifers. The measures below show how municipalities can move from general protection principles to practical controls, approval processes, monitoring systems and stewardship mechanisms that reduce contamination risks while supporting safe water, sanitation and environmental health outcomes.

- **Developed Standards for Pollution Pathway Control Measures:**
  - Updated **sanitation, wastewater, stormwater and solid waste** standards and bylaws to minimise infiltration and migration of contaminants (e.g., lining specifications for landfills, leak detection requirements, diverting high-risk stormwater away from strategic aquifers).
  - Requirements for **hydrogeological assessments** for developments within or near protection zones.
  - Rural and peri-urban WASH programmes are informed by prevailing hydrogeological conditions.
- **Risk-Informed Approvals and Compliance Workflow:**
  - Mapped and classified strategic aquifers and recharge areas, assigned risk-based protection tiers, and integrated into the MSDF and development screening tools.
  - Introduced screening tools within spatial development planning processes. Captured development decisions, conditions of approval, and mitigation plans linked to the protection zone layers.
  - Designed automated triggers for referral to hydrogeologists during spatial development and planning approvals.
- **Groundwater Quality and Early Warning Network:**
  - Established and/or rehabilitated monitoring boreholes across high-risk zones. Institutional capacity, skills and knowledge will be required for monitoring and data management. Where feasible, install telemetry systems at priority sites to continuously monitor water level and quality parameters (e.g., EC, nitrate, microbial indicators).
  - Implemented thresholds and alarms tied to operational responses and compliance enforcement.
- **Asset Integrity and Source Protection for Municipal Systems:**
  - Prioritise rehabilitation of leaking sewers, pump stations, and waste facilities near recharge areas; include backflow prevention and secondary containment at municipal depots.
  - Deploy stormwater infiltration management (e.g., water-sensitive urban designs, pollution traps, controlled infiltration away from sensitive zones).
- **Community and Developer Stewardship Mechanisms:**
  - Develop targeted groundwater education awareness campaigns for developers and landowners. Additionally,

incorporate groundwater quality status **into existing dashboards** to build accountability and transparency.

- Enable cross-sector and departmental collective action with key stakeholders like DWS, DFFE, DMRE, Water User Associations and other interested and affected parties for high-risk locations through established platforms.

Together, these measures provide the operational link between municipal planning decisions and day-to-day groundwater protection. They also show that contamination risk management depends on more than technical assessment: it requires enforceable controls, coordinated approvals, functioning infrastructure, monitoring data, public transparency and shared responsibility across municipal departments and external stakeholders.

Table 4: Groundwater contamination, land use & planning risk management, dependencies and enablers

Risks	Risk Management Actions	Dependencies & Enablers
Regulatory gaps or fragmented mandates delay enforcement	Municipal adoption of best practice protection zones via bylaws; embed controls in **SDBIP** and internal audit formal; **MOUs** for collective action and data sharing.	Timely amendments to **bylaws**, approval of the **policy** affecting g**roundwater protection**, and incorporation within IDP/WSDP revisions and the MSDF update cycle.
Land use pressure overrides environmental concerns in approvals.	**Mandatory risk screening and hydrogeologist sign-off for projects in protection zones; high-risk approvals linked to enforceable conditions and financial provisions**	**Adoption of best practice protection zone frameworks, updated sanitation, wastewater, stormwater and solid waste standards and bylaws to mitigate pollution and land use pressures;** Integrated case management for approvals and enforcement
Legacy infrastructure leakage (sewers/stormwater/waste	**Risk-based asset renewal program** prioritising protection zones; ring-fenced	Training, stakeholder engagement plans, and internal **performance**

sites) contaminates recharge areas.	CapEx/OpEx; continuous monitoring and leak detection.	**incentives** tied to groundwater quality KPIs.
Data gaps hinder timely decisions.	**Integrated data platform** (GIS, monitoring data, project approvals); publish groundwater quality dashboards; annual technical review of groundwater quality thresholds to inform policy and standards	**Adopted** protection zones **GIS layers**, telemetry for (remote) monitoring points, and groundwater incorporated into public dashboards. Dedicated budget lines in **SDBIP/MTREF** for monitoring network, asset rehabilitation in strategic aquifers

3.6. EXTREME CLIMATIC EVENTS

Extreme climatic events, especially droughts and floods, are increasing pressure on municipal water supply systems and changing how groundwater is used. During droughts, groundwater is often the first alternative source considered because it is less visible, locally available in many areas, and naturally buffered by aquifer storage. However, if groundwater is used without planning, monitoring and clear operating rules, drought response can quickly lead to over-abstraction, water-quality deterioration, infrastructure strain and conflict with other users. Floods can also affect groundwater systems by damaging infrastructure, mobilising contaminants, overwhelming sanitation systems and increasing the risk of pollution entering aquifers through recharge zones, boreholes and fractured ground.

The main threats arise from drought, floods and increasing climate variability. Drought reduces surface-water availability, increases demand for alternative supplies, concentrates pollutants, and can place sudden pressure on municipal and private boreholes. Floods can damage pump stations, borehole headworks, pipelines, electrical systems, treatment works and sanitation infrastructure, while also transporting contaminants into sensitive recharge areas or poorly protected boreholes. Climate variability may also change groundwater recharge patterns, water quality, demand peaks, and the number of households, businesses, farmers and institutions turning to groundwater during water shortages.

For municipalities, the key planning challenge is to define the role of groundwater before extreme events occur. Municipalities should assess

groundwater as part of the overall water supply portfolio, including surface water, reuse, storage, demand management, and emergency supply options. This requires municipalities to understand aquifer yields, recharge behaviour, abstraction limits, water-quality constraints, infrastructure capacity and the operational rules needed to switch between sources during different climate conditions.

These requirements bridge climate risk awareness and municipal governance. In practice, the resilience value of groundwater depends on whether municipalities have already established the policies, institutional mandates, operating rules and accountability mechanisms needed to guide abstraction before, during and after extreme events. The following subsection therefore sets out the policy, legal and institutional considerations that should anchor groundwater within municipal climate-resilience planning.

3.6.1. Policy, legal and institutional considerations

Building on the preceding discussion, extreme and increasingly erratic climatic events are putting pressure on water supply, shifting demand patterns, and accelerating third-party groundwater abstraction, placing service delivery commitments at risk. Because groundwater is often the most accessible alternative source during these periods, it must be formally positioned as a strategic buffer for resilient water systems to sustain reliable water service delivery and protect groundwater-dependent ecosystems during drought cycles, rather than treated as an ad hoc emergency measure.

Policy and institutional direction for transformed groundwater governance and management in climate change resilience planning:

- **Recognise groundwater in climate adaptation policy**: Explicitly define groundwater's role as a drought mitigation buffer within climate adaptation plans, WSDP/IDP updates, and SDBIP performance cycles.

Institutionalise conjunctive use rules: Adopt context-appropriate operating rules for switching, blending, banking, and adjusting between surface and groundwater sources across seasons and drought stages to inform water resource planning (see Table 5, which translates these governance and operating requirements into practical drought-response options).

- **Integrate across bylaws and strategies**: Align planning, land-use, sanitation, stormwater, and waste bylaws/policies to control water

quality and mitigate threats to strategic aquifers and support conjunctive use and recharge zone protection.

- **Integrated early, cross-departmental screening**: Requires groundwater considerations in water resource planning, water supply scheme design, and resource allocation, so long-term groundwater use opportunities and risks are proactively addressed without bias towards the status quo.
- **Move from interim to institutionalised**: Formally incorporate groundwater schemes, including those that are considered interim solutions, within the municipal water supply portfolio, clarifying skills and capacity needs, O&M standards, knowledge and information management (data) obligations, and accountability

These governance and operating requirements are translated into practical drought-response options in Table 5. The table summarises the main conjunctive-use strategies that municipalities can consider when using groundwater and surface water together to manage drought and seasonal variability. The strategies show that groundwater can play different roles depending on local conditions: it may be reserved as a drought buffer, used seasonally when surface-water availability declines, developed intensively during early growth phases, or combined with other approaches in a mixed operating strategy. Municipalities should therefore use the table as a planning aid to match water-source operating rules to aquifer behaviour, infrastructure capacity, institutional readiness and long-term climate-resilience objectives.

Table 5: Conjunctive water uses drought mitigation strategies

Drought cycling strategy	Seasonal cycling strategy	Initial intensive exploitation	Mixed strategy
Manage climate-driven interannual variability	Manage annual seasonal variability	Based on the development stage of the area	A combination of the different stages
Aims to create water supply stability	Surface water is used during wet periods, and MAR is implemented	Financial and institutional resources for large-scale systems are limited	

Drought cycling strategy	Seasonal cycling strategy	Initial intensive exploitation	Mixed strategy
Surface water use dominates during wet years	Groundwater used during dry periods	Intensive use of one resource as a trade-off for economic growth	
Excess surface water used for MAR	Dampen the difference in supply and demand peaks through groundwater storage	Intended to support the phased approach of large-scale infrastructure	
Assumes institutional capacity and efficient infrastructure			

While Table 5 identifies the broad drought-cycling options available to municipalities, the same governance and monitoring disciplines are also needed to prevent groundwater schemes from being pushed beyond their sustainable limits.

3.6.2. Enabling integrated water systems for conjunctive water use

To make conjunctive use operational, municipalities need to treat surface water, groundwater, storage, reuse and demand-management measures as parts of one integrated water system rather than as separate supply options. For groundwater to provide a reliable buffer during droughts and other climate stresses, municipalities need clear operating protocols, monitoring thresholds, infrastructure standards, recharge protection measures and data systems that guide when, where and how groundwater is used. This section therefore outlines the practical enabling actions needed to translate conjunctive-use policy into coordinated planning, scheme design, early warning, water-quality protection and routine municipal operations.

- **Integrated Water Systems for Conjunctive Use and Water Resource Planning**
  - Define operating protocols and standards for conjunctive use (e.g., utilise surface water in wet seasons and trigger increased groundwater use during dry seasons; implement

managed aquifer recharge to manage low yield and water quality risks).

- Scenario-based modelling to set demand thresholds and drought stage response triggers; integrate aquifer yield, recovery times, and quality constraints.
- Groundwater scheme design standards: wellfield spacing (centralised vs decentralised schemes), integrated reticulation system, water quality blending capacity, and power resilience (backup/solar), recognising trickle-down impacts on management systems, required skills and resource capacity for successful integration.

- **Monitoring and Early Warning**
  - Alert threshold triggers and SOPs are predefined operational responses for declining water levels, quality, and demand spikes that are informed by appropriate monitoring network data and model outputs.
  - Groundwater is integrated into data governance to ensure a transformed standardised data management system, QA/QC, and central data repository for tracking trends and informing conjunctive use strategies and water resource planning.
- **Protection of Recharge Zones and Water Quality**
  - Spatial development planning and pollution pathway controls in sanitation, stormwater, and waste management are linked to building water resilience in extreme climatic conditions.
- **Community and Developer Stewardship Mechanisms:**
  - Enable **cross-institutional and sector collaborations with high-demand users and key stakeholders like DWS, DFFE, DALR&RD to establish aligned catchment-scale** conjunctive water use strategies.
  - Community-based water demand management campaigns incorporate groundwater resource use.

Table 6 brings together the principal risks associated with extreme drought events and sets out practical management actions, dependencies and enabling conditions for municipal response. It shows that drought resilience depends not only on identifying alternative groundwater sources, but also on having operating rules, monitoring systems, institutional capacity, funding arrangements and coordinated decision-making in place before drought conditions escalate.

Table 6: Extreme drought events risk management, dependencies and enablers

Risk	Risk Management Actions	Dependencies & Enablers
Fragmented mandates or insufficient regulations delay adoption	Approve municipal conjunctive water policy and strategies; amend bylaws to formalise roles, thresholds, and enforcement.	Adoption of Groundwater Governance Policy; bylaw amendments for registration, siting, and monitoring; integration into **IDP/WSDP/MSDF** cycles
Reliance on groundwater without safeguards degrades aquifers and water schemes	Formalised groundwater schemes: SOPs for conjunctive use rules, abstraction limits, seasonal recovery periods, and enforced thresholds tied to operations.	Conjunctive use is mainstreamed into water resource planning and budgeting; Adoption of best practice guidelines for groundwater scheme development and O&M
Contamination of strategic aquifers & destruction of recharge areas undermine drought capacity and water service delivery	Water security and aquifer protection in spatial development risk screening and project approvals linked to resilience against extreme climatic conditions	**Adoption of best practice protection zone frameworks and updated spatial development approval processes and WASH standards to manage trade-offs during project appraisal process**
Limited and/or scattered data and skills gaps erode decision quality.	Established MoUs for data sharing; Standardised monitoring requirements for water resource modelling and dashboards; Targeted skills capacity building; aligned framework with key stakeholders.	Established community and sector partnerships to foster **stewardship, data sharing, and self-regulation**; Groundwater scheme O&M skills training for staff; Data management systems designed for integrated data storage and reporting.
Emergency procurement cost shocks and misalignment	Early adoption of conjunctive use for long-term water resilience; Phased integration of groundwater scheme	Dedicated **MTREF/SDBIP** lines for groundwater scheme development to achieve climate adaptation goals; Cooperative engagements with sector

Risk	Risk Management Actions	Dependencies & Enablers
	development; Standardised equipment specifications	stakeholders to ensure aligned equipment and infrastructure standards.

The next section therefore turns from climate-driven demand shocks to the more persistent problem of low or declining yields and over-abstraction, where resource stress often develops gradually but can ultimately compromise supply reliability, water quality, infrastructure performance and confidence in groundwater as a municipal water source.

3.7. LOW/DECLINING YIELDS AND OVER-ABSTRACTION

Strategic groundwater sources are most at risk where abstraction is poorly planned, insufficiently regulated or undertaken without a clear understanding of aquifer limits. Unregistered boreholes, informal abstraction, increasing rural and agricultural demand, and competing sectoral pressures can place cumulative stress on low-yield aquifers, particularly during drought periods or in areas where groundwater is treated as a supplementary rather than strategic resource.

These pressures are compounded where monitoring systems are limited or fragmented. Inadequate data on groundwater levels, abstraction rates, borehole performance and water quality reduces the municipality's ability to detect early signs of yield decline, distinguish between localised borehole failure and wider aquifer stress, and adjust abstraction rules before damage becomes difficult or costly to reverse.

Institutional capacity constraints further increase the threat. Where hydrogeological expertise, operational resources, enforcement mechanisms and cross-sector coordination are limited, groundwater decisions may be reactive rather than evidence-based. This weakens the municipality's ability to regulate use, manage cumulative impacts, maintain infrastructure and protect strategic groundwater sources as long-term components of the municipal water portfolio.

Together, these threats show that declining yields are not only a technical groundwater issue, but also a planning, governance and institutional challenge. The response therefore needs to start with the policy and strategic framework that determines how the municipality recognises, regulates, funds, and manages groundwater.

3.7.1. Aligning policies, legislation and strategies

The municipality must formally integrate strategic groundwater sources into its planning, policy and operational systems to enable sustainable abstraction, sound hydrogeological management and long-term protection of yields. This requires institutionalising groundwater resource development through stronger governance oversight, improved internal hydrogeological capability, adequate resourcing, and a robust regulatory environment.

Low-yield aquifers are essential to rural water security, agricultural resilience and climate adaptation, but they are often underrepresented in water resource planning. When these aquifers face uncontrolled abstraction, limited monitoring, and weak institutional oversight, the risk of declining yields, permanent aquifer damage, and service delivery instability increases. Unregistered boreholes, informal abstraction and sectoral pressures from mining, forestry and land-use change add cumulative stress to already vulnerable systems. Without coordinated decision-making, reliable data and strengthened bylaws, the municipality faces escalating risks of over-abstraction and long-term groundwater resource degradation.

Safeguarding strategic groundwater sources against over-abstraction and declining yields requires:

- **Aligned policies, bylaws and strategies** that support sustainable groundwater use, including long-standing rural abstractions and informal users. This includes drilling bylaws that track private abstraction and groundwater-use bylaws that require submission of borehole coordinates, intended use and estimated abstraction volumes.
- Strengthened **institutional** capacity through the appointment of a hydrogeologist to provide expert oversight of groundwater-related projects.
- **Formal recognition of low-yield aquifers** as part of the municipal water portfolio, not only for bulk supply, but also for their cumulative socio-economic value.
- Defined groundwater-use patterns within the municipal jurisdiction so that cross-sector impacts from mining, forestry, land-use change and climate variability can be addressed through coordinated engagement and decision-making.

- Integrated groundwater schemes into **budgeting, performance management, planning approvals and risk management frameworks** to strengthen institutional accountability.
- Promoted a governance culture in which groundwater is treated as a **shared resource** requiring stewardship beyond compliance and enforcement.

Once groundwater is embedded in municipal policy, governance and accountability systems, the next priority is to translate these commitments into practical planning tools. This requires integrated water resource planning that connects aquifer behaviour, scheme design, demand management and operational decision-making.

3.7.2. Enabling integrated water resource planning and demand management

Integrated water resource planning is essential for ensuring that groundwater schemes are developed, operated and monitored within the limits of the aquifers that support them. For low-yield systems in particular, planning must move beyond individual borehole performance and consider cumulative abstraction, seasonal variability, recharge potential, land-use pressures and the long-term reliability of supply.

Demand management provides the operational link between groundwater availability and water service requirements. By classifying schemes, modelling abstraction scenarios, setting operating rules and aligning infrastructure design with aquifer behaviour, the municipality can reduce the risk of over-abstraction while improving drought preparedness, investment prioritisation and the resilience of groundwater-dependent communities.

- **Water Resource Planning and Abstraction Management**
  - Identify existing groundwater use and formally classify **groundwater schemes according to** use type, such as rural, agricultural, industrial or bulk supply, so that investment, operational standards and strategic interventions can be appropriately targeted.
  - Apply scenario**-based modelling** to determine cumulative abstraction rates, long-term safe yield, aquifer recovery periods and drought-response triggers. Groundwater scheme operations should be guided by appropriate standard operating procedures and standardised operations and maintenance requirements.

- Optimise groundwater scheme designs through the following measures:
- Use managed aquifer recharge to support aquifer recovery and store water for periods of peak demand.
    a) Develop decentralised schemes for low-yield aquifers that serve high-demand communities.
    b) Implement risk mitigation measures, such as seawater intrusion barriers in coastal zones or seasonal abstraction limits informed by sector impacts where applicable, including forestry, mining and agriculture.

These planning and design measures provide the foundation for sustainable abstraction, but they depend on reliable and timely information. Monitoring and early warning systems are therefore needed to test assumptions, track aquifer response and support adaptive operating rules.

- **Monitoring and Early Warning Systems**
    - Establish a minimum monitoring network for groundwater levels, yields, water quality and abstraction patterns, including private users where possible, to inform operating rules and support sustainable long-term use.
    - Integrate groundwater information into data management systems so that long-term datasets can inform water risk management, water resource planning and modelling.
    - Equip data management systems, through appropriate design and skills, to standardise quality assurance and quality control procedures and ensure groundwater data remains reliable and usable.
    - Integrate groundwater data into public water resource status dashboards to support a more informed society and encourage sustainable groundwater use and protection.

Monitoring data is only useful when it informs action. The municipality must therefore pair improved information systems with the operational readiness, skills and asset integrity needed to respond to risk, maintain scheme performance and protect strategic aquifers over time.

- **Operational Readiness and Asset Integrity**
    - Identify and secure the internal skills, knowledge and resources required to support groundwater schemes effectively.

- Implement risk-ranked rehabilitation programmes for existing groundwater infrastructure and delineate buffer zones around strategic aquifers.
- Develop operational protocols for low-yield or drought-stressed systems that align with municipal conjunctive-use drought strategies.
- Standardise equipment specifications and operations and maintenance practices across municipal groundwater schemes, while enabling cooperative alignment with corporate social investment projects across sectors.

These measures show how policy alignment, planning, monitoring, and operational readiness work together to reduce the risk of declining yields and over-abstraction. Table 7 consolidates these requirements into a practical risk management framework by linking each key risk to targeted management actions and the institutional conditions needed for implementation. The dependencies and enablers highlight the policies, resources, partnerships and data systems required to move from risk recognition to sustained groundwater protection.

Table 7: Declining yields and over-abstraction risk management, dependencies and enablers

Risk	Risk Management Actions	Dependencies & Enablers
Uncontrolled abstraction leading to irreversible yield decline (and potentially, water quality)	Enforce borehole registration for private users and implement abstraction limits and recovery thresholds informed by monitoring data.	Policies recognise low-yield aquifers as strategic resources; groundwater is integrated into the IDP and WSDP to institutionalise its role in water service delivery; and bylaws are amended to provide for groundwater registration, drilling permits and abstraction controls.
Weak institutional capacity and limited hydrogeological expertise to provide the necessary oversight	Appoint an in-house hydrogeologist, standardise equipment specifications, and develop training and operations and maintenance capability programmes.	Hydrogeological expertise is recognised as a critical skill, and mechanisms are established for cooperative engagement with key stakeholders in the NGO and private sectors.

Risk	Risk Management Actions	Dependencies & Enablers
Cross-sector impacts (mining, forestry, land-use decisions)	Strengthen cross-institutional coordination for risk screening and use established monitoring committees to support joint compliance mechanisms.	Maintain collaboration with national departments and institutions such as DWS, DMRE, DFFE, CMAs, Water User Associations, the private sector, and NGOs.
Data gaps and unreliable monitoring	Implement monitoring and early warning networks supported by quality assurance and quality control protocols, and integrate groundwater data into municipal systems and platforms.	Data management systems are designed to store, validate, analyse and report groundwater data. Governance arrangements enable the archiving of long-term data to support water resource modelling and data-driven decision-making, with MTREF allocations for monitoring networks, data systems, asset rehabilitation and specialist capacity.
Community non-compliance and conflict over drying boreholes	Promote transparency through partnerships and shared stewardship to reduce conflict and non-compliance, and establish groundwater education and awareness campaigns for communities and schools.	Local catchment management forums and platforms recognise the need for shared responsibility; partnerships with agriculture, industry and rural communities encourage self-monitoring and regulation; and collective data sharing is promoted to strengthen holistic water resource management.

3.8. FUNDING GROUNDWATER DEVELOPMENT, OPERATION AND MAINTENANCE

Funding for groundwater development, operation, and maintenance is often fragmented across short-term projects, emergency responses, or externally supported interventions that are not fully integrated into municipal planning

and asset-management systems. This creates a cycle in which schemes are developed to address immediate supply pressures, but without the financial commitments, procurement arrangements and institutional responsibilities needed to sustain performance over time.

Weak lifecycle costing reinforces these funding gaps. If appraisal, drilling, equipping, monitoring, energy, routine maintenance, rehabilitation and eventual renewal are not costed from the outset, the real cost of groundwater service delivery remains hidden. As a result, schemes may be under-designed, maintenance may be deferred, and infrastructure may fail prematurely even where the underlying groundwater resource could have supported a reliable supply.

Institutional discontinuity is a further threat. Incomplete asset registration, poor handover of borehole data and limited in-house technical capacity reduce the municipality's ability to manage groundwater schemes after implementation. Without clear ownership, reliable records and dedicated operational capability, externally funded or emergency schemes can become isolated assets rather than integrated components of the municipal water services portfolio.

These threats show that groundwater funding gaps are not simply budget shortfalls; they reflect weaknesses in governance, planning, asset stewardship and institutional continuity. Addressing them requires a shift from project-by-project groundwater development to lifecycle-based management in which schemes are planned, funded, owned and maintained as long-term municipal service delivery assets.

3.8.1. Policy, legal and institutional considerations

The municipality should **institutionalise groundwater resource development as a planned, funded and maintained** component of **municipal water service delivery**, rather than treating it as a reactive response to drought or short-term supply failures. This requires financing groundwater development, operation, and maintenance across the full asset lifecycle, including appraisal, drilling, equipping, monitoring, energy, maintenance, rehabilitation, and eventual renewal. By integrating groundwater into governance, financial planning and partnership frameworks, the municipality can reduce funding gaps, prevent scheme failure and protect long-term water security investments.

Groundwater is often mobilised during droughts through emergency procurement processes that increase costs, compress technical appraisal and weaken long-term maintenance planning. Many schemes fail not

because the aquifer is inherently unsuitable, but because the supporting governance arrangements are incomplete. Common weaknesses include fragmented budgeting, under-resourced operations and maintenance systems, limited asset recognition, poor data handover after donor or emergency projects, and insufficient continuity once external funding ends. These gaps are compounded by limited institutional capacity, weak coordination with groundwater users and poor visibility of the costs required to sustain schemes over time.

The strategic and governance response must therefore connect financial planning with clear legal mandates and institutional accountability. The following priority actions set out how the municipality can create the policy basis, ownership model and cross-sector partnerships needed to sustain groundwater schemes beyond initial implementation.

Reducing groundwater funding gaps requires the municipality to shift from short-term project financing toward lifecycle-based investment and asset stewardship. Priority actions include:

- **Explicitly integrate groundwater schemes into financial and asset governance:** Ensure that all groundwater infrastructure is formally recognised as municipal assets, with lifecycle costs reflected in budgets, asset management systems and operations and maintenance plans.
- **Shift from emergency response to planned investment:** Integrate groundwater development and maintenance into IDP, WSDP, SDBIP and MTREF processes to avoid costly emergency procurement and under-designed schemes.
- **Strengthen collective stewardship and cost protection:** Promote community-level engagement platforms that build shared responsibility for groundwater schemes and reduce vandalism, misuse and premature asset failure.
- **Enable partnerships with clear institutional ownership:** Leverage partnerships with agriculture, industry, NGOs and rural communities while ensuring that the municipality retains oversight, asset ownership and post-project support capacity for continued water service delivery.
- **Institutionalise data sharing and transparency:** Support collective data sharing and self-monitoring arrangements to improve visibility of groundwater use, inform funding decisions and strengthen accountability for sustainable abstraction.

These policy and institutional actions provide the enabling framework for a more practical funding model. Sustainable funding depends on integrating groundwater into the same planning, budgeting, procurement, and asset-management systems that support other municipal water infrastructure, so schemes are treated as long-term service-delivery assets rather than standalone emergency interventions.

3.8.2. Integration for sustainable funding

This section sets out the practical mechanisms required to convert groundwater policy commitments into sustainable funding arrangements. It focuses on integrating groundwater into municipal planning, budgeting, procurement, asset management, and partnership systems so schemes are designed, operated, and maintained according to their full lifecycle requirements. This approach reduces reliance on emergency funding, improves investment certainty, and ensures groundwater infrastructure remains functional, accountable, and aligned with long-term water service delivery objectives.

- **Proactive Resource Planning and Financial Integration**
  - Embed groundwater development and operations and maintenance requirements into IDP, WSDP, SDBIP and MTREF cycles to reduce reliance on emergency funding.
  - Adopt project lifecycle costing approaches that account for exploration, drilling, equipping, monitoring, energy, maintenance and rehabilitation for all municipal groundwater projects.
  - Register all municipal boreholes and associated infrastructure as municipal assets to enable depreciation, timely maintenance planning and reinvestment.

With planning and financial integration in place, investment decisions can then focus on the appropriate scale, design and affordability of each groundwater intervention. Cost optimisation should not reduce technical quality; it should ensure scheme design matches aquifer conditions, community demand, operating capacity, and long-term maintenance requirements.

- **Scheme Appropriate Design and Cost Optimisation**
  - Apply fit**-for-purpose scheme typologies**, including rural, bulk supply, managed aquifer recharge, industrial, centralised and decentralised schemes, to align design complexity and cost with institutional capacity and water service objectives.

- Use hydrocensus data, desktop studies and phased investigations to reduce upfront appraisal costs while protecting the long-term sustainability of investment decisions.
- Standardise technical specifications where possible to reduce procurement, spares and operations and maintenance costs, and to avoid misalignment between donor-funded schemes and municipal operating requirements.

Appropriate design reduces the likelihood of premature failure, but scheme sustainability ultimately depends on the municipality's ability to operate and maintain the infrastructure once commissioned. Operations and maintenance therefore determine whether planned investment translates into reliable service delivery.

- **Sustainable Operations and Maintenance Models**
  - Ring-fence operations and maintenance budgets for groundwater schemes, including skilled personnel, equipment, monitoring, energy and routine maintenance.
  - Introduce risk-based operations and maintenance prioritisation, focusing resources on high-dependence or high-risk schemes and reducing bias toward surface-water infrastructure.
  - Align procurement systems and processes with the different types of municipal groundwater schemes so that repair, replacement and maintenance needs can be addressed efficiently.

Even with stronger internal funding and maintenance arrangements, groundwater schemes may still require external support where benefits are shared across sectors or where capital costs exceed municipal capacity. Partnerships and blended financing can therefore extend available resources, provided that they are structured around clear ownership, data handover and long-term municipal accountability.

- **Partnerships and Blended Financing**
  - Leverage NGO, donor and private-sector investment through formal partnerships while retaining municipal oversight and long-term responsibility for groundwater assets and service delivery outcomes.
  - Establish handover protocols, data-transfer requirements and asset-registration processes for externally funded projects to prevent post-project collapse.

- Explore and implement co-funding and shared-benefit models with water user associations, agriculture, industry and other partners where groundwater resources are jointly relied upon.

Taken together, the measures above show how linking planning, design, operations, and partnerships into a single lifecycle-management approach can reduce groundwater funding risks. Table 8 consolidates these risks and identifies the management actions, institutional dependencies and enabling conditions required to close groundwater scheme funding gaps, protect municipal investments and support reliable long-term performance.

Table 8: Groundwater scheme funding gap risk management, dependencies and enablers

Risk	Risk Management Actions	Dependencies & Enablers
Emergency-driven groundwater development inflates costs	Pre-approved groundwater investments and MTREF allocations, aligned with adopted conjunctive water use strategies	Council-approved groundwater investment, asset-management, and O&M policies. Established alignment between water services, infrastructure and climate change adaptation strategies.
O&M under-funding and limited in-house knowledge and skills gaps lead to scheme failure	Ring-fenced O&M budgets; resource allocation and asset-linked groundwater maintenance plans; Targeted recruitment and training.	Groundwater development is integrated into the IDP, WSDP, SDBIP, and MTREF to ensure long-term financial capacity for O&M and institutional capacity
Loss of institutional memory after the implementation of emergency schemes and/or donor projects	Mandatory groundwater scheme asset registration; Data handover of externally funded projects to ensure municipal ownership of schemes	Centralised groundwater database supporting planning, appraisal, and budgeting; Shared responsibility models that reduce long-term fiscal pressure on the municipality
Misaligned donor-funded groundwater schemes; Poor project appraisal	Project appraisal requirements are informed by a hydrogeologist and	Collaboration with NGOs, donors, the private sector, and communities is structured; the groundwater

Risk	Risk Management Actions	Dependencies & Enablers
drives unsustainable designs	phased groundwater investigations	project appraisal framework is informed by hydrogeological expertise, balancing cost efficiency with sustainability.
Fragmented procurement delays repairs	Standardised specifications and O&M protocols	Groundwater scheme requirements are incorporated into procurement frameworks to reduce procurement delays and cost escalation

By framing groundwater as a funded and maintained municipal asset, this section also helps address the perception risks discussed in the next section. Where schemes are poorly funded, poorly maintained or visibly fail after implementation, they reinforce negative stakeholder perceptions; where they are planned, resourced and managed transparently, they can build confidence in groundwater as a strategic water resource.

3.9. NEGATIVE STAKEHOLDER PERCEPTIONS

Negative stakeholder perceptions are reinforced when groundwater schemes are poorly planned, underfunded or weakly maintained, and when stakeholders have limited understanding of groundwater resource dynamics. These perceptions are also shaped by a persistent bias toward surface-water development, particularly where groundwater is introduced only during droughts or supply crises and is therefore viewed as an emergency or interim option rather than a planned component of long-term water security.

In response, the municipality should reposition groundwater as a strategic water resource that supports reliable service delivery, food security, drought resilience and climate adaptation. This shift requires groundwater to be reflected consistently in municipal policies, bylaws, IDP and WSDP processes, investment plans, and adopted conjunctive-use strategies, so stakeholders encounter groundwater as a planned and managed resource rather than a crisis-driven intervention.

However, changing perceptions requires more than policy recognition. Negative views of groundwater often reflect institutional experience rather than resource potential: poorly designed, underfunded or weakly

maintained schemes create visible service failures that undermine confidence, even where the underlying aquifer could support sustainable use under appropriate management. These perceptions are reinforced by limited institutional knowledge, inadequate technical support, fragmented intergovernmental coordination and historic preference for surface-water infrastructure.

This creates a reinforcing cycle: poor scheme performance weakens stakeholder confidence, reduced confidence limits investment and institutional attention, and underinvestment further increases the likelihood of scheme failure. Reversing this cycle requires deliberate communication, visible improvements in scheme performance, and governance arrangements that demonstrate groundwater can be planned, monitored, funded and managed to the same standard as other water resources.

Figure 11 illustrates this relationship by showing how negative perceptions, underinvestment and groundwater scheme collapse can reinforce one another when groundwater is not fully institutionalised within municipal planning and service delivery systems.

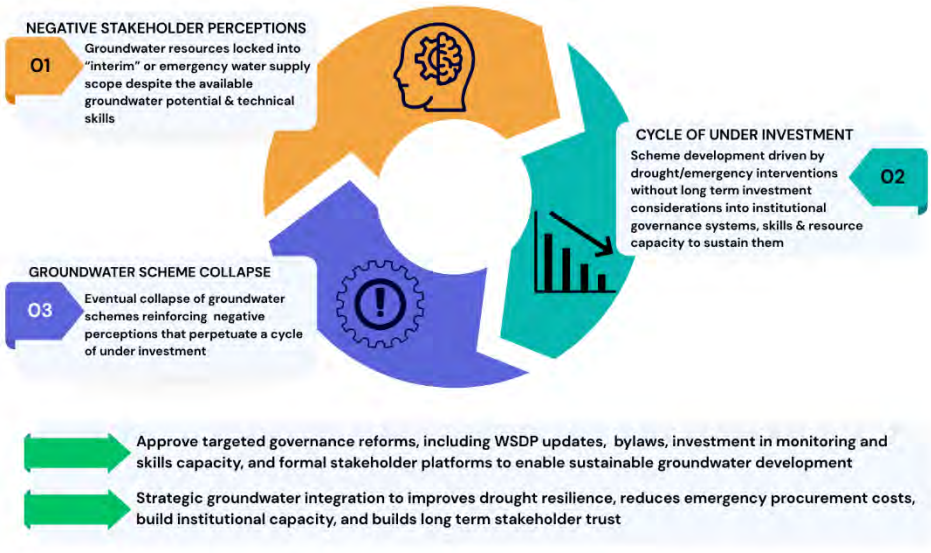


Figure 11: Reinforced cycle of negative perceptions of groundwater, underinvestment and groundwater scheme collapse

3.9.1. Education & Awareness for Stakeholders

Education and awareness initiatives are therefore a critical governance response. They should support the broader repositioning of groundwater by helping stakeholders understand both the value and constraints of groundwater, building confidence in evidence-based

management, and reinforcing the investment required to use groundwater sustainably within conjunctive water-use strategies.

To support this shift in perception and practice, targeted education and awareness initiatives should aim to:

- **Build foundational groundwater literacy across municipal staff and stakeholders** by developing a shared understanding of how groundwater systems function, their natural limitations and their associated risks. This should include practical awareness of how local geology influences borehole yields, water quality variability and vulnerability to contamination or localised over-abstraction.
- **Clarify the need for specialised expertise in groundwater management** by recognising that sustainable aquifer management requires professional hydrogeological input. Leadership awareness of these technical requirements can support better decisions on resourcing, procurement, institutional design and long-term operational oversight.
- **Support the intentional integration of groundwater into the municipal water supply portfolio** by positioning it as a planned, monitored and managed resource rather than a reactive intervention. This strengthens governance by embedding groundwater in planning, oversight and performance management systems, and reduces the risk of scheme failure linked to inadequate operations and maintenance or limited institutional capacity.

3.10. TOOLS AND RESOURCES

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PART C:

4. PLANNING, IMPLEMENTATION AND MANAGEMENT

Part C focuses on the practical requirements for planning, implementing and managing groundwater schemes within municipal systems. It addresses the main risks that can compromise groundwater supply, including declining borehole yields, over-abstraction, pollution, saline intrusion, inadequate operation and maintenance, weak abstraction controls, infrastructure vandalism and insufficient protection of strategic aquifers and recharge zones. These risks are considered in relation to the decisions that municipalities make through spatial development frameworks, integrated development planning, water services planning, infrastructure design, licensing, monitoring and day-to-day scheme operation.

The chapter is intended to support a shift from reactive groundwater use to proactive and adaptive groundwater management. It provides municipalities with prompts, management approaches and practical tools that can be used to diagnose risks early, assign responsibilities, strengthen institutional coordination, protect groundwater-dependent infrastructure and ensure that groundwater schemes remain reliable over the long term. It should be read together with the technical and operational guidance on groundwater schemes to ensure that planning decisions are supported by appropriate hydrogeological information, operational procedures and monitoring systems.

4.1. TARGET AUDIENCE

Part C is intended primarily for municipal Water Resource Planners, Town Planners and Groundwater Scheme Engineers who are responsible for integrating groundwater into spatial planning, infrastructure development, water resource management and scheme operations. It is also relevant to municipal managers, infrastructure and technical services officials, environmental management practitioners, water services authorities, consultants and decision-makers involved in groundwater development, licensing, protection, monitoring and long-term operation. The chapter supports both strategic planning and practical implementation by clarifying

the roles, information needs and management considerations required to protect groundwater as a reliable municipal water supply source.

4.2. PURPOSE

This chapter clarifies the requirements, obligations and standards associated with the planning, installation, operation and protection of municipal groundwater schemes. It provides practical approaches for integrating groundwater into municipal spatial planning, water resource planning, infrastructure design, licensing, monitoring and compliance processes. The chapter also sets out source-directed controls and groundwater protection measures that help municipalities prevent declining yields, over-abstraction, pollution and saline intrusion before they compromise water security. In doing so, it supports informed decision-making, proactive risk management and adaptive operation of groundwater schemes as part of a resilient municipal water supply system.

With the intended users and purpose of the chapter defined, the next step is to translate these planning and management responsibilities into practical review questions. These questions help municipalities test whether groundwater is sufficiently embedded in the frameworks, systems and decisions that influence long-term scheme performance.

4.3. QUESTIONS FOR CONSIDERATION

The following questions are intended to help municipalities assess whether groundwater has been adequately recognised, protected and integrated into planning, infrastructure development, water services, environmental management and operational decision-making. Use them as a practical prompt to review existing frameworks, identify gaps, and determine where additional technical input, governance arrangements, or management interventions may be required.

- Does the spatial planning framework include strategic aquifers and recharge zones?
- Are the groundwater schemes, including associated infrastructures, known and reflected in key frameworks and strategies?
- Have the protection zones of existing and potential groundwater schemes been delineated and included in the spatial planning framework?

- Is groundwater explicitly mentioned in the stormwater management policies, water demand & conservation campaigns, bylaws and strategic frameworks?
- Is groundwater explicitly considered in proposed projects, relevant authorisations and water resource demand and conservation planning?

The questions above move the chapter from broad institutional readiness to the practical risks that affect groundwater scheme performance. The first risk considered is low or declining yield, because it is often the earliest and most visible indication that the aquifer, borehole infrastructure, operating regime or monitoring system requires closer assessment.

Low or declining borehole yields are among the most common indicators that a groundwater scheme is under stress. Yield decline may reflect natural variability in recharge, long-term drought conditions, aquifer depletion, borehole ageing, clogging, biofouling, pump inefficiency or unsustainable abstraction. Because several of these causes can occur at the same time, municipalities should treat a decline in yield as an early warning signal that requires investigation rather than as a purely mechanical failure.

4.4. LOW/DECLINING YIELDS

Declining yields commonly result from reduced recharge, over-abstraction, non-compliance with recommended pumping rates, changes to pumping regimes, borehole deterioration, biofouling, mineral precipitation and clogging of borehole screens, casings, pumps or pipework.

Declining yields may originate from both natural and human-induced pressures. Natural drivers include reduced rainfall, changes in recharge patterns and prolonged dry periods, while human-related causes include over-abstraction, poor adherence to hydrogeologist-recommended pumping rates and changes in pumping schedules that do not allow sufficient recovery time. Operational changes can also alter oxygen conditions inside boreholes and associated infrastructure, encouraging iron or manganese precipitation, biofouling and clogging. These processes reduce water flow into the borehole and can progressively lower scheme performance if not detected and addressed early.

A structured response should therefore combine operational data review, field inspection, water-level monitoring, abstraction records, water-quality testing and, where required, repeat yield testing. The purpose is to distinguish between aquifer-scale stress, borehole-specific deterioration and infrastructure-related failure. This distinction matters because each

cause requires a different intervention, ranging from revised pumping schedules and demand management to borehole rehabilitation, infrastructure replacement, improved monitoring, or more detailed hydrogeological assessment.

4.4.1. Establish strong integrated governance and management interventions

Preventing low or declining yields requires more than technical borehole interventions; it also depends on whether municipal governance instruments recognise groundwater in planning, budgeting, regulation, operations, and enforcement. When bylaws, policies, strategies, institutional capacity plans, information systems, and stakeholder engagement processes explicitly address groundwater, municipalities have a stronger basis to act early, allocate responsibilities, and implement interventions before yield decline becomes a service-delivery failure.

- **Update of bylaws, policies and strategies**
  - Stormwater management – delineated strategic aquifers and recharge zones (where applicable) are explicitly mentioned and not assumed as incorporated as part of the catchment and river management plans or stormwater receiving environments water quality objectives. Initiatives such as Water Sensitive Urban Design, e.g., the use of stormwater retention ponds, factor in potential impacts on groundwater yields and water quality.
  - Water demand management – bylaws acknowledge and put measures in place to regulate Schedule 1 groundwater use through requirements to register boreholes and abstraction volumes. Enforcement is supported by awareness campaigns that highlight unique water stewardship requirements for groundwater and encourage transparency to avoid the “tragedy of the commons”. Additionally, the Department works with industry to enforce borehole registration, ensuring municipalities can monitor trends in Schedule 1 groundwater use.
  - Mining, agriculture and rural development – targeted programmes are put in place where groundwater reliance is high and characterised by competing users like mining, forestry, agriculture and rural water supply. Proactively instituted strategies, engagements, and educational

campaigns are needed to ensure users understand the limitations of the resource and the effects of competing use

- **Institutional skills and knowledge capacity**
  - Analysis of skills capacity – aligned with the IDP intentions to develop and manage groundwater, the skills analysis and audits acknowledge that groundwater schemes need hydrogeological expertise to provide the necessary operational oversight to successfully implement conjunctive water use. This ensures the municipality identifies the need for hydrogeological expertise to inform standard operating procedures (SOPs) for abstractions and implement adaptive management strategies to optimise aquifer yields.
  - Human resource development and skills planning – skills planning and identification processes recognise that, e.g., technicians and artisans assigned to groundwater scheme operations need a basic understanding of groundwater systems and unique management. Although personnel will have transferable skills, training needs should be identified to ensure that SOPs (e.g., procedures for data recording, pumping regimes, and equipment specifications) are executed in ways that support quality assurance and inform adaptive aquifer yield management and sustainable O&M planning.
  - Information management and business reporting – reporting on the status of groundwater resources is incorporated into existing water resource information management systems and status reports. Municipal systems are equipped to capture monitoring data and provide key early-warning indicators, such as aquifer water-level trends and changes in abstraction volumes and water quality, to inform water resource planning, water security risk, and adaptation.
  - Communication and partnerships – the risk of declining yields due to competing abstractions and/or cumulative impacts of misinformed Schedule 1 abstractions is mitigated through intentional education and awareness campaigns. The municipality establishes and/or facilitates internal collaborations with key stakeholders, such as industry and the agricultural sector, to promote transparency, shared responsibility, and self-regulation.

4.4.2. Groundwater yields for water resource modelling and allocations

Sustainable groundwater use depends on understanding how much water an aquifer and its boreholes can reliably yield under defined operating conditions. Pumping tests and slug tests provide the primary field evidence for characterising borehole performance and aquifer hydraulic properties, including transmissivity, hydraulic conductivity and storage. These data are used to estimate sustainable yields, set appropriate abstraction rates, inform pump and infrastructure specifications, support water resource modelling and guide allocation decisions. Establishing this baseline at the planning or commissioning stage also enables municipalities to detect changes during operation, assess whether yields are declining and adjust management before service delivery is affected.

Box 12 summarises the key aquifer properties that are commonly derived from pumping tests and used to interpret groundwater system behaviour. These parameters help municipalities and hydrogeologists understand how easily groundwater moves through the aquifer, how much water can be released from storage, and how the resource may respond to continued abstraction. This information is essential for estimating sustainable yields, designing appropriate pumping regimes, supporting groundwater models and informing allocation or licensing decisions.

Box 12: Determining aquifer properties (hydraulic characteristics)

This is the most common and critical reason for conducting a pumping test. By measuring the water level response (drawdown) in the pumping well and nearby observation wells, we can calculate key parameters that govern groundwater flow:

- Hydraulic Conductivity (K): A measure of how easily water can move through the pore spaces or fractures of the aquifer material (e.g., sand, gravel, rock).
- Transmissivity (T): The rate at which water is transmitted through the entire saturated thickness of the aquifer. It is essentially hydraulic conductivity multiplied by the aquifer's saturated thickness (T = K * b). This is the single most important parameter for determining an aquifer's water-supply potential.
- Storativity (S) or Storage Coefficient: A measure of the volume of water an aquifer releases from or takes into storage per unit surface area per unit change in head (water level). This tells us how much water is available from the aquifer as the water level declines.
- Leakance: In a leaky aquifer system (where a confined layer is not perfectly impermeable), pumping tests can quantify the rate of vertical leakage from adjacent aquitards.

Why this is important: Without these parameters, it's impossible to build accurate groundwater models, predict long-term yield, or understand how the aquifer will behave under stress.

4.4.3. Step drawdown tests

The main use of this step-drawdown test is to establish the pumping rate for a borehole's constant-discharge test. In other words, what is the maximum rate at which the borehole can be pumped without lowering the groundwater level too low. It also helps define the optimum yield at which the borehole can be subjected to constant-discharge testing, if required.

The step drawdown test involves:

- The test involves pumping the borehole at three or more sequentially higher pumping rates, each maintained for an equal length of time, generally not less than 60 minutes and seldom longer than 120 minutes.
- A step length of 100 minutes is recommended
- The magnitude of the water level drawdown in the borehole in response to each of these pumping rates must be measured and recorded in accordance with a prescribed time schedule
- The actual pumping rate maintained during each "step" must also be measured and recorded
- As a rule, the rate of water level recovery for a period immediately following the period of pumping should also be monitored according to the same time schedule as during pumping.

Who should do this test, and what information should the municipality receive?

- The test should be performed by either a hydrogeologist, a hydrogeological consultant, or a pumping test consultant
- They should furnish the municipality with all collected data, graphs and a report which documents the findings of the test
- Important information that should be contained in the report includes drawdown vs time data, graphs showing this data, and recommended safe or sustainable yield information.

4.4.4. Constant discharge tests

A constant-discharge test is like the step test in that the borehole is pumped for a set time; however, the pumping rate is kept constant, typically based on results from a step test or observations from a slug test. This test is done over a much longer period. Constant discharge tests can run for 24 or more hours.

This test, along with the Step discharge test, is usually performed on newly drilled boreholes to establish their sustainable yields and to determine whether the selected pumping rate will cause a large change in water level or affect nearby boreholes. It can also assess whether borehole yield is declining, as changes in water levels may indicate that a pumping rate is no longer sustainable.

Pumping test contractors should perform this test in the presence of a hydrogeologist; alternatively, a hydrogeologist can perform it.

If performed immediately after drilling a borehole, this test can determine aquifer properties such as storage, transmissivity, and hydraulic conductivity. Doing this test later can indicate whether the pumping rate remains sustainable by considering the drawdown measured at the same rate.

4.4.5. Slug tests

The slug test is a fundamental method used to determine a borehole's yield. It provides a rapid assessment of the anticipated output, particularly in boreholes with outputs below 1 L/s. The results can inform the practicality and justification for further testing. Moreover, a slug test can be performed on any borehole, whether newly drilled or not.

The slug test involves measuring the water-level response in a borehole to the rapid displacement of water within it. To interpret the results, use the following. The displacement might cause either:

a) a rise in water level as would result from the introduction of a slug below the rest water level

b) a drop in water level as would be caused by the removal of a quantity of water from the borehole

In instances where a slug is introduced, the water level will recede to its original level. The sudden removal of water from the borehole will cause the water level to rise to its original level. The rate of recession or rise indicates the borehole's yield. In qualitative terms, the more rapid this is, the higher

the potential yield of the borehole. In other words, a rapid rise in water level means a higher-yielding borehole, while a slower rise or recession relates to a lower-yielding borehole. You can use the results of this test to decide whether further yield testing is warranted. It may be advisable to consult a hydrogeologist when interpreting the results.

Whether groundwater will be used to build resilience to drought or supplement the water supply, water planners need to estimate the aquifer's hydraulic properties and yields so they can account for the resource's contribution to water service provision. Several factors need to be accounted for, like:

- **Water use and demand management** – hydrogeologists use outputs from the hydraulic test to evaluate the demand limits that can be met without negatively impacting aquifer yields and exceeding the available individual borehole drawdown capacity. Water use and demand management considerations need to be addressed at the borehole and aquifer levels, since individual boreholes within the same aquifer may need to be pumped at different rates and for different durations. The cumulative borehole responses, in turn, inform aquifer-scale management.

- Using predictive numerical models, the groundwater balance can be estimated and future scenarios simulated. Use appropriate software capable of representing the level of hydrogeological complexity within the municipality. Scenario simulation should be designed to provide insightful data regarding the feasibility of different wellfield designs, the risk of decreasing yields for the selected conjunctive use strategy(s), risk of over-abstraction due to competing use, water quality risks, which can, e.g., inform the design of the monitoring network or decisions to implement MAR and risk of negative impacts on groundwater-dependent ecosystems.

- **Infrastructure design and capacity** – borehole yields are to inform the type of wellfield (centralised or decentralised), and design of the distribution network. A single large-scale wellfield may be more feasible for an aquifer with relatively high-yielding boreholes, whereas an aquifer characterised by lower-yielding boreholes may require a more decentralised approach, thereby affecting infrastructure and maintenance needs. Additionally, low-yield boreholes may need to operate in pumping-and-recovery cycles, with storage tanks to meet supply needs during recovery periods.

- **Data and information management systems** – data collection from exploration to operation phase is vital for conceptualising the groundwater system, identifying the risk of declining yields, developing operating procedures and an early warning monitoring network. A municipal decision support system for water management, designed to record key groundwater scheme performance indicators, will support the adaptive management approach needed for groundwater schemes.

4.4.6. Water quality aspects

Water quality testing allows the municipality to identify the primary water types in its wellfield and assess whether groundwater contains elevated levels of chemical compounds or natural substances. Water quality in each area is affected by local geology. As a result, some areas may show higher mineralisation than others. When a wellfield is located near land-use activities that could cause pollution, the monitoring process should include any chemicals from those activities. Consistent application of standardised sampling methods is essential for each wellfield. Correct sampling and borehole testing procedures are crucial to ensure that the data collected is both reliable and valid. The SOPs for borehole development describe various types of borehole testing and offer municipalities comprehensive, step-by-step guidance.

Which water-quality parameters affect declining yields?

Many wellfields experience declining yields because of clogging or biofouling. Most cases involve iron or manganese clogging. Factors that influence clogging include the following:

- Iron concentration (ferrous iron and ferric iron)
- Manganese concentration (Mn (II) and Mn (III))
- Dissolved oxygen levels
- pH
- Oxidation-reduction potential (ORP)
- Temperature
- Pumping regimes

These parameters need routine monitoring, as they influence the likelihood of clogging from biofouling or mineral precipitates. Evidence from wellfields shows that changing the pumping regime in a system with iron in reduced

form introduces oxygen into an otherwise reducing environment. This forms iron oxides, which can precipitate on borehole casings. Resident bacteria in boreholes facilitate this reaction. This leads to clogging of borehole screens and a subsequent decline in yield.

Box 13: Borehole clogging

Several municipal wellfields experience Iron clogging. Due to the presence of Iron in the aquifer under reduced conditions and the introduction of oxygen during the switching up of pumps. Over time, iron precipitates can completely clog screens, casings, pipes, and valves, often leading to borehole decommissioning. Some examples of places where this phenomenon has been observed include Atlantis and Calitzdorp. In Eastern Cape villages, water from handpumps is immediately found to contain iron that settles to the bottom of white buckets commonly used to collect water.

Pictures of what the equipment can look like after a long period of undetected or unmeasured iron clogging.



Who should measure these parameters?

Water treatment works that use groundwater can incorporate some of these tests into their monitoring and testing. Groundwater measurements can also

be made using field instruments. A hydrogeologist or geochemist may need to be consulted to interpret the results.

Box 14: Table Mountain Group (TMG) and iron clogging

Work done during the 2000s highlighted the following in TMG aquifers, based on experiments with rock samples from areas experiencing iron clogging and on parameters for different areas regarding the sources of iron biofouling and clogging in wellfields. The following conclusions came from the work:

- Redox – Most Fe is released into solution under anoxic conditions[2] independent of the pH of the solution, suggesting that the most effective dissolution process is reductive dissolution.
- Form of Fe in the rock – Iron present in the amorphous Fe oxide phase is most readily mobile, although there is a suggestion of a more slowly released Fe(II) form.
- pH – The effect of pH was only notable under oxic[3] conditions suggesting that proton-promoted dissolution dominates in the presence of O_2. Even at low pH, the Fe in solution was oxidised and precipitated, inhibiting further dissolution. The equilibrium concentration of Fe in solution was pH-dependent in the oxic samples.
- Presence of organic ligands[4] – Organic acids were found to catalyse Fe dissolution in arenaceous rocks under anoxic conditions but did not increase the extent of dissolution. Adsorption of organics onto clay minerals in argillaceous samples may inhibit the catalytic action of organic acids.
- Lithology – Lithology affects the pH of the groundwater through buffering, the mineralogical host of Fe, and the inhibition of the catalytic effect of organic acids.

At the borehole scale, the signs of clogging could be one of a few things:

- The occurrence of reddish-brown slimy deposits
- A metallic taste or foul smell
- Reduced flow or pressure

[2] Aquifers are frequently naturally anoxic because the soil above has depleted all available oxygen prior to water infiltration. Consequently, deep groundwater often exhibits elevated concentrations of dissolved iron and manganese, as these elements remain in their soluble forms owing to the oxygen deficiency. The term "anoxic" fundamentally means "without oxygen." In the context of water, soil, or the environment, it refers to a condition in which molecular oxygen (O_2) is entirely absent.

[3] Oxic conditions describe an environment where molecular oxygen (O_2) is available.

[4] Organic ligands are molecules (usually based on carbon) that can bind to metal ions, such as iron (Fe) or manganese (Mn), to form a complex.

- Rusty coloured water (reddish-brown)

Iron clogging emerged as an issue decades ago, prompting efforts to clean up and remediate. In 2004, the Vyredox technique was considered—a method that alters subsurface conditions to oxidise and precipitate iron in aquifers, using agents such as oxygen or ozone. In Atlantis, it proved effective at reducing iron and manganese concentrations [52].

Preliminary testing of a method similar to the Vyredox approach from 2004 was pilot tested in Atlantis in 2014. The Calitzdorp wellfield was initially part of the study but was not used as a test site due to challenges in implementing in-situ treatment in fractured aquifers, including the heterogeneous geological setting, complex fracture patterns, intersecting aquifers, depths, difficulties in delivering and distributing oxidant, mixing of water qualities, and logistical and financial issues like drilling costs in hard rock. The Fe in Atlantis groundwater is derived from naturally occurring iron- and sulphate-rich minerals in the Sandveld Group and weathered Malmesbury Group bedrock, with high DOC (5-10 mg/L) creating reducing conditions. This method has proven safest. Other approaches involve altering pH, pumping, and re-adjusting pH after chemical iron removal, but concern exists that harsh chemicals may affect the aquifer's microbial ecosystem [52].

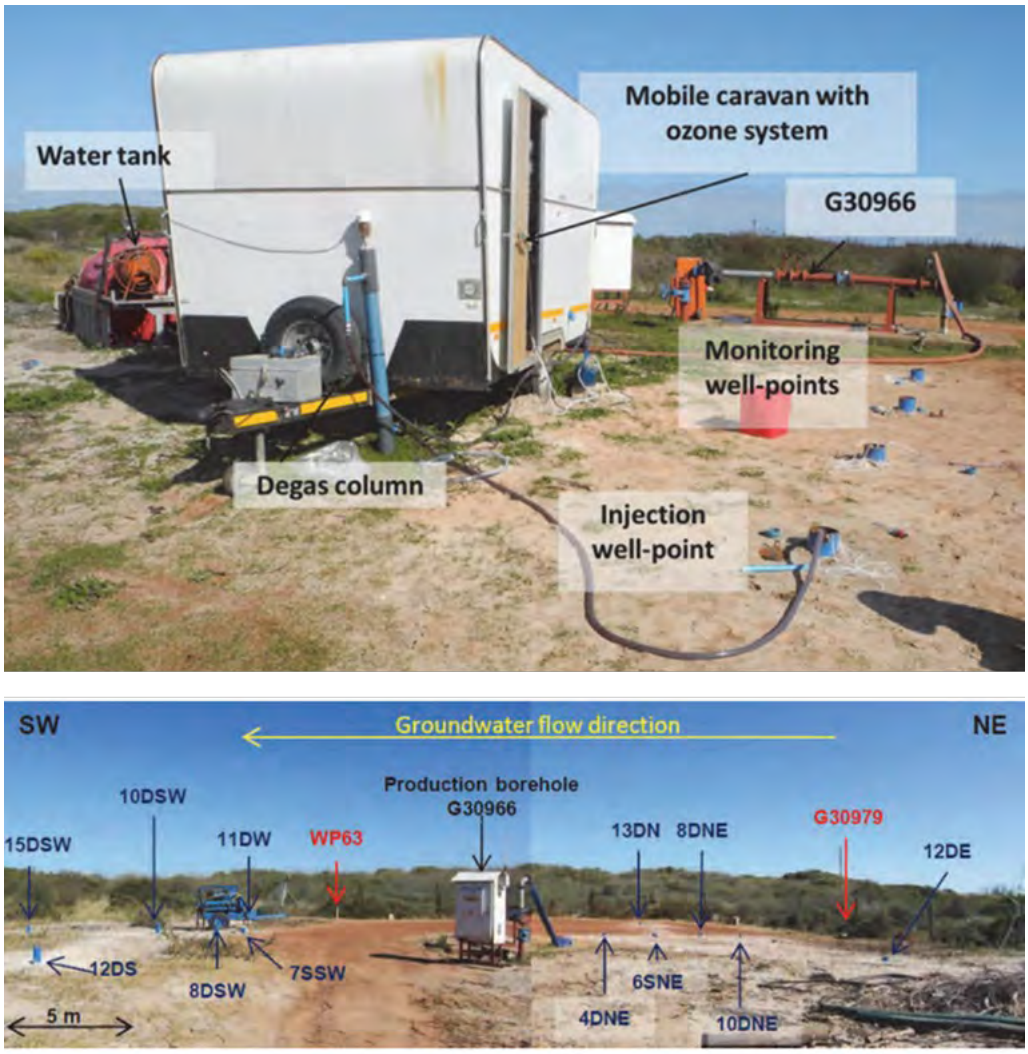


Figure 12: Pilot denitrification system

Other methods used include removing iron deposits and bacteria through shock chlorination, acid treatment, or specialised cleaners such as Boresaver[5], or by dissolving iron oxide. These methods can be harsh on the borehole ecology. Physical methods like scrubbing the casing, agitating it with brushes, or using high-pressure injection to dislodge deposits have also been employed.

In Calitzdorp, an acid treatment was tested that dramatically reduced the pH; the pumped-out water contained much higher iron levels than before the treatment. Subsequent addition of a strong base returned the pH in the aquifer to near neutral after the scaling and biofilm were removed. The

[5] BoreSaver is the trade name for a range of chemical products specifically designed for the rehabilitation and maintenance of water wells, boreholes, and associated infrastructure

treatment improved groundwater flow and cleaned the casing of deposits, but the ecological impact may not have been considered.

Site visits in the Eastern Cape during 2010, as part of a project to investigate the sustainability of rural water supply, revealed that although hand pumps were installed on boreholes in rural villages, the water pumped from these boreholes contained iron levels that could stain clothing during washing. Residents of the villages had resorted to using the water for washing their bodies and gardening. While pumping water into a white bucket, iron immediately begins precipitating from the water and settling at the bottom.

An article published in the Eastern Cape about boreholes on farms showing signs of clogging recommended treating them with both chemical (acid treatment) and physical (stainless steel wire brush) methods to remove deposits. Although this approach will remove iron deposits and clean the screen, it is temporary and may negatively impact the aquifer or the borehole's ecology.

A treatment method should remove the problem while causing the least harm to the system. Methods in which iron precipitates in the aquifer rather than on the casing may be better suited, as they require only oxygen or ozone, as in the tests performed in the Atlantis Aquifer system.

The preceding discussion shows that declining yields can arise from aquifer conditions, water-quality processes, pumping regimes and borehole deterioration. However, even where the groundwater resource remains adequate, poor operation and maintenance can reduce the water actually delivered to users. The next section therefore shifts from diagnosing yield decline to strengthening the O&M systems that help prevent avoidable performance losses.

4.5. O&M-RELATED DECLINING YIELDS OR LOW YIELDS

Declining or low yields are often linked to weaknesses in the operation and maintenance of groundwater infrastructure, even where the aquifer itself still has sufficient water available. Poorly maintained pumps, blocked or deteriorating borehole components, damaged electrical systems, leaking pipework, inadequate monitoring and delayed responses to performance changes can all reduce the volume of water delivered by a scheme. For this reason, municipalities should distinguish between aquifer-related yield decline and O&M-related performance decline, and should manage boreholes, pumps, meters, controls and associated infrastructure through a

proactive maintenance programme. To build a robust O&M programme for groundwater infrastructure, municipalities should focus on the following:

- **Transition from reactive to proactive maintenance**: Implement a scheduled preventive maintenance programme for all borehole pumps and equipment, with frequency based on pumping intensity.
- **Invest in monitoring and data management**: Equip boreholes with water level meters (even low-cost ones) and flow meters. Use simple mobile apps to collect data regularly, creating a clear picture of infrastructure performance and enabling rapid responses to issues.
- **Develop skills and standardise procedures**: Train pump operators and groundwater officials. Develop clear SOPs for all routine O&M tasks.
- **Use a structured approach for rehabilitation**: When faced with declining yields, follow a phased process to diagnose the problem, plan the intervention, and monitor the outcome.
- **Engage with new regulations**: Stay informed about the evolving regulatory landscape, including the new draft groundwater regulations and rehabilitation guidelines, to ensure compliance and access to the latest standards.

An effective SOP must include systematic data collection to detect problems early:

- **Daily monitoring**: Record flow rate, pumping hours, and any sand content in the water.
- **Water level measurements**: Measure static and pumping water levels regularly using a dipper or water level logger.
- **Annual yield testing**: Compare current specific yield (discharge per unit drawdown) with the original value. If a 10-15% decrease is observed, investigate causes. If the decline reaches 25%, initiate rehabilitation procedures.
- **Electrical monitoring**: Track current input, voltage, and insulation resistance. Changes may indicate pump wear or motor problems.

A municipality can only maintain groundwater infrastructure effectively if it also understands how much water is being abstracted, whether that abstraction is authorised, and whether pumping remains within sustainable

limits. The next section therefore links operational monitoring to licensing, metering, compliance tracking and abstraction management.

4.6. ABSTRACTION MANAGEMENT AND LICENSING TOOLS

Groundwater abstraction and licensing are essential components of sustainable resource management. The National Water Act (NWA) 38 of 1998 serves as the basis for water governance in the country. Despite the robustness of the framework, its implementation regarding abstraction and licensing has always been a significant challenge, resulting in poor enforcement of groundwater use licensing, particularly for small-scale and domestic users, and making it difficult to monitor abstraction rates effectively. If abstraction is not monitored, this can lead to over-abstraction [46].

Key licensing and compliance tools:

- **Groundwater abstraction permit application checklist**: Complete the application and submit to DWS or online via the e-WULA system pre-submission, following the checklist. Required information includes borehole coordinates, pump test data, reserve determination, and impact assessment. Required supporting documents include step-drawdown or constant-rate test results, hydrogeological report, and environmental authorisation (where applicable). Step-by-step guide to the DWS Integrated Water and Waste Management System (e-WULA) portal.
- **Water-use licence conditions tracking template:** Excel calendar with automated reminders for annual reporting, volumetric metering, water quality sampling and licence renewal dates. A compliance dashboard showing percentage compliance per condition.
- **Over-abstraction early-warning threshold calculator:** A simple spreadsheet tool based on aquifer classification, such as major, minor, and poor. This enables the calculation of the maximum allowable abstraction as a percentage of the Groundwater Reserve, typically in the range of 30-70% of recharge. The system triggers colour-coded alerts when monthly abstraction exceeds 80% of the licensed volume.

- **Volumetric metering and telemetry options:** This is a recommended smart water meter based on electromagnetic or ultrasonic systems, which enable remote data logging and reporting of daily, weekly, and monthly readings against authorised volumes. Cloud-based telemetry systems that are compatible with the DWS National Groundwater Archive upload requirements are also recommended.
- **Conjunctive use planning spreadsheet:** An integrated surface water and groundwater allocation tool that shows a monthly balance. It automatically calculates optimal switching between sources to protect the aquifer during dry seasons.
- **Resource Directed Measures (RDM) and Reserve Determination tools:** DWS Groundwater Reserve Determination guidelines and Excel templates, and Basic Ecological Reserve calculator for small schemes.

Table 9 Decision matrix for licensing and abstraction risk

Situation	Licence Status	Recommended Action	Urgency
New borehole or increased yield	No licence	Submit e-WULA application with pump test data	Immediate
Existing licence – volume exceeded	Over-abstraction alert	Reduce abstraction + submit variation application	High
Licence conditions not being met	Non-compliance	Implement tracking template + corrective action plan	Medium
Sustainable yield confirmed < demand	Licence insufficient	Apply for additional volume or conjunctive use	Medium

Licensing, metering and abstraction controls depend on the continued availability of functional groundwater infrastructure. If pumps, headworks, cables, meters, and access points are damaged, stolen, or inaccessible, municipalities lose the ability to supply water, measure use, enforce licence

conditions, and respond to risks. The chapter therefore turns next to infrastructure protection and vandalism prevention.

4.7. INFRASTRUCTURE PROTECTION AND VANDALISM PREVENTION RESOURCES

Vandalism and theft hinder the sustainability of groundwater infrastructure. In municipalities experiencing civil unrest, investment in water infrastructure fell short, further aggravated by infrastructure destruction and, consequently, a regression in supply [47]. Vandalism is widespread in both urban and rural settings and takes many forms. These acts usually include water theft, which directly results in revenue loss for the utility, and vandalism and theft of valuable metal pipes, fittings, and manhole covers, which increase the utility's maintenance costs (WSUP 2014). These acts of theft and vandalism remain the leading causes of declining yields and prolonged service interruptions in rural and peri-urban water schemes across South Africa. Experience has shown that physical protection measures in conjunction with community ownership significantly reduce incidents and downtime [36].



Figure 13: Borehole installed by the Vhembe municipality more than 30 years ago. Residents say the cables and water pump were stolen in 2004. However, it was repaired four years ago, but it is still not functional.[6]

Key infrastructure protection and vandalism protection tools:

(a) Security risk assessment checklist for borehole and pump installation.

This rapid field checklist before and after any new installation or rehabilitation is to be considered:

- Is the borehole within 500 metres of a settlement, informal crossing or footpath?
- Are headworks visible from a public road?
- Is there existing fencing, lighting or CCTV?
- Are electrical cables exposed or easily accessible?
- Has theft or vandalism occurred in the surrounding area in the past 12 months?
- Are community leaders actively involved in borehole oversight?

[6] https://groundup.org.za/article/women-in-magangeni-village-in-limpopo-dug-a-well-to-access-underground-water-amid-severe-shortages/

Based on the responses above, a risk assessment will be carried out for low, medium, and high risks. If the average score is low risk, then the borehole or pump can be installed; if the average score is medium risk, then implement basic protection. For high risk, implement urgent, comprehensive protection measures.

(b) Recommended minimum standards for new or upgraded boreholes

- Lockable steel or reinforced concrete headworks chamber with a heavy-duty hinged lid and padlock.
- Submersible pump installed at least 5 m below the lowest expected water level.
- Armoured underground cable from pump to control panel.
- Solar-powered or 12 V DC systems with battery enclosures inside locked chambers, 2.4 m high anti-climb fencing with barbed or razor wire, and a locked gate.
- Optional solar-powered CCTV with GSM alert to designated community members or municipal control room.



Figure 14: Example of vandal-proof infrastructure

The policy, legal and institutional response should therefore position groundwater as a strategic climate-resilience asset. This requires municipalities to move beyond emergency use and formally define how groundwater will support drought mitigation, flood recovery, water quality protection, ecosystem protection and service-delivery continuity. Institutional arrangements must also clarify who is responsible for

groundwater monitoring, abstraction decisions, infrastructure readiness, source protection, communication with users and escalation during drought or flood events.

(c) Community-based borehole management agreement template

Community involvement in the development and protection of groundwater infrastructure has been effective in preventing theft and vandalism [48]. The following considerations can be taken to effectively involve the community based on a simple agreement, which should include:

- Names and contact details of elected borehole committee members.
- Clear roles and responsibilities based on weekly visual inspections and immediate fault reporting.
- Rules on access, livestock exclusion and prohibited activities.
- Penalty clauses for vandalism or theft by community members.
- Agreement to allow municipal access for maintenance.
- Signatures of traditional leaders, including ward councillors and municipal representatives.

(d) Insurance and risk management guidelines

- Register all boreholes on the municipal asset register with current replacement value.
- Include rural water infrastructure under existing municipal public liability and asset insurance policies.
- Maintain photographic records and maintenance logs as proof of due diligence

Physical protection helps keep schemes operational, but it does not by itself protect the aquifer that supplies them. Groundwater quality can be compromised by land-use activities, sanitation systems, industrial or agricultural practices, mining and poor management of recharge areas. The next section therefore broadens the focus from protecting infrastructure to preventing, detecting and responding to groundwater pollution.

4.8. POLLUTION PREVENTION, PROTECTION AND REMEDIATION TOOLS

The MSDF is a key tool of the IDP, providing a visual expression of the outlined vision and goals that guide decision-making to balance competing sectors and activities. Therefore, it is expected that an IDP that identifies groundwater as a critical resource for basic water service provision is accompanied by the necessary municipal spatial development and planning that reflect important aquifer system(s), recharge zone(s), and existing groundwater schemes within the municipality (Table 3).

The extent to which the MSDF highlights strategic groundwater resources also indicates how fully it has considered the implications of land-use trade-offs between groundwater protection and development for resilient water supply and strategic sectors. Groundwater pollution from various sources, including on-site sanitation, agriculture, mining, and industrial activities, is a growing threat to borehole yields and water quality in South Africa. Once contaminated, aquifers are extremely difficult and expensive to remediate. However, preventive measures can be put in place to reduce pollution, delineate protection zones, screen for risks, and select appropriate remediation options when contamination occurs ([49], [50]).

Spatial layouts and development plans can be used to proactively:

(a) **Identify potential contamination sources or contaminating activities.** Ideally, municipal wellfields should be located in unimpacted natural environments or in locations with little to no potential for contamination. However, this is not always possible, especially in urbanised environments. Overlapping the different stormwater management infrastructure and land zoning layers with strategic aquifers and recharge locations can 1) serve as part of the first level of risk screening for suitable wellfield locations 2) provide insights into potential contaminating activities that pose a risk to water quality 3) highlight groundwater sources that are already at high risk of poor water quality and 4) provide an indication of the pollution prevention measures and monitoring needed.

- A high-level risk screening based on zoning categories can then be used to inform more detailed risk screening checklists and sampling protocols at the site level, like:
    - Setting minimum setback distances for septic tanks, fuel storage, and waste sites.

- o Septic tank and soakaway setback distances should be a minimum of 30–50 m from boreholes.
- o Protection zone signage and land-use restriction templates
- o Bunded fuel and chemical storage areas.
- o Proper waste disposal and livestock exclusion fencing.
- o Rainwater diversion channels around headworks.
- o Community education posters on responsible behaviour near a borehole.
- o Remediation option matrix includes pump-and-treat, permeable reactive barriers, and bioremediation.

(b) **Identify groundwater contamination pathways.** Understanding how an aquifer can be polluted is closely linked to the groundwater conceptual site model. Overlapping the different zoning layers with a layer of conceptualised (delineated) aquifers and recharge zones can provide insights into the mechanisms, migration pathways, and risk of water quality deterioration.

- Aquifers that are directly connected to surface and recharge zones can be at greater risk of contamination depending on their proximity to, e.g., agricultural and industrial zoning.

(c) **Determine the risk of contamination of the municipal groundwater schemes, including decentralised groundwater schemes.** The following groundwater vulnerability mapping tools can be used, with input from a hydrogeologist, to assess the vulnerability of identified groundwater schemes/aquifers and recharge zones to contamination:

- Simple vulnerability scoring system for local-scale assessments using DRASTIC or the modified South African method. DRASTIC is an acronym for the parameters accounted for in the assessment, including: D = Depth to water table, R = Net recharge, A = Aquifer media, S = Soil media, T = Topography, I = Impact of the vadose zone, and C = Hydraulic conductivity. A hydrogeologist familiar with local groundwater conditions can help develop vulnerability maps for the identified locations.
- Downloadable GIS vulnerability map layers from DWS and the Council for Geoscience. In the absence of site-specific data, the readily available maps can be used for initial assessments,

including the National Groundwater Quality Monitoring Programme data

- QGIS plugin for rapid vulnerability mapping using existing borehole and land-use data. In addition to the DRASTIC method, other vulnerability assessment approaches (e.g., PI = Protective cover and Infiltration conditions) are available and may be more suitable for the municipal context.

(d) **Determine feasible resource protection options.** Feasibility and consideration of implementing protection zones will be influenced by the type of groundwater schemes and spatial zoning. Several approaches can be used to develop GIS layers of protection zones for spatial development and planning. These methods are captured in the source protection zoning guidelines produced by WRC and DWS.

- Source protection zoning guidelines provide a step-by-step methodology to delineate inner (Zone 1), outer (Zone 2), and catchment (Zone 3) protection zones [49]. The objective of the delineated zones is to reduce the risk of direct contamination of groundwater in the immediate location of the abstraction boreholes or wellfields by limiting certain activities within the different protection zones
- Overlaying groundwater protection zones for strategic aquifers and recharge zones will highlight factors that should inform the water protection measures in the different zoning categories.

Table 10: Remediation option matrix

Contaminant Type	Remediation Option	Feasibility in SA	Relative Cost
Nitrates / E. coli	Pump-and-treat + disinfection	High	Low–Medium
Heavy metals	Permeable reactive barrier	Medium	Medium
Hydrocarbons	Bioremediation or air sparging	High	Medium
Saline intrusion	Managed aquifer recharge (MAR)	Medium–High	Medium–High
Mixed organic pollutants	Activated carbon filtration	High	Medium

Pollution prevention is especially important in coastal areas, where groundwater quality can also be affected by the movement of saline water into freshwater aquifers. Unlike many point-source pollution risks, saline intrusion is closely linked to abstraction patterns, groundwater levels and the balance between inland recharge and seawater pressure. The following section therefore treats saline intrusion as a specific coastal groundwater management risk that requires targeted monitoring, modelling and mitigation tools.

4.9. SALINE INTRUSION MANAGEMENT TOOLS (COASTAL AREAS)

In coastal aquifers, seawater intrusion is a prevalent concern, driven by both static changes in the groundwater table and dynamic effects of incoming saline water during pumping. Seawater intrusion into freshwater aquifers can degrade water quality and increase the risk of corrosion to water infrastructure [51]. Coastal aquifers in the Western Cape, Eastern Cape, and KwaZulu-Natal are at serious risk, necessitating practical tools for early detection, monitoring, modelling, and mitigation of saline intrusion.

(a) Coastal groundwater monitoring network design guide

- Recommended borehole spacing and depth for coastal monitoring transects.
- Minimum network, i.e., one coastal monitoring borehole and two inland observation boreholes per 5 km of coastline.
- Installation specifications for multi-level piezometers or depth-specific sampling ports.
- Automatic data logger settings, ideally, hourly EC, TDS and water-level recording.

(b) Salinity profiling tools

- Handheld or downhole EC and TDS loggers, preferably with an accuracy of ± 1 %.
- Depth-specific sampling protocol using bailers or low-flow pumps.
- Field calibration and quality control checklist.
- Simple field interpretation guide:
    - o EC < 150 mS/m - fresh

- EC 150–300 mS/m - transition zone, thus requires close monitoring.
- EC > 300 mS/m - saline intrusion confirmed

(c) Numerical modelling guidelines for saltwater intrusion

- Recommended software includes MODFLOW with SEAWAT package, which is free, or FEFLOW, which is a paid option.
- Step-by-step modelling workflow for coastal aquifers.
- Calibration and validation checklist using historical EC and water-level data

(d) Managed aquifer recharge (MAR) feasibility checklist

Use this quick checklist to assess MAR suitability for coastal intrusion control:

- Is there surplus surface water or treated wastewater available?
- Does the aquifer have sufficient storage and transmissivity?
- Are there suitable infiltration basins or injection wells?
- Will recharge raise the water table enough to push back the saltwater wedge?
- Are there any contamination risks from the recharge source?

If the scoring is such that 4–5 is “Yes”, then there is an opportunity, and one can proceed to scoping.

Taken together, sections 1.1 to 1.9 present groundwater management as an integrated municipal function rather than a set of isolated technical tasks. The chapter moves from institutional responsibility and planning questions, through yield diagnosis, O&M, licensing, infrastructure protection, pollution prevention and saline intrusion management. The tools and resources below provide supporting references for municipalities that need to strengthen any of these linked components.

4.10. TOOLS AND RESOURCES

- De Bruin, K., Rademan, Z. & Towers, L. (2023). Guidance document for management of a groundwater scheme. Water Research Commission, Report No. TT, 906/22.
- De Lange, J., Molaolwa, G., Kotzé, Y. L., van der Merwe, J., Esterhuizen, L., & Mantyeane, A. M. (2019). Training manual for groundwater resource management and groundwater governance for municipalities in South Africa. Water Research Commission, Report No. TT, 790, 19.
- Pietersen, K., Titus, R., (2022). Guidance document on groundwater scheme development. Water Research Commission: Pretoria, WRC Report no. TT 903/22.
- SADC-GMI (2020). Training manual for operation and maintenance of groundwater infrastructure in SADC. SADC-GMI report: Bloemfontein, South Africa.
- Parsons, R., Eichstadt, L., Crowther, J. & Blood, J. (2008). Groundwater Licensing Guide: Application procedure for the development and use of groundwater. Water Research Commission, Report No. 1510/1/08.

PART D

5. TECHNICAL AND OPERATIONAL MANAGEMENT OF GROUNDWATER SCHEMES

Part D presents practical management tools for addressing the technical and operational challenges associated with groundwater schemes. These include field protocols, assessment kits and equipment, monitoring and assessment checklists, corrective measures, software recommendations, databases and, where appropriate, relevant case studies. The tools are aligned with the requirements of the Water Research Commission (WRC), the SANS 10299 standards, the National Groundwater Strategy, and Resource-Directed Measures [39].

Any standard operating procedures (SOPs) for boreholes in South Africa must be aligned with the SANS 10299 series: Development, maintenance and management of groundwater resources. This multi-part standard provides the technical foundation for all aspects of borehole lifecycle management. The standard is divided into several distinct parts, each addressing a critical phase or component of groundwater resource management[7]:

- **Part 0: Glossary of Terms** – Provides definitions for terminology used throughout the groundwater industry
- **Part 1: The location and siting of water boreholes** – Covers methodologies for identifying and selecting appropriate drilling sites.
- **Part 2: The design, construction and drilling of boreholes**- Specifies requirements for borehole design and proper drilling techniques.
- **Part 4: Test-pumping of water boreholes** – Outlines procedures for test-pumping to determine long-term sustainable yield and aquifer properties.
- **Part 5: The design, selection and performance of pumping equipment for production boreholes** – Addresses the selection criteria and performance standards for production pumps.

[7] There is no Part 3.

- **Part 6: The installation and commissioning of pumping equipment for production boreholes** – Details the correct installation and commissioning process for pumping equipment.
- **Part 7: The rehabilitation of water boreholes** – Provides methods for restoring and improving the performance of existing boreholes.
- **Part 8: The management of water boreholes** – Covers the ongoing operational management and monitoring of boreholes.

The standards are maintained by the South African Bureau of Standards (SABS) and are reviewed periodically to ensure they remain relevant and effective

5.1. TARGET AUDIENCE

This section is intended primarily for borehole practitioners, field technicians, municipal water services officials, operations and maintenance personnel, hydrogeologists, consulting engineers, drilling contractors, pump installers and scheme managers who are responsible for the planning, development, operation, monitoring, maintenance and protection of groundwater supply schemes. It is also relevant to catchment management agencies, water service providers and decision-makers who need to understand the technical requirements, field procedures and compliance expectations associated with borehole management.

For practitioners and field teams, the chapter provides practical guidance on equipment selection, field testing, data collection, diagnostics, rehabilitation, monitoring and reporting. For municipal officials and scheme managers, it supports informed oversight of contractors, interpretation of technical reports, budgeting for operation and maintenance, and the implementation of corrective actions where borehole performance, water quality or infrastructure reliability declines.

The content is therefore written for both technical and non-technical users: it explains what should be done in the field, why each activity matters, what information should be recorded, and when specialist input is required. This is important because the SANS 10299 series covers the development, maintenance and management of groundwater resources, including borehole siting, construction, test-pumping, equipment, rehabilitation, management and decommissioning. The target audience should use this chapter as a practical reference for applying those requirements consistently across groundwater schemes.

5.2. PURPOSE

The purpose of Part D is to support the practical, on-the-ground implementation of groundwater supply management, source-directed controls and groundwater protection measures. It translates technical standards, policy requirements, and hydrogeological concepts into usable procedures that guide planning, commissioning, operation, monitoring, maintenance, and corrective action for boreholes and groundwater schemes.

In practical terms, the chapter helps users move from policy intention to field execution. It explains how to assess groundwater sources, diagnose operational problems, collect data, structure routine monitoring, and make management decisions when borehole performance, water levels, water quality, or infrastructure condition changes over time.

- Provide a clear operational basis for managing boreholes from development and commissioning through to routine operation, maintenance, rehabilitation and decommissioning.
- Support consistent implementation of SANS 10299 requirements, Water Research Commission guidance, the National Groundwater Strategy and Resource-Directed Measures in municipal and community water supply contexts.
- Improve the early detection of declining yields, over-abstraction, groundwater pollution, saline intrusion and infrastructure-related failures.
- Promote reliable record-keeping, trend analysis and evidence-based decision-making for groundwater schemes.
- Clarify when routine operational action is sufficient and when specialist hydrogeological, engineering or regulatory input is required.

The chapter also strengthens accountability by defining the minimum information that should be available for every production borehole, including construction records, pump-test results, operating rules, water-level measurements, abstraction volumes, water-quality results, maintenance history and incident records. These records enable scheme managers to compare current performance with baseline conditions and to justify timely management interventions before operational problems become critical. The next section therefore begins with field assessment and diagnostic tools, because reliable diagnosis underpins every subsequent O&M, abstraction, protection, and remediation decision.

5.3. FIELD ASSESSMENT AND DIAGNOSTIC TOOLS: LOW YIELDS AND DECLINING YIELDS

Low yield and declining yield are among the most common operational problems experienced in groundwater supply schemes. A low-yielding borehole is one that cannot provide the expected or required volume of water for its intended use, while a declining-yield borehole shows a measurable reduction in output over time, even when the pump, power supply and operating conditions appear unchanged. These conditions may be caused by over-abstraction, falling groundwater levels, drought-related recharge reduction, borehole clogging, screen incrustation, sand pumping, pump wear, inadequate borehole development, poor pump setting, interference from nearby abstraction, or changes in water quality that promote scaling or biological growth. Sustainable yield is therefore not a fixed value; it must be confirmed through testing, monitored during operation, and reviewed when field conditions change. Sustainable yield is defined as the maximum volume of water that can be withdrawn annually from a groundwater resource without eliciting undesirable effects [40].

The first step in any yield assessment is to distinguish between a true aquifer limitation and a mechanical or operational problem. A borehole may appear to have a low yield because the aquifer cannot transmit enough water, but the same symptom can also result from a worn pump, a blocked screen, a leaking rising main, incorrect pump depth, a damaged electrical supply, blocked valves, inaccurate flow measurement, or excessive operating hours. For this reason, diagnosis should follow a structured sequence: confirm the reported yield problem, inspect the pumping system, compare current water levels and discharge against historical records, assess recovery after pumping, and then decide whether a formal pumping test, rehabilitation investigation or wellfield-level review is required.

- **Reduced discharge at the same pump setting:** indicates possible drawdown increase, pump wear, clogging, valve restriction or reduced aquifer inflow.
- **Increasing drawdown during normal operation:** may indicate over-abstraction, reduced recharge, borehole losses or interference from nearby pumping.
- **Slow recovery after pumping:** suggests limited aquifer transmissivity, reduced storage, boundary effects or excessive pumping duration.
- **Sand, silt or turbidity in discharge water:** may indicate screen damage, gravel-pack failure, over-pumping or poor borehole

development.

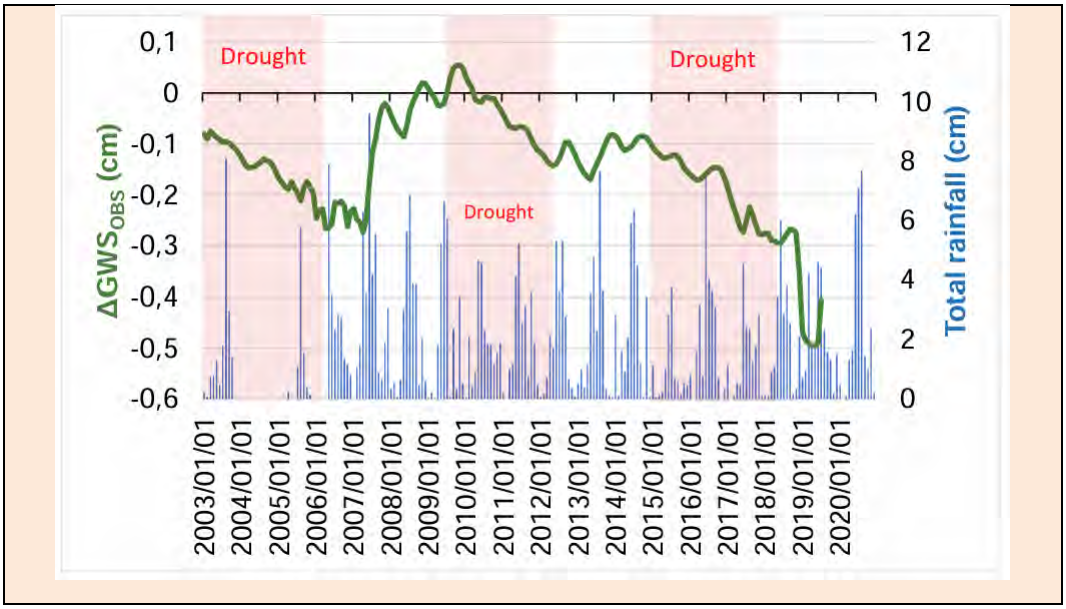
- **Higher electricity use for the same volume supplied:** can indicate declining well efficiency, increased pumping lift, pump wear or hydraulic restrictions.
- **Frequent pump trips or dry-run alarms:** may indicate that the water level is approaching the pump intake or **that** the pump duty cycle is too intensive.

A rapid field assessment should therefore record, as a minimum, the static water level, pumping water level, discharge rate, pump depth, total borehole depth, pump run time, recovery behaviour, borehole construction details, water strike depths, visible water quality changes, and any recent changes in demand or operating schedule. Compare these data with drilling records, previous pump-test results, commissioning reports, and routine monitoring records. Where the current discharge has declined by more than about 20% from the commissioned yield, or where the water level approaches the pump intake during normal operation, the borehole should be treated as a priority for further investigation.

Box 15: Groundwater storage changes in the Langebaan Road Aquifer [41]

Remote sensing from the National Aeronautics and Space Administration's Gravity Recovery and Climate Experiment (GRACE) provides continuous, freely accessible datasets that support evaluation of trends and fluctuations in groundwater storage. A study used GRACE data, combined with the Global Land Data Assimilation System (GLDAS), to monitor groundwater storage in the Langebaan Aquifer.

In the Langebaan Road Aquifer, groundwater storage showed a rapid downward trend (~ -0.2 cm) from February 2003, which abruptly ended in April 2007. It then increased until November 2009 (0.3 cm). Afterwards, the volume declined by -0.2 cm from November 2009 to May 2012. Groundwater storage remained stable from June 2012 to November 2016, then declined steeply, reaching a peak decline in May 2019. Overall, groundwater storage decreased by about 0.6 cm from November 2009 to May 2019. In the aquifer, groundwater storage increased from March 2003 to May 2004, then declined steeply until November 2005. It remained stable until February 2008, then increased through November 2009, with two major peaks in November 2008 and November 2009. From November 2009, groundwater storage declined sharply until March 2013 (-0.8 cm), then increased abruptly, peaking in May 2015 with a 1 cm rise. Since then, it declined significantly, with the largest drop in the entire series occurring in May 2018, at about -1.23 cm. Groundwater storage increased again from May 2018 to December 2018 by 0.7 cm.



While detailed groundwater sustainability analysis is difficult, the pumping test is one of the most valuable tools for evaluating groundwater resources. It assesses borehole performance, borehole yield, the borehole's zone of influence, 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 [42]:

- Improved conceptual understanding of the aquifer system
- Quantification of the hydraulic characteristics and properties of the aquifer system
- 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. The response of water levels to pumping is analysed to derive information on borehole efficiencies and the hydraulic parameters of the aquifer system. Thus, hydrogeologists must properly oversee pumping tests.



Figure 15: Taking measurements during a pumping test

There are different types of pumping tests:

- Step-Drawdown test
- Constant-rate test
- Recovery test
- Slug test

Although the municipal official is not accountable for executing and overseeing the pumping test, it is essential that the procedures and analytical steps are understood. Specifically, the standard operating protocols for borehole pumping are derived from the pumping test, thereby forming a dependable engineering plan.

5.3.1. Step-drawdown test

Step drawdown tests aim to establish the short-term relationship between yield and drawdown for the tested borehole. This test determines the optimal yield for the constant-discharge test. Under certain conditions, such as in screened and filter-packed boreholes, data collected from this test helps identify the borehole's efficiency.

Equipment

The equipment required for step-drawdown are; submersible pump with variable-speed drive or valve for precise discharge control, flow meter (electromagnetic or propeller type, accurate to ±5 %), two water-level transducers or dippers (one in the pumped borehole, one in a nearby observation borehole if available), data logger capable of 10–60 second intervals, discharge hose and measuring tank (for low yields), generator or reliable power supply, stopwatch and field notebook.

Data collection procedure

- Measure and record the static water level (SWL) to the nearest 1 mm before starting
- Install the pump and transducers, ensuring the pump intake is at least 2 m above the top of the screen. The primary reason is to prevent the water level from falling below the top of the screen, which could cause the screen to dewater and damage the pump.
- Start the pump at the lowest planned discharge rate (e.g., 20–30 % of estimated yield).
- Maintain each step for 60–120 minutes (or until water level stabilises) while recording drawdown every 10–60 seconds.
- Increase the discharge rate in 4–6 equal steps (typical increments: 20 %, 40 %, 60 %, 80 %, 100 %, 120% of target yield).
- At the end of the final step, switch off the pump and record recovery for at least 60 minutes.
- Measure final SWL after full recovery.

***Precaution: Never run the pump dry. Monitor discharge and water level continuously.**

Data recording and quality control

- Record date, time, borehole internal diameter, SWL, discharge rate per step, and any changes in pump speed or valve setting.
- Plot drawdown vs. time on semi-log paper in the field to check for stabilisation.
- Ensure each step reaches near-equilibrium (drawdown change < 5 mm in the last 10 minutes).

Data interpretation

The step drawdown test is used to evaluate well efficiency. This metric provides a critical result for municipal water supplies, indicating the proportion of energy – specifically, the pumping lift – effectively utilised in extracting water from the aquifer (useful) rather than the energy spent overcoming turbulence within the well (wasteful). Determining well efficiency goes beyond mere technical analysis; it is a vital economic and operational requirement for a municipal water supply system. This assessment acts as an indicator of the well's overall 'health' and directly affects the municipality's financial stability and long-term water security. The well-loss is expressed as a percentage, guiding the hydrogeologist on whether to proceed with the constant discharge test.

Table 11: Well-losses threshold guidance

Well-loss percentage	Interpretation	Recommended Action
< 20 %	Excellent well efficiency	Proceed with the constant-rate test
20–40 %	Acceptable	Consider mild rehabilitation
40–60 %	Poor efficiency	Urgent rehabilitation or redevelopment
> 60 %	Severe well losses	Borehole likely requires major work or abandonment

If well efficiency decreases over time, the well requires rehabilitation. A typical high-capacity municipal borehole often follows this pattern:

- **Years 0-5: High efficiency (80%+).** The well is clean and performing optimally.
- **Years 5-15: Efficiency gradually declines** (70% down to 60%). Minor clogging and encrustation begin. The operator might notice a slight increase in pumping costs or a decrease in specific capacity. In simple terms, specific capacity tells you how many litres per minute the boreholes produce for every metre the water level drops.
- **Years 15-25**: Efficiency drops more steeply (60% down to 40-50%). Energy costs rise significantly. The borehole may require rehabilitation (chemical treatment and mechanical cleaning) to restore efficiency.
- **Years 25+:** Without intervention, efficiency drops below 30-40%. The pump may cavitate, or the borehole may start pumping sand. At this point, rehabilitation may be too expensive or impossible, and the borehole must be redrilled or abandoned.

Once the acceptable well-loss percentage is established, the pumping rate for the constant discharge test is selected. The objective is to choose a rate that is: (i) sufficiently high to generate a measurable drawdown in observation boreholes for the purpose of evaluating aquifer properties; and (ii) sufficiently low to avoid drying out the well, damaging the pump, or inducing excessive turbulence that could compromise data accuracy. The pumping rate is determined by calculating the specific capacity, defined as the pumping rate divided by the drawdown. The goal is to identify a sustainable, manageable drawdown that does not exceed the borehole's available drawdown capacity, while maintaining a relatively stable drawdown-to-discharge ratio.

5.3.2. Constant-rate and recovery test

The constant-rate test, also known as the constant-discharge test, followed immediately by a recovery test, constitutes the standardised procedure for determining a borehole's sustainable yield, calculating aquifer parameters (such as transmissivity and storativity), identifying boundary effects, and collecting data necessary for water-use licence applications. This test provides critical information regarding the optimal yield for long-term and medium-term utilisation. It involves conducting a constant-rate test at a single pumping rate over an extended period, ensuring the rate remains as steady as possible throughout. The rate should be maintained at a level that is sustainable throughout the duration and utilises more than 70% of the available drawdown [42]. The available drawdown must not be entirely exhausted. Drawdown monitoring should be performed within the well and, if available, within the observation well. The actual pumping rate applied during the test should be measured and recorded regularly. Subsequently, the pumping rate should be verified whenever water-level measurements are taken.

At the end of the constant-rate test, the recovery within the well should be measured [38].

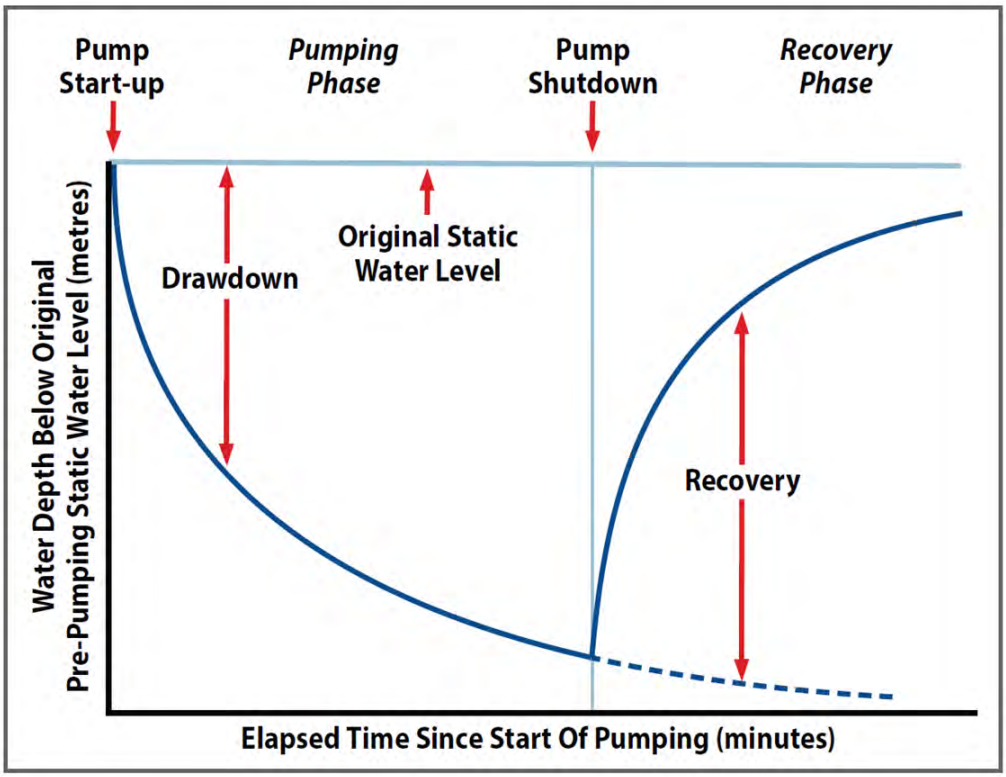


Figure 16: **Graph showing the different phases of a constant rate pumping test – the pumping phase and the recovery phase[8]**

Constant rate and recovery tests are conducted when

- A reliable long-term yield and licence application data are needed
- The borehole is intended for municipal, irrigation or industrial supply
- Boundary effects such as recharge boundaries, faults or saline intrusion must be investigated

Equipment

Submersible pump with variable-speed drive or control valve, accurate flow meter such as electromagnetic or ultrasonic, with ±2 % accuracy, two water-level transducers or data loggers with one in the pumped borehole, and the other one in an observation borehole (if available), generator, discharge

[88] https://www2.gov.bc.ca/assets/gov/environment/air-land-water/water/water-wells/guide_to_conducting_pumping_tests.pdf

hose and measuring tank or weir for verification, rain gauge and barometric logger. WRC constant-rate test field sheet and analysis spreadsheet.

Data collection procedure (constant rate test)

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

***Precaution – Monitor discharge and water level continuously. Never allow the pump to run dry. Follow confined-space and electrical safety protocols.**

Data recording and quality control

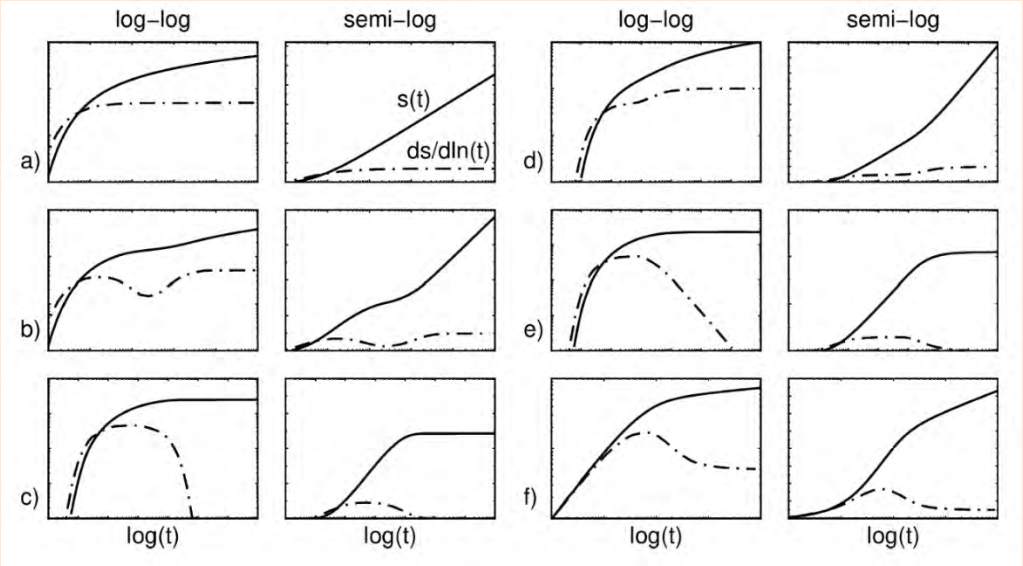
- Record every change in discharge rate, power interruptions or rainfall.
- Plot drawdown vs. time on semi-log paper in the field to check for stabilisation and boundary effects.
- Correct drawdown for barometric pressure and earth tides if necessary.

Data interpretation

Analysing drawdown and recovery responses in the stress borehole and in nearby monitored observation wells facilitates the estimation of the aquifer's hydraulic properties and the identification of flow conditions within the formation or non-formation zones (e.g., wellbore storage, wellbore damage, or the presence of boundaries).

Analysis generally commences with diagnostic plotting to identify flow patterns and determine the appropriate analytical model. The primary techniques are categorised into two types**. Type-Curve Matching** (Log-Log Plots) involves plotting measured drawdown data on a log-log scale and matching their shape to predefined “type curves”, which represent theoretical solutions for aquifer flow. By establishing the best fit, one can estimate aquifer properties and recognise flow conditions such as wellbore storage or boundary effects. The application of pressure derivative plots significantly enhances this method, aiding in diagnosing specific flow regimes (for instance, early-time wellbore storage, middle-time radial flow, late-time boundary effects). In **Straight-Line Methods** (Semi-Log Plots), during a substantial portion of many tests, particularly in confined aquifers,the drawdown manifests as a straight line on a log-time plot. The slope of this line is employed in straightforward formulas (such as the Cooper-Jacob method) to directly compute transmissivity (T) and hydraulic conductivity (K).

Box 16: Type curves with their derivative, as adapted from Renard et al. (2009 as cited by [43])



The theoretical models above are for a confined aquifer (a), an unconfined aquifer (b), a leaky confined aquifer (c), a no-flow boundary (d), a constant-head boundary (e), and wellbore storage and skin effect (f). The vertical axis represents drawdown (s), and the horizontal axis represents time (t). The solid line represents the theoretical model and the dashed line, the model's derivative.

- Confined aquifer (a) – For true confined aquifer conditions, the drawdown will reach a steady rate of decline as the radius of influence expands. Because the rate of drawdown is constant, the derivative (dashed line), indicating the rate of change, is flat.
- Unconfined aquifer (b) – The characteristic shape of the theoretical model for unconfined aquifer conditions is dominated by delayed yield. The concept of delayed yield can be observed at mid-time, where the rate of drawdown is reduced due to induced drainage from the unsaturated zone. Note that unconfined conditions are not the only flow regime where delayed yield is observed. In systems with double porosity, such as a confined fractured aquifer, the same characteristic shape is observed.
- Leaky confined aquifer (c) – The type of curve for the leaky confined aquifer represents flow within an aquifer with a semi-confining aquitard. At an early time, the plot appears similar to that of a confined aquifer; however, at mid-time, the effect of leakage becomes visible as the drawdown stabilises. At late times, the leakage is balanced by the withdrawal rate at the pumping well, and the derivative (dashed line) drops to zero, indicating steady-state conditions.
- No-flow boundary (d); – The theoretical model presented here for a no-flow boundary assumes an infinite linear boundary to groundwater flow. The identifying characteristic of this flow regime is the inflexion in the drawdown rate at the no-flow boundary. This is best represented by a semi-log plot,

where the rate of drawdown appears to double with the observed change in the derivative (dashed line).

- Constant-head boundary (e) – For the purpose of comparison, the flow regime appears identical in early time as the no-flow boundary condition discussed above. However, once a constant-head boundary is encountered, the drawdown rate stabilises. At a late time, the reduced discharge and/or increased recharge from the constant-head boundary is balanced by the rate of withdrawal, and the derivative (dashed line) drops to zero, indicating steady state conditions.

- Wellbore storage and skin effect (f) – The effects of wellbore storage and skin effect (positive) produce the same theoretical model (Renard et al., 2009). The identifying characteristic of the flow regime is a reduced drawdown rate at mid-time, which stabilises at the reduced rate in late-time. The change to a reduced drawdown rate creates a hump shape that depends on the amount of wellbore storage and/or on the reduced transmissivity due to the positive skin effect around the well.

5.3.3. Slug test equipment and field protocols (bailers, transducers, data loggers)

The slug test is a common first-order assessment for fractured rock aquifers that primarily helps estimate potential yield. This rapid field method estimates the hydraulic conductivity (K) and transmissivity (T) of the aquifer immediately surrounding a borehole. It is suitable for diagnosing low or declining yields in existing boreholes. The test requires no pumping and typically takes between 30 and 90 minutes. The slug test records the change in water level in a well when water is rapidly displaced. Displacement causes the water level to either rise when the slug is introduced below the static water level or fall as water is removed from the well. The rate at which the water level recovers, or drops, indicates the borehole yield [44].

Equipment

The essential equipment for conducting a slug test generally comprises water level transducers or a dipper equipped with data loggers, a steel or PVC slug (alternatively, a weighted bailer or solid cylinder may be employed), a stopwatch or automated data logger, a measuring tape or calibrated dipper, a field notebook, clean water, and a slug test spreadsheet template.



Figure 17: **This photograph shows a solid weighted slug (capped white PVC pipe), a pressure transducer recording box, and an electric tape used to conduct slug tests [45]**

Data collection procedure

- Open the well.
- Measure and record the static water level in the well. Allow time for equilibration with atmospheric pressure in wells with unvented caps. If a dedicated bailer or other sampling apparatus is in place and interferes with the initial reading, minimise disturbance as much as possible and allow time for re-equilibration. Wait and recheck the measurement to confirm the well is at steady state.
- Remove any equipment which will interfere with placing the transducer or conducting the slug test.
- Measure and record the total depth of the well to ensure that the screen has not been partly silted in.
- Place the transducer in the well to the appropriate depth (see depth limits for individual transducers, or manufacturer's specifications). Do not place the transducer so that its range will be exceeded, or so that the transducer interferes with the movement of the slug.
- Place the slug in the well above the transducer. If desired, you can run a falling head test at this point. It is often found in highly permeable materials; however, the time required for the slug to fall through the water column may be comparable to the recovery time,

making this data unusable.

- When the water level has returned to static height, initialise the data logger.
- Remove the slug. Use the auto-start feature if available, or start the data logger by hand.
- Test may be terminated after recovery is complete, or after 10 to 15 minutes for wells with slow recovery. If possible, screen data in the field to ensure data quality prior to demobilisation.

Quality assurance

The following measures will help ensure quality data and analytical procedures.

- Determine the depth of each well before testing. Sediment infilling may affect well response.
- Determine the static water level before placing any equipment in the well. Ensure that the water level has returned to static before conducting the test or taking baseline samples with the data logger.
- If practical, allow the well to return to static level prior to termination of data collection.
- Generally, do not analyse ambiguous data.
- If any wells must be discarded (e.g. the response may have been too fast to record, etc.), be sure to note this in the overall summary of hydraulic properties and in the determination of averages and other statistics.
- Always compare actual water displacement to the slug volume. Large discrepancies may warrant discarding a data set.
- Use slugs that can be removed in one continuous pull. Remove the slug rapidly.
- If the sand pack grain size is greater than that of the aquifer, use the dimensions of the sand pack to determine well geometry. For a finer sand pack, consider using casing dimensions.
- Beware of computer-generated drawdowns. The data logger's baseline may not be correct. If the test is long enough, always check to confirm that the drawdown converges to zero.
- If tests are analysed by Thiem-based methods, use only the linear part of the response curve. If the log-response is not linear, you cannot analyse the test with this method.
- Duplicate tests should be conducted at least every tenth well, and once per site. In addition, duplicates may be advisable for rapidly recovering wells because accurately logging rapid responses is

difficult. At many sites, duplicate tests are conducted for each well, and only a subset of the tests will be analysed.

Data analysis

The two most commonly used methods for slug-test data analysis are the Hvorslev method, which is well suited to partially penetrating wells, and the Bouwer and Rice method, which is commonly applied to unconfined aquifers. Together with step-drawdown, constant-rate and recovery testing, these diagnostic methods establish the technical baseline needed to manage borehole performance. The following section builds on that baseline by focusing on routine operation and maintenance, where monitoring data are translated into day-to-day management actions.

5.4. OPERATION AND MAINTENANCE (O&M) TOOLS AND CHECKLISTS

Operation and Maintenance (O&M) of a borehole pump comprises all activities needed to keep the system operational. These activities include routine tasks such as replacing worn components, refuelling, servicing, cleaning, and monitoring, as well as addressing irregular incidents such as breakages, outages, and malfunctions [24]. While hydrogeological factors such as recharge, transmissivity, and groundwater quality are significant, O&M deficiencies can have a more detrimental effect on a borehole scheme than a severe drought. Although many assume a lack of technical expertise is the primary cause of borehole failure or low reliability, growing awareness shows that proper “operation and maintenance” (O&M) of groundwater sources is equally essential. O&M includes all routine actions required to maintain a groundwater source or wellfield in operational condition, such as servicing, repairs, monitoring, parts replacement, adherence to pump duty cycles or maximum yields, and testing [16].

Effective O&M should therefore be treated as an asset-management function rather than a reactive repair activity. Each production borehole should have a defined operating envelope that includes the approved abstraction rate, maximum daily pumping volume, allowable drawdown, minimum recovery level, pump duty cycle, alarm levels, inspection frequency and reporting responsibility. These limits should be derived from pump-test results, commissioning records, and routine monitoring data, and should be reviewed whenever the borehole is rehabilitated, the pump is replaced, demand changes significantly, or water-level trends indicate aquifer stress.

A practical O&M programme should combine preventive maintenance, condition-based maintenance and corrective maintenance. Preventive maintenance includes scheduled inspections, cleaning, lubrication, calibration and replacement of consumables before failure occurs. Condition-based maintenance uses trends in flow, drawdown, specific capacity, current draw, vibration, sand content, electrical conductivity and water quality to trigger intervention. Corrective maintenance is reserved for breakdowns or emergencies, but should always be followed by a root-cause review so that repeated failures are not treated as isolated events.



Figure 18: Submersible pump

5.4.1. Common O&M causes of yield decline

- Mechanical wear, including failure of the pump and motor.
- Screen incrustation due to mineral scaling, iron bacteria or biofilm.
- Sand pumping and siltation of the screen and gravel pack.
- Poor borehole development or incomplete gravel-pack placement.
- Incorrect pump setting depth or excessive drawdown causing cavitation.
- Power supply instability leading to frequent start-stop cycling.
- Declining specific capacity caused by progressive clogging of the screen or gravel pack, even where the static water level remains broadly unchanged.
- Hydraulic shock from frequent start-stop cycling, which can mobilise fines, destabilise the gravel pack and accelerate wear on non-return valves, rising mains and pump components.
- Corrosion of casing, screens, fittings or rising mains, particularly where aggressive water chemistry, stray electrical currents, incompatible metals or poor earthing are present.

5.4.2. Routine inspection and maintenance checklists

Monthly checklist

- Visual inspection of headworks, security and electrical connections
- Measure and record static water level, pumping water level and discharge rate
- Check for sand or silt in discharge water
- Inspect the pump control panel for error codes or overheating
- Record pump run hours, start frequency and any dry-run, overload, phase-failure or low-pressure alarms.
- Confirm that the discharge meter, water-level access tube, sampling tap and pressure gauge are functional and accessible.

Quarterly checklist

- Measure specific capacity and compare with previous tests

- Check pump and motor current draw and vibration
- Clean or replace air-release valves and non-return valves
- Video inspection of the borehole in the case that the yield has dropped >20 %.
- Compare current specific capacity against the commissioning baseline and flag any decline greater than 10% for review and any decline greater than 20% for investigation.
- Check electrical protection settings, cable condition, earthing continuity, panel ventilation, telemetry signal strength and battery or backup power condition.

Annual checklist

- Full step-drawdown test or constant-rate test
- Pump removal, inspection and servicing
- Chemical treatment or surging if incrustation is evident
- Update asset register and maintenance history
- Verify the safe yield, abstraction schedule and alarm thresholds against the latest water-level, flow and water-quality trends.
- Review the emergency spares inventory, including pumps, control components, non-return valves, cable joints, pressure switches, fittings and chlorination consumables.

Rehabilitation and maintenance tools

Prescribe rehabilitation only after diagnosis. The minimum diagnostic package should include a comparison of current and historical specific capacity, inspection of the pump and rising main, review of electrical performance, water-quality screening, sand-content observation, and, where possible, downhole video inspection. This distinction matters because a borehole with clogged screens requires a different intervention than a borehole affected by pump wear, casing failure, aquifer depletion, or excessive abstraction.

- Downhole video camera inspection protocol and service provider list

- Chemical rehabilitation agents (hydrochloric acid, sulfamic acid, chlorine) and dosage guidelines
- Mechanical surging and air-lift tools
- High-pressure jetting equipment specifications
- Pump puller and crane hire checklist
- Rehabilitation decision matrix
- Specific-capacity trend analysis tool to compare litres per second per metre of drawdown before and after rehabilitation.
- Deposit identification protocol to distinguish carbonate scaling, iron and manganese incrustation, biofouling, clay invasion, corrosion products and formation fines.

Mechanical methods such as brushing, surging, air-lifting, and high-pressure jetting are most suitable where the borehole structure is sound, and the main problem is loose fines, soft deposits, biofilm, or partial screen blockage. Select chemical methods only after confirming the likely deposit type: acid treatment is generally used for carbonate, iron, and manganese deposits; dispersants are used for clay and fine-sediment bridging; and approved biocides may be used where biofouling is confirmed. After any rehabilitation treatment, pump the borehole to waste until the water is clear and chemically safe, retest to establish a new performance baseline, and return it to service only after updating the operating rules. These O&M controls are also central to preventing over-abstraction, because poor operating rules, excessive pump run times and delayed maintenance can intensify aquifer stress.

5.5. OVER-ABSTRACTION OF GROUNDWATER

Over-abstraction of groundwater occurs when the rate, duration or cumulative volume of pumping exceeds the aquifer’s ability to recover without unacceptable impacts. It is not limited to pumping above the yield recommended by a hydrogeologist; it can also occur when recharge declines during drought, when multiple boreholes in the same aquifer interfere with one another, when operating hours are increased without revising the safe yield, or when the water level is repeatedly drawn below critical borehole or aquifer thresholds. Over-abstraction is therefore a management failure as well as a hydrogeological risk: it reflects a mismatch between demand, pump operation, aquifer response and monitoring-based operating rules.

Typical warning signs include a progressive decline in static water level, increasing pumping drawdown at the same abstraction rate, slow or incomplete recovery after pump shutdown, declining specific capacity, reduced discharge, frequent dry-run alarms, air entrainment, sand pumping, deterioration in water quality, or evidence that neighbouring boreholes are responding to the same pumping cycle. A borehole that stops producing water shortly after start-up has not necessarily “dried up” permanently; it may be temporarily dewatered, pumped below the intake, affected by pump malfunction, or influenced by regional water-level decline. The immediate task is to separate these possibilities using water-level, flow, operating and construction data.

The following minimum information should be collected before concluding that over-abstraction is the primary cause of poor borehole performance:

a) Consider/record the total depth of the borehole that is on record, if available.

b) At which level is the casing present? At what depth is the casing screened?

c) To what depth is the pump lowered down the borehole?

d) What was the rest water level recorded for the borehole?

e) Are you able to measure the depth to water?

f) Record the current pumping rate, daily pumped volume, pump run hours, start-stop frequency and any recent changes in demand or operating schedule.

g) Compare current static and pumping water levels with commissioning records, previous pump-test results, routine monitoring records and nearby monitoring boreholes.

h) Check whether rainfall, recharge conditions, drought restrictions, upstream surface-water changes or neighbouring abstraction could explain the observed trend.

How the information should be interpreted:

a) The total depth of the borehole will help you understand how deep the hole is and the possible water column that the casing can contain. If possible, measure the current total depth of the borehole and compare it to the original drilled depth. It may be that a section of the borehole has caved in.

b) Knowing the depth of screens will give you an indication of where water is likely to enter the borehole from the formations.

c) If you can find information about the depth to which the pump is lowered and take a measurement of the current depth to water, it may be that the water is below the pump depth.

d) If you measure the rest water level (measured before any pumping), and it is very different from the original rest water level, it shows that considerable pumping has lowered the rest water level over time.

e) A declining specific capacity trend indicates that more drawdown is required to produce the same flow. This may reflect over-abstraction, borehole clogging, pump deterioration or increased interference from other boreholes.

f) If water levels recover overnight but decline rapidly during pumping, the operating schedule may be too intensive. If recovery remains incomplete over days or weeks, the aquifer or wellfield may be under broader stress.

Where over-abstraction is suspected, the operator should follow a conservative response procedure: reduce or stop pumping immediately, measure recovery at defined intervals, confirm the pump intake depth and available drawdown, inspect the abstraction meter and control panel, and compare the current pumping response with the original safe-yield recommendation. Resume pumping only at a reduced duty cycle once the water level has recovered to an agreed operational threshold. If recovery is poor, if the static water level remains depressed, or if multiple boreholes show the same trend, a hydrogeologist should reassess the wellfield yield and operating rules.

Monitoring and testing to prevent over-abstraction

Testing and characterisation to prevent over-abstraction is described in the SOPs for groundwater development on community water supply schemes. It states the following:

A practical monitoring system must track both abstraction pressure and aquifer response. At a minimum, each production borehole should have a flow meter, a water-level access point or dedicated monitoring tube, a record of pump run hours, an agreed abstraction limit, a low-water-level alarm, and a clear instruction for when pumping must be reduced or stopped. For municipal or community schemes, the monitoring network should include

production boreholes and, where possible, observation boreholes positioned up-gradient, down-gradient and between neighbouring production boreholes to detect interference and regional decline.

- Groundwater abstraction monitoring systems need to be installed in each borehole under the project area for at least three years to monitor abstraction.
- It is recommended in the SOPs for borehole development that automated data collection be used to monitor water level changes at 5-minute intervals if this is possible.
- This enables daily reporting of water level changes.
- Weekly, monthly and annual reporting is also recommended to have a sound understanding of responses of boreholes to abstraction over a longer term and to have an early warning of potential over-abstraction.
- Characterisation of abstraction rates forms part of the initial pump testing. Step tests and constant-discharge tests are used to determine safe abstraction rates for boreholes.
- The safe pumping or discharge rate that is determined needs to be used by the owner of the borehole or manager of the wellfield.
- Failure to abide by this may lead to over-abstraction or lowering the water level below the pump depth. SOPs for step and constant-discharge tests are described in the development of groundwater at the community level.
- Trigger levels should be defined for each borehole, including an advisory level, a reduced-pumping level and a shutdown level. These should be based on pump depth, screen position, available drawdown, historical recovery and water-quality risk.
- Abstraction records should be reviewed together with rainfall, recharge indicators, reservoir demand, electricity interruptions, water-quality changes and maintenance events so that operational decisions are based on trends rather than isolated readings.

The monitoring requirements summarised below provide a practical schedule for detecting over-abstraction early, verifying whether pumping remains within approved limits, and identifying when borehole performance or water quality requires further investigation.

Table 12: Recommended monitoring schedule for preventing over-abstraction

Monitoring item	Minimum frequency	Purpose
Static water level	Monthly, or before pumping where practical	Detect long-term aquifer decline and recovery after rest periods.
Pumping water level and discharge	Monthly, and during any yield complaint	Track drawdown, pump performance and specific-capacity trends.
Automated water-level logging	5-minute to hourly intervals where telemetry is installed	Identify rapid drawdown, recovery behaviour, interference and alarm events.
Abstraction volume and pump run hours	Daily to weekly	Confirm compliance with licensed or approved abstraction limits.
Specific capacity	Quarterly or after pump maintenance	Identify declining borehole efficiency or aquifer stress.
Water quality screening	Quarterly to annually, depending on risk	Detect salinity, turbidity, nitrate or other quality changes linked to over-pumping.

Abstraction of water from a wellfield or borehole creates a drawdown cone, which, over time, progressively moves laterally and vertically in terms of its area of influence. This draws water from further away from the actual borehole over time. To monitor the extent of the drawdown cone and the depth of drawdown in the wellfield or borehole, we use water-level loggers and dip meters to detect water-level changes. This allows us to track changes over time and improves understanding of groundwater behaviour and aquifer properties. Several municipal wellfields currently use water-level loggers to monitor water levels, enabling near-real-time detection of potential problems, such as drawdown exceeding a threshold or water falling below the pump installation depth. This can indicate when the pump should rest and allow the borehole to recover. Examples include the Cape Flats, the Table Mountain Group Aquifer, the Atlantis Wellfield, and several Catchment Management Agencies.

Infrastructure requirements for monitoring abstraction and water-level changes resulting from abstraction are clearly outlined in the SOPs for community-level borehole development. With respect to infrastructure:

- The casing of monitoring points needs to be constructed of a minimum of UPVC.
- The diameter of the casing needs to be suitable for the monitoring equipment that will be used to fit, e.g. 32 mm or 40 mm will be suitable for a cable and a small logger to be inserted. In comparison, larger than 60 mm would be suitable for a small pump to be lowered.
- Infrastructure should be designed to suit the desired monitoring protocols for each site or municipality. e.g., if sampling water is desired, ensure the PVC pipe diameter is large enough for a pump; alternatively, purchase a pump suitable for the diameter of the smallest PVC casing.

Water-level monitoring should account for daily, weekly, monthly, seasonal, and annual variations in the dynamic groundwater system. Automated monitoring systems (telemetry) are recommended for daily or hourly measurements, as well as for shorter periods. SOP recommendations include automatically reporting collected data to an online portal for analysis. Also take hand-recorded readings to verify the automated measurements.

Record data for each borehole on separate sheets in Excel or another database program. Important data that needs to be captured for each borehole includes:

- Drilling information.
- Borehole construction information.
- Blow yields.
- Rest water level.
- Pumping test data after drilling.
- Along with subsequent monitoring data of depth to water in each borehole.

This information enables data processing that can reveal long-term trends, provide early warning of over-abstraction and indicate whether higher abstraction rates may be possible in a wellfield or individual borehole. A useful example of near-real-time monitoring is provided by Hermanus, where water-level and conductivity monitoring support early warning of over-abstraction and saline intrusion. Because the same pumping stresses

that lower water levels can also draw poor-quality water toward a borehole, abstraction management must be linked directly to groundwater protection.

5.6. GROUNDWATER POLLUTION, GROUNDWATER PROTECTION

Groundwater pollution refers to the introduction or mobilisation of chemical, biological or radiological constituents in an aquifer at concentrations that exceed natural background levels or make the water unsuitable for its intended use, including domestic supply, livestock watering, irrigation, industry or ecosystem support. Groundwater protection is a coordinated set of planning, engineering, monitoring, land-use control, and operational measures used to prevent pollution from reaching an aquifer, a borehole, or a wellfield. Because groundwater is hidden, slow to recover, and expensive to remediate, protection should be applied proactively rather than only after contamination is detected.

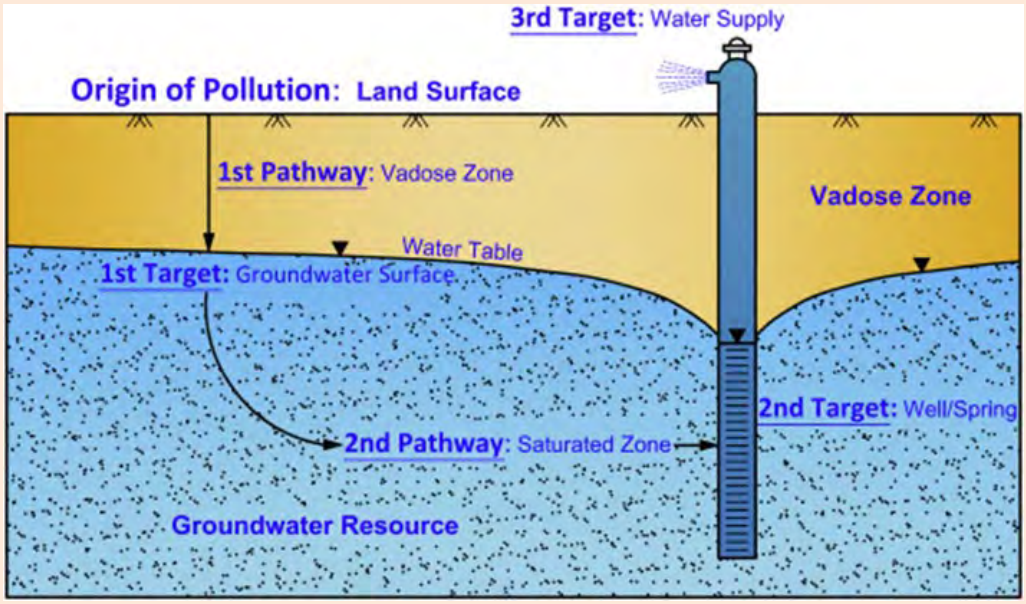
Pollutants may reach groundwater through direct entry at poorly sealed boreholes, infiltration through the vadose zone, leakage from sanitation systems, seepage from waste facilities, spills from fuel or chemical storage areas, return flows from irrigation, mine drainage, cemetery leachate, animal-waste handling areas, stormwater infiltration, or contaminated surface water that recharges the aquifer. Risk depends on contaminant load, distance from the borehole, groundwater flow direction, aquifer vulnerability, soil and unsaturated-zone attenuation capacity, depth to water, borehole construction quality, and the pumping regime. Pumping can increase risk by drawing contaminated water toward the borehole through an induced hydraulic gradient.

A municipal groundwater protection SOP should begin with a source inventory and risk screening, followed by sanitary inspection, hydrogeological assessment, protection-zone delineation, water-quality monitoring, land-use control and periodic review. Each production borehole should have an up-to-date record of its construction details, sanitary seal, casing condition, apron and drainage, nearby pollution sources, water-quality history, abstraction rate and protection status. Where information is missing, classify the borehole as having uncertain risk until the missing data are collected.

- **Confirm borehole integrity:** check headworks, sanitary seal, casing, apron, drainage, lockable cap, air vent protection and the absence of ponding near the borehole.

- **Identify pollution sources:** map sanitation, waste disposal, fuel storage, cemeteries, agriculture, animal enclosures, workshops, stormwater systems, mines and industrial activities within the likely capture area.
- **Assess aquifer vulnerability:** consider aquifer type, depth to water, fractured zones, dolomite, recharge areas, soil cover, groundwater flow direction and the presence of preferential pathways.
- **Define protection measures:** establish exclusion zones, controlled-use zones, monitoring points, incident-response procedures and land-use restrictions appropriate to the risk level.
- **Maintain monitoring records:** trend microbiological, chemical and field parameters against baseline conditions and relevant drinking-water or resource-quality objectives.

Depending on the aquifer type in a given area, take special care when planning land-use activities. Unconfined aquifers lack a protective layer from surface pollution. This makes unconfined aquifers vulnerable to surface activities that may pollute them. If pollutants dissolve in water, they can easily enter the vadose zone through infiltration and reach the aquifer through recharge. This makes planning and zoning for protection critical to aquifer protection. The figure below shows how land-surface activities can pollute the vadose zone, then reach the water table and, when pumping occurs, move with groundwater flow toward the borehole, ultimately polluting the area's water supply.



The cornerstone of future groundwater protection will be the new Regulations for the Protection and Management of Groundwater Resources, drafted under the National Water Act. While these were recently

open for public comment (until February 2026), they signal the government's intent to create a unified national standard.

The proposed regulations should be read together with existing groundwater-quality management policy, the National Water Act, Resource-Directed Measures, municipal by-laws, water-use licence conditions and site-specific risk assessments. For municipal schemes, this means that groundwater protection should not be treated as a once-off compliance exercise. It should be embedded in spatial planning, development control, borehole registration, operational monitoring, incident reporting and enforcement.

Based on expert analysis and emerging best practice, an effective municipal SOP for groundwater protection should include the following elements:

- **Control of groundwater development**: Clear procedures for borehole applications, including mandatory registration with the municipality and DWS/CMAs.
- **Protection of recharge zones**: Identify and regulate land use in areas that feed aquifers to prevent pollution and maintain recharge.
- **Management of polluting land uses**: Procedures to assess and mitigate risks from activities like waste disposal, cemeteries, and industrial sites near boreholes.
- **Data management**: Protocols for collecting, storing, and sharing groundwater data (water levels, quality, abstraction) with DWS and the CMAs.
- **Dolomite stability management**: Specific, stringent procedures for areas underlain by dolomite rock, where drilling can trigger sinkholes.
- **Enforcement Protocols**: Clear steps for monitoring compliance, investigating violations, and applying penalties (fines, work stoppage, legal action).
- **Emergency response and alternative supply:** procedures for isolating polluted sources, issuing notices, supplying safe alternative water, sampling confirmation and recommissioning only after risks have been addressed.

Groundwater pollution or contamination arises from both the natural geological conditions and significant land-use activities within a designated area. Such land-use activities include landfill, septic tank, and cemetery operations; mining activities; wastewater treatment plants; industrial effluents; animal feedlots; agricultural practices involving fertilisers and pesticides; manufacturing industries; and improper waste disposal on open land. All these activities can pollute both surface and groundwater sources.

The minimum monitoring suite should be selected according to source risk, but should normally include field parameters such as electrical conductivity, pH, temperature and turbidity, microbiological indicators such as E. coli and total coliforms, and key chemical indicators such as nitrate, fluoride, chloride, sulphate, sodium, iron, manganese and any site-specific contaminants associated with nearby land uses. Where pollution risk is high, increase sampling frequency after rainfall, flooding, pump failure, sanitation incidents, chemical spills, or major changes in pumping rate.

Contaminant risk screening checklist (Dennis et al., 2002)

- Are there septic tanks, pit latrines, or animal waste within 50 m?
- Is there fuel storage, chemical mixing, or mining activity upslope?
- Are fertilisers or pesticides applied within 200 m?
- Is there visible staining or unusual odours in the borehole water?
- Has the borehole ever been tested for nitrates, E. coli, or heavy metals?

Scoring: 3 or more “Yes” answers indicate that the source is at high risk, and immediate sampling and protection measures are required.

Delineate protection zones using a phased approach that matches available data and the importance of the groundwater source. A basic approach may use fixed-radius sanitary protection around individual boreholes, while an intermediate approach should consider groundwater flow direction, estimated travel time, recharge areas and nearby contaminant sources. For strategic municipal wellfields, use numerical modelling, particle tracking, vulnerability mapping, and monitoring data to define inner protection zones, outer protection zones, and broader recharge-management areas. Review these zones when abstraction rates change, new monitoring data become available, or land-use pressure increases.

A water resource is deemed polluted or contaminated when the concentration of one or more chemical constituents exceeds a guideline value established by an authoritative body, indicating potential health or environmental risks to flora (agriculture), fauna, or recreational pursuits. Typically, resource-quality objectives are established for various areas based on their intended use. However, at times, the natural geological conditions may cause water quality levels to fall outside these objectives. The following discussion pertains to some constituents that exceed the South African guidelines.

5.6.1. Nitrate

The guideline values for nitrate, as specified by DWS (1998), indicate that levels below 6 mg/L are optimal for drinking purposes. Levels ranging from 6 mg/L to 10 mg/L may pose health risks to infants, although they rarely affect adults. When nitrate concentrations exceed 20 mg/L in drinking water, they can cause adverse health effects in both infants and adults who consume it. The impact of nitrate on humans and animals involves its conversion to nitrite in the bloodstream, where it interacts with oxygen-carrying haemoglobin to produce methaemoglobin. Since methaemoglobin is incapable of transporting oxygen, this process may result in choking or asphyxiation, leading to severe oxygen deficiency and potentially causing death.

Given the potential toxicity of nitrate, ingested nitrate is not toxic to adults. The oral LD50 for sodium nitrate is 4300 mg/kg, which is equivalent to an intake of 300 g for a 70 kg person. Nitrite, on the other hand, which is formed by the reduction of nitrate, is highly toxic. The oral LD50 for sodium nitrite is 120 mg/kg, which is equivalent to an intake of only 8.4 g for a 70 kg person. Sodium nitrite, a salt used in meat processing, can, therefore, be fatal to all, i.e. also adults, at intakes above the threshold.

Nitrate-containing deposits and high nitrate concentrations in groundwater are found in many arid and semiarid regions worldwide. While anthropogenic sources can be controlled or limited, naturally occurring high nitrate levels cannot. In the semi-arid to arid regions of the Northern Cape Province and Namibia, significant groundwater nitrate occurrences occur across large areas where anthropogenic influences can be excluded. In these areas, even confined groundwater with an apparent age of several thousand years may still have significant nitrate levels, despite low human and animal populations – as shown in a map compiled by Tredoux et al. [53] shows the distribution of high-nitrate areas in Southern Africa.

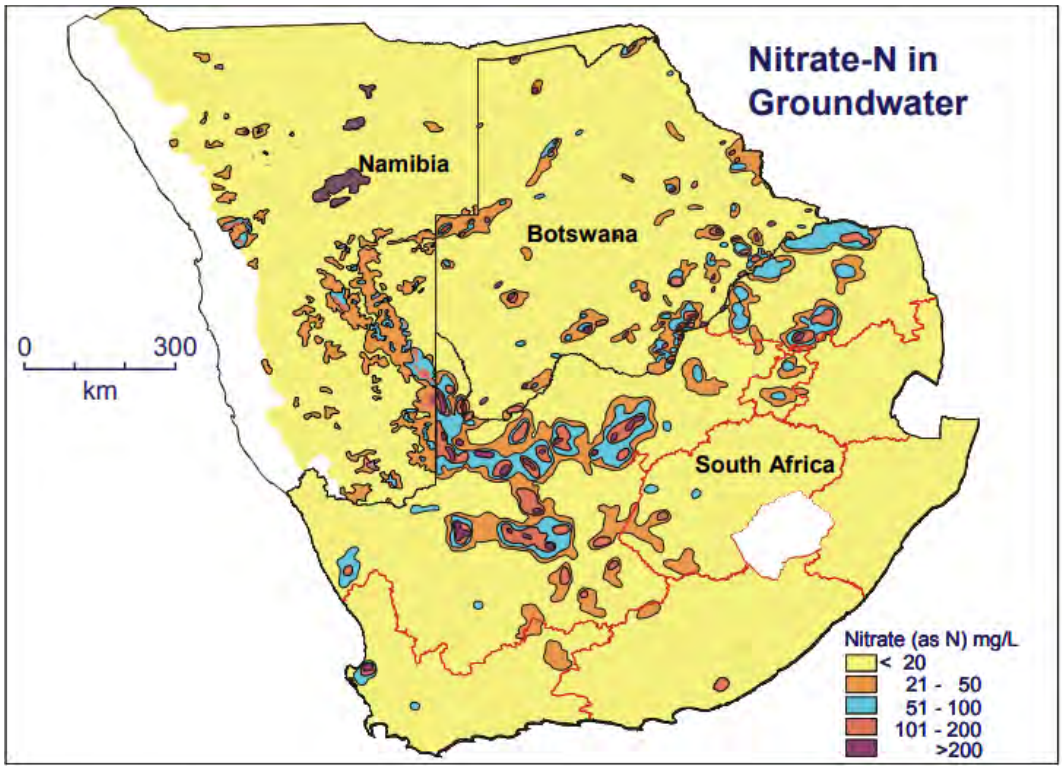
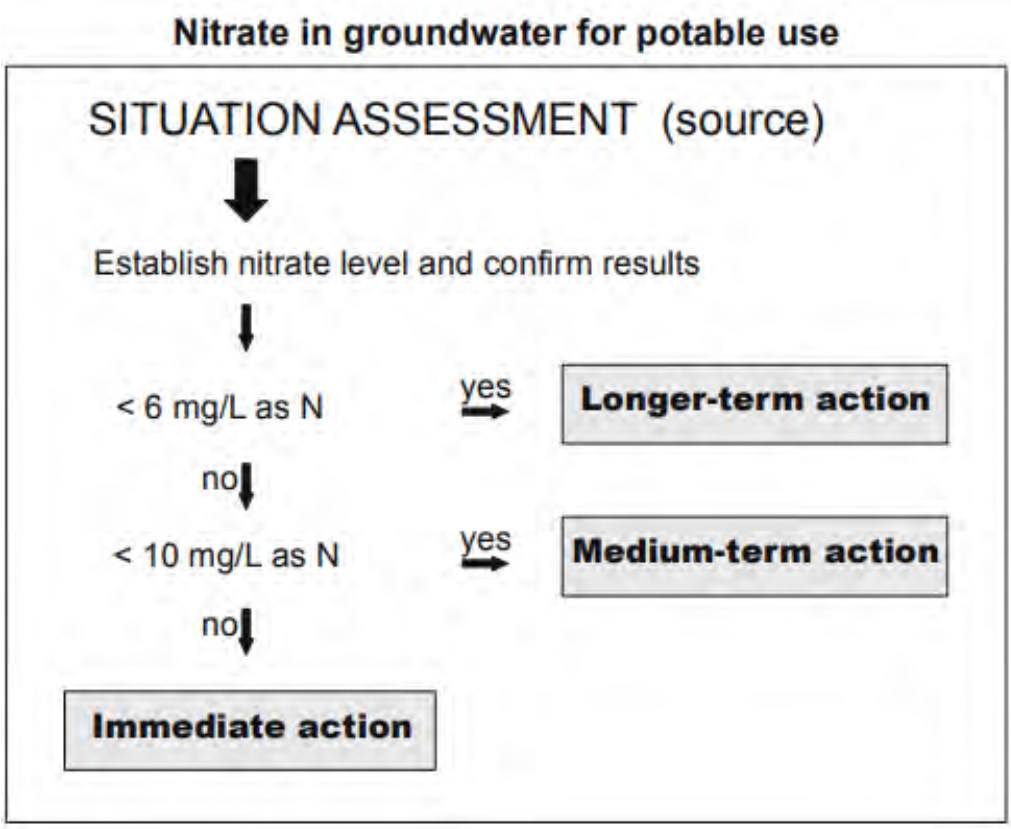


Figure 19: **Nitrate concentrations for Southern Africa based on over 50000 data records [53].**

A more recent assessment of nitrate concentration distribution may be required for South and Southern Africa. Anthropogenic sources of nitrate include farming activities such as soil tilling, fertiliser application, animal feedlots, stock watering, and irrigation with nitrogen-containing fertilisers. Other sources may include on-site sanitation facilities such as pit latrines or seepage drains. Point sources can be managed by implementing measures to reduce the amount of nitrate reaching the soil zone and groundwater. Diffuse sources, such as fertilisers on large areas of land, may be more difficult to control or prevent.

Tredoux et al. [53] developed an action plan that outlines how to address nitrate in your groundwater.



Step 1: Assess the nitrate concentration. Depending on the concentration, take the appropriate action. [53].

If the nitrate concentration exceeds the ideal or marginal levels, immediate action must be taken to protect the residents who consume the water. Tredoux et al. [53] outlined a diagrammatic action plan for a municipality to address elevated nitrate levels.

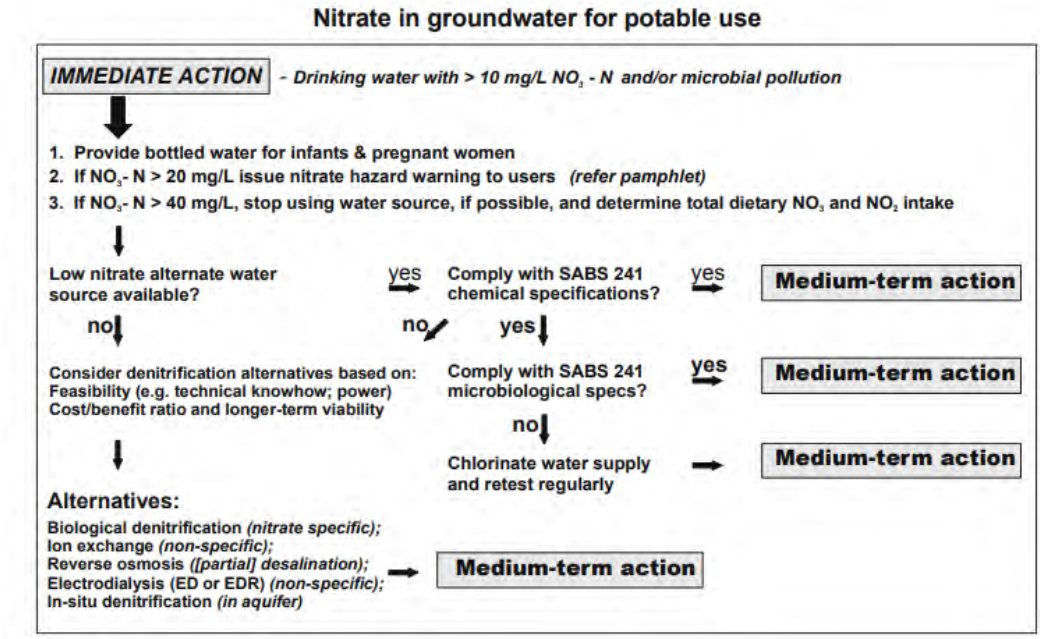


Figure 20: Immediate actions proposed by Tredoux et. al. [53]

Medium-term actions include:

- Monitoring to understand the longer-term nitrate concentration trends,
- Understanding the hydrogeological setting,
- Identifying the point sources of nitrate,
- Assessing if it is possible to remove the source, then
- Assessing the feasibility of remediation.
- Selecting an appropriate remediation technique.
- Where natural sources occur, in-situ remediation (within the aquifer) may be more suitable.

If your area is large and you occasionally have elevated nitrate concentrations, you need a full understanding of the hydrogeology and the processes that cause them (whether from a point, diffuse, or natural source). Once you understand these, evaluate appropriate techniques to reduce nitrate levels to acceptable levels.

Box 17: Case Study: In Situ Nitrate Remediation

A site used for the manufacturing of explosives had a nitrate spill. The spill affected the soil zone and, in turn, the groundwater nitrate concentrations. The site was monitored for a few years to understand soil and groundwater nitrate levels. Groundwater nitrate levels reached 600 mg/L, well above the guideline value. Immediate Actions taken at the site:

- The groundwater was not used

- Assessment of the geological environment, including soil chemistry and GW chemistry
- Long-term trend analysis of nitrate concentrations among other parameters such as pH, EC, TDS, DO, Eh
- Feasibility assessment of in situ denitrification
- Pilot testing and longer-term testing of denitrification at the site

Results showed that nitrate concentration was reduced considerably by using a slow-release carbon source, such as woodchips, to stimulate denitrification in the aquifer, which contained low levels of dissolved organic carbon, a limiting factor for natural denitrification in the system. A permeable reactive barrier was designed for the site, allowing water to flow through the barrier and interact with the woodchips, which readily dissolved and provided carbon for denitrification.

5.6.2. Fluoride

High fluoride levels in South African groundwater, often exceeding the 1.5 mg/L safe limit, are a significant health concern, particularly in the Limpopo, North West, and Northern Cape provinces. Fluoride is naturally released from geological sources like fluorite and mica; this contamination causes dental and skeletal fluorosis in rural communities. High concentrations are prevalent in the western Bushveld, parts of the Limpopo province, and in arid areas such as Namaqualand. Bone charcoal, activated alumina, or specific clay minerals are recommended for water treatment.

Box 18: Case Study: Limpopo Shiloane [54]

In response to the reported high incidence of dental fluorosis in the area, sources of elevated fluoride in the groundwater were investigated. Results revealed that groundwater fluoride concentration ranged from 3.92 to 4.95 mg/L. Na-Cl water type was found to be dominant in the water samples. The possible source of fluoride has previously been inferred to be fluorite minerals at greater depth. However, this study proves that fluoride decreases with depth, and the elevated fluoride in the groundwater is caused by smectite-kaolinite clay, muscovite and chlorite minerals abundant in the area. The geothermal temperature of the groundwater in the area is a major factor in enhancing the release of fluoride from the clay materials.

Evaluating the impacts of fluorides on human health: A survey done by Odiyo and Makungo [54] in Limpopo showed the following results

- 87% of households that use groundwater, 85% have members with mottled teeth
- 50% of school learners between the ages of 11 and 14 also have mottled teeth. -52.7% of the respondents indicated that 1-5 people in their households had mottled teeth
- 91°% of the respondents have neighbour(s) with mottled teeth while

- 77.3% are aware of the presence of mottled teeth in residents of Siloam Village

The survey also showed that residents of Siloam Village are aware of the problems associated with the use of groundwater with high fluoride levels, and 80% of respondents are aware of the treatment for mottled teeth. The lack of a reliable, adequately treated water supply forces residents to resort to untreated groundwater.

Protection zones are areas where land-use activities are restricted to prevent groundwater quality deterioration. They include the immediate sanitary area around a borehole and broader zones that may extend kilometres up-gradient, depending on groundwater flow direction, travel time and contaminant mobility. Planning for wellfields should therefore account for protection zones when locating waste sites, cemeteries, agricultural land, sanitation systems and industrial activities. This approach has previously been applied at Atlantis, where modelling was used to estimate travel time and define areas where specific activities are prohibited in major recharge zones. The same protection-zone logic is particularly important in coastal aquifers, where abstraction can also draw saline water toward freshwater production boreholes.

5.7. SALINE INTRUSION IN COASTAL AREAS

Saline intrusion occurs where saline or brackish water moves into a freshwater aquifer and degrades groundwater quality. In coastal aquifers, this is commonly driven by a change in the balance between freshwater heads and seawater, allowing the denser saline wedge to move landward or upward toward production boreholes. The risk increases when groundwater abstraction lowers the water table, recharge declines during drought, sea level or tidal influence affects the aquifer, or pumping induces vertical leakage from deeper saline zones. Inland salinity problems may occur where palaeo-saline groundwater, evaporite minerals, mine-affected water or naturally saline formations are hydraulically connected to freshwater units. Because recovery after saline intrusion can be slow and expensive, prevention and early warning are more effective than remediation.

The key management objective is to maintain a protective freshwater hydraulic gradient that prevents saline water from migrating toward the abstraction zone. This requires understanding the position of the freshwater–saltwater transition zone, the aquifer geometry, the depth and screened intervals of production boreholes, tidal and seasonal water-level variation, recharge conditions, and the response of electrical conductivity

and chloride to pumping. A gradual increase in electrical conductivity, chloride, sodium, bromide or total dissolved solids, especially when accompanied by falling water levels or increased pumping, should be treated as an early warning signal.

- The location of areas of high salinity needs to be identified prior to pumping
- Careful consideration of the extent of the drawdown cone produced during pumping needs to be considered
- Prevention is better than a cure. Steps should be taken to prevent mixing saline water with the fresh water used for drinking, as remediation may be costly
- It is important to know the vertical and lateral distribution/extent of the saline-freshwater interface.
- Special attention should be paid to the available drawdown
- Borehole configuration in a wellfield has to be carefully decided to increase the sustainability of abstracting fresh water
- Establish baseline EC, TDS, chloride, sodium, bromide, water-level elevation and abstraction-volume data before production pumping begins.
- Define trigger thresholds for warning, reduced pumping and shutdown based on water-level elevation, EC/TDS trends and distance from the saline interface.

Tests that should be done:

- In order to get a good understanding of the freshwater-saltwater interface, Geophysical techniques can be employed to get a 2- or 3-dimensional view of the subsurface salinity variations.
- Water level measurements and water table elevation should be measured frequently (automated if possible)
- Measurements of TDS or EC on a regular basis in the wellfield as well as between the wellfield and the source of salinity (within the fresh water salt water interface.
- Major-ion chemistry should be sampled periodically to distinguish seawater mixing from other salinity sources such as evaporation, rock-water interaction, mine drainage or older saline groundwater.
- Where the aquifer is complex, or the saline interface is poorly defined, install nested monitoring points at different depths to detect vertical movement of saline water.

Infrastructure requirements for early warning and prevention of saline intrusion include production-borehole meters, dedicated monitoring

boreholes, piezometers, water-level loggers, electrical-conductivity sensors, sampling taps, telemetry where feasible, and clearly defined alarm thresholds. Monitoring points should be positioned between the production boreholes and the saline source, within the expected transition zone, and inland of the wellfield to separate regional recharge effects from saline movement.

Monitoring points should be designed to measure both water level and water quality. Where possible, dedicated observation boreholes should be screened at selected depths rather than open across long intervals, because long open screens can mix water from different zones and mask the position of the saline interface. In higher-risk wellfields, monitoring should include at least one coastal or saline-source sentinel point, one transition-zone point, and one inland/background point.

Operations to aid in preventing intrusion and facilitating effective use of fresh water available include the following:

- **Keep the gradient head low**: This is best done by reducing the pumping rate and hours. Cyclic pumping could be useful.
- **Maintain a shallow and consistent head gradient**: This can be achieved by using a higher number of boreholes, with low discharge and cyclic pumping.
- **Maintain the hydraulic gradient**: This can be done by artificially recharging the aquifer to raise the water table head, ensuring that flow occurs toward the saline water body rather than the other way around.
- **Limit saline intrusion by controlling the gradient: Developing** a pumping trough in the region adjoining the coast will limit the likelihood of intrusion. In other words, you are pumping saline water out and lowering the head along the coast, preventing it from flowing towards the freshwater resource. This can also be done by combining injection and recharging wells along the coast with shallow tunnels or infiltration galleries.
- **Apply staged response rules:** when EC or chloride begins to rise, first reduce pumping from the affected borehole, then redistribute abstraction to lower-risk boreholes, increase monitoring frequency and only resume the original duty cycle after water levels and salinity have stabilised.

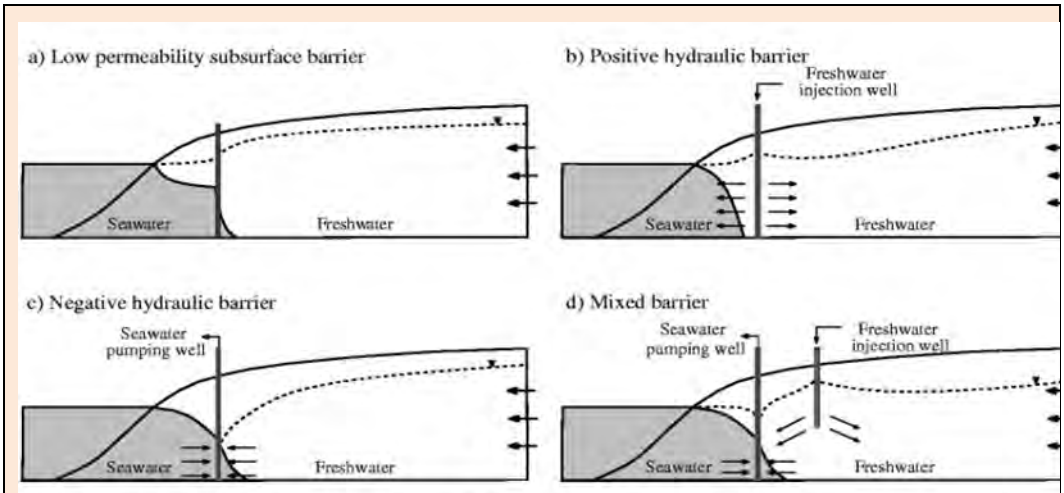
The saline-intrusion SOP should therefore operate as a trigger-based management system. Under normal conditions, pumping follows the approved duty cycle and monitoring confirms that water levels and salinity remain within baseline ranges. At advisory level, the operator increases

monitoring frequency and checks recent abstraction, rainfall, tidal influence and equipment performance. At action level, pumping is reduced or redistributed, and the hydrogeologist reviews the wellfield response. At shutdown level, the affected borehole is stopped, alternative supply is activated, confirmatory sampling is undertaken, and recommissioning occurs only after recovery criteria have been met.

Table 13: Recommended monitoring and response schedule for saline intrusion risk

Monitoring item	Minimum frequency	Management use
Water-level elevation	Hourly to daily where telemetry is installed; monthly where manual	Confirms whether the freshwater head remains protective against saline movement.
Electrical conductivity or TDS	Continuous or weekly in high-risk wellfields; monthly in lower-risk areas	Provides the earliest operational warning of increasing salinity.
Chloride and major ions	Quarterly to annually, depending on risk	Distinguishes seawater mixing from other salinity sources and confirms EC trends.
Abstraction volume and pump run hours	Daily to weekly	Links salinity change to pumping intensity and duty cycle.
Geophysical or downhole profiling	Baseline, then after significant trend change or wellfield expansion	Maps the position and movement of the freshwater–saline transition zone.
Trigger-level review	Annually or after a threshold exceedance	Updates warning, action and shutdown levels using the latest monitoring data.

Box 19: Different methods to control or prevent seawater intrusion [55],



Types of barriers to control seawater intrusion: a low permeability subsurface barrier, b positive hydraulic barrier c negative hydraulic barrier, d mixed barrier (injection-pumping system)

Your monitoring frequency depends on whether you are located along the coast or inland near saline lenses or other saline areas. Coastal regions are susceptible to tidal influences, which often necessitate more frequent monitoring. Successful monitoring programs in coastal zones have employed telemetry systems as early-warning mechanisms to detect variations in electrical conductivity or TDS that exceed predetermined thresholds. The hydraulic gradient is significant; therefore, measuring water table elevation is vital for effective control and oversight of this gradient. Regular water level (WL) measurements are indispensable and can be conducted either manually or automatically. Automated systems can be programmed to collect data more frequently, such as hourly or daily.

Parameters that are important to measure include:

- Salinity
- Inorganic ions
- Total Dissolved Salts
- Electrical conductivity
- Temperature
- Water table elevation

For operations and maintenance, it is crucial to establish thresholds for each parameter listed above, as they may serve as early warnings or indicators of potential saline intrusion. Additionally, maintaining a comprehensive database of all recorded time-series data for the site is imperative. This will help identify trends and interpret anomalies in regularly measured parameters.

Surface water supply in Hermanus began to decline as early as 2002. The town had to develop a new plan to ensure its water resources remained

sustainable and sufficient to meet the population's needs. Three wellfields have been established in the town. These wellfields could potentially supplement the annual municipal allocation of 2.8 million m³ of water from the De Bos Dam by up to 3.2 million m³ of groundwater annually [56].



Box 20: **The three Hermanus wellfields and associated monitoring sites. The red block represents the Gateway wellfield, the green block Camphill, and the yellow block Volmoed (Umvoto as cited by** [56]**.**

Each wellfield has dedicated boreholes for both production and monitoring. Monitoring activities began before water extraction from these boreholes to establish baseline data on water quality and water-level fluctuations. Investigations into groundwater-surface water interactions and connectivity among aquifer units were also conducted in advance to improve understanding of the natural system. All collected data contributed to developing a system model, facilitating its conceptualisation and establishing a foundation for an adaptive management approach in Hermanus. This process resulted in the formulation of standard operating procedures, subject to revision as additional knowledge and data become available.



Box 21: An example of a production borehole in Hermanus [56]

Most borehole monitoring instruments integrate with a telemetry system that transmits data every 30 minutes or every 12 hours. Additionally, certain remote monitoring boreholes require manual data downloads quarterly.

The near real-time availability of data facilitates meticulous oversight of wellfield operations for both the consulting team and the municipality. Automated sensors, including flow meters, record pumped flow rate and flow rate entering pipelines. Water levels are recorded at intervals ranging from 30 minutes to one hour at both monitoring and production boreholes. Where boreholes are not equipped with sensors or loggers, manual water level measurements are conducted quarterly.

One wellfield is approximately 2 km inland from the coast, requiring monitoring of water levels and abstraction to prevent seawater intrusion. A specific water level threshold has been established for this wellfield to prevent saline water from entering the aquifer. When the water level approaches or exceeds this threshold, the system is configured to reduce or cease pumping operations to promote recovery. Additionally, since electrical conductivity (EC) reliably indicates saline water intrusion, an EC threshold of 150 mS/m has been established. When the EC threshold is reached or exceeded in any borehole, the system sends an SMS to the municipality and the consultant.

The Hermanus example illustrates the value of adaptive management in coastal wellfields: baseline monitoring is established before abstraction, production and monitoring boreholes are instrumented, telemetry provides near real-time review, and operational thresholds link monitoring data directly to pumping decisions. This approach should be replicated in other coastal schemes where abstraction occurs close to the sea, estuaries, tidal rivers or known saline groundwater zones. The chapter closes with a consolidated list of tools and resources that support the diagnostic, O&M, abstraction-control, groundwater-protection and saline-intrusion measures described above.

5.8. TOOLS AND RESOURCES

- 2001 – SADC Water Sector Coordination Unit: A Code of Good Practice and Guidelines for Groundwater Development in the SADC Region
- 2002 – Sami, Status Groundwater Exploration in Geologically Complex and Problematic Terrain – Guidelines, WRC Report No. 966/1/02 (clear schematic diagram also in a paper in 2009 – WRC: The basement aquifers of southern Africa, WRC Report No. TT 428-09)
- 2011 – Riemann, Groundwater Management Framework, WRC Report No. 1917/1/10 2019 – SADC-GMI, Guidance Document: Operation and Maintenance of Groundwater Schemes,
- 2020 – SADC-GMI, Training manual for operation and maintenance of groundwater infrastructure in SADC.
- Guidelines on Protecting Groundwater from Contamination (NORAD)
- A Guideline for the Assessment, Planning and Management of Groundwater Resources in South Africa (DWS, March 2008)
- Guidelines for the Monitoring and Management of Groundwater Resources in Rural Water Supply Schemes (R Meyer, WRC Report No 861/1/02a)
- National Groundwater Strategy (DWS, 2017)
- Standard Descriptors for Geosites (NORAD)
- Groundwater Monitoring for Pump Operators (NORAD)
- SANS 10299

PART E

6. INDIVIDUAL GROUNDWATER USERS

Part E helps individual groundwater users understand how groundwater systems work, how their use may affect nearby users and water resources, and what information municipalities may require when a borehole is installed or used on private property.

Many local municipalities already have information, requirements, or application processes for drilling a borehole on private property. In water-scarce municipalities, responsible groundwater use can help reduce pressure on conventional water supplies, provided that users understand and follow the relevant municipal requirements.

A borehole application usually requires information about the proposed drilling site, the intended water use, and the expected abstraction rate. This helps ensure that the user understands the process and that the municipality can consider potential impacts on groundwater resources, neighbouring users, and municipal infrastructure.

Because groundwater use on one property can affect both municipal management and nearby users, the local municipality may request the following information to support its groundwater management efforts:

- Distance of the drilling site to a nearby water resource (river, lake, wetland, stream, etc.)
- Type of pump to be installed
- Yield of the supply
- Depth to water level
- Rate of pumping in litres per second
- Operating days per year
- Annual rainfall in the area
- What is the purpose of the water from the intended abstraction (toilet flushing, irrigation, etc.)?

When you connect borehole water to your household's municipal supply, the municipality may want to ensure there is no risk of contaminating the municipal supply if groundwater quality is compromised. A municipality may also want to confirm that the water installation complies with the Water Bylaws (2010).

In addition to the basic borehole details, users should be prepared to answer broader operational questions about volumes, water quality, treatment, monitoring, and timing of abstraction:

- The municipality may also want to know how much water a single user intends to use. As a single user, you may need to determine this volume.
- In terms of the water quality, the Municipality may request that the water be tested to establish whether it is suitable for the desired use.
- Questions around details of intended pre-treatment of the water may also be asked of the single-borehole user if this is part of the user's plan.
- How do you propose to log/record the amount of water abstracted?
- When do you propose to abstract and use this source of water? The municipality may want to know the full duration of abstraction.

Once the intended abstraction and use have been described, users should also consider what will happen to the water after it has been used, particularly where the use may produce effluent or wastewater:

- Will the borehole/wellpoint water usage generate effluent or wastewater?
- How do you plan to handle that effluent or wastewater?
- Do you intend to discharge this effluent or wastewater from this source?
- Where will you discharge the effluent/wastewater?
- Do you have consent to discharge the wastewater from this site into the City's sewer system?
- Will the discharge be measured? If so, how?

Although these questions are detailed, they help protect the user, neighbouring properties, the municipality, and the groundwater resource itself. The following sections explain who this guidance applies to and how individual users can manage borehole abstraction, water quality, pollution risks, and household or farmstead activities responsibly.

Individual users need to consider that neighbouring boreholes are likely to affect each other through the resulting drawdown cone and, therefore, the resulting depth to water. Implications of excessive pumping of a single user include the following:

- If one user pumps continuously for 24 hours at a high rate, their pumping may lower the water table at their neighbour's borehole

- In some cases, especially where larger volume users are located, e.g. farms or large homesteads with subsistence farming, neighbours may considerably impact each other's available water resources
- Depth from which the pump needs to operate
- One neighbour could experience water stress if excessive water is pumped by another

6.1. TARGET AUDIENCE

Part E is intended for Schedule 1 groundwater users, including households using groundwater for domestic purposes, single farms, small-scale landowners, and companies or facilities in industrial zones that abstract groundwater for limited on-site use. These users typically operate one borehole or wellpoint on a single property and use the water for activities such as household supply, garden irrigation, livestock watering, small-scale crop irrigation, sanitation, cleaning, or other non-commercial operational needs.

The guidance is especially relevant where groundwater is used as a supplementary source during periods of municipal water restrictions, drought, intermittent supply, or increased local demand. It also applies where the borehole water is connected, directly or indirectly, to plumbing, irrigation systems, storage tanks, or other infrastructure on the property.

For this audience, the focus is on understanding basic groundwater responsibilities: using water efficiently, monitoring abstraction where required, protecting groundwater quality, preventing cross-connections with the municipal supply, and considering the possible effects of pumping on neighbouring boreholes, nearby water resources, and municipal infrastructure. These responsibilities provide the basis for the purpose of the guidance set out in the next section.

6.2. PURPOSE

The purpose of this section is to provide individual groundwater users with practical guidance on the responsible development, use, monitoring, and protection of groundwater on private properties. It explains why municipalities may require information about borehole installation and use, and how users can support sustainable groundwater management by

understanding their abstraction, water quality, infrastructure, and potential impacts on neighbouring users and nearby water resources.

The section also aims to help users make informed decisions before drilling, equipping, or operating a borehole, particularly where groundwater supplements the municipal water supply. By setting out key considerations, the section encourages efficient water use, pollution prevention, compliance with applicable municipal requirements, and early engagement with the local municipality where approvals, records, water quality testing, or safeguards may be required. The first practical step is to understand how pumping from one borehole can influence neighbouring users and the shared groundwater resource.

6.3. HOW SINGLE USERS CAN MANAGE BOREHOLES TO REDUCE IMPACTS ON NEIGHBOURS

Single borehole users can reduce impacts on neighbouring users by understanding their borehole's sustainable yield and managing pumping within that limit. This means considering the pumping rate, pumping duration, total volume abstracted, and the time allowed for groundwater levels to recover between pumping periods.

Where boreholes are located close to one another, users should avoid continuous high-rate pumping, especially during dry periods or when neighbouring boreholes are also in use. A practical management approach is to pump at a moderate rate, schedule use during lower-demand periods where possible, and keep basic records of pumping times, estimated volumes, and water-level changes.

Managing pumping is only one part of responsible borehole use. Users should also recognise that activities on their properties can affect the quality of the groundwater they depend on. Poorly managed sanitation systems, waste-disposal areas, cemeteries, agricultural chemicals, animal feedlots, fuel storage, and household waste can create pathways for pollutants to enter the aquifer. These risks are greater where the water table is shallow, soils are sandy or permeable, or fractured rock provides a direct route to groundwater.

Individual property owners should test groundwater to confirm that it is suitable for the intended use, particularly where the water may be used for drinking, food preparation, livestock watering, irrigation, or connection to household systems. Samples should be collected and submitted to an accredited laboratory, or through the local municipality where this service is

available, and the results should be compared with the relevant water-quality guidelines for the intended use.

6.3.1. Standard operating procedures for single-borehole users

The following standard operating procedures provide a practical routine for individual groundwater users to operate a borehole responsibly, reduce interference with neighbouring boreholes, protect groundwater quality, and maintain information the local municipality may request.

a) **Confirm borehole information before operation.** Keep a record of the borehole location, depth, pump installation depth, static water level, estimated or tested yield, intended use, and any municipal reference or approval information. Where the sustainable yield is unknown, avoid high-rate pumping and seek technical guidance before increasing abstraction.

b) **Operate within the sustainable yield.** Set the pump to a rate that the borehole can sustain without excessive drawdown. Avoid continuous 24-hour pumping unless a yield assessment confirms this is sustainable and will not unreasonably affect neighbouring users.

c) **Schedule pumping to allow recovery.** Use shorter pumping cycles with rest periods where possible, especially during dry periods, municipal restrictions, or periods of high local groundwater demand. If water levels do not recover adequately between pumping periods, reduce the pumping rate or duration.

d) **Monitor abstraction and water levels.** Record pumping dates, start and stop times, estimated volumes, pumping rate, and water-level observations. Where a flow meter is installed, take regular meter readings; where no meter is available, estimate use from pump capacity and operating time.

e) **Check for impacts on neighbouring users.** Be alert to reports of declining yields, increased pumping depth, pump failure, or water stress in nearby boreholes. If impacts are suspected, reduce pumping, increase recovery time, and engage with affected neighbours and the municipality where necessary.

f) **Protect groundwater quality.** Keep the borehole head sealed and raised where possible, prevent surface water from ponding around the borehole, and maintain a safe separation from sanitation systems, waste areas, fuel storage, chemical storage, animal pens, and fertiliser or pesticide application areas.

g) **Prevent cross-contamination.** Do not connect borehole water directly to the municipal supply unless the installation complies with municipal requirements and includes appropriate backflow prevention. Inspect and maintain any connection to household plumbing, tanks, irrigation systems, or treatment equipment to prevent contamination of either supply.

h) **Test water quality for the intended use.** Test groundwater before using it for drinking, food preparation, livestock watering, irrigation, or household systems, and repeat testing periodically or whenever the taste, colour, odour, turbidity, or nearby land-use conditions change.

i) **Maintain equipment and infrastructure.** Inspect the pump, electrical connections, pressure system, pipes, valves, storage tanks, treatment units, and borehole casing for leaks, damage, corrosion, or unsafe conditions. Repair faults promptly to reduce water loss and prevent contamination pathways.

j) **Respond to abnormal conditions.** Stop or reduce pumping if the borehole begins producing sand, cloudy water, unusual odours, a sudden drop in yield, excessive drawdown, pump overheating, or evidence of contamination. Resume normal use only after investigating and correcting the cause.

At a minimum, users should keep a simple borehole logbook containing borehole details, pump specifications, abstraction estimates, water-level readings, water-quality results, maintenance records, complaints or observations from neighbours, and any correspondence with the municipality. These records support responsible management and provide evidence that the user is operating the borehole with due care. The next section builds on this operational routine by focusing on practical methods to reduce water waste and prevent pollutants from reaching groundwater.

6.4. MANAGEMENT METHODS TO REDUCE WASTE AND PREVENT GROUNDWATER POLLUTION ON SINGLE-BOREHOLE PROPERTIES

Building on the operational controls described above, single-borehole users should actively manage activities on their properties that may waste water or introduce pollutants into the ground. Common risk sources include fertilisers and nitrate-rich materials, pesticides and herbicides, household and farmstead waste, animal waste from intensive farming areas, irrigation return flows, fuel and chemical storage, wastewater systems, and any

activity that allows polluted water to infiltrate into the soil near a borehole, wellpoint, drainage line, wetland, stream, or other water resource.

- **Identify pollution sources.** Map boreholes, septic systems, chemical stores, fuel tanks, animal pens, irrigation areas, fertiliser storage, waste areas, drainage lines, and nearby water resources.
- **Separate high-risk activities from boreholes.** Keep fertilisers, pesticides, fuels, wastewater systems, animal waste, and waste-disposal areas away from boreholes and wellpoints, especially where soils are sandy, fractured, shallow, or highly permeable.
- **Control water movement.** Prevent contaminated runoff from flowing towards boreholes, storage areas, stormwater channels, streams, wetlands, or soak-away systems.
- **Use inputs efficiently.** Apply fertilisers, pesticides, manure, effluent, and irrigation water only at rates and times that match crop, soil, and weather conditions.
- **Monitor and maintain.** Inspect pollution-control measures regularly, test groundwater where contamination is possible, and keep records of products used, application dates, water-quality results, incidents, and corrective actions.

Standard operating procedures for preventing groundwater pollution and water waste

The following procedure provides a practical routine for single-borehole users to identify pollution risks, reduce unnecessary water loss, protect groundwater quality, and maintain records that support responsible property-level groundwater management.

a) Prepare a property risk map. Mark the borehole or wellpoint, septic tanks, soak-aways, pit latrines, wastewater discharge points, chemical and fuel storage areas, fertiliser and pesticide application areas, livestock camps, manure stockpiles, irrigation areas, stormwater routes, wetlands, streams, and neighbouring boreholes where known.

b) Classify high-risk areas. Give priority attention to areas with shallow groundwater, sandy or permeable soils, fractured rock, karst conditions, steep drainage towards a borehole, or repeated ponding of contaminated water.

c) Establish protection zones around boreholes. Keep the immediate borehole area clean, sealed, raised where practical, and free of chemicals, waste, fertiliser, manure, fuel, wastewater, standing water, and vehicle wash-off.

d) Store chemicals and fuels safely. Keep pesticides, herbicides, fertilisers, fuel, oils, and cleaning chemicals in sealed containers on an impermeable surface, under cover, with spill-control materials available. Do not store hazardous substances where leaks can drain towards a borehole, watercourse, or soak-away.

e) Apply fertilisers, manure, pesticides, and irrigation water responsibly. Apply only the required quantity, avoid application before heavy rainfall, avoid bare ground where practical, and keep application away from boreholes, drainage lines, wetlands, and surface-water resources.

f) Manage wastewater and effluent. Confirm where wastewater is generated, how it is stored, whether it is treated, and where it is discharged. Ensure septic systems, soak-aways, effluent ponds, and discharge points are properly maintained and do not allow uncontrolled seepage into vulnerable groundwater areas.

g) Prevent water waste. Inspect pipes, tanks, valves, troughs, irrigation systems, pumps, and fittings for leaks. Repair leaks promptly, avoid unnecessary overflow from storage tanks, and schedule irrigation according to crop and soil-water needs.

h) Inspect after rainfall or spills. After heavy rain, flooding, chemical spills, fuel leaks, or wastewater overflow, inspect the borehole area and drainage routes. Stop activities that may carry pollutants into the ground and clean up spills immediately using appropriate containment and disposal methods.

i) Test and monitor groundwater quality. Test groundwater where it is used for drinking, household supply, livestock watering, irrigation, or food production, and repeat testing if land use changes, contamination is suspected, or there are changes in taste, colour, odour, turbidity, salinity, or nitrate levels.

j) Keep a pollution-prevention logbook. Record inspections, water-quality results, chemical and fertiliser applications, pesticide use, irrigation periods, spills, wastewater incidents, maintenance actions, complaints, and any communication with the municipality.

If contamination is suspected, users should stop the activity that may be causing the problem, prevent further runoff or infiltration, avoid using the water for sensitive purposes until testing confirms it is suitable, and contact the municipality or an appropriately qualified specialist for guidance where the risk extends beyond the property or may affect neighbouring users. The following explanatory notes provide additional background on groundwater quality, aquifer vulnerability, and common agricultural or property-level pollutants to consider when applying these procedures.

What is groundwater quality?

This term refers to the water chemistry and microorganisms living in it. Groundwater naturally contains many dissolved substances, such as calcium and chloride. Soluble materials applied to land may also be transported into the aquifer, and some are harmful to health and/or the environment.

NB: Groundwater is recharged by water infiltrating through the soil. Farmers' activities can significantly affect the quantity and quality of this recharge water.

Some of the most far-reaching measures to protect groundwater quality are also practical and cost-effective because they reduce long-term losses of fertilisers, water or pesticides. By protecting groundwater quality, farmers keep it fit to drink and to apply to the land. These measures minimise the risk of disease to people and livestock, and the risk of fouling surface waters.

WRC, (1999)

AQUIFER VULNERABILITY

Some aquifers are very vulnerable to contamination, whereas others are afforded a good degree of natural protection. A shallow aquifer covered by only a few metres of sandy soil in a regularly irrigated area would be very vulnerable to contamination. Groundwater in a deep aquifer with low-permeability clays between the aquifer and the surface is unlikely to be contaminated locally. However, that same groundwater may have been contaminated in a recharge area where the aquifer occurs closer to the surface or is overlain by more permeable deposits.

6.4.1. Nitrates

Nitrate poses a risk to water quality above 10 mg/L nitrate-nitrogen, which is equivalent to 45 mg/L nitrate. At concentrations higher than this, there is an increased risk of methemoglobinemia, “blue baby syndrome”, in infants, as well as a risk to livestock using the water for stock watering. Livestock can withstand higher nitrate concentrations.

Sources of nitrate on farms and other single users

Inputs of nitrogen on farms include:

- Soil organic matter (typically low in South Africa)
- Inorganic fertiliser
- Manures
- Effluent
- Irrigation water
- Residual nitrogen in soil water

Nitrate is used by processes such as uptake by crops (also referred to as crop requirements) and volatilisation to the atmosphere. Whatever is not taken up by these processes can leach to groundwater or it becomes runoff which can reach rivers or streams.

Conditions that make it more likely for nitrate to reach groundwater

- High rates of nitrogen loading from fertiliser, manure and organic matter in the soil
- High soil temperatures, which increase the rate of nitrification
- Well-aerated soil also encourages nitrification
- Low levels of plant uptake due to bare ground, low crop requirements or seasonally variable requirements
- High levels of precipitation or irrigation
- Permeable soil and unsaturated zone
- Shallow water table

Practises to prevent or manage nitrate inputs on farms include ensuring that fertiliser use does not exceed crop requirements. Actions that can be taken to properly manage your nitrogen inputs include the following:

- Research your crop requirements (including timing) and the rate of nitrogen uptake by cover crops and pasture (especially important where effluent is being irrigated to pasture)
- Account for additional sources of nitrogen, such as manure and effluent.
- Efficiently load and schedule inorganic fertiliser application according to nitrogen uptake
- Schedule irrigation efficiently to reduce excess water percolating beneath the root zone, taking dissolved nitrate with it.
- Monitor the crops for signs of over-application and alter the loading accordingly.
- If possible, monitor infiltrating soil water beneath the root zone for nitrate to give an early indication of leaching.
- Monitor groundwater quality annually for any indication of contamination, but be aware that this may take years to show.

- Do not apply fertiliser close to boreholes, as infiltration may affect the groundwater quality
- Avoid using fertilisers on bare ground before planting, as this may leach into the groundwater when it is not being taken up by crops

6.4.2. Pesticides

The maximum allowable concentration of pesticides in drinking water is very low because pesticides are highly toxic. South African drinking water guidelines for pesticides are based on the World Health Organisation (WHO) guidelines, which set a maximum level of 2 parts per billion (2 micrograms per litre) in drinking water.

In groundwater, contamination from pesticides can occur over large areas (diffuse sources) of pesticide application, as well as from point sources where pesticides may be stored (e.g., the homestead or storerooms on the premises).

Leaching of pesticides to groundwater is dependent on the following factors:

- The rate of pesticide application
- The availability of water (rain or irrigation) to dissolve and transport the pesticides to the water table
- The solubility of the pesticide. On the whole, herbicides tend to be more soluble than insecticides
- The persistence of the pesticide in the soil. Some pesticides are broken down quite quickly, whereas others are more likely to survive until they reach the water table.
- Persistence is dependent on other factors such as soil pH and temperature. Pesticides usually break down more quickly at higher soil temperatures.

The organic matter and clay content of the soil in the area where the pesticide is sprayed. These can remove pesticides from the dissolved phase by absorbing them, preventing them from leaching into groundwater.

The vulnerability of the aquifer to contamination depends on the depth to the groundwater table, the thickness of the unsaturated zone, and the amount of permeable material (rock or soil type) in the area.

NB!! These conditions need to be considered when using pesticides.

Landowners are encouraged to do the following:

- Before intending to spray pesticides, watch the weather forecast, as too much rain may cause quick infiltration, leading to the pesticides reaching the groundwater.
- At farms where pesticides are regularly used, the best practice to minimise the risk of contamination from the handling area is to construct a pesticide spillage safety trap. This makes use of the natural processes of breakdown and pesticide adsorption to clays and organic matter.
- Dispose of pesticide containers responsibly. They should go to a licenced hazardous waste site or return to the supplier.
- Always follow the limitation recommendations on the containers, as this will ensure that the concentrations are environmentally acceptable.
- Try to reduce the rate of application, select good weather conditions to ensure that a slower application rate is possible.
- Contamination should be avoided at all costs. Pesticides should be stored in a covered area with a concrete base which prevents seepage into the groundwater, should there be a leak in containers.
- Always dispose of excess rinse water and mixtures responsibly.

Intensive farming activities

Where many animals occupy the same space, their waste can often be a source of groundwater contamination. This is especially true during periods of rainfall or runoff over the area, and subsequent infiltration of water into the groundwater. A complicating factor is whether the aquifer is vulnerable. This includes a shallow water table, highly permeable soils, or a fractured rock or karst aquifer, which allows direct infiltration of potential contaminants into the aquifer.

Nitrogen in urea, ammonium, and organic matter in manure is converted to nitrate under certain conditions. This is then leached to vulnerable groundwater during periods of high rainfall or irrigation.

Animal effluents typically have TDS (salinity) levels of 3 000 to 15 000 mg/L. This is much higher than the TDS of fresh groundwater; an increase in salinity indicates contamination. The high nutrient levels in animal wastes

increase the biological oxygen demand (BOD) of the water. This disrupts the balance of aquatic ecosystems. Microorganisms such as viruses, bacteria, protozoa and helminth eggs are present in animal excreta. Microbiological pathogens do not usually represent a major risk to groundwater quality. Most are effectively sieved by the soil due to their size, or they adsorb to surfaces and do not survive the time it takes to transport them to the water table. However, where fractures or cracks exist, or where the soil is very sandy with little clay and organic matter, microorganisms can reach the water table.

How to minimise the chances of contamination on your land:

Natural processes can be harnessed to control or prevent contamination of your groundwater.

Where feedlots and effluent lagoons are present on land, an impermeable material can be used to prevent infiltration into the groundwater.

If you intend to use effluent lagoons, be certain that the underlying geological material or soil is not highly permeable or fractured, as this will increase the risk of seepage into groundwater. In these cases, the use of a lining is encouraged.

In the presence of more impermeable materials, the accumulation of heavier materials at the bottom of the lake may seal pore spaces and reduce or inhibit the infiltration of potentially contaminated water.

The siting of feeding and drinking areas should take into account the slope of the area and the underlying materials. The slope should allow for run-off of water; if possible, this allows for the collection of water in canals and reduces standing water, which would be a source for contamination.

The risk of leaching is greatest where high volumes of effluent are applied, or irrigation is carried out in addition to waste application over land. A limit of 250 kg of nitrogen per hectare per year in manure applied to land is recommended.

Large amounts of manure often accumulate at feeding and drinking areas. This can be a cause for contaminants. It is advisable to use mobile feeding and drinking troughs, if possible, to avoid accumulation in one area. In this way, it does not exceed the carrying capacity of a certain area of land with respect to manure accumulation.

6.4.3. Irrigation

Irrigation of land is a source of land salinisation and can therefore also be a source of groundwater salinisation if these salts dissolve and infiltrate. It can also cause declines in water levels where groundwater is used for irrigation, or increases in groundwater levels where surface water is used for irrigation. In some cases, leaching of contaminants from fertiliser, pesticides and feeding areas can infiltrate via irrigation water.

Salinisation originates from irrigation return flow being reused and becoming much more concentrated, and from natural salts in the soil being leached and accumulating on the soil surface.

To minimise salinisation, the following should be considered.

- Efficient irrigation scheduling closely tied to crop requirements to reduce overirrigation and the volume of water that percolates beneath the root zone.
- Using more controlled irrigation methods, e.g. drip irrigation.
- Monitoring soil moisture at and below the root zone to establish whether the irrigation method is efficient.
- Reduce the amount of leakage by the construction of canals and dams with impermeable linings.
- Try to reduce the input of waterborne soluble salts by using water of better quality for irrigation.
- Try not to irrigate during fertiliser application, as this will enhance the amount of fertiliser chemicals that can seep into the groundwater.
- Carefully choose areas and timing of new land development. The most vulnerable time for salts to leach from the soil is during periods of bare land or in areas of new development. It is therefore important to prepare the soil properly for planting and irrigation.
- Where fertigation is carried out, install check valves to prevent back siphoning of the fertiliser solution into the borehole.
- Where you have boreholes, monitor the groundwater level at least every 3 months.
- Sample regularly for TDS and nitrates to determine if the water quality is being affected by any practices on the land. Similarly, monitor the quality of soil water beneath the root zone.

The same pollution-prevention principles also apply at the household or farmstead scale, where smaller but concentrated sources of wastewater, chemicals, fuel, and waste can pose a direct risk to nearby boreholes.

6.5. THE HOUSEHOLD AND FARMSTEAD

Households, farmsteads, staff accommodation, workshops, storage rooms, ablution facilities, and other buildings on a property can create concentrated pollution risks to groundwater. Although these areas may be small compared with the rest of the property, they often contain wastewater systems, pit latrines, septic tanks, soak-aways, detergents, bleaches, fuels, oils, fertilisers, pesticides, cleaning products, and other materials that can enter the ground if they are poorly stored, spilled, washed into drains, or disposed of incorrectly.

Septic tanks, soak-aways, pit latrines, greywater systems, and other on-site sanitation systems must be properly located, operated, and maintained because they can release nutrients, pathogens, detergents, and household chemicals into the soil. The risk is higher where the system is close to a borehole, where groundwater is shallow, or where soils, fractured rock, or karst conditions allow rapid infiltration.

Storage areas around the household or farmstead should be managed so that chemicals, fertilisers, pesticides, fuel, oil, paint, solvents, and cleaning products cannot leak into soil, stormwater drains, septic systems, or areas that drain towards boreholes. Containers should be sealed, clearly labelled, stored under cover on an impermeable surface, and kept away from children, animals, ignition sources, and water-flow pathways.

Pollution-prevention measures are especially important where:

- A drinking water supply borehole is located in or close to the farmstead.
- Groundwater occurs at a shallow depth.
- The soil in the farmstead area is permeable or
- The farmstead is located on fractured hard rock or Karst terrain

Standard operating procedures for household and farmstead groundwater protection

The following procedure helps household and farmstead users prevent contamination from domestic wastewater, sanitation systems, storage areas, and everyday household activities that may affect boreholes and groundwater quality.

a) **Identify household pollution sources.** Record the location of the borehole, septic tank, soak-away, pit latrine, greywater outlet, outside drains, chemical stores, fuel or oil storage, refuse area, washing area, workshop, animal enclosures, and stormwater flow paths.

b) **Maintain safe separation from the borehole.** Keep sanitation systems, waste-disposal areas, fuel storage, chemical storage, vehicle-washing areas, and wastewater discharge points as far from the borehole as practical, and follow applicable municipal requirements for siting and approval.

c) **Inspect sanitation systems routinely.** Check septic tanks, soak-aways, pipes, pit latrines, and greywater systems for leaks, odours, blockages, overflows, ponding, erosion, or unusually wet areas. Arrange repairs or desludging before failure occurs.

d) **Control what enters wastewater systems.** Avoid disposing of fuel, oil, paint, solvents, pesticides, medicines, strong disinfectants, fats, nappies, sanitary products, or excessive detergents into toilets, basins, drains, septic tanks, or soak-aways.

e) **Store household and farmstead chemicals safely.** Keep chemicals, fertilisers, pesticides, fuel, oil, paint, and cleaning products in labelled, sealed containers under cover on an impermeable surface. Keep spill-control material available and clean up spills immediately.

f) **Prevent polluted runoff.** Direct clean stormwater away from waste, fuel, chemical, washing, and sanitation areas. Do not allow contaminated runoff to pond around the borehole, enter drains, or flow towards wetlands, streams, or soak-aways.

g) **Protect the borehole head.** Keep the borehole area clean, sealed, raised where possible, and free from standing water, rubbish, chemicals, animal waste, vehicle wash-off, and damaged pipework.

h) **Test water used for domestic purposes.** Test borehole water before it is used for drinking, cooking, bathing, food preparation, or household plumbing, and repeat testing after sanitation failures, flooding, chemical spills, land-use changes, or changes in taste, colour, odour, or turbidity.

i) **Respond to contamination incidents.** If wastewater, fuel, chemicals, or other pollutants may have reached the ground near the borehole, stop using the affected activity, contain the source, avoid using the water for sensitive purposes, and seek municipal or specialist guidance.

j) **Keep household groundwater records.** Retain records of inspections, septic maintenance, desludging, repairs, spills, water-quality tests, chemical storage checks, borehole maintenance, and any communication with the municipality.

Where a household relies on borehole water, the user should treat water-quality testing, sanitation maintenance, and safe storage as routine management tasks rather than once-off actions. Any new or altered septic system, soak-away, pit latrine, borehole connection, or domestic plumbing arrangement should be checked against municipal requirements before installation or use. Users can refer to the tools and resources in the next section for further technical guidance and supporting material.

6.6. TOOLS AND RESOURCES

Resources:

C Colvin, Handbook of groundwater quality protection for farmers (WRC report no. TT 116/99), 1999, https://www.wrc.org.za/wpcontent/uploads/mdocs/TT-116-99.pdf • Centre for Agriculture, Food and the Environment,

Pesticides and groundwater protection, not dated, https://ag.umass.edu/ greenhouse-floriculture/greenhouse-best-managementpractices-bmp-manual/pesticides-groundwater

K de Bruin et al, Guidance document for management of a groundwater scheme (WRC report no. TT 906/22), 2022, https:// wrcwebsite.azurewebsites.net/wp-content/uploads/mdocs/ TT%20906%20final%20web.pdf

LD van Rensburg et al, On-farm water and salt management guidelines for irrigated crops: Level Two Decision Support (WRC report no. TT 847/2/21), 2021, https://wrcwebsite.azurewebsites. net/wp-content/uploads/mdocs/TT%20847%20Volume%20 2%20final%20web.pdf M Nel, Groundwater – The myths, the truths, the basics (WRC report no. SP 108/17), 2017, https://www.wrc.org.za/wp-content/ uploads/mdocs/Groundwater%20book_web.pdf

Potatoes SA, Groundwater guidelines, Managing an unseen resource, 2019, https://geoss.co.za/wp-content/uploads/2022/02/ PSA_GEOSS_GroundWaterGuidelines_Jul2019_English.pdf

Van Vuuren, L., (1999) A Concise guide to groundwater quality protection for farmers, based on: Handbook of groundwater quality protection for farmers (WRC report no. TT 116/99):/99):

Part F

7. GROUNDWATER POTENTIAL AND OCCURRENCE IN SOUTH AFRICA

This section emphasises the geological, hydrological, and climatic controls that govern the occurrence, movement, storage, and quality of groundwater in South Africa. By outlining the key aquifer types and hydrostratigraphic regions, the chapter establishes the essential concepts required for informed groundwater planning and management.

South Africa's groundwater resources are highly variable and largely controlled by geology. Most aquifers are fractured or karstic in nature, with limited primary porosity, low and often episodic recharge, and strong spatial heterogeneity. As a result, groundwater yields, sustainability, and vulnerability to contamination differ significantly over short distances. Understanding these characteristics is critical, as inappropriate assumptions about aquifer behaviour can lead to failed boreholes, declining yields, deteriorating water quality, and long-term resource degradation. This underscores the importance of developing robust conceptual site models, supported by appropriate geological, geophysical, hydraulic, and water-quality data, as the basis for all groundwater decision-making.

Fundamentally, groundwater is neither invisible nor unlimited. Its sustainable use depends on recognising natural constraints, monitoring system responses, and applying fit-for-purpose technical approaches. The principles introduced in this section form the building blocks for the strategic, institutional, and operational guidance presented in subsequent chapters. A sound understanding of groundwater basics is therefore essential for municipalities, practitioners, and decision-makers seeking to integrate groundwater effectively into resilient, long-term water supply systems.

Groundwater occurrence in South Africa is influenced by the country's complex geological history (Figure 20; Figure 21). A schematic of the major aquifer types and settings has been made [57]. Ten hydrogeological settings that typify major stratigraphic units are identified (Table 14; Figure 23). Most South African aquifers occur in fractured rock ranging in age from the earliest Precambrian to the Jurassic. Aquifers consisting of recent to Tertiary formations are restricted to coastal dune belts and unconsolidated deposits associated with rivers and aeolian sands.

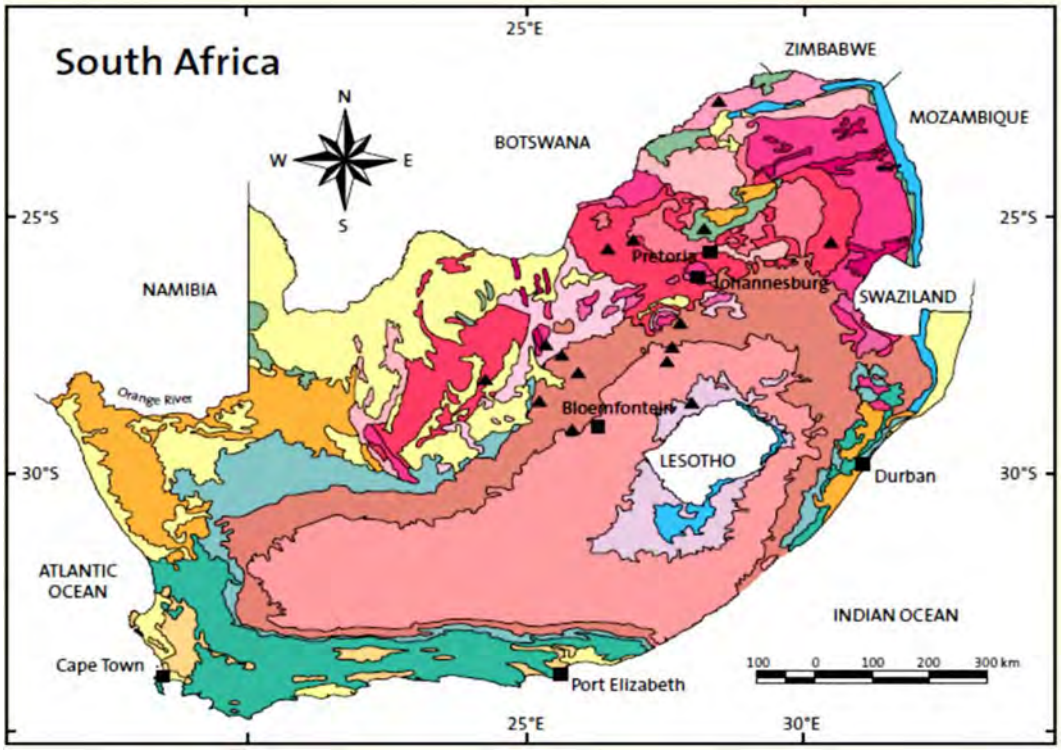


Figure 21: **Generalised geological map of South Africa (legend key see Figure 21) [58].**

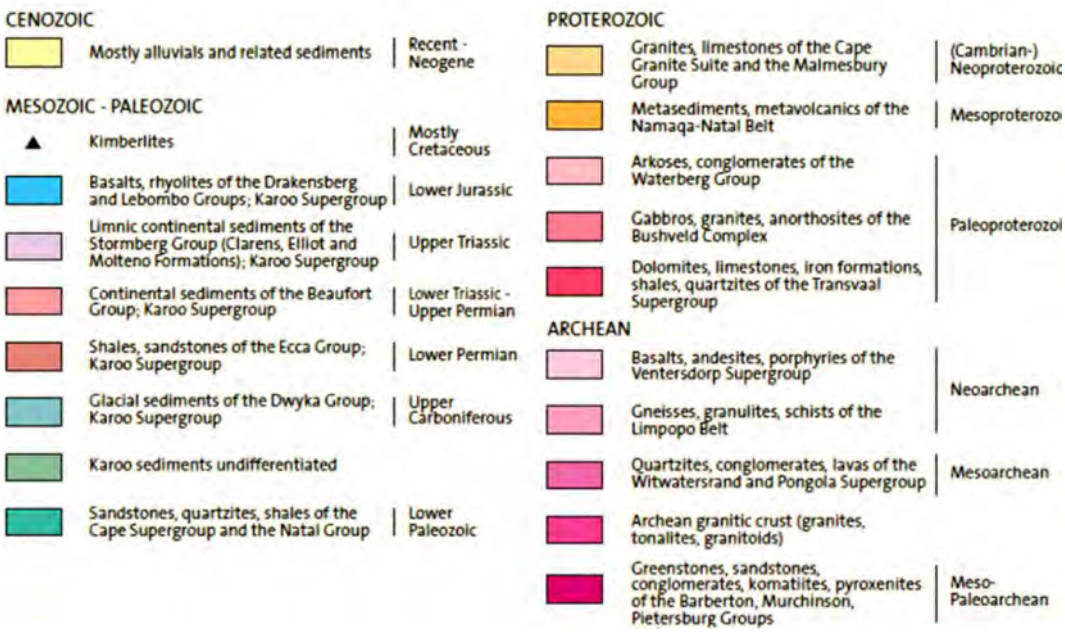


Figure 22: **Legend key for Figure 20, showing the main geological features and groups** [58].

To understand the historical development and relationships among geological events, geologists use a geologic time scale (Figure 22). The geologic time scale is a system of chronological dating that relates geological strata (rock layers) to time. It is essentially a calendar that Earth scientists use to describe the timing and relationships of events in Earth's history. An eon is the largest span of time, encompassing hundreds of millions to billions of years, while an era is a major subdivision of an eon, typically lasting tens to hundreds of millions of years. A period is often defined by the life forms that thrived during that time (e.g., the Jurassic Period is known for its dinosaurs). Periods last millions to tens of millions of years. An epoch is a subdivision of a period, representing smaller time intervals (millions of years or less). The age is the smallest formal unit, often corresponding to a specific stage in rock layers.

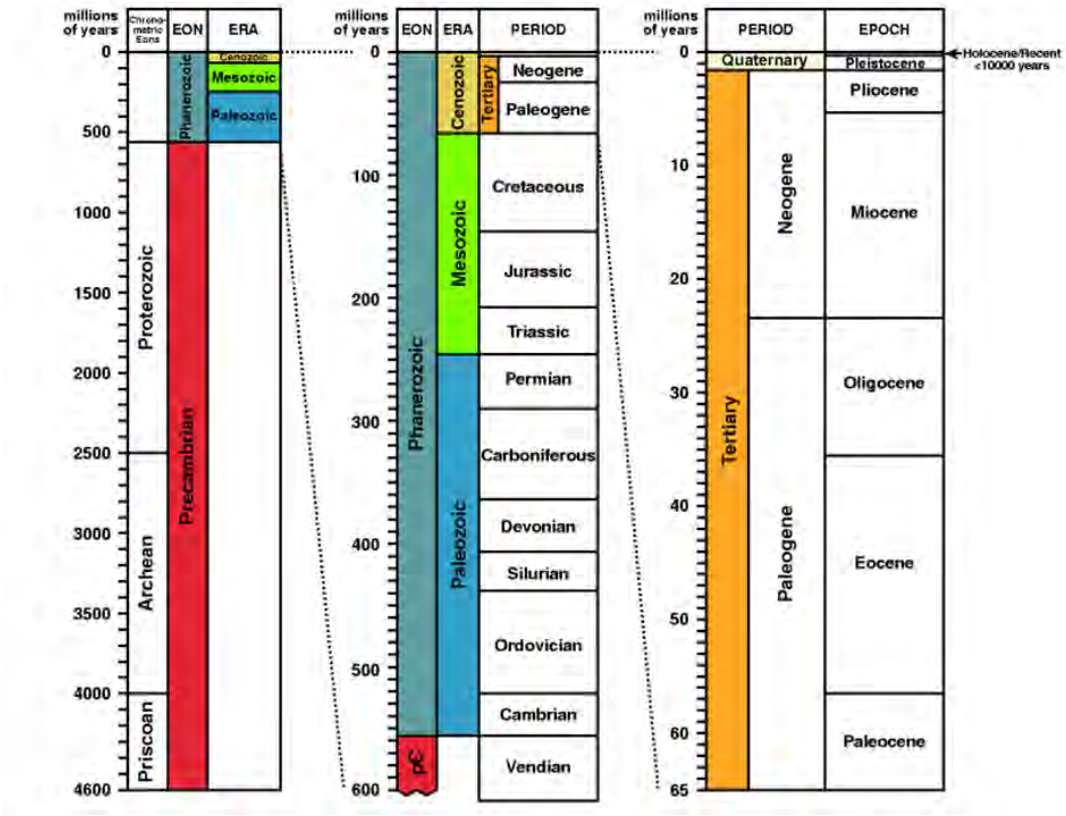


Figure 23: Geology time scale.

Table 14: Description of the hydrogeological properties of the significant South African lithostratigraphic sequences [57].

Hydrostratigraphic area	Rock types	Climate	Landscapes	Porosity	Aquifers	Recharge	Borehole yield	System yield	Sustainability issues	Water quality
Coastal	Unconsolidated sediments and calcarenite	Perennial rain	hilly to flat	Primary	Sand, gravel	Regular	High	Moderate	Groundwater surface water interaction	Rural and agricultural impacts
Kalahari	Unconsolidated sediments, sandy, and surface	Semi-arid, summer rain	Very flat with sand dunes	Primary	Sand, gravel	Episodic	High	Low	Groundwater-dependent towns and farms have low recharge	Natural salinity and nitrates
Karoo	Sandstone, siltstone, mudstone, dolerite	Semi-arid, summer rain	Steep rocky hills and plains	Secondary	Fractured sandstone	Episodic	Moderate	Low	Groundwater-dependent towns and farms have low recharge	Agricultural high U
Cape Fold Belt	Quartzite with minor siltstone, conglomerate, tillite	Mediterranean, winter rain	Steeply mountainous	Secondary	Fractured quartzite	Annual	High	High	Baseflow to springs and rivers from TMG	Low, TDS, naturally acidic
Saldanian Basement	Metasediments, shale, phyllite, hornfels, Metavolcanics	Mediterranean, to semi-arid winter rain	Hilly	Mixed	Saprolite, fractures, veins	Irregular	Moderate	Low	Groundwater-dependent wetlands, low recharge	Minor salinity, agricultural
Namaqua Metamorphic	High-grade metamorphic, gneiss, schist, shears, veins, pegmatites	Semi-arid	Very flat with small rocky hills	Mixed	Saprolite, fractures, veins	Episodic	Low	Low	Low recharge	Salinity, high U
Waterberg	Sandstone, Conglomerate	Subtropical, summer rain	Gently mountainous	Minimal	Scree	Annual	Moderate	Low	Small aquifers	Good, shallow aquifers
Malmani Dolomite	Dolomite, chert, wad	Subtropical, summer rain	Flat to undulating	Tertiary and primary (wad)	Karst and saprolite (wad)	Annual, fast	High	High	Fast ingress of pollutants, some urban issues (sinkholes)	Good, possible pollution in developed areas
Witwatersrand	Quartzite slate	Subtropical, summer rain	Flat with minor hills	secondary	fractured quartzite, faults	annual	Moderate	Moderate	Mine voids, urban and industrial issues	AMD, urban and other developments, high TDS U
Archaean Granitoids	Granite, gneiss	Subtropical, summer rain	Hilly	mixed	saprolite, fractures	irregular to annual	Moderate	Low	Small aquifers, flow complex in fractures and saprolite	Town, mining and agricultural impacts

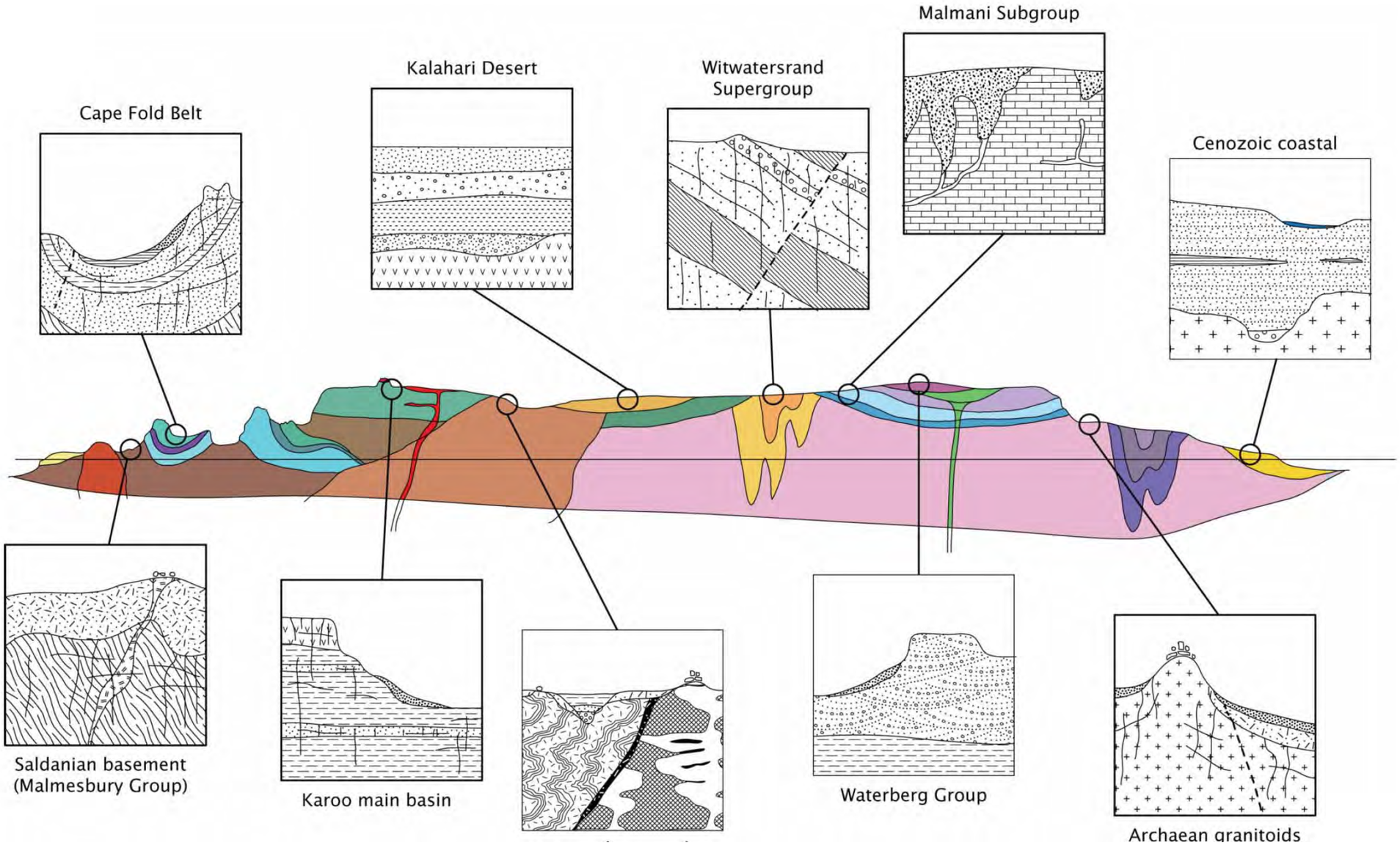


Figure 24: **Hydrogeological properties of the significant South African lithostratigraphic sequences** [57].

The rock record in South Africa preserves over 3,600 million years (Ma) of Earth history, passing through six stages of development [58], [59].

a) Early crustal development (Figure 24)

b) Increasing stability of the crust to form the Kaapvaal craton during the Archean permitted accumulation of volcano-sedimentary sequences from the Archean to the Proterozoic (e.g. Witwatersrand and Ventersdorp Supergroups). The sequences consist of a range of rock types, including vast outcrops of dolomite, quartzite, conglomerate, ironstone and shale that form a veneer over the granitoid-greenstone basement

c) In part contemporaneous with (b) above, collision of crustal plates to yield the Limpopo metamorphic terrane as well as emplacement of large plutonic intrusions (e.g. Gaborone Granite Suite, Bushveld Complex)

d) Accretion of depositional basins, subsequently deformed and metamorphosed at various times (e.g. Namaqua-Natal Mobile Belt), along the southern and western margins of the Kaapvaal Craton, thereby increasing the size of the continent (Kalahari Craton)

e) Amalgamation of continental plates to form the Gondwana supercontinent, on which extensive intracratonic basins (e.g. Cape and Karoo Basins) developed (Figure 25). The Cape Basin developed along the southern margin of Gondwana, where a southward-thickening wedge of Ordovician to Early Carboniferous passive continental margin sediments accumulated, reaching thicknesses of more than 8 km. The clastic shallow-marine, deltaic, and nearshore fluvial sandstones, shales, and minor conglomerates of the Cape Supergroup extend for more than 1,000 kilometres (km) across the southern and western Cape of South Africa, deposited largely on the rocks of the Pan-African Saldania Belt. The Late Carboniferous to Jurassic sediments of the Karoo Supergroup (cumulative thickness: 12 km) were deposited in numerous basins across large tracts of Gondwana.

f) Fragmentation of Gondwana during the Mesozoic, accompanied by the extrusion of great volumes of basaltic and locally rhyolitic magma and the generation of fault-bounded basins both onshore and offshore, with the development of the widespread Kalahari Basin after breakup. Cenozoic deposits of littoral marine, estuarine, fluvial, lacustrine, and aeolian origin were extensively developed along the coastal plains.

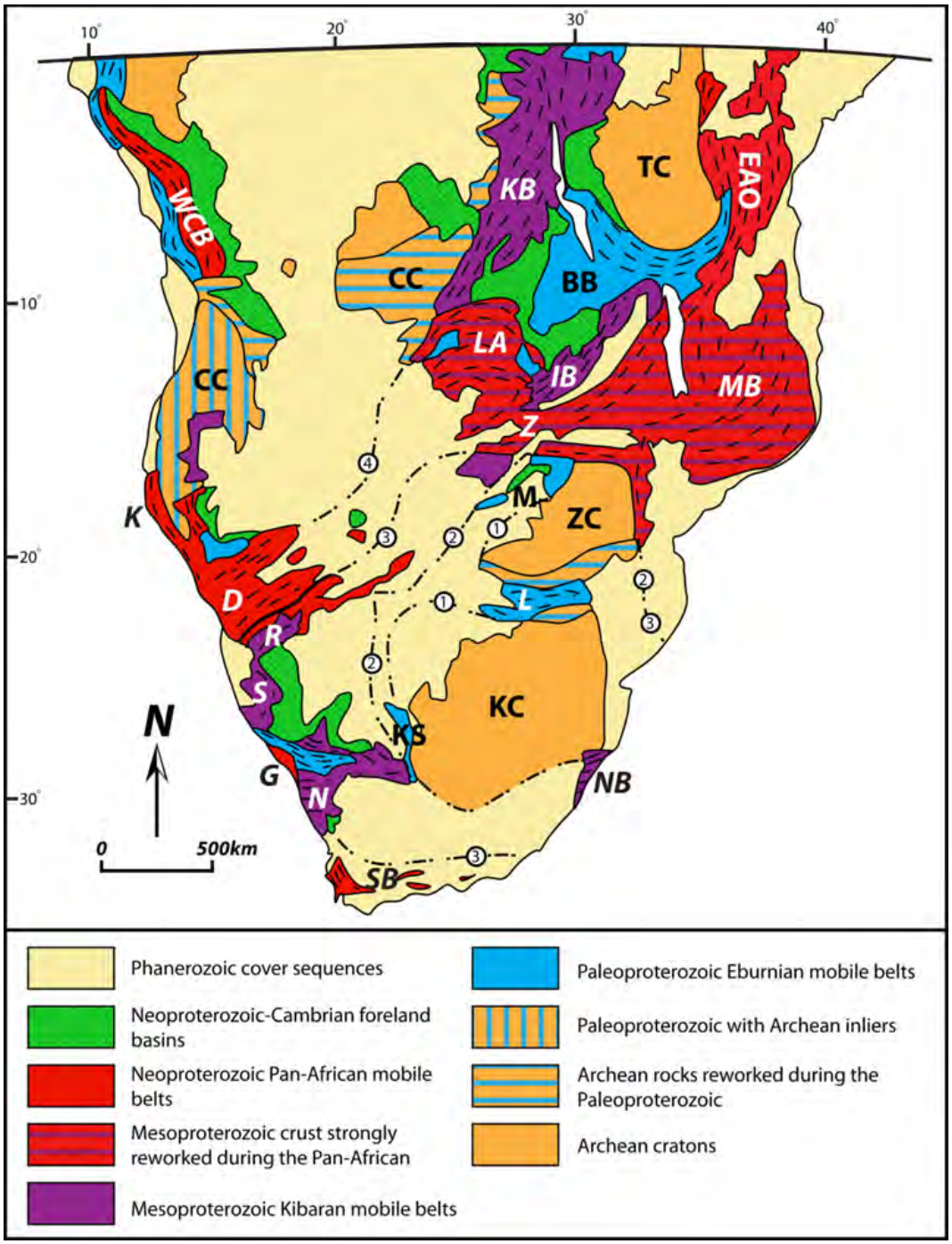


Figure 25: **A regional tectonostratigraphic map of the Southern African Development Community (SADC) region showing the location of Archean cratonic regions surrounded by Proterozoic mobile belts and overlain by Phanerozoic cover sequences.**

KC=Kaapvaal craton, ZC=Zimbabwe craton, TC=Tanzania craton, BB=Bangweulu Block, CC=components of Congo craton; R=Rehoboth Belt, L=Limpopo Belt, KS=Kheis Belt; M=Magondi Belt; S=Sinclair Belt, N=Namaqua Metamorphic Province, NB=Natal Province, IB=Irumide Belt, KB=Kibaran Belt, MB=Mozambique Belt, D=Damara Belt, K=Kaoko Belt, G=Gariep Belt; SB=Saldanian Belt, EAO=East African Orogen, LA=Lufilian Arc, Z=Zambezi Belt, WCB=West Congolian Belt. 1=extent of Kaapvaal and Zimbabwe cratons; 2=Extent of Kaapvaal-Limpopo-Zimbabwe craton; 3=Extent of Kalahari craton; 4= southern extent of Congo craton (diagram modified after Hanson, 2003, as cited by [59]).

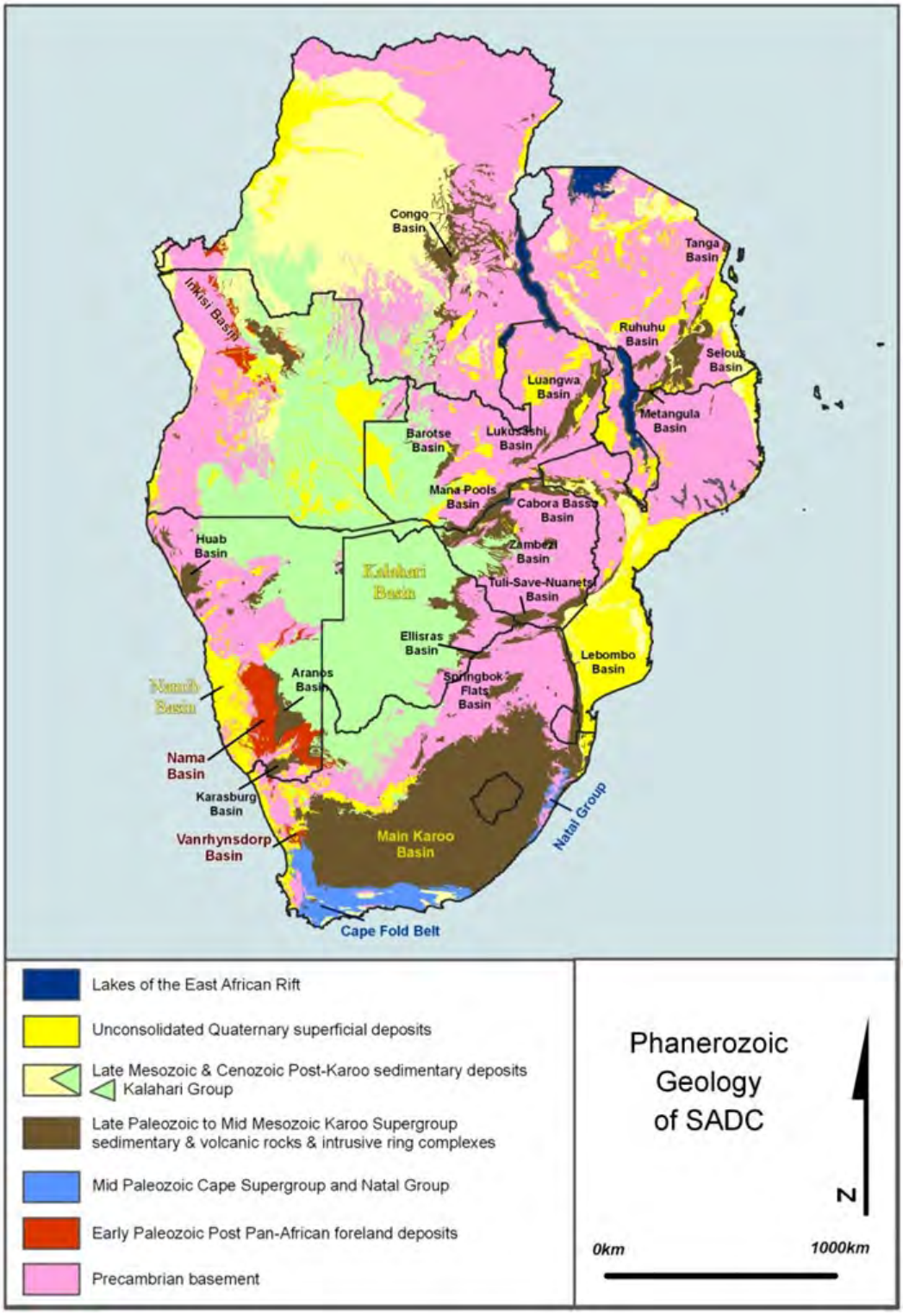


Figure 26 **The Phanerozoic geology of the SADC region, with the main sedimentary basins labelled. The Proterozoic mobile belts are shown in blue and the Archean cratons in pink. This map represents a simplification of the SADC geology map compiled by Hartzer (2008), as cited by** [59].

South Africa's current landscape results from geomorphic processes acting on rocks of different types and ages. The large-scale geomorphic evolution is driven by periods of tectonic uplift, which have caused erosion, the removal of the Karoo rocks, and the formation of drainage patterns. Several erosion surfaces have been identified. The oldest and most widespread is known as the African surface. The surface beneath the African in the interior is called the Post-African. Seaward of the Great Escarpment, however, two Post-African age surfaces have formed, named Post-African I and Post-African II. These erosion surfaces are important for the development of basement aquifers. The deeper weathering profiles are linked with the oldest erosion surfaces.

The Kalahari basin formed because of subsidence of the interior during the Late Cretaceous. Rivers were back-tilted into the Kalahari basin, resulting in the deposition of the Kalahari sediments. Pliocene uplift eroded Karoo rocks and basal Kalahari sediments, reworking and depositing the eroded sand. This reflects the extensive dune fields that are preserved today.

The resulting geologic and geomorphic development of South Africa reflects rock type, consolidation, and fracturing, all of which play a critical role in determining the presence and type of aquifer.

7.1. COASTAL HYDROSTRATIGRAPHIC AREA

The coastal regions consist mainly of unconsolidated sediments and calcarenite. The prevailing climate is perennial rain, while the landscapes are predominantly hilly to flat. Coastal regions have primary porosity, with sand-and-gravel aquifers that receive regular recharge. Borehole yields are typically high, while system yields are moderate. Sustainability issues in coastal regions may be linked to interactions between surface water and groundwater, as well as to the potential for saline intrusion. Coastal regions may have water quality issues linked to rural and agricultural impacts.

In South Africa, the development of Cenozoic coastal aquifers was shaped by geological processes originating from the Mesozoic-era breakup of Gondwana. This tectonic activity led to significant erosion within the southern African interior, resulting in substantial sediment transport to adjacent ocean basins [60]. Although sediment accumulation reached its maximum during the Cretaceous period, rates declined markedly throughout the Cenozoic, enabling the subsequent reworking and redistribution of sediments along coastal environments that define these

aquifers. The Cenozoic era also experienced considerable sea-level fluctuations, driven by glacial–interglacial cycles that alternately submerged and exposed the continental shelf. In northern KwaZulu-Natal, lower sea levels during the Mio-Pliocene allowed rivers to incise deep channels into the Cretaceous and Palaeocene strata beneath; these paleochannels ultimately formed the foundation for major coastal lakes such as St. Lucia, Sibaya, and Kosi, all of which maintain hydraulic connections to the regional aquifer systems [61].

The most extensive coastal aquifers include:

- **The North Zululand Coastal Plain aquifer** contains a primary aquifer within unconsolidated sands. The region is a groundwater-driven system with minimum surface-water inflows, relying entirely on local rainfall for recharge and therefore highly sensitive to rainfall variability. During dry periods, the aquifer sustains rivers, lakes and most wetlands, while during wetter periods these surface systems contribute to recharge, reflecting a dynamic hydrological exchange. The geology is characterised by high-permeability cover sands of low relief that gently slope towards the Indian Ocean. Wetland development is strongly influenced by weathering of the Kosi Bay Formation, which produces a clay layer that restricts subsurface flow.[9]

Box 22: Developing groundwater in the Zululand Coastal Plain aquifer [62]

The Zululand Coastal Aquifer is divided vertically into two main systems with distinct characteristics. The shallow aquifer has high permeability and porosity, with an unconfined water table. The deeper aquifer is a leaky, semi-confined-to-confined system, with productivity related to its thickness and karstification. Hand-dug wells are common in rural areas across the coastal aquifer because they access the shallow, unconfined aquifer. Field observations during the drilling of several investigative boreholes into the deeper aquifer revealed abundant shell fragments and showed variability in vertical thickness over a 15-metre distance. Dry boreholes occurred where the calcrete was strongly cemented, and dissolution channels were absent (Schapers, 2011, as cited by [11]). Thus, the deeper aquifer exhibits lateral and vertical heterogeneity. A borehole intended for high-volume supply should target the deep aquifer, while a borehole for low-yield rural community supply might successfully tap into the shallow system. Geophysics plays a vital role in identifying the most suitable drilling locations before any drilling begins, significantly increasing the success rate. Strategically placing a limited number of test boreholes based on geophysical results is

[9] https://deims.org/721de4a4-87ee-47b8-a74e-b5adf0053b9d

essential. The data from these boreholes will "ground-truth" the geophysical interpretations, confirming the depth and composition of each hydrostratigraphic unit. In a coastal aquifer, water quality is just as important as quantity. Collected samples must be analysed for basic chemistry (major ions such as Cl^-, Na^+), Electrical Conductivity (EC), and Total Dissolved Solids (TDS). This serves two purposes: (i) to confirm the absence of saline intrusion and ensure the targeted aquifer zone contains fresh, potable water; and (ii) to establish a baseline, as this data is crucial for future monitoring to detect any changes in water quality caused by abstraction or climate variations.

- **Southwestern Cape Coastal Sandveld, Bredasdorp Coastal Belt and Stillbaai Coastal Belts:** Along the Western and Southern Cape coastlines, primary aquifers are formed in sand deposits. These are generally restricted to coastal strips and are important local water sources.

- The **Atlantis Aquifer** is a globally significant example of long-term managed aquifer recharge (MAR) implementation, with research evolving from operational documentation to sophisticated modelling and emerging contaminant assessment. The Atlantis Aquifer is a primary coastal aquifer system formed of unconsolidated Cenozoic sediments (Sandveld Group) overlying Malmesbury Group bedrock, with sand cover averaging 25 metres and saturated thickness seldom exceeding 35 metres. The Atlantis Water Supply Scheme was developed in the mid-1970s as an alternative to discharging marine wastewater, recognising that the town's natural groundwater yield was insufficient for its long-term needs. The system functions by:
    - Collecting urban stormwater runoff and treated domestic wastewater
    - Recharging these waters artificially via infiltration basins
    - Abstracting the blended groundwater at wellfields for municipal supply

- The **Cape Flats Aquifer** is a major coastal aquifer underlying much of Cape Town and is now being developed as a key component of the city’s strategy to diversify water supply and enhance drought resilience following the 2015–2018 “Day Zero” crisis. It is a primary, unconfined aquifer composed of unconsolidated Cenozoic (Quaternary) sands of fluvial, marine, and aeolian origin, reaching thicknesses of 50–55 m in places. The aquifer forms a low-lying coastal plain between the Cape Peninsula and the Boland Mountains

and overlies Malmesbury Group bedrock. While its substantial storage capacity makes it suitable for water-supply development, its unconfined nature renders it highly vulnerable to surface-derived contamination. Key threats include agricultural chemicals, leaking sewer infrastructure and wastewater treatment works, informal settlements, historical waste sites and industrial activities. Recent studies have identified Contaminants of Emerging Concern, including pharmaceuticals and illicit drugs, with the highest concentrations detected near wastewater treatment works, underscoring the risks associated with recharge using recycled water.

- The **Bredasdorp Group** forms a significant coastal primary aquifer along the southern Cape. The De Hoopvlei Formation, primarily composed of calcarenites, is the basal marine unit of the Cenozoic Bredasdorp Group Formation. The De Hoopvlei Formation unconformably overlies the Cape Supergroup rocks. The De Hoopvlei Formation is a reliable aquifer that provides significant quantities of good-quality groundwater, sustaining the groundwater supply for several coastal towns. The De Hoopvlei Formation is a loosely packed layer of calcareous pebbles at the base of the Bredasdorp Formation that forms a reliable, widely used aquifer in the towns of Albertinia, Stilbaai, Melkhoutfontein, and Jongensfontein.

7.2. KALAHARI HYDROSTRATIGRAPHIC AREA

The Kalahari hydrostratigraphic area is characterised by unconsolidated sediments, which are predominantly sandy at the surface. This region is located in a semi-arid climate zone that can experience summer rainfall. The landscape is very flat with sand dunes. This is also a primary porosity hydrogeological region, with aquifers composed of sand and gravel. Recharge in this region is episodic. Borehole yields are high, while system yields are often low. Sustainability-related issues stem from the region's many groundwater-dependent towns and farms, as well as low recharge rates due to the semi-arid climate. The main water quality issues in this region stem from natural salinity and nitrate levels.

The Kalahari aquifer is a complex system of multiple aquifers underlying the Kalahari Basin in Southern Africa. These aquifers cross international borders and require cooperative management. This includes the Stampriet Aquifer System, which spans Botswana and Namibia. The usefulness of the

Kalahari Group aquifers is severely limited by high salinity and limited active recharge. Tectonic activity created paleochannels that formed deep aquifers. Clay layers block recharge, and the formations' heterogeneity creates complex, multi-layered flow paths.

Some of the key challenges identified are:

- **Water quality**: A primary challenge is the widespread occurrence of saline and brackish groundwater, which severely limits the availability of potable water. Saline zones, with a Na-Cl-SO_4 composition, can be highly resistant to natural freshening. This is due to low modern recharge, high groundwater storage, and the aquifer's physical structure, which limits interaction between fresh and saline zones.
- **Low and uncertain recharge rates**: Groundwater replenishment is generally very low and spatially variable, making it difficult to estimate sustainable yields. While some areas, such as the Stampriet Basin, show direct recharge rates of 7-46 mm per year, other regions receive negligible modern recharge. For instance, a regional-scale study in Botswana found that the flow regime is only "slow" and that groundwater is often "fossil," with ages exceeding 20,000 years, meaning it is a non-renewable resource on human timescales.
- **Geological complexity and aquifer heterogeneity**: The Kalahari Group's geology is highly complex, with multi-layered aquifers, thick unsaturated zones (up to 100m), and clay-rich matrices. This complexity makes it difficult to map aquifer geometry and locate productive zones. Geophysical methods like TDEM, while useful, can pose interpretation challenges due to clay layers and saline groundwater.
- **Mixing of different water types**: In many areas, groundwater from different sources and ages mixes, which complicates the interpretation of flow regimes and water origins.
- **Ineffectiveness of some exploration techniques**: Traditional exploration methods can be unreliable in the Kalahari. A detailed hydrogeochemical study in Namibia concluded that, in areas where target rocks are buried under thick Kalahari sand and calcrete (46 to 103m), hydrogeochemical exploration was "not practicable." The study found that geochemical anomalies were often "spurious" and not linked to actual mineralisation, as the thick overburden disconnected surface expressions from the deeper geology.

- **Difficulty in distinguishing fresh and saline zones**: Even with advanced geophysics, distinguishing between freshwater and saline groundwater zones remains a challenge, leading to "uncertainties in the interpretation" of subsurface data. This can result in drilling costs for unproductive or poor-quality water.
- **Lack of long-term monitoring data**: Research into groundwater-climate interactions is hampered by limited monitoring networks. Studies often rely on satellite data (such as GRACE) to understand how droughts and climate variability affect groundwater storage, underscoring the need for more on-the-ground data collection.
- **Transboundary management complexity**: The Kalahari aquifers are often transboundary systems, shared by multiple. This requires international cooperation on water management, which is difficult to achieve, especially given a lack of shared data and differing national priorities.

The challenges are deeply interconnected in the Kalahari hydrostratigraphic areas. The geological complexity makes exploration difficult and expensive. When water is found, it is often saline or fossil, with low recharge rates that limit its sustainability. This scarcity makes the resource highly vulnerable to climate change and intensifies conflicts with economic development. The transboundary nature of the aquifers adds a layer of political complexity to an already difficult hydrogeological framework.

7.3. KAROO HYDROSTRATIGRAPHIC AREA

The Karoo hydrostratigraphic area comprises alternating sandstones, siltstones, and mudstones, with dolerite intrusions in places. It lies in a semi-arid climate zone that receives summer rainfall. The landscape of this region consists of steep rocky hills and plains, which are typically formed due to the variable resistance to weathering of the geological materials of which it is composed. Secondary porosity dominates in this region, and the aquifers are predominantly fractured sandstone lithologies. The recharge events are episodic, with borehole yields categorised as moderate and system yields as low. The main sustainability issues in this region are groundwater-dependent towns and farms, and low recharge. The main water quality issues in the region are linked to agricultural activities and mining, as well as the presence of a uranium province, which results in elevated uranium levels.

The Karoo hydrostratigraphic area consists primarily of fractured-rock aquifers with negligible primary porosity and permeability. Groundwater is found in secondary openings like fractures, joints, bedding planes, and dolerite contact zones. They are multi-layered, heterogeneous, and anisotropic. Dolerite intrusions (dykes and sills) are the single most important control. They can act as both conduits (along fractured contact zones) and barriers (the dyke core itself) to groundwater flow. Dolerite ring complexes and inclined sheets also create specific, often high-yielding target zones. Transmissivity (T) is highly variable, ranging from <1 to >300 m^2/d. Storativity (S) is also variable, generally from 10^{-3} to 10^{-5}. Borehole yields are unpredictable, typically low (<0.5 l/s) in undisturbed rock but can exceed 5-10 l/s near favourable structures like dolerite contacts or tectonic fracture zones.

Recharge is low (estimated at 2-5% of mean annual precipitation) and occurs primarily via preferential pathways (e.g., along dyke contacts and fractures) rather than through slow matrix flow in the soil. Recharge is highest in hilly areas with thin soil cover and lowest in valleys with thick, clay-rich soils. Water quality is highly variable. Chemistry evolves from a Ca-HCO_3 type in topographically high recharge areas to a more evolved, often Na-Cl type in low-lying discharge areas due to processes like ion exchange, silicate/carbonate weathering, and evaporation. High salinity, fluoride, and nitrate are common in certain regions, especially the western Karoo.

Flow direction is generally controlled by topography and major structures, flowing from higher to lower elevations. Flow is predominantly through fractures, with the rock matrix acting as the primary storage reservoir that slowly feeds the fractures. Water levels are typically shallow (<20 m) but can be much deeper.

Located in an arid to semi-arid region with high evaporation and variable, low rainfall. This makes aquifers vulnerable to over-exploitation. Sustainable management requires an understanding of fracture-controlled flow and storage, and techniques like Managed Aquifer Recharge (MAR) are critical for enhancing resilience.

The complex nature of Karoo aquifers has profound implications for their use and protection.

- **Exploration challenge**: The heterogeneity makes siting high-yielding boreholes difficult, requiring a combination of remote sensing (lineament analysis), geophysics (magnetic and resistivity

surveys), and detailed geological understanding to identify permeable structures.

- **Vulnerability**: While the thick, low-permeability matrix can protect deeper groundwater, the fractures that make aquifers productive also create direct pathways for contaminants. This makes the aquifers vulnerable to pollution from surface activities, especially in the near-surface weathered and fractured zones. Nitrate contamination from sanitation and agriculture is a common concern.
- **Resource sustainability**: Recharge is low and episodic. Groundwater abstraction, especially for irrigation, can easily exceed the long-term sustainable yield, leading to declines in water levels. Management strategies must account for this, using techniques like the saturated volume fluctuation (SVF) method to estimate recharge and inform safe abstraction limits. The concept of a "capture zone" or borehole protection area is critical for safeguarding water quality and quantity.

7.4. CAPE FOLD BELT HYDROSTRATIGRAPHIC AREA

The Cape Fold Belt hydrostratigraphic area is composed of quartzites with minor siltstone, conglomerates and tillites. The climate is Mediterranean, with winter rain. The landscape consists of steep mountainous terrain with secondary porosity. Aquifers in this terrain are largely fractured quartzite. Recharge occurs annually, and borehole yields are typically high, with resultant high system yields. Sustainability issues in the Cape Fold Belt concern baseflow to springs and rivers from the Table Mountain Group (TMG). The region's water quality is characterised by low electrical conductivity and slightly acidic ph.

The TMG aquifer is hosted in folded, faulted, and fractured quartzitic sandstones of the Table Mountain Group, which form the prominent mountains of the Western and Eastern Cape. Its primary porosity is negligible, meaning groundwater storage and movement occur almost exclusively through secondary features such as fractures, faults, and cleavage planes. This fracturing can extend to depths of kilometres, creating a complex aquifer system.

Stable isotope studies (deuterium and oxygen-18) have been instrumental in tracing water sources. Research consistently shows that groundwater in the TMG aquifer is recharged at high altitudes in the mountains, not from local rainfall at lower elevations. The time water spends in the TMG aquifer varies significantly across the system. In the Paarl area, a combination of

noble gas data and tritium indicated a relatively short residence time, with a probable maximum of about 40 years. This suggests a slow flow rate through interconnected fractures, making this part of the aquifer vulnerable to changes in climate and rainfall patterns. In contrast, much older groundwater has been documented in the Uitenhage Artesian Basin in the Eastern Cape. Here, radiocarbon (^{14}C) dating revealed groundwater ages ranging from 1,500 to 28,000 years, with a calculated flow rate of just 0.8 metres per year. This highlights the significant heterogeneity in flow dynamics across the vast extent of the TMG aquifer.

Quantifying the immense storage capacity of the TMG's main water-bearing units – the Peninsula and Skurweberg Formations – has been a major research focus, particularly to assess their potential to augment Cape Town's water supply. A detailed storage model for the southwestern Cape estimated confined pore volumes of approximately 29 to 173 billion m^3 for the Peninsula Aquifer and 4 to 26 billion m^3 for the Skurweberg Aquifer, depending on the assumed porosity (2.5% to 15%). The study emphasised that, even with a significant regional water-level decline of 20 metres, the water released from storage represents a tiny fraction (0.24%) of the total volume in deep circulation. This indicates that a vast amount of groundwater is not economically extractable. However, the aquifer can be highly productive where fractures are well connected, with borehole yields commonly ranging from 5 to 10 L/s and sometimes exceeding 30 L/s. Key hydraulic parameters from a study in the Kwanokathula area in Plettenberg show a transmissivity of 70 m^2/d and a storage coefficient of 0.5%, with recharge estimated at 7% of mean annual rainfall.

The management of the TMG Aquifers presents a complex interplay of scientific, technical, social, and ethical challenges.

- **Aquifer characteristics and recharge:** The TMG aquifer's primary porosity is negligible, meaning groundwater storage and movement occur almost exclusively through secondary features like fractures, faults, and cleavage planes. This fracturing can extend to depths of kilometres, creating a complex aquifer system.
- **Groundwater age and flow rates**: The time water spends in the TMG aquifer varies significantly across the system.
- **Storage, yield, and hydraulic properties**: A vast amount of groundwater is not economically extractable. However, the aquifer can be highly productive when fractures are well-connected.
- **Ecological connections and conceptual models**: There is an intimate link with the aquatic ecosystems of the Cape Folded

Mountains.

- **Iron and Manganese**: In some fractured zones, particularly those with deeper circulation and reduced oxygen, dissolved iron (Fe) and manganese (Mn) can be high. When pumped to the surface and exposed to air, this leads to clogging.

7.5. SALDANIAN BASEMENT HYDROSTRATIGRAPHIC AREA

This hydro-stratigraphic region is composed mainly of metasediments. These include shale, phyllite, hornfels, and metavolcanics. The climatic zones in which this region occurs range from Mediterranean to semi-arid, and it typically receives winter rain. The landscapes in this region are mostly hilly due to the resistance of the geological materials to weathering. The porosity is a mixture of primary and secondary porosity. Aquifers are composed mainly of saprolite, which contains fractures and veins. Recharge events are irregular, and borehole yields are moderate. System yields are also documented as being low. The main sustainability issues are linked to groundwater-dependent wetlands and low recharge. Water quality issues in this region may arise from agricultural activity, and minor salinity issues may occur.

The “Saldanian Basement” hydrostratigraphic unit comprises two main components formed during the Saldanian Orogeny:

- **Malmesbury Group**: This is the metasedimentary (and minor metavolcanic) rock sequence, representing deformed fore-arc basin fill and accretionary complex rocks. It includes units such as the Tygerberg, Swartland, and Boland terranes.
- **Cape Granite Suite**: These are voluminous granitic intrusions that were emplaced into the Malmesbury Group during the later stages of the orogeny (~540–530 Ma).

As a hydrostratigraphic unit, the Saldanian basement hydrostratigraphic area functions as a fractured, weathered basement aquifer system. The original (primary) porosity of the metamorphic and igneous rocks is negligible. Groundwater storage and movement depend entirely on secondary permeability developed through fracturing, faulting, and weathering. The potential of these aquifers varies widely and depends on the extent of fracturing and the thickness of the weathered zone. They can

be important local water sources, but yields are typically lower and less predictable than in the adjacent TMG Group aquifers.

The most fundamental management challenge is the inherent unpredictability of fracture-dependent yields. Natural salinity presents a major constraint on groundwater use. Consequently, management cannot consider the Saldanian basement aquifers in isolation. In the Cape Flats, for example, the sandy aquifer is underlain by Precambrian and Palaeozoic rocks, including the Malmesbury Formation, Cape Granite Suite, and Table Mountain Group. This stratigraphic complexity means:

- **Hydraulic connections between aquifers may transmit abstraction impacts or contamination across formation boundaries**
- **Recharge to the Malmesbury aquifers may depend on the overlying units**
- **Groundwater chemistry evolves through interaction with multiple lithologies**

Understanding these inter-aquifer relationships requires integrated conceptual models that few studies have yet developed

7.6. NAMAQUA METAMORPHIC REGION HYDROSTRATIGRAPHIC AREA

This region is composed primarily of high-grade metamorphic rocks, formed under high-pressure, high-temperature conditions. The main rock types found here include gneiss, schist, shear pressure features, quartz or other veins and pegmatites. The climate here is semi-arid, with high temperatures and low rainfall. The landscapes are very flat with small rocky hills. The area is characterised by mixed porosity, i.e., both primary and secondary porosity, depending on location. Aquifers occur in saprolite, fractures and veins that are interconnected. Recharge events are episodic, and borehole yields are classified as low; similarly, system yields are also considered low. The main sustainability issue for this region is low recharge. While water quality stems from high salinity, common in arid areas due to the concentration of salts in rocks from weathering processes such as salt weathering, and the occurrence of high Uranium. The Namaqua region is also a mining region and contains copper, nickel, and zinc, which occur in sulphide deposits. These may also affect the groundwater quality in regions near mining areas.

The Namaqua Metamorphic Region hydrostratigraphic area is a complex geological terrain dominated by high-grade metamorphic and igneous rocks, such as gneisses and granites. The primary porosity of these crystalline rocks is negligible. Therefore, groundwater occurrence and movement are almost entirely dependent on secondary porosity created by fracturing, shearing, and weathering. The region is characterised by a semi-arid to arid climate, which further constrains groundwater recharge and availability.

The groundwater is predominantly classified as a Na-Cl water type. It is characterised by elevated levels of Electrical Conductivity (EC), Total Dissolved Solids (TDS), chloride (Cl^-), sodium (Na^+), and fluoride (F^-). Uranium (U) is widespread in groundwater, with concentrations ranging from 1.2 to 5,120 parts per billion (ppb). This vastly exceeds the World Health Organisation (WHO) drinking water guideline of 15 ppb. Consequently, a significant portion of the groundwater in the study area was deemed unsuitable for human consumption based on the WHO and South African (SANS 241) standards. The uranium is associated with the potential for calcrete-hosted (surficial) uranium deposits in palaeochannels. The high salinity also makes much of the shallow groundwater unsuitable for irrigation without treatment, though some deeper boreholes may yield better-quality water.

The most pressing challenges are related to the groundwater's natural chemical composition, largely a result of the surrounding geology and the arid climate.

- **Elevated uranium and trace metals**: A significant concern is the presence of high concentrations of uranium and other toxic metals.
- **Mechanisms of enrichment**: The elevated metal content is driven by active geochemical processes in this arid environment. These include oxidation, leaching, and evaporation, alongside constant water-rock interaction with the highly mineralised metamorphic rocks. The lack of regular aquifer flushing due to minimal recharge allows these metals to concentrate, especially in shallow groundwater zones.
- **Fracture-dependent flow**: Groundwater in the Namaqua Metamorphic Region hydrostratigraphic areas is not found in a continuous, porous layer but is instead contained within secondary openings like fractures, joints, and the weathered zone of the crystalline basement rocks. This makes the aquifer "fissured" and its behaviour complex.

- **Structural control and heterogeneity**: Groundwater flow is highly dependent on the orientation, density, and interconnectivity of these fractures. This structural control leads to high spatial variability, with borehole yields differing dramatically over short distances, making successful drilling challenging. The weathered fractured zone can be up to 80 meters thick, but its water-bearing capacity is inconsistent.
- **Aridity and minimal recharge**: The region is semi-arid, meaning rainfall is scarce, and groundwater recharge is negligible. This makes the aquifer a non-renewable or slowly replenishing resource.
- **Concentration of contaminants**: The high evaporation rates in this dry climate play a critical role in degrading water quality. As water evaporates from the shallow soil and aquifer zones, it leaves behind salts and metals, further increasing their concentration in the remaining groundwater.
- **Health risks**: The elevated levels of uranium and other toxic metals pose potential health risks to humans, animals, and plants, highlighting the need for medical geology studies in the area.

Successful groundwater targeting requires a thorough understanding of the region's structural history. Analysing fracture patterns, stress fields (such as the current NW-SE neotectonic stress field), and lineaments from satellite imagery is crucial for predicting the most promising drilling zones.

7.7. WATERBERG HYDROSTRATIGRAPHIC AREA

The Waterberg hydrostratigraphic region consists of sandstone and conglomerate. The occurrence of this region coincides with a subtropical climatic zone which experiences summer rain. The landscapes are gently mountainous. The porosity is described as minimal, while the aquifers are typically composed of scree. Recharge is viewed as an annual process, and borehole yields are moderate, while system yields are characterised as low. Sustainability concerns in this region include the small size of the aquifer units. The water quality in the Waterberg region is good, but it has areas with high fluoride levels, and the aquifers are shallow and prone to microbial pollution from on-site sanitation systems.

The Waterberg Group is a thick succession of predominantly sedimentary rocks laid down between about 2.06 and 1.88 billion years ago during the Paleoproterozoic era. It's important to distinguish it from the contemporaneous but separate Soutpansberg Group. The rocks are

primarily siliciclastic red beds—sedimentary rocks like sandstone and conglomerate, rich in oxidised iron (giving them a red colour), with minor volcanic layers. The Waterberg Group accumulated in large, fault-bounded basins on the Kaapvaal Craton. These basins were controlled by major tectonic structures:

Because the original sedimentary rocks have low primary porosity, groundwater is found almost exclusively in fractures, joints, and faults—the secondary permeability created by tectonic forces. This is why the Waterberg is considered a potential deep aquifer system, with deep circulation often indicated by thermal springs along major faults. The Waterberg Group sediments were largely derived from the erosion of granitic source areas. These felsic igneous rocks are rich in fluoride-bearing minerals. Interaction between groundwater and these fluoride-rich rocks, combined with deep circulation and alkaline conditions, primarily drives elevated fluoride concentrations in the region's thermal springs and boreholes. The variety of depositional environments (from coarse river gravels to fine lakebed muds) creates a complex, layered sequence. This heterogeneity, overprinted by fractures, makes it difficult to predict groundwater flow paths and successful borehole yields without a detailed understanding of the structural geology.

The Waterberg hydrostratigraphic area poses unique challenges for groundwater exploration and management:

- **Matrix porosity**: The actual rock (sandstone) is typically dense with very low primary porosity. It does not act like a sponge.
- **Fracture dependence**: Groundwater occurrence is entirely dependent on the presence of secondary fractures, joints, or faults. This means you can drill a "dry hole" just meters away from a high-yielding borehole. You cannot simply drill anywhere and expect water. While some boreholes in the Waterberg can yield excellent quantities of water (sometimes >5 L/s) if they hit a major fracture zone, the vast majority tend to have low to mediocre yields. Yields are often sufficient for domestic or small community use (0.5 L/s – 2 L/s), but securing enough water for irrigation, mining operations, or large towns is a major hydrogeological challenge.
- **Springs**: The contact zones between the Waterberg sandstone and the underlying basement rocks (like the Bushveld Igneous Complex) often result in springs. While these are good water sources, they might be susceptible to contamination or drying up.
- **Acidity:** Due to the sandstone geology, the water is often slightly

acidic (low pH). This can be corrosive to metal borehole casing and pumps if not properly designed with stainless steel or PVC.

- **Health risks**: Elevated fluoride levels can occasionally be encountered in certain geological structures within the Waterberg, posing a health risk if used for drinking.

7.8. MALMANI DOLOMITE HYDROSTRATIGRAPHIC AREA

The Malmani Dolomite hydrostratigraphic region consists mainly of dolomitic limestones, chert-rich formations, some shales and clastic rocks in the basal regions, and some iron-rich, soft formations known as wad, formed by the weathering of dolomitic limestones. This lithostratigraphic region occurs mainly in subtropical zones that experience summer rainfall. The landscapes are typically flat to undulating. The porosity can be considered tertiary and primary. Tertiary porosity is caused by the formation of void spaces in soluble rocks (like dolostones) created by post-depositional chemical weathering and dissolution, often enhancing existing secondary porosity. Primary porosity exists in the wad. The major aquifer types in this region are Karst and Saprolite. Recharge processes are annual and faster than rec processes. Boreholes and systems in this type of geology are typically high-yielding. The main sustainability issues relate to the system's vulnerability to aboveground pollutants entering via preferred pathways, and to the occurrence of sinkholes in the urban environment. Water quality in this environment is generally good; however, development may pose a risk.

The Malmani Dolomite aquifers, part of the Chuniespoort Group, are some of South Africa's most important aquifers. However, they face a unique and complex set of management challenges that arise from the interaction between their unusual geology and intense human activity. These challenges range from sinkhole risk to deep-seated institutional failures.

The aquifer is not continuous but is often divided into **compartments** by dolerite dykes. These dykes can act as barriers (aquitards) to groundwater flow, meaning each compartment functions somewhat independently. While this can create discrete management units, the contact zones between dykes and dolomite are often fractured, creating preferential flow paths and making the overall system highly heterogeneous and anisotropic (its properties vary by direction).

Dolomite aquifers are karst systems, meaning water dissolves the rock over time, creating caves and other open structures. When excessive pumping

or mining lowers groundwater levels (dewatering), the buoyant support water provides to the surface layers can be removed. This can trigger ground collapse into underlying cavities, leading to the sudden formation of devastating sinkholes that pose a massive risk to infrastructure and human life.

A critical example is the Grootfontein aquifer near Mahikeng [28]**. Over-abstraction since the 1970s, primarily for irrigation and municipal supply, has caused the natural groundwater level to drop by about 0.4 meters per year, leading to declines of up to 28 meters in parts of the aquifer** [28]. This directly reduces the volume of stored and available water. Compounding the problem of overuse, these aquifers are in a semi-arid region. Active groundwater recharge is very limited, estimated at less than 5% of mean annual rainfall. This means the system recovers slowly from over-abstraction.

Mining legacies pose a severe threat. In the Klip River and Natalspruit basins, for example, the volume of effluent discharged into the aquifer from sewage works and gold treatment plants was estimated to be three times the natural recharge, causing extensive deterioration of water quality. At the Mooiplaas Dolomite Quarry, nitrate from explosive residue was found at levels marginally above drinking water limits in groundwater [63]. The same study at Mooiplaas found that ammonia levels in the nearby Hennops River were unacceptably high due to municipal sewage outfalls. Because karst systems can have rapid flow paths through fractures and solution channels, such surface contaminants can quickly enter the groundwater system and spread, posing a direct health risk to communities that use the water for drinking.

Research on the Grootfontein aquifer has revealed a classic case of institutional failure. Despite being one of South Africa's best-studied aquifers, efforts to address declining water levels have largely failed. The system is described as a "hydro-social system," in which the root cause of the problem is institutional [29]. The situation has created a suboptimal and undesirable "Nash equilibrium" in which major groundwater users are unable or unwilling to reduce abstraction, even though they know it is unsustainable [29]. This is driven by a lack of trust, inequality, and ineffective governance. While large-scale development plans exist, such as the Olifants River Water Supply System, which proposes developing 48 wellfields with a combined yield of >40 million m^3/a, their success hinges on coherent implementation and adaptive management. The strategy itself acknowledges the need for a phased “monitor-model-manage” approach to

build confidence and address mistrust in the groundwater potential, but this requires a level of institutional capacity and oversight that has historically been lacking [29].

7.9. WITWATERSRAND HYDROSTRATIGRAPHIC AREA

The Witwatersrand hydrostratigraphic region consists of quartzite and slate. The Witwatersrand region also receives summer rainfall in a subtropical climate. The landscape is relatively flat, with some minor hills. Secondary porosity dominates the region. The main aquifers occur in fractured quartzite and along faults. Recharge is considered to occur annually. Borehole and system yields are considered moderate. Sustainability issues stem from mine voids and urban and industrial development. The main water issues arise from acid mine drainage and urban and other development. The region has areas of high total dissolved solids and uranium occurrence. For decades, deep-level gold mines have had to pump large volumes of water from overlying dolomitic aquifers to remain operational. This necessary process has led to serious consequences, including the drying up of natural springs and a long-term challenge for water management [13]. When the mines close and pumping stops, the underground voids gradually fill with water. This water reacts with exposed sulphide minerals, such as iron pyrite, in the mine workings, producing AMD. This acidic, metal-rich water eventually seeps from old shafts or flows through springs, causing significant ecological damage. A clear example is the degradation seen in the Cradle of Humankind World Heritage Site. Managing this polluted water presents a substantial financial and technical challenge for mine closure.

7.10. ARCHEAN GRANITOIDS HYDROSTRATIGRAPHIC AREA

The dominant rock types in this hydrostratigraphic region are granites, which are widespread, deformed, foliated, and metamorphosed. The climate is subtropical, with summer rainfall. The landscape is mainly hilly, with mixed porosity. Aquifers consist of saprolite and fractures. Recharge processes range from irregular to annual. Borehole yields are moderate, while system yields are low. Sustainability concerns include the small aquifer size and complex groundwater flow through fractures and saprolite. Water quality issues are linked to urban development, mining activities, and agriculture.

Part G

8. CASE STUDIES: GROUNDWATER SCHEMES IN SOUTH AFRICAN MUNICIPALITIES

This section introduces municipal groundwater schemes in South Africa by outlining the range of supply configurations, operational contexts, and management challenges encountered across different hydrogeological and institutional settings. It provides practical examples that demonstrate how groundwater schemes function in municipalities, why some systems perform reliably, and why others experience declining yields, infrastructure failure, water-quality constraints, vandalism, or governance difficulties. This section aims to help municipalities recognise common risks and success factors so groundwater schemes can be planned, operated, monitored, and protected as dependable components of local water supply systems.

8.1. LIMPOPO, MOGWADI (DENDRON)

The water supply situation in Mogwadi (formerly Dendron), Limpopo, is characterised by a contrast between intensive groundwater use for agriculture and significant challenges in providing reliable municipal water services. The region's semi-arid climate means the aquifers are mainly recharged by infrequent, heavy rainfall events. This makes the water supply highly susceptible to climate variability and drought, as the link between rainfall and groundwater replenishment is nonlinear and poorly understood.

The aquifer systems developed in the region are[25] :

- Composite aquifers, comprising a variable thickness of regolith overlying bedrock, the upper part of which is frequently fractured.
- Deeper fractured aquifers are composed mainly of crystalline material (igneous and metamorphic rocks), characterised by an intact, relatively unweathered matrix and a complex arrangement of interconnected fracture systems.
- Alluvial aquifers: alluvial material overlies or replaces the weathered overburden and develops a distinct intergranular aquifer type. These elongated aquifers follow rivers (so-called valley trains), sand rivers, or drainage lines with limited width and depth, which typically vary with topography and climate.

The Dendron aquifer is a fractured aquifer recognised as a high-potential resource based on local standards). It exemplifies the region's hard-rock

aquifers, which are typically shallow and possess relatively limited storage capacity, with water yields largely dependent on fracture networks. Contemporary hydrogeological models describe it as a two-layer system, with dykes that may block horizontal groundwater flow. The primary challenge concerns the long-term imbalance between water abstraction and natural replenishment. Intensive irrigation over several decades has led to a severe and persistent decline in groundwater levels. Scientific studies confirm that the rate of water level decline has accelerated over time, contrary to some local perceptions that the situation is improving. Consequently, the aquifer becomes susceptible to overexploitation, particularly during drought periods. [26], [27]

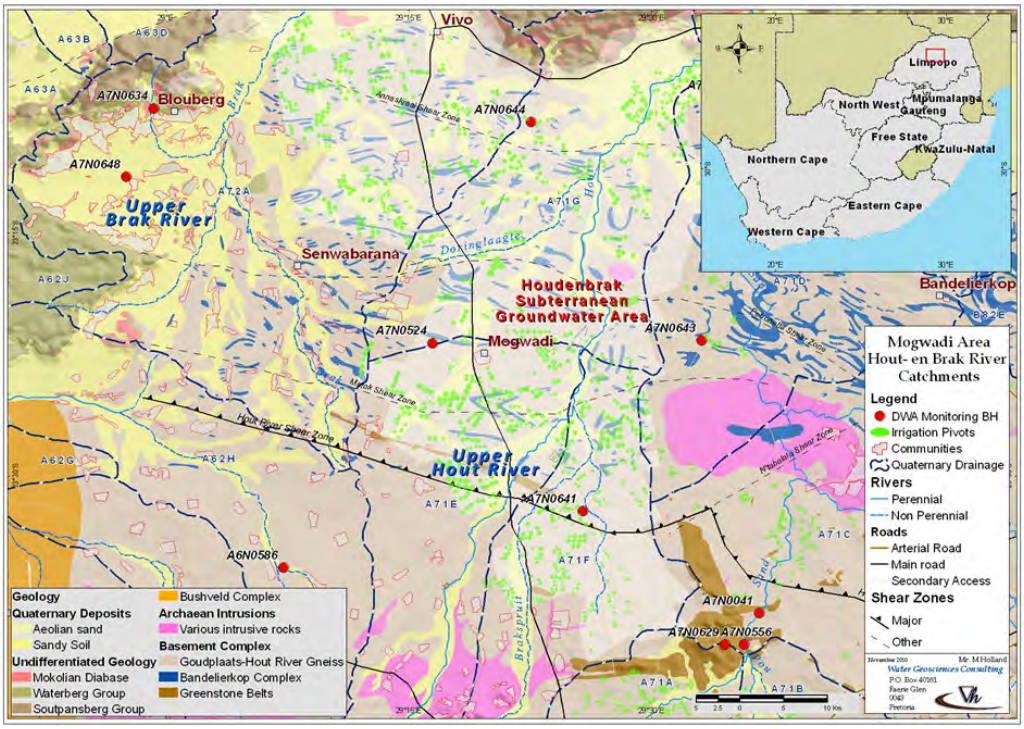


Figure 27: Basement aquifers in the Mogwadi area [25]

Long-term water-level trends are best observed from a monitoring borehole on the western outskirts of the Houdenbrak subterranean area. The Houdenbrak area in Limpopo, South Africa, was designated as a government-controlled subterranean groundwater control area. It was established to manage what has become a primary example of intensive groundwater use and over-exploitation in the country. Although over-abstraction occurs during periods of below-average rainfall, groundwater levels have decreased by 6 meters from the early 1970s to the present day; notably, they fell steadily over a decade from 1990 to 2000. Management interventions implemented in the 1990s, coupled with above-average rainfall in 2000, led to a recovery in groundwater levels in 2001/2002 [27].

The continued decline in groundwater levels after 2002 suggests that these management interventions were ineffective in curbing over-abstraction. One contributing factor is the Government's lack of communication and support, which may have influenced farmers' perceptions of aquifer management. Persistent below-average rainfall over multiple consecutive years has further exacerbated declines in groundwater levels. [25]

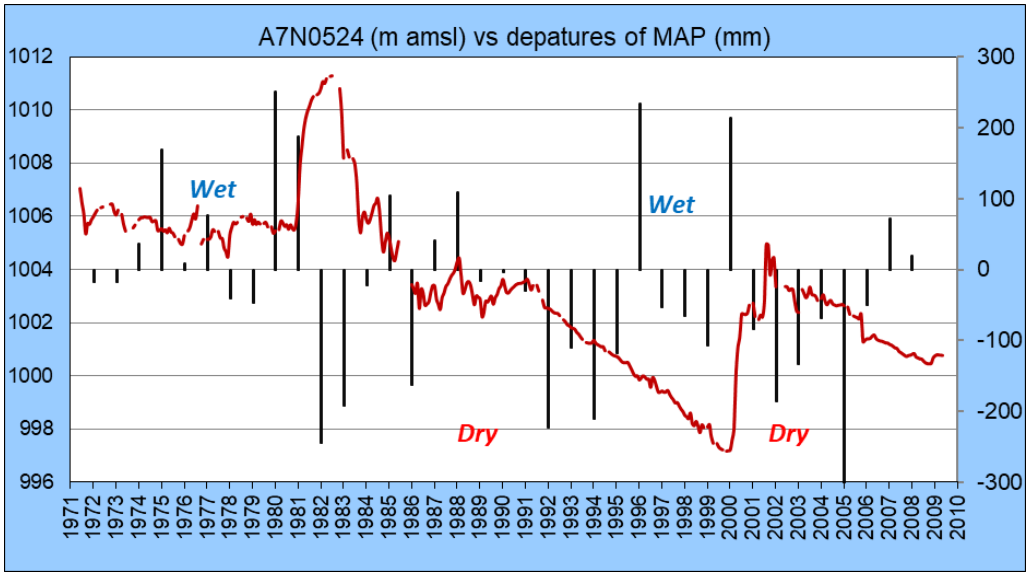


Figure 28: **Well hydrograph of long-term monitoring station A7N0524 near Mogwadi (Holland, 2010, as cited by [25])**

In the expanded Mogwadi-Vivo area, elevated nitrate levels are predominantly observed in rural communities to the west of the designated underground control zone. Substandard on-site sanitation and wastewater management, improper drying and disposal of sewage sludge, and livestock gathering at watering points near boreholes contribute to increased nitrate concentrations. Elevated nitrate levels in groundwater east of the Mogwadi-Vivo region result from both anthropogenic activities, such as agricultural practices and fertiliser use, and non-anthropogenic sources, including evaporative enrichment of dry and wet depositions, biogenic point sources via nitrogen-fixing organisms, or geogenic origins (Tredoux and Talma).

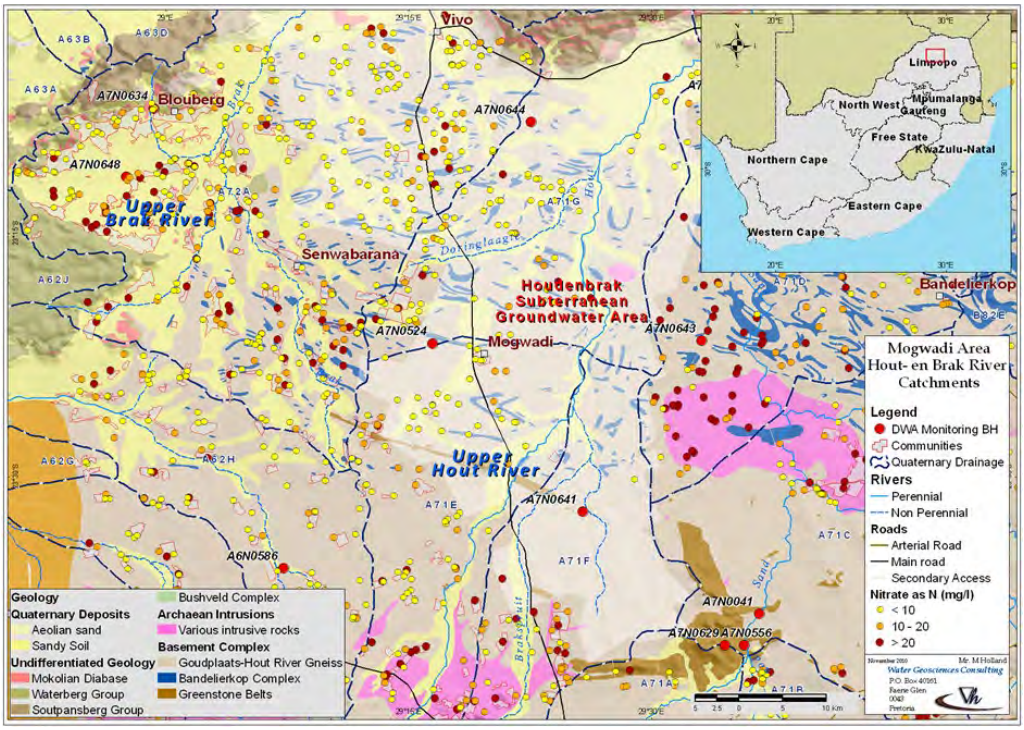


Figure 29: **Nitrate concentrations of Houdenbrak basement aquifers [25]**

8.2. NORTHERN CAPE, GARIES

The geology of the Garies area is complex and mainly defined by its location within the high-grade metamorphic terrane of the Namaqua Metamorphic Complex in South Africa. The region is characterised by a range of supracrustal gneisses, intrusive granites, and evidence of deep-crustal metamorphic and deformational processes. The Namaqua Metamorphic Complex functions as a basement aquifer. The upper portion of the rock has undergone chemical and physical weathering, transforming into a clay-rich, sandy material known as saprolite or regolith. This layer can retain some water.

Tectonic activity, including faults, folds, and shearing, has created a network of fractures within the deeper, unaltered bedrock. These fractures serve as primary conduits for groundwater flow and storage in deeper boreholes. The region's semi-arid climate presents a significant constraint, characterised by low and unpredictable rainfall. Notable recharge to the aquifer occurs predominantly during intense rainfall events that exceed high evaporation rates, allowing water to infiltrate the soil and permeate the fracture network below. Consequently, groundwater resources are limited and subject to careful management. The quality of groundwater holds paramount importance for its utilisation. As rainwater infiltrates and percolates through the rock, it dissolves minerals; in granite and gneiss, this generally results

in water with low to moderate salinity. However, in areas with limited recharge or near playas (salt pans), evaporation can concentrate salts in shallow groundwater, resulting in brackish or saline conditions unsuitable for drinking or irrigation.

The bulk of Garies’s potable water is supplied by three boreholes located east of the town, supplemented by a well in the Groenrivier on the northern side of the town. While the quantity of water from the new boreholes was sufficient, the quality was found to be unfit for human consumption due to high levels of dissolved salts and chlorides. The municipality invested in a desalination plant. This plant is designed to treat saline groundwater from local boreholes, making it potable.

8.3. NORTH WEST, MAHIKENG

The groundwater in Mahikeng predominantly originates from the Grootfontein aquifer, a productive dolomite formation situated approximately 20 km southeast of the town. Recognised as one of South Africa's most extensively researched aquifers, it is nevertheless experiencing a long-term decline. Currently, it supplies approximately 20% of Mahikeng's water requirements, amounting to about 10 million litres per day. The principal challenge is over-extraction. Since the 1970s, excessive pumping, primarily by irrigating farmers and municipal boreholes, has led to the drying up of the natural spring known as 'the Grootfontein' in 1981. Scientific investigations suggest that, to ensure the sustainable management of the aquifer, current abstraction rates must be decreased by between 19 and 36 million litres per day. [28], [29]

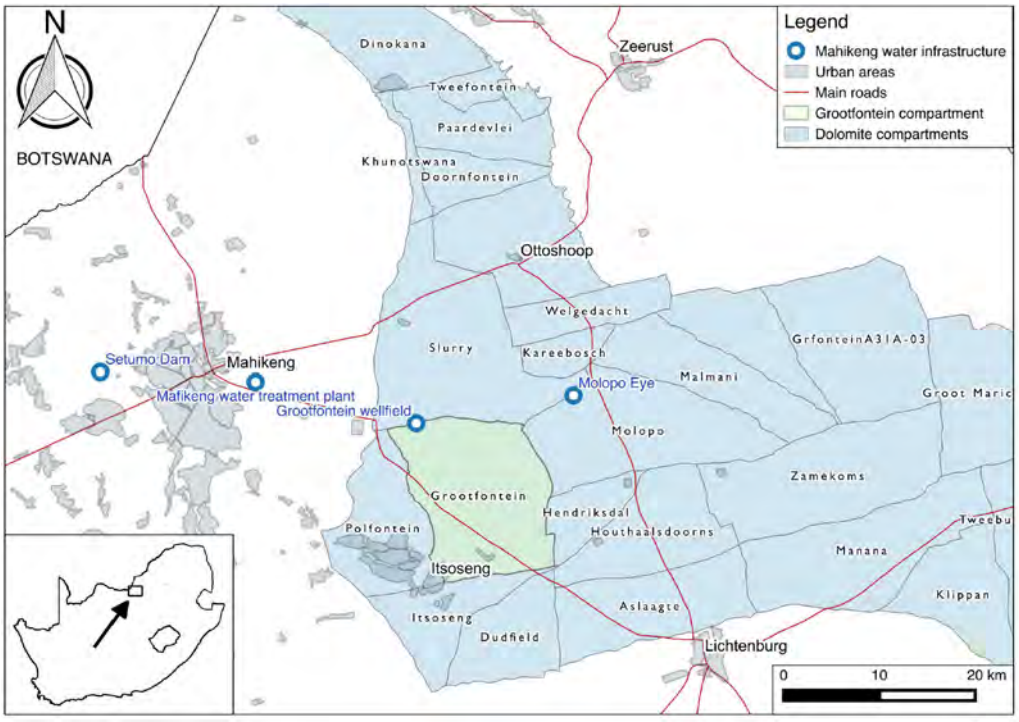


Figure 30: **The Grootfontein compartment, neighbouring compartments (after Holland and Wiegmans, 2009), and Mahikeng's water infrastructure [28]**

The paradox of Grootfontein lies in the fact that, despite possessing comprehensive hydrogeological knowledge and being situated within South Africa's progressive legal framework for water management, sustainable resource management has not been achieved. Researchers characterise this as a "hydro-social system" in which institutional failure is the primary obstacle. This "sub-optimal and undesirable Nash equilibrium" results in major groundwater users being either unable or unwilling to collaborate to reduce abstraction, notwithstanding the long-term benefits such cooperation would entail. Contributing factors include weak enforcement of licensing requirements, the absence of penalties for overuse, and the sluggish development of local cooperative management entities, such as Water User Associations. Such inadequate management practices incur tangible costs, as exemplified by municipal expenditure exceeding R30 million to treat lower-quality surface water sourced from the Setumo Dam, despite the aquifer's groundwater being of inherently high quality and more economical to treat. [29]

Borehole D4N0014 monitors the water level in the Grootfontein Eye, a significant natural spring (artesian eye) that historically flowed freely into the Molopo River system. It serves as a vital indicator of aquifer stress, as it was the first point to exhibit signs of excessive extraction. Prior to the 1970s, the

artesian flow, where water naturally overflowed at the surface, was observed, indicating that the aquifer was in a pristine, balanced condition. In 1981, the Grootfontein spring ceased to flow entirely, marking the first major indication that water abstraction through pumping exceeded the natural recharge rate. Between 1970 and 2015, the water level declined by approximately 28 metres, as noted above, confirming a long-term, persistent reduction attributable to over-extraction by agricultural and municipal users. Recent data indicate the water level continues to decrease at an average rate of 0.4 metres per year. The aquifer remains under stress, showing no signs of recovery.

8.4. WESTERN CAPE, ALBERTINIA

The town of Albertinia, located in the Hessequa Local Municipality, receives raw water from six boreholes in the Table Mountain Group (TMG) aquifers and the Buffelsfontein spring. The spring naturally flows from Cenozoic Bredasdorp Group sediments. Some of the spring water is collected in a sump and pumped to the Albertinia water treatment works. The boreholes (AG1, AG2, AG3, AG4, N2, and Albertinia Deep Borehole) all target the deeper fractured aquifer associated with the Skurweberg Formation (Nardouw Subgroup of the TMG). The production boreholes (AG1, AG2, AG3, and AG4) are situated close to each other. Buffelsfontein Spring is a major water source for Albertinia, accounting for about 48% of the total supply, with an average abstraction rate of 0.42 ML/d in 2024. The five deep production boreholes (AG1, AG2, AG3, AG4, and N2) contribute roughly 43% of the water supplied, averaging 0.38 ML/d in 2024. The Albertinia Deep Borehole has not yet been connected to the town’s water supply system (Figure 11). In 2024, the average daily abstraction rate from the production boreholes ranged from 0.57 ML/d in November to 0.05 ML/d in January, when most boreholes were not operational.



Figure 31: **The Photo of the sump area and abstraction point at Buffelsfontein (photo courtesy of Kevin Pietersen).**

Overall, the production boreholes also represent a sustainable and constant supply of raw water (to meet the water demand of Albertinia) when all boreholes are operational.

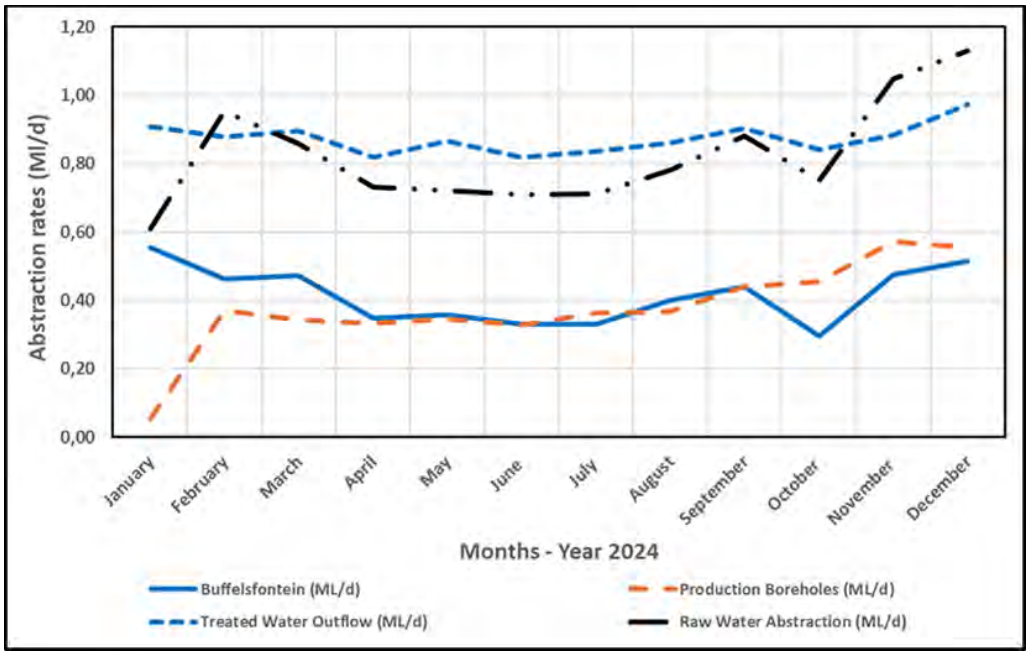


Figure 32: **Average daily water abstraction rates (ML/d) for all individual raw water sources (Buffelsfontein and production boreholes), average daily raw water abstraction rates (combined), as well as average daily treated water outflow rates to Albertinia for the year 2024.**

The wellfield layout is not optimal, resulting in interference of the groundwater levels of the pumping boreholes, over-abstraction and associated wellfield management challenges. The wellfield layout likely results in suboptimal performance of the production boreholes due to borehole/well interference. The likely enhanced drawdown (due to borehole/well interference) results in lower yields from the affected production boreholes.

- However, the combined yields of all the production boreholes, together with the abstraction at Buffelsfontein, were adequate to meet the daily water demand for Albertinia. The imminent connection of the newly drilled Albertinia Deep Borehole to the Albertinia water supply system will improve the water supply.
- The average daily abstraction rates for 2024 (in ML/d) exceeded the recommended borehole yields for production boreholes AG1 and AG3 (40% and 22%, respectively).
- The average daily abstraction rate (2024 data) of all the production boreholes tapping the Nardouw aquifer (Skurweberg Formation) equalled 0.14 Mm3/a (0.38 ML/d). In comparison, the recommended sustainable yield/abstraction rates (based on pump test data) for all the production boreholes were 0.16 Mm^3/a (0.43

ML/d) without the Albertinia Deep Borehole and 0.22 Mm^3/a (0.60 ML/d) with the Albertinia Deep Borehole.

8.5. WESTERN CAPE, ATLANTIS

The Atlantis Water Resource Management Scheme (AWRMS) near Cape Town is a globally recognised and longstanding example of the use of Managed Aquifer Recharge (MAR) to develop a sustainable, drought-resistant water supply. Initiated in the 1970s, it has become a model for integrated water management. Originally set up to provide water for Atlantis, Pella, and Mamre, about 50 km north of Cape Town, it exemplifies cost-effective water recycling through innovative town planning. Its enduring, sustainable operation over decades has made it a prototype for optimising water use and protecting the environment.

The core of the AWRMS is a sophisticated cycle of collection, treatment, natural storage, and recovery. Instead of letting treated wastewater and stormwater run into the ocean, the scheme captures and uses them to replenish the area's intergranular aquifer. The scheme provides 12 megalitres per day (ML/day) to the population.

A key factor in the scheme's success is the separation of water based on source and quality. Domestic wastewater is fully treated through secondary processes, including nitrification and denitrification, then polished in maturation ponds. This higher-quality effluent is used for indirect reuse. Industrial wastewater undergoes pre-treatment separately. Stormwater is also collected and kept apart from the main sewage system. The treated water is used to recharge groundwater by mixing conditioned domestic effluent with urban stormwater runoff in the main recharge basins. It gradually filters through sand, recharging the aquifer, which acts as a natural underground reservoir. Lower-quality treated industrial effluent, along with stormwater from industrial zones, is directed to infiltration ponds near the coast. This creates a mound of freshwater, maintaining a high water table and preventing seawater intrusion into the freshwater aquifer. Water is abstracted from the aquifer through boreholes in the Witzand and Silverstream wellfields, then pumped to a treatment plant to meet drinking water standards before being supplied to the municipal system.

The scheme is currently undergoing significant upgrades and expansion as part of Cape Town's broader New Water Programme, a strategic response to enhance the city's water security and resilience to climate change and population growth. Upon completion, the scheme intends to add 10 ML/day.

8.6. WESTERN CAPE, BEAUFORT WEST

Beaufort West is located in the eastern part of the Western Cape province. It's located 500 kilometres east of Cape Town. The town is the administrative centre of the Beaufort West Local Municipality, which includes Merweville, Nelspoort, and Murraysburg. The geology of Beaufort West mainly includes the deposition of the Ecca and Beaufort Group and the intrusive Karoo Dolerites ([30], [31], [32]). Beaufort West currently uses seven wellfields, totalling around 44 boreholes. The wellfields are located around the town, with the Brandwaght and Rhenosterkop wellfield 35 km away [33].

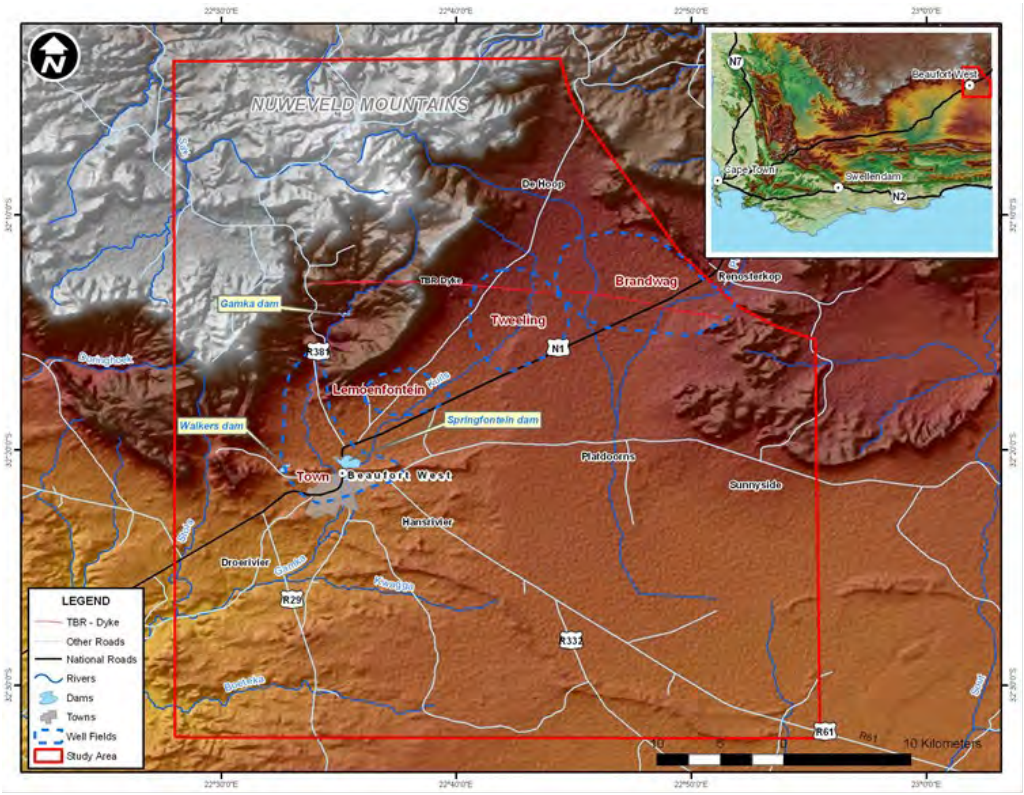


Figure 33: Localities of the Beaufort West field [34]

The aquifer consists mainly of sedimentary rock from the Beaufort Group, including the Poortjie Member and the Middelton Formation. According to L Chevallier Pers. In Communication 2024, this formation has the most freshwater and is also the Formation that hosts the uranium deposits [31]. The sedimentary rock is being compartmentalised by intruding dolerite dykes and sills. Water strikes are mainly located in the Poortjie and Abrahamskraal layers north of the town.

Water quality, according to DWAF 2005, is marginal (70–300 mS/m) in the town and target area, while the recharge area is deemed pristine in the

Nuweveld Mountains, and the southeastern side of the groundwater is of much poorer quality. Over the years, various quality tests have been conducted, but during droughts and high-rainfall events, the chemistry often changes.

The Brandwacht wellfield has been drilled and extensively explored, but the aquifer has almost run dry due to over-abstraction, infrastructure failures, water losses, and declining rainfall. The boreholes are also continually vandalised.

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