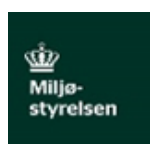


THE SOUTH AFRICAN GROUNDWATER MAPPING AND ASSESSMENT APPROACH (SAGMAA)

GUIDELINE



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1. INTRODUCTION

While groundwater remains a vital source of drinking water for many rural communities and smaller towns in South Africa, surface water continues to be the primary supply for most major urban centres. In a semi-arid country like South Africa, surface water systems are particularly vulnerable to climatic variability and extended dry periods. This vulnerability was starkly illustrated during the severe drought from 2015 to 2018, which affected the western regions of the country and led to significant water shortages. The event underscored the need for a more climate-resilient and diversified water supply strategy. Although groundwater is also impacted by extended droughts due to reduced aquifer recharge, it typically responds more gradually to climatic fluctuations. This slower response offers a natural buffering capacity against interannual climate variability. Given that groundwater remains underutilised at the national scale, expanding its use could enhance the resilience and diversification of South Africa's water supply system, making it better equipped to withstand future droughts and climate-related stresses.

The potential of groundwater as a vital water resource in South Africa has long been acknowledged. Over the past decade, several national strategies have been formulated to encourage its utilisation. However, despite these efforts, groundwater continues to contribute only modestly to the country's overall water supply, with surface water remaining the dominant source. Moreover, the development and management of groundwater resources have received comparatively limited attention. Regrettably, the strategic frameworks established have not yet been effectively translated into consistent, operational practices that support the sustainable and equitable use of this critical resource.

In contrast to South Africa, Denmark relies almost exclusively on groundwater for its drinking water needs, with surface water used only sparingly, primarily for industrial applications. Danish groundwater is typically of high quality, requiring minimal treatment, often limited to aeration and sand filtration. The protection of this vital resource is a cross-party political priority, reflecting a national commitment to safeguarding groundwater for both current and future generations. This dedication was formalised through the launch of a national groundwater mapping programme in 2000. The initiative established a standardised framework for all groundwater investigations and provided funding for the development of comprehensive guidelines, innovative methodologies, advanced instruments, and specialised software to support its implementation. This programme has played a pivotal role in ensuring the sustainable management and long-term security of Denmark's groundwater resources.

The objective of this guideline is to provide steps relating to the extent to which elements of the Danish groundwater mapping approach can be adapted to South African conditions. This is based on a review of the methodologies used in both countries (**Appendices A and B**), followed by a comparison of key elements in **Appendix C** (SSC, 2022). The Appendices are available in a separate report

2. BACKGROUND

Groundwater mapping and assessments serve a variety of purposes, and as such, the steps and activities involved can differ depending on the specific objectives. As a result, multiple flowcharts can be developed to guide the process.

Groundwater Mapping refers to activities aimed at analysing and understanding the groundwater system. These activities are generally universal and must be carried out regardless of the purpose, and they are detailed in Section 3.

Groundwater Assessments, on the other hand, build upon the understanding gained through mapping to evaluate specific aspects of groundwater resources. These are tailored to particular objectives and are discussed in Section 4.

The development of a wellfield, specifically the drilling of production boreholes, can only commence after the assessment phase has been completed. This development phase is distinct and more targeted, focusing on the high-potential areas identified during the assessment of the aquifer(s). By concentrating efforts on these promising zones, the development process becomes more efficient and aligned with the resource's sustainable use. **This Guideline only deals with Groundwater Mapping and Groundwater Assessments phases and does not include the Wellfield Development, Equipping and Operational phases.**

The following guidelines can be used for wellfield development, equipping, operation and management of a groundwater scheme:

- Pietersen, K., Titus, R., 2022 Guidance document on groundwater scheme development. Water Research Commission: Pretoria, WRC Report no. **TT 903/22**
- De Bruin, K., Rademan, Z. and Towers, L., 2022 Guidance document for management of a groundwater scheme. Water Research Commission: Pretoria, WRC Report No. **TT 906/22**

3. APPROACH FOR GROUNDWATER MAPPING

Groundwater mapping can vary significantly in both detail and scale. A generalised approach is typically suitable for *regional-scale* mapping, while a more detailed mapping approach is often linked to the groundwater assessment (see Section 4) and is necessary when focusing on specific *aquifers* or *wellfields*.

The scope and detail of activities required in a groundwater mapping project depend on both the scale and complexity of the project. Not all tasks are necessary for every project; instead, each activity is evaluated based on the project's complexity level. The complexity level is determined by two main factors: *physical complexity* – including geological and hydrogeological conditions, and *project complexity* – influenced by project size, availability of funding, the criticality of meeting water demands, and the number and type of stakeholders involved.

In accordance with the National Water Act, 1998 (Act 36 of 1998), the approach in the exploration of new groundwater abstraction opportunities, projects can broadly be categorised into three levels of complexity, each with distinct regulatory and technical requirements:

- *Low Complexity* – involves groundwater development for domestic or small-scale use on private properties. No formal water use authorisation is required, as these typically fall under Schedule 1 water use. These projects are generally low-impact and straightforward.
- *Medium Complexity* – applies to groundwater developments with limited environmental or resource impact. These may require a General Authorisation (GA) under water use authorisation and are suitable for small-scale agricultural or community supply initiatives.
- *High Complexity* – encompasses large-scale wellfield developments or other uses with significant potential impact on groundwater resources. They require a Water Use License (WUL) and must be supported by a comprehensive hydrogeological report to ensure sustainable and responsible use.

3.1 General or Regional Mapping Approach

Table 1 provides an overview of the three (3) generic steps involved in groundwater mapping, along with their associated activities, including the level of complexity. These steps are further detailed in the subsequent sections of the document. However, depending on scalability and accountability/responsibility, the approach can therefore be further distinguished into two distinct categories:

- *Category 1*: This includes the core steps and activities essential for conducting groundwater mapping, as well as key factors that support the mapping process. These elements can typically be implemented at the project level, for instance, by clients or project teams.

- **Category 2:** This focuses on enhancing the groundwater mapping process through the development and management of supporting systems. Unlike Category 1, these aspects require attention and investments from the national government level to ensure long-term sustainability and effectiveness.

Table 1: Steps and activities for groundwater mapping at the regional scale in South Africa.

Steps and Activities		Complexity Level		
		Low	Medium	High
1. Desktop study				
1.1	Collection of data			
1.1.1	Data from databases, reports, etc.	X	X	X
1.1.2	Consultation of maps and aerial photos	(X)	X	X
1.1.3	Reports and other publications on previous studies	X	X	X
1.2	Gap analysis	X	X	X
1.3	Stakeholder identification		(X)	X
1.4	Inception report			X
2. Field Verification				
2.1	Hydrocensus	(X)	X	X
2.2	Collecting new data	X	X	X
2.3	Baseline monitoring		(X)	X
2.4	Stakeholder engagement		(X)	X
3. Modelling				
3.1	Developing a conceptual model	(X)	X	X
3.2	3D geological modelling			X
3.3	Hydrostratigraphical modelling			X
3.4	Geochemical modelling			(X)
3.5	Flow modelling/Hydrological modelling			X
3.6	Mapping (producing actual 2D maps)		(X)	X
3.7	Stakeholder engagement		X	X
	Legend (X) - Optional X - Compulsory			

3.1.1 Step 1: Desktop Study

A desktop study is a primary step that involves collecting and analysing existing *data* and *information* without fieldwork. This process typically includes:

- Retrieving *relevant data* from databases, technical reports, and published literature;
- Reviewing *maps* and *GIS datasets* to assess topography, geology, and hydrogeology; and
- Analysing *aerial imagery* to support the development of an initial conceptual model of the groundwater system.

The main objective of a desktop study is to establish a foundational understanding of groundwater conditions within the project area. This baseline information is then used to

conduct a *gap analysis*, which identifies deficiencies in the available data and highlights areas requiring further/detailed investigation.

For projects classified as high complexity, the following additional activities are strongly recommended:

- *Stakeholder Identification*: This activity assists in recognising individuals or organisations with relevant expertise or interests. Early stakeholder engagement fosters collaboration and enhances project acceptance. It is also advisable to consider this activity for medium complexity projects.
- *Inception Report*: This consolidates all findings from the desktop study, summarises identified data gaps, and outlines stakeholder involvement. It serves as a key reference document that guides subsequent phases of the project.

3.1.2 Step 2: Field Verification

To enhance the understanding of groundwater features within a project area, various field-based methods can be employed. The most fundamental of these is the *hydrocensus*, which involves the systematic collection of field data, including:

- *Dug wells and boreholes* – records the locations, depths, construction details, water strike and water levels.
- *Water quality* – measure the basic parameters to assess the suitability of groundwater for various uses.
- *Surface water–groundwater interactions* – identify other features such as wetlands, pans, springs, and any additional indicators of hydrological connectivity.
- *Groundwater-dependent ecosystems* – mapping and characterisation of ecosystems relying on groundwater inputs.

The data collected during these investigations contribute to refining the conceptual groundwater model, which serves as a basis for further studies and development planning.

To address remaining data gaps, additional field investigations may be undertaken, including:

- *Geophysical surveys* to delineate subsurface features.
- *Drilling* of new boreholes to obtain direct subsurface data.
- *Aquifer/borehole yield testing* to evaluate the productivity of aquifers/boreholes.
- *Water quality analysis* to obtain the quality of groundwater and assess compliance with water quality standards.

Before drilling any new boreholes, yield testing data and information from existing boreholes, as is often conducted through initiatives such as the Groundwater Resource Information Project (GRIP) www.griplimpopo.co.za and the National Groundwater Archive (NGA), <https://www.dws.gov.za/Groundwater/NGA.aspx>, may provide valuable insights into groundwater availability and quality.

A diverse array of geophysical techniques is available to support *groundwater exploration*; each tailored for specific hydrogeological features and project objectives. The selection of an appropriate geophysical method should be guided by the following considerations:

- *Hydrogeological Setting*: A thorough understanding of *geological* and *aquifer characteristics* is essential to determine the most suitable geophysical approach.
- *Required Resolution and Scale*:
 - *Large-scale* methods, such as *airborne electromagnetic surveys*, are well-suited for *extensive wellfield developments* where both *abstraction zones* and *potentially impacted areas* span broad regions.
 - *High-resolution* methods are preferable in *geologically complex settings* that demand detailed, site-specific data to inform decision-making.
 - For *small-scale or low-complexity* projects, where groundwater abstraction is limited, the emphasis should be on acquiring *localised, high-quality data* to support accurate *borehole siting*. In such cases, broad spatial coverage is less critical, and precision in data acquisition becomes key.

Baseline monitoring is essential when the development or expansion of wellfields may pose risks to the environment or to existing water users. The scope of baseline monitoring can range from a single initial water level measurement to a comprehensive, long-term programme spanning several years.

It is strongly recommended that baseline monitoring be initiated before commencing any groundwater abstraction activities. Ideally, data should be collected over a full annual cycle to capture seasonal variations in groundwater levels and quality. However, even with time constraints, shorter monitoring periods can still yield valuable insights, depending on the specific context and urgency.

Establishing a robust baseline provides a critical reference point for:

- Mapping and assessing groundwater conditions;
- Evaluating potential environmental and user impacts; and
- Informing the sustainable management of the resource throughout the project lifecycle.

The development of a *Stakeholder Involvement Plan* should be tailored to the scale and complexity of the groundwater abstraction project, as well as the diversity and interests of the stakeholders involved. Proactive and consistent engagement with relevant role players is essential, as it helps to:

- Minimise potential conflicts;
- Promote transparency and accountability; and
- Enhance the overall effectiveness and sustainability of project outcomes.

The other proven tactic is the establishment of *monitoring committees* comprising stakeholder representatives. While these committees typically do not possess formal decision-making authority, they serve as valuable platforms for:

- Facilitating two-way communication between project teams and stakeholders;

- Building trust and fostering collaborative relationships; and
- Gathering stakeholder input and recommendations that can inform and improve groundwater mapping, assessment, and management efforts.

Such inclusive and participatory structures contribute significantly to the *long-term success* and *community acceptance* of groundwater projects.

3.1.3 Step 3: Modelling

A *conceptual model* is critical for groundwater mapping, constructed using all available data and continuously refined as new information emerges. Its primary purpose is to develop a coherent understanding of the groundwater system, which in turn guides the direction of further investigations and modelling efforts.

When groundwater flow modelling is part of the scope, the conceptual model must integrate both *geological and hydrogeological components* of the system. Key elements to be included are:

- *Aquifer geometry and connectivity* – understanding the spatial configuration and interlinkages between aquifers.
- *Recharge and discharge zones* – identifying areas where groundwater enters and exits the system.
- *Surface water–groundwater interactions* – assessing the dynamic relationships between rivers, wetlands, springs, and groundwater.
- *Groundwater-dependent ecosystems* – mapping ecosystems that are reliant on groundwater for their health and sustainability.

The *conceptual model* is typically developed as a *semi-3D representation* that captures both vertical and lateral relationships within the groundwater system. Even when the project area is geographically limited, the model must account for broader connectivity between aquifers, surface water bodies, and the surrounding environment to ensure a comprehensive understanding of the system. Importantly, the conceptual model serves as the foundation for *numerical and analytical modelling*, including *flow and transport simulations*. However, it is not a static construct; it should be iteratively refined as new data and insights emerge from ongoing investigations and modelling activities. A well-developed conceptual model not only supports accurate simulation and prediction through numerical modelling but also *enhances decision-making* in groundwater resource management and protection.

In South Africa, *detailed 3D geological modelling* has predominantly been applied in the context of mineral resource development and management. Its use in groundwater investigations, however, remains limited, despite the significant overlap and interaction within the subsurface environment. Nevertheless, *3D geological modelling offers considerable potential to improve understanding of hydrogeological systems*. To fully leverage its benefits, 3D model development should be initiated early in the project lifecycle, enabling clearer interpretation of the physical system and supporting more informed decision-making from the outset.

Currently in South Africa, *hydrostratigraphic modelling* is not widely practised as a distinct activity. Geological modelling often focuses on lithological formations, which may not

adequately represent the water-bearing characteristics of sediments or bedrock. These formations can exhibit substantial variability in hydraulic properties, even within the same unit, such as in fractured rock horizons. While geological models tend to be complex and detailed, *hydrostratigraphic models* offer a simplified representation by *grouping geological units* based on *similar hydrological behaviour*.

This approach enhances the practicality of integrating geological data into groundwater flow models. To improve the usefulness of geological models in hydrogeological investigations, it is recommended that they be complemented with *hydrostratigraphic considerations*. This can be achieved either through:

- Separate hydrostratigraphic interpretation, or
- Incorporating hydrological attributes directly into the geological modelling process.

Such integration ensures that models are not only geologically accurate but also hydrologically meaningful, thereby improving the reliability of groundwater simulations and resource management strategies.

In South Africa, *geochemical modelling* is currently applied predominantly at contaminated sites. However, its broader potential in groundwater studies should not be underestimated. Geochemical modelling can serve as a powerful tool for:

- Identifying groundwater flow paths;
- Understanding water–rock interactions; and
- Investigating subsurface geochemical processes.

In regions where groundwater quality varies significantly, geochemical modelling can provide critical insights by analysing the chemical composition of aquifers. These insights can help *delineate recharge areas, trace contaminant sources, and assess natural attenuation processes*. Given its value in enhancing understanding of groundwater flow dynamics and the evolution of groundwater quality, it is recommended that geochemical modelling be actively considered and promoted, particularly in areas with complex hydrogeochemical conditions.

In South Africa, *hydrogeological flow models* are primarily applied to large-scale groundwater developments or projects with the potential to significantly impact groundwater resources or surface water systems, including groundwater-dependent ecosystems. One of the key strengths of flow modelling lies in its ability to integrate diverse datasets and knowledge into a unified framework. This enables a *comprehensive representation* of the groundwater system and supports informed decision-making.

By comparing model outputs with field observations, the accuracy of the model, and by extension, the understanding of the system, can be evaluated:

- Small discrepancies between modelled and observed data suggest a robust conceptual understanding of the system.
- Large discrepancies may indicate gaps in data or limitations in the conceptual model, highlighting the need for further investigation or refinement.

Flow modelling thus serves not only as a *predictive tool* but also as a *diagnostic mechanism*, guiding the *iterative improvement of groundwater assessments and resource management strategies*.

Flow models are particularly valuable tools for *evaluating sustainable groundwater yields*, enabling the *determination of abstraction volumes* that do not result in *unacceptable environmental impacts*. This is especially critical in areas where groundwater supports sensitive ecosystems or contributes to surface water systems. It is strongly recommended that flow models be developed for projects with potential environmental consequences, particularly in layered hydrogeological systems where multiple aquifers interact. These models help:

- Quantify the impact of abstraction on aquifer dynamics;
- Assess long-term resource availability;
- Evaluate risks to groundwater-dependent ecosystems; and
- Support regulatory compliance and resource management decisions.

By simulating various abstraction scenarios, flow models provide a scientific basis for defining *sustainable yield thresholds*, ensuring that groundwater development remains environmentally responsible and economically viable.

Integrated groundwater–surface water models are particularly valuable in regions where groundwater *abstraction may influence wetlands, rivers, or lakes*, and where *quantifying these impacts is essential for sustainable resource management*. These models enable a holistic understanding of the hydrological connectivity between subsurface and surface systems, supporting more accurate predictions of environmental responses to groundwater use.

Flow models are also critical for projects with high-risk or sensitive consequences, such as those involving:

- Groundwater-dependent ecosystems;
- Protected or ecologically significant surface water bodies; and
- Areas with competing water use demands.

By simulating interactions across the hydrological system, integrated models provide a robust framework for evaluating environmental risks, informing *regulatory decisions*, and guiding *adaptive management strategies*.

The decision to develop a *3D groundwater flow model* should be guided by the *complexity of the hydrogeological system and the availability and quality of supporting data*. While 3D models offer detailed spatial representation and can enhance understanding in many contexts, they are not universally appropriate. In systems dominated by discrete features, such as fractures, faults, or dykes, that exhibit limited interaction with the surrounding bedrock matrix, *3D modelling* can be particularly challenging. These environments require:

- High-resolution structural and hydraulic data;
- A deep understanding of the spatial variability and connectivity of features; and
- Sophisticated modelling techniques to accurately represent flow dynamics.

In the absence of sufficient data, the value of a 3D model may be limited, and its outputs may be unreliable. In such cases, alternative modelling approaches, such as *simplified conceptual models*, *2D cross-sectional models*, or *analytical solutions*, should be considered.

While *3D geological mapping* offers a comprehensive understanding of subsurface conditions, its outputs often need to be translated into *2D visual formats* for effective communication and stakeholder engagement. Plan-view maps and cross-sectional diagrams are particularly effective for presenting complex 3D data in a clear and accessible manner. These *2D representations* allow for the intuitive demonstration of:

- Spatial relationships between geological units;
- Subsurface structures such as faults, aquifers, and dykes; and
- Depth and extent of impacted areas.

To enhance relevance and foster stakeholder understanding, these maps should incorporate contextual layers such as:

- Farm boundaries;
- Roads and infrastructure;
- Administrative or property divisions; and
- Recognisable landmarks.

Overlaying geological data with familiar geographic references improves transparency, strengthens stakeholder trust, and facilitates informed decision-making by making technical information more relatable and easier to interpret.

Engaging stakeholders following the modelling phase is essential for building trust, fostering collaboration, and enhancing the overall credibility of groundwater projects. Trust is strengthened when stakeholders see that their local knowledge and understanding of the groundwater system have been acknowledged and meaningfully incorporated into the model. In return, stakeholders gain valuable insights from the modelling results, which can inform their planning, decision-making, and resource management strategies. This two-way exchange of knowledge:

- Validates stakeholder contributions;
- Improves the relevance and accuracy of the model;
- Encourages shared ownership of outcomes; and
- Lays the foundation for more effective and accepted stakeholder engagement in future initiatives.

By promoting transparency and mutual learning, post-modelling feedback processes contribute significantly to the long-term success and sustainability of groundwater management efforts.

4. APPROACH FOR GROUNDWATER ASSESSMENTS

Below are three (3) types of groundwater assessments identified, each designed to fulfil specific objectives critical to water resource management. These are:

- **Wellfield Development** – these assessments are conducted to identify suitable locations and estimate the volume of groundwater available to support individual boreholes or wellfields. The scope can vary widely, from small-scale domestic drilling operations to the planning and development of extensive municipal wellfields.
- **Resource Quantification and Allocation** – these assessments are typically undertaken at the national level, focusing on evaluating aquifer properties and estimating groundwater availability. Prominent examples include the two Groundwater Resource Assessment initiatives, Phase I (GRAI) and Phase II (GRAII), undertaken in South Africa during the early 2000s.
- **Resource Protection** – these assessments are aimed at protecting critical surface water and groundwater resources. In South Africa, these may be in areas designated as Strategic Water Source Areas (SWSAs) and/or recharge areas. These evaluations support the implementation of targeted protection and management approaches to ensure long-term sustainability of the resource.

The following sections provide tailored recommendations aligned with each of the three assessment categories outlined above.

4.1 Assessments for Wellfield Development

In South Africa, the most commonly conducted groundwater assessments are those focused on exploring new water supplies. As a consequence, the bulk of practical experience and technical expertise is mostly focused on *wellfield development assessments*, resulting in a substantial number of professionals and stakeholders involved in wellfield development. This reflects the importance of wellfield development assessment in meeting domestic, agricultural, and municipal water requirements.

When mapping activities are incorporated into wellfield development assessments, they significantly enhance the evaluation and typically encompass a range of tasks, outlined in **Error! Reference source not found.**, further detailed in the texts below. These contribute to a more comprehensive understanding of aquifer characteristics, recharge potential, and water quality.

The initial phase of understanding a groundwater system involves comprehensive data acquisition, encompassing both *desktop-based* data gathering and *field-based* data collection. These activities collectively provide critical insights into the behaviour and dynamics of the groundwater system, with particular emphasis on groundwater abstraction patterns. This includes identifying areas at risk of over-abstraction, where impacts must be carefully monitored and assessed.

Once a foundational understanding has been established through these data-driven activities, the information is used to assess and quantify the volume of groundwater that can be

sustainably abstracted. This ensures that abstraction practices are aligned with the long-term availability of the resource and the protection of sensitive zones.

Table 2: Recommended groundwater assessment steps and activities related to wellfield development.

Steps and Activities		Complexity Level		
		Low <i>Schedule 1*</i>	Medium <i>General Authorisation*</i>	High <i>Water Use License*</i>
1.	Feasibility	X	X	X
1.1	Desktop study			
1.1.1	Collection of data from databases, reports, etc.	X	X	X
1.1.2	Consultation of maps and aerial photos	X	X	X
1.1.3	Reports and other publications on previous studies	X	X	X
1.1.4	Gap analysis	X	X	X
1.1.5	Stakeholder identification		(X)	X
1.1.6	Inception report			X
1.2.	Field Verification			
1.2.1	Hydrocensus		X	X
1.2.1.1	<i>Borehole information</i>	(X)	X	X
1.2.1.2	<i>Water Quality</i>	(X)	X	X
1.2.2	Developing a conceptual model	X	X	X
1.2.3	Collecting new data			
1.2.3.1	<i>Test pumping existing boreholes</i>	(X)	X	X
1.2.3.2	<i>Geophysics and borehole siting</i>		(X)	X
1.2.3.3	<i>Drilling (Exploration)</i>		(X)	X
1.2.3.4	<i>Test pumping new boreholes</i>		(X)	X
1.2.4	Baseline monitoring	(X)	X	X
1.2.5	Stakeholder engagement	(X)	X	X
2.	Modelling			X
2.1	Update the conceptual model	(X)	X	X
2.2	3D geological modelling			X
2.3	Hydrostratigraphical modelling			X
2.4	Geochemical modelling			(X)
2.5	Flow modelling/Hydrological modelling			X
2.6	Stakeholder engagement		(X)	X
3.	Assessment Report	(X)	X	X
4.	Stakeholder engagement	(X)	X	X
	Legend * - Recommend mapping for Water Use (X) – Optional X - Compulsory			



4.1.1 Step 1: Feasibility

Arguably, the entire groundwater assessment process related to wellfield development may be broadly referred to as *Feasibility*, in which both the potential of an aquifer to deliver water and its sustainable yield are evaluated. This involves determining not only how much water an aquifer is likely to produce, but also how much can be abstracted without causing unacceptable environmental impacts.

This corresponds to the *Reconnaissance level* as defined by Riemann et al. (2011), representing the initial phase of a groundwater assessment. Accordingly, a feasibility is conducted at the outset of all wellfield development projects to establish baseline conditions and guide subsequent actions.

The outcome of the feasibility, along with the project's complexity level, will determine the appropriate next steps. For low-complexity projects, such as Schedule 1, it may be sufficient to confirm that existing boreholes in the vicinity are yielding adequately, thereby allowing progression directly to the drilling phase. However, when a higher degree of certainty is required, mapping activities are incorporated to develop a more detailed understanding of the groundwater system and its potential yield. This ensures that decisions are informed by robust data and that resource development is both efficient and sustainable.

Furthermore, these activities thus determine whether the groundwater system can reliably provide the yield necessary to support the economic viability of a proposed wellfield development. This evaluation forms the basis for applying for a groundwater abstraction license, which requires a thorough understanding not only of the aquifer's capacity but also of the potential ecological impacts of abstraction.

4.1.1.1 Step 1.1: Desktop Study

A *desktop study* involves collecting and analysing all available *data* without conducting fieldwork. This includes retrieving information from *databases, technical reports, and scientific publications*. The data is used to develop a *preliminary conceptual model* of the groundwater system. Geographic Information System (GIS) resources, such as topographic, geological, and hydrogeological *maps*, along with aerial imagery, are instrumental in this process. These resources help to *visualise and interpret the spatial characteristics* of the groundwater system. Additionally, existing literature and previous studies relevant to the area are reviewed to enhance the understanding of local hydrogeological conditions.

The findings from the desktop study are synthesised into a *gap analysis*, which identifies areas where critical information is lacking. This analysis forms the basis for planning further investigations and fieldwork.

For high-complexity projects, two additional activities are recommended: *stakeholder identification* and the preparation of an *inception report*. Stakeholder engagement should also be considered for medium-complexity projects. Early identification of stakeholders can help uncover valuable local knowledge and foster support for the project. The inception report

documents all relevant findings from the desktop study, highlights identified data gaps, and outlines the key stakeholders involved. This report provides a structured foundation for the next phases of the groundwater assessment.

The licensing process considers how groundwater withdrawal may affect natural systems dependent on groundwater, such as wetlands, springs, and riparian ecosystems. Therefore, the desktop study component of the assessment must include the identification of potentially vulnerable systems that could be impacted by pumping activities. This ensures that abstraction is planned and managed to minimise ecological disruption and support sustainable resource use.

4.1.1.2 Step 1.2: Field Verification

Field verification activities focus on collecting new data to estimate the availability and yield of the groundwater resource. This process encompasses *hydrocensus*, *geophysical surveys*, *aquifer/borehole yield testing*, and *drilling of exploration boreholes*. During this activity, baseline monitoring may be necessary, although it is not sufficient to establish monitoring data for evaluating aquifer yields. The monitoring should be targeted at potentially vulnerable locations to establish baseline data for a pre-abstraction period, against which groundwater levels during abstraction can be compared. Although *stakeholder engagement* is listed as a final step, stakeholders must be actively involved throughout the entire process, particularly during the *hydrocensus*.

Understanding the groundwater characteristics of a project area can be enhanced through several approaches, beginning with a *hydrocensus*. This field-based survey collects information on dug wells, boreholes, and potential surface-water–groundwater interactions, including wetlands and pans. The hydrocensus provides valuable insights into borehole depths, water strike levels, water quality, and the presence of groundwater-dependent ecosystems.

Based on the collected data, a *conceptual model* should be developed to establish a comprehensive understanding of the groundwater system.

New data collection efforts include *geophysical investigations*, *drilling of new boreholes*, *yield testing*, and *water quality analysis*. Yield testing of existing boreholes is conducted to gather preliminary information before drilling new ones. A variety of geophysical methods are available, each suited to specific hydrogeological settings. Therefore, selecting an appropriate method should be guided by the project area's characteristics.

Baseline monitoring is essential in areas where the development or expansion of wellfields may pose environmental risks or affect existing activities. This monitoring may range from a single initial water level measurement to a comprehensive programme spanning several years. Ideally, baseline monitoring should precede any groundwater development activities. While a year of monitoring data is preferred, shorter durations may be acceptable depending on the context. These data are crucial for mapping, assessment, and long-term resource management.

When designing a *monitoring programme*, it is essential to consider regulatory authorisation requirements and resource management, including water-level measurements, water-quality sampling, and chemical analysis.

A *stakeholder engagement plan* should be tailored to the scale and complexity of the groundwater abstraction project, as well as the number and type of stakeholders involved. Regular engagement with relevant stakeholders is recommended to minimise conflict and improve project outcomes. One practical approach is to establish monitoring committees that include stakeholder representatives. Although these committees do not hold formal authority, they provide a valuable platform for information exchange and for stakeholders to offer recommendations that can enhance groundwater assessment efforts.

4.1.2 Step 2: Modelling

A *conceptual model* is a foundational tool in groundwater projects, developed to enhance understanding of the geological and hydrogeological system. This should be continuously updated as new data and insights become available, and its purpose is to identify key system characteristics and prioritise areas requiring focused attention throughout the assessment process. Conceptual models are typically semi-3D, capturing the connectivity between aquifers, surface water bodies, and the surrounding environment. Although the project area may be limited in spatial extent, the model must still evaluate these interconnections. It serves as the basis for more detailed numerical models and may be refined as results from those models become available.

In the South African context, *detailed 3D geological modelling* is generally reserved for geologically complex systems. When applied, it provides valuable insights into the subsurface's physical structure, aiding interpretation of hydrogeological processes. Ideally, geological modelling should be initiated early in the project to support the development of a robust conceptual framework.

While *hydrostratigraphic modelling* is not commonly conducted as a standalone activity in South Africa, it plays a critical role in simplifying geological complexity. Geological models often focus on lithological formations, which may not align with hydrogeological behaviour. For instance, fractured zones within a single formation can exhibit vastly different hydraulic properties. Hydrostratigraphic models group units with similar hydrological characteristics, making them more suitable for integration into groundwater flow models. It is therefore recommended that geological models be supplemented with hydrostratigraphic interpretations, either independently or by incorporating hydrological considerations directly into the geological modelling process.

Geochemical modelling is used to assess groundwater quality before the development of new abstraction boreholes or wellfields. This evaluation is essential to determine whether the groundwater meets the intended use requirements and to identify any protective measures needed to ensure the long-term sustainability of the resource. Understanding the chemical

composition of groundwater also helps in identifying potential contamination risks and natural geochemical processes that may affect water quality over time.

Groundwater flow modelling is a critical tool for estimating sustainable yield, the volume of groundwater that can be abstracted without causing unacceptable impacts. This process involves two key components:

- *Defining Acceptable Impacts* – criteria must be established to determine the limits of acceptable change, such as maximum allowable drawdown of groundwater levels or reductions in baseflow to surface water systems. These criteria are typically based on balancing environmental, social, and economic considerations.
- *Simulating Abstraction Scenarios* – the flow model is used to simulate various pumping scenarios, including different abstraction rates and borehole locations. The impacts of each scenario are assessed by comparing them to a baseline (non-abstraction) condition.

The *modelling approach* supports informed decision-making for groundwater development and management, ensuring that abstraction remains within environmentally and socially acceptable limits.

4.1.3 Step 3: Assessment Report

The results of groundwater assessments should be compiled into a comprehensive Assessment Report that serves the following purposes:

- *Regulatory Support* – the report must be structured to provide a clear and defensible basis for the *issuance of water use authorisations*. It should include all relevant technical findings, methodologies, and interpretations that support decision-making.
- *Stakeholder Information* – the content should be tailored to address the *interests and concerns of stakeholders*. Clear communication of potential impacts, mitigation measures, and sustainable use recommendations is essential.
- *Future Use* – to maximise the value of the collected data and enhance subsurface understanding; datasets, conceptual models, and interpretations must be *well-documented and stored in formats that facilitate reuse*.

4.1.4 Step 4: Stakeholder Engagement

Stakeholder engagement is a critical component of groundwater assessment and is represented in Step 1: Desktop (Item 1.1.5 Stakeholder Identification) and Field Verification (Item 1.2.5 Stakeholder Engagement), as well as in Step 2 (Item 2.6 Stakeholder Engagement). While stakeholder engagement is particularly essential for high-complexity level developments, it should go beyond merely informing the public about project outcomes. The ideal approach is to involve stakeholders throughout the entire process, from planning and data collection to modelling and decision-making.

4.2 Assessments for Resource Quantification and Allocation

The Groundwater Resource Assessments (GRA I and GRA II) were conducted as part of South Africa's national water resource planning efforts, with the primary objective of estimating groundwater availability at a national scale. Building on these foundational studies,

the follow-up programme, GRA III, is currently under development, with a central focus on integrating and utilising data, knowledge, and assessments from a wide range of previous groundwater studies conducted at various scales across the country.

Combining results from different studies presents several challenges. A key issue is ensuring that the types of results produced are compatible and can be meaningfully compared or integrated. Variations in project objectives, methodologies, and stakeholders often lead to differences in terminology and interpretation. For example, terms such as groundwater recharge, net precipitation, and infiltration may be used interchangeably across studies, even though they refer to distinct hydrological processes. Similarly, the concept of sustainable yield is not a fixed physical quantity but rather a management threshold that must be defined in relation to acceptable environmental impacts from groundwater abstraction.

Without consistent, clearly defined terminology, there is a significant risk of misinterpretation when synthesising results from multiple sources. Therefore, careful consideration must be given to the context and definitions used in each study.

Another critical aspect of reusing project results is the ability to assess the quality, uncertainty, and representativeness of the data. It is essential to determine whether results are specific to local conditions or can be extrapolated to broader regions with similar hydrogeological settings. While some studies explicitly address these aspects, in others, such information must be inferred from the documentation, if available, which can limit the reliability of cross-study comparisons.

A further complication arises from differing conceptual models of the subsurface. Local studies often focus on specific aquifer systems, while national assessments target broader regional systems. As a result, estimates of parameters such as storage or yield may not be directly comparable. To address this, a shared conceptual framework is needed to relate findings across different spatial scales and geological contexts. Such a framework would enhance the interpretation of subsurface systems and facilitate the integration of data beyond individual project boundaries.

To support the effective reuse of existing study results in national groundwater assessments, the following developments are recommended:

- *National Terminologies* – develop a standardised vocabulary for groundwater mapping and assessment to ensure consistency in the use and interpretation of key terms and quantities.
- *National Standards and Guidelines* – introduce minimum quality standards for groundwater projects, including requirements for data reporting, documentation, and storage. Complement these with flexible guidelines that accommodate the unique characteristics of individual projects while promoting best practices.
- *Development of Common Conceptual Frameworks* – develop conceptual geological and hydrostratigraphic models tailored to different regions of the country with similar hydrogeological settings. Initial efforts could focus on strategic areas such as the

Strategic Water Source Areas (SWSAs) and Catchment Management Areas (CMAs) with current or anticipated municipal water supply needs.

Given the country's diverse geology, a single national framework is not feasible. Instead, region-specific frameworks should be developed and refined through pilot projects. Suitable pilot sites include:

- Langebaan Road – representing a regional coastal aquifer,
- Beaufort West – characterised by fractured aquifers,
- Ramotswa – featuring a karst aquifer system.

These sites are well-documented, with extensive datasets and airborne geophysical surveys available for two of the three locations.

4.3 Assessments for Groundwater Protection

The foundation of groundwater vulnerability assessments lies in comprehensive geological, geochemical, and hydrogeological modelling. Central to this process is the detailed mapping of aquitard thickness, primarily clay-rich sediments and shale, which serve as protective barriers over underlying aquifers. These assessments also encompass the identification of groundwater chemical processes, the delineation of wellfield catchment areas based on a 200-year groundwater travel time, and the establishment of wellhead protection zoning.

In scenarios where groundwater resources are critical and hydrogeological complexity is high, such as municipal water supply well fields, detailed vulnerability assessments are particularly beneficial. As illustrated in Table 1, it is recommended that a groundwater flow model be developed in such cases. This model enables the mapping of wellfield capture zones and facilitates the evaluation of potential contamination threats, including those from agricultural activities or mining operations. Through this approach, the relative hydrogeological vulnerability of different areas can be determined, allowing for targeted protective measures.

Furthermore, prioritisation of vulnerability zones can be guided by modelled contaminant transport times from the surface to the production wells. Areas with shorter transport times are considered higher risk and should be prioritised for protection.

In addition to delineating capture zones, safeguarding the immediate vicinity of production wells is essential. Establishing a wellhead protection zone, a 10-meter radius around each municipal drinking water well, serves as a critical measure to prevent direct contamination from chemical spills or agricultural pollutants. Within these zones, activities that pose a pollution risk are strictly prohibited. Given its simplicity and effectiveness, the implementation of a 10-meter protective buffer around all municipal water supply wells is strongly recommended.

5. REFERENCES

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