GUIDANCE DOCUMENT FOR MANAGEMENT OF A GROUNDWATER SCHEME

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Ministry of Environment of Denmark
Environmental Protection Agency

WATER RESEARCH COMMISSION

TT 906/22

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Report to the

Water Research Commission

by

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WRC Report No. TT 906/22
ISBN 978-0-6392-0374-4

March 2023

Obtainable from
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This is the final report of WRC project no. C2021/22-01076.

EXECUTIVE SUMMARY

The Guidance Document for Management of a Groundwater Scheme aims to promote groundwater management principles applicable to common types of groundwater schemes and associated users. It incorporates outcomes of the Strategic Water Sector Cooperation (SSC) between Denmark and South Africa. The SSC is a long-term cooperation that has contributed Denmark's well proven practical knowledge of legal frameworks, practices, and technologies to the sustainable use, protection and management of groundwater resources in South Africa. The guidance document aims to offer an outline of best practice for monitoring, operation, and maintenance (O&M) of various groundwater schemes in the context of South Africa's governance and legislative structures, international principles of Integrated Water Resource Management (IWRM), and the hierarchy of stakeholders involved in a groundwater scheme.

This document includes a generalised blueprint for establishing a monitoring network and programme, informed by monitoring objectives, that may be applied to groundwater schemes of various types and scales. Monitoring objectives are integrated with O&M requirements to outline tools, procedures and best practice methodologies toward scheme optimisation, longevity and environmental sustainability. Finally, the management structures for groundwater schemes in the South African legislative hierarchy are shown, and principles of groundwater conflicts are briefly discussed. Any reader of the Guidance Document can effectively fulfil their role as a stakeholder in managing a groundwater scheme of any type or scale, at any location in South Africa.

A groundwater scheme is defined by the physical infrastructure required to abstract, reticulate, treat and supply groundwater (such as boreholes, pumps, and pipework, etc.), as well as the stakeholders that are involved in operating and managing the groundwater resource and the various scheme components. Groundwater schemes cannot exist without the people and their associated management practices. Effective management of any groundwater scheme requires monitoring of various direct, indirect, static and dynamic components and processes. Monitoring can be considered the entry point to management, with monitoring networks and analytical and numerical models constituting tools for adaptive management. Adaptive management is widely applied in natural resource management and involves a "learn-by-doing" approach (Holling, 1978). At the heart of adaptive water management is the principle of Mobilise-Monitor-Model-Manage. It is critical to agree on *what* must be monitored by *whom*, *when* and to what *standards*.

Establishing monitoring objectives throughout a scheme's development, commissioning, and operational phases guide data collection towards producing information that can aid decision making and actions taken by all levels of management. Monitoring not only provides insights into aquifer response and effects on the environment, but it is also important for observing operational effects on scheme infrastructure. There are certain best-practice concepts and operating rules that can be implemented, and monitored, to manage impacts to a scheme (and groundwater resource alike) allowing a proactive, rather than reactive, response by managers on various levels.

Aquifer utilisation, i.e. groundwater scheme development and operation, comprises various principles, requirements, or unknowns that collectively need to inform decisions toward optimal use of the groundwater resource and sustainable function of the scheme. These principles include supply-demand and consumer relationships; aquifer characteristics and responses; scheme design and layout; the surrounding environment and other users. Decisions and designs adopted in the development phase of the scheme should incorporate and in turn be informed by long-term use of the scheme. Aspects requiring integration from early on include location (of the overall scheme and individual scheme components); drilling and testing methods and techniques; borehole design and construction; borehole pumping and interactions; downhole and surface equipment requirements, interaction with the environment (springs, rivers, wetlands, fauna and flora); groundwater quality and treatment requirements; user requirements and water demand; surface storage and reticulation networks; and various legislative requirements.

Groundwater schemes can vary in scale depending on the type of scheme. Common groundwater schemes explored in this guidance document include rural, private, commercial agricultural, industrial, municipal/bulk water; any of these may further benefit from or rely on a managed aquifer recharge (MAR) component. While general monitoring and O&M principles are universally applicable across all types of groundwater schemes, individual schemes should have specific and unique procedures encompassing resource monitoring, operational performance, maintenance requirements, stakeholder roles and responsibilities and action plans.

An integral part of scheme management is implementing and maintaining standards. This can be done through management tools such as Quality Management Systems (QMS), Standard Operating Procedures (SOP),

South African National Standards, maintenance plans, incident and emergency response plans, training workshops, reporting, auditing and evaluation.

The monitoring and O&M tasks that are carried out, if carried out correctly, can generate an abundance of data over time which must be captured, stored, and interpreted correctly. It goes toward making informed, real-time decisions for proactive management. It is important that this data is not only utilised for the immediate management of the groundwater scheme, but also in the management of the groundwater resource. Groundwater resource management is accounted for from the highest levels of the South African legislative framework. Overall, South Africa’s groundwater legislation and governance structures are considered comprehensive and align with international principles. Generally, challenges and concerns in South African groundwater management do not lie with the legislation, but in the implementation and compliance thereof.

Groundwater conflicts, and principles of hydrodiplomacy and water sharing are explored to guide conflict prevention, and resolution. It is likely that conflicts will arise as competition for water resources continues to grow due to population growth and the effects of climate change. Conflict related to groundwater schemes are centred around the groundwater resource’s availability and use (overexploitation and pollution). Such conflicts may arise in transboundary aquifers where water demands and approaches to water resource governance between relevant nations are misaligned or locally where groundwater resources are poorly understood and agreements for shared use and mutual benefit are lacking. Coordinated management with collaborative learning, objective optimisation and compromise, underpinned by robust science and thorough public engagement are cornerstones to prevent and resolve groundwater related conflict.

ACKNOWLEDGEMENTS

The project team wishes to thank the following people for their contributions to the project.

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ACRONYMS & ABBREVIATIONS

CCP	Critical Control Point
CMA	Catchment Management Agency
CWL	Critical Water Level
DWS	Department of Water and Sanitation
EC	Electrical conductivity
GA	General Authorization
GPZ	Groundwater Protection Zone
HACCP	Hazard Analysis and Critical Control Point
IWRM	Integrated Water Resource Management
NGS	National Groundwater Strategy
NORAD	Norwegian Agency for Development Cooperation
NWA	National Water Act
O&M	Operations and Maintenance
OWL	Operating Water Levels
PCA	Potential Contaminating Activity
SADC	Southern Africa Development Community
SANS	South African National Standards
SAWQG	South African Water Quality Guidelines
S_C	Specific Capacity
TPC	Threshold of Potential Concern
WMA	Water Management Area
WRC	Water Research Commission
WSA	Water Services Authority
WSI	Water Service Intermediaries
WSP	Water Services Provider
WUA	Water User Association

CHAPTER 1: BACKGROUND

1.1 INTRODUCTION

The Guidance Document for Management of a Groundwater Scheme aims to promote groundwater management principles applicable to common types of groundwater schemes and associated users. It incorporates outcomes of the Strategic Water Sector Cooperation (SSC) between Denmark and South Africa. The SSC is a long-term cooperation that has contributed Denmark's well proven practical knowledge of legal frameworks, practices, and technologies to the sustainable use, protection and management of groundwater resources in South Africa. The guidance document aims to offer an outline of best practice for monitoring, operation, and maintenance (O&M) of various groundwater schemes in the context of South Africa's governance and legislative structures, international principals of Integrated Water Resource Management (IWRM), and the hierarchy of stakeholders involved in a groundwater scheme.

Use of a groundwater resource needs to be carefully managed through continued monitoring and iterative modelling to define and achieve true sustainability and longevity for the benefit of society and the environment. To effectively make use of the groundwater resource, a groundwater scheme of some kind is developed. A scheme is typically defined by the physical infrastructure required to abstract, reticulate, treat and supply groundwater (such as boreholes, pumps, and pipework), as well as the stakeholders involved in operating and managing the scheme and water resources. A groundwater scheme cannot exist without the people and their management practices and, to effectively manage a groundwater scheme, an approach that integrates the three elements of Aquifer Management, Water Services (Risk Management) and Operations & Maintenance is needed.

Monitoring can be considered the entry point to management, with monitoring networks and modelling being tools for adaptive management. Adaptive management is widely applied in natural resource management and involves a "learn-by-doing" approach whereby information gained through monitoring of a system informs new and adapting management approaches (Holling, 1978). At the heart of adaptive water management is the principle of *Mobilise-Monitor-Model-Manage*. It is critical to agree on *what* must be monitored by *whom*; *when* and to what *standards*.

A walk through the iterative cycle of adaptive management can be expressed as:

- Mobilise/Monitor: information about a system is gained from baseline monitoring, for example, during groundwater exploration phase.
- Model: models (conceptual, analytical or numerical) are then developed to test the understanding and sensitivity to unknown variables/factors, and to express the collective understanding of how the groundwater system operates.
- Manage: initial management decisions can be taken based on this understanding, for example, perhaps the decision to proceed with groundwater development, or revise abstraction rates to avoid adverse effects.
- Monitor: monitoring is continuous and monitoring objectives and programmes are updated to address unknowns.
- Model: the models then become iterative, and predictions are updated as new data, insight and understanding of the system is available. The model calibration can be refined where required based on the comparison of predicted and actual data (verification and validation).
- Manage: future predictions of the validated model are used in management of the aquifer, for example to inform a change in operating rules.

Establishing monitoring objectives throughout the development, commissioning, and operational phases of a scheme guides data collection towards producing knowledge and information that can aid development of conceptual, analytical, and numerical models. Because analytical and numerical models can provide information on conditions that are not yet observed (i.e. the response of the aquifer to increased abstraction rates, or the response to un-tested timescales), their use is inherent to adaptive management of natural resources, groundwater systems and wellfield operations. Bidwell (2003) describes the role of groundwater models in adaptive management as "*expressing the collective understanding of the participants about how the* *groundwater system operates, assessing the uncertainties, and predicting the effects of various management actions*".

It is critical to integrate water resource management (IWRM) with environmental and social management, using a systematic approach, with fair inclusion and participation of all stakeholders. IWRM can be strengthened through the integration of Environmental Impact Assessments (EIA's), water resources modelling and land use planning. It should also be understood that a catchment or watershed approach implies that water should be managed alongside that of co-dependent natural resources. Driven bottom-up by local needs and priorities, and top-down by regulatory responsibilities, it must be adaptive and evolve dynamically with changing conditions (social, political, climatic). The relevant stakeholders should, therefore, collaborate in designing and implementing strategic elements of capacity building of scheme operators and managers as part of the evolving IWRM process.

A key unknown in the adaptive management approach is to answer what the long-term achievable aquifer yield is (considering withdrawal from storage, as well as long term average recharge), which the local stakeholders and regulators are keen to understand for water supply planning purposes. In addition, the regulators need to know the effects of abstracting these volumes, in terms of impacts to recharge zones and natural discharge, and whether these impacts are environmentally, socially, and economically acceptable. It is imperative to develop and understand mitigation options that are available and under what circumstances certain impacts are deemed to be acceptable.

Using principles of adaptive and proactive management, the Guidance Document for Management of a Groundwater Scheme includes a generalised blueprint for establishing a monitoring network and programme, informed by monitoring objectives, that may be applied to groundwater schemes of various types and scales. Monitoring objectives are integrated with O&M requirements to outline tools, procedures and best practice methodologies toward scheme optimisation, longevity and environmental sustainability. This guidance document explores management structures for groundwater schemes in the South African legislative hierarchy, and realities of groundwater conflict. Any reader of the Guidance Document can gain a better understanding of their role as a stakeholder in managing a groundwater scheme of any type or scale, at any location in South Africa.

1.2 SUMMARY OF WORK

Table 1-1 summarises work done in support of the development of this Guidance Document for Management of a Groundwater Scheme.

Table 1-1 Supporting work done for the Guidance Document for Management of a Groundwater Scheme

No.	Task	Summary of work
1	Desktop Assessment, Literature Review and Skills Gap Analysis	A review of existing documents (national and international) regarding Groundwater Scheme Management, and a gap analysis on local and national groundwater scheme management informed by the literature review.
2	Document detailing Groundwater Governance Structures in South Africa, and a conceptual Monitoring Plan and Operations and Maintenance Protocol.	Listing of stakeholders that are involved in the Groundwater Management Scheme, and their associated responsibilities. A management plan for the optimised monitoring of a groundwater scheme to ensure high quality data collection and analysis

No.	Task	Summary of work
		A protocol for O&M of a groundwater scheme with aims of minimising strain on wellfield infrastructure and aquifers.
3	Final Report	A final Guidance Document for Management of a Groundwater Scheme for all types and scales

CHAPTER 2: GROUNDWATER SCHEME DEVELOPMENT AND MANAGEMENT

2.1 INTRODUCTION

This Guidance Document for Management of a Groundwater Scheme addresses principles of groundwater abstraction (Aquifer Utilisation), operations, maintenance and monitoring. WRC (2011) outlines four interlinked key aspects of groundwater management in the Groundwater Management Framework (**Figure 2-1**):

- Aquifer Protection
- Aquifer Utilisation
- Monitoring, Data Management and Evaluation
- Aquifer Economics

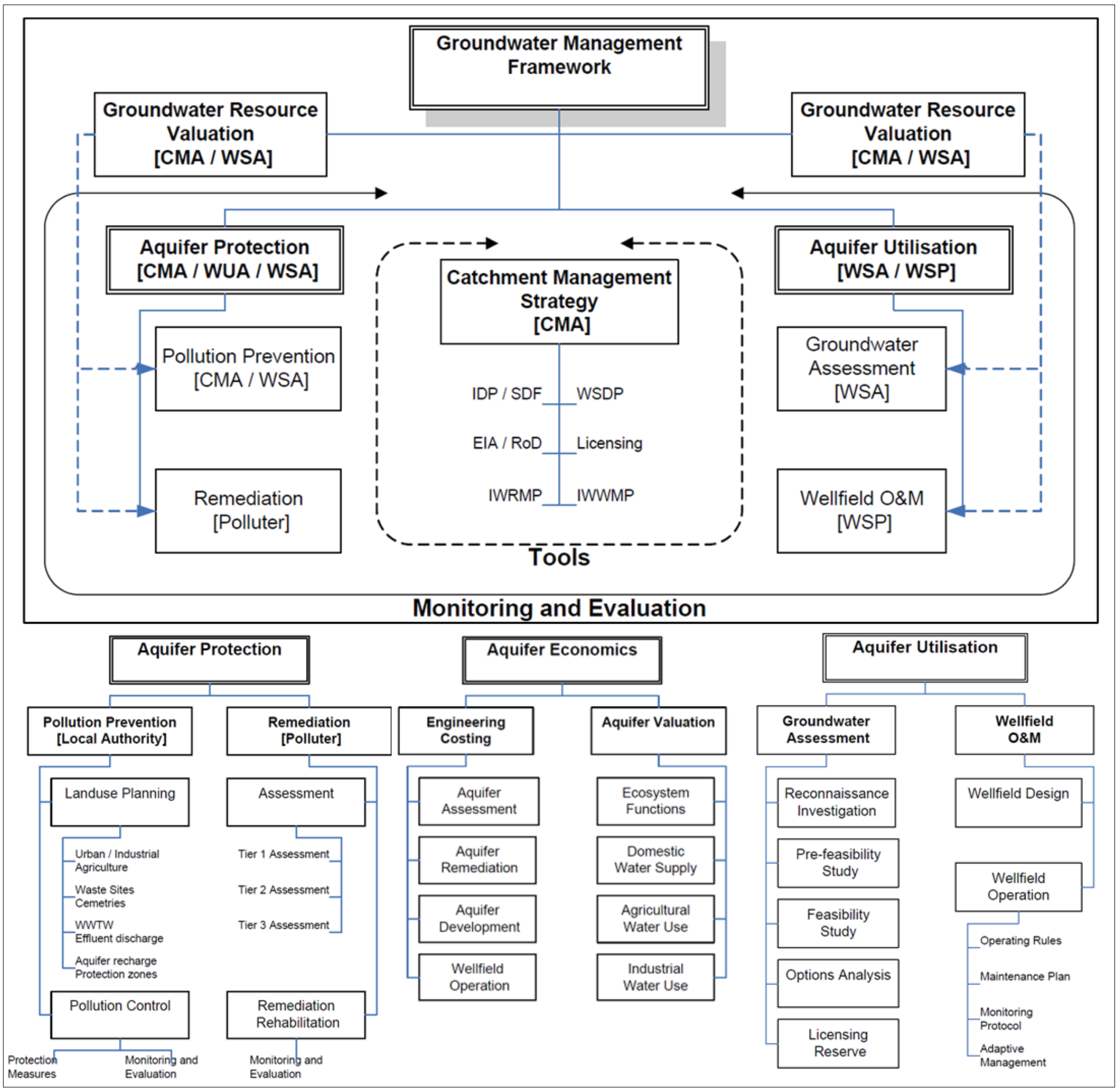

Figure 2-1 **The four key aspects of the Groundwater Management Framework developed by WRC (2011) are Aquifer Protection, Aquifer Utilisation¸ Aquifer Economics, and Monitoring, Data Management and Evaluation. These pillars comprise a series of interlinked and interdependent requirements that support managers to take evidence-based resource, infrastructure, and risk management decisions.**

Aquifer Protection

Aquifer Protection entails safeguarding the resource from deteriorating groundwater quality and reduction in recharge or storage. It includes all pollution prevention, mitigation, remediation, and rehabilitation activities – some of which link to how a wellfield is operated and monitored. For example, abstraction from coastal wellfields needs to be managed so that risk of seawater intrusion is minimised. Land use planning, groundwater protection zoning and vulnerability assessments are considered vital to aquifer protection against anthropogenic activities that contribute to groundwater contamination and aquifer depletion. Aspects of Aquifer Protection are further discussed in the Guidance Document on Protection Zones (Delineation and Protection) (WRC, 2022) and should be considered in conjunction with this document.

Aquifer Utilisation

Aquifer Utilisation entails minimising the detrimental impacts of groundwater abstraction and use while ensuring that it is long-lasting and sustainable. It requires ongoing monitoring and assessment of aquifer and environmental responses prior to and during groundwater abstraction, while attempting to meet water demands. Regional and local aquifer investigations are required during scheme design and development stages, with monitoring, operations and maintenance (O&M) objectives and protocols being adhered to during long term scheme operation. Aspects of wellfield design and development are further explained in the Guidance Document for Development of a Groundwater Scheme (WRC, 2022) and should be considered in conjunction with this document.

This document deals with short term and long-term operations, maintenance, and monitoring activities and sound groundwater scheme management principles. Day-to-day O&M is a critical element of groundwater scheme management. It entails routine tasks carried out when operating a groundwater scheme, such as maintaining infrastructure (pipes, pumps, etc.), monitoring groundwater levels, abstraction volumes, groundwater quality and water demand. Of importance is how this data collection is transformed into information in support of proactive resource and scheme management. In most cases, it is failure of O&M rather than failure of the groundwater resource that leads to unsuccessful groundwater schemes. Basic O&M is absolutely necessary for sustainable wellfield operation and scheme longevity.

Aquifer Economics

Water is a commodity and must be treated as an economic asset. Above being a basic human need, water provides many additional values from environmental and social perspectives, and people are generally willing to pay for improved quality and quantity of water. It is important to attain full cost recovery for the expenses associated with groundwater scheme development, operation, and continued assurance of groundwater quality and quantity. Therefore, the economic value of groundwater depends on the use (anthropogenic) and non-use (environmental) valuation of the aquifer, the engineering and specialist costs associated with developing and utilising the resource, as well as the demand and outputs of the resource's use (e.g. rural or municipal supply, mining, industrial or agricultural use).

Monitoring, Data Management and Evaluation

The above aspects are underpinned and enabled by ongoing and iterative monitoring of appropriate parameters at representative locations at the correct time, through well-established monitoring and O&M protocols. This will provide information to assess and evaluate compliance against management goals with respect to aquifer protection, aquifer utilisation and resource valuation. Reporting against these objectives in a feedback loop results in well informed decision making, adaption, and update of strategies and management plans, actioned through the implementation of decisions on an ongoing basis.

Groundwater related data can be collected through different techniques, in many forms and from various sources. Traditional methods of data acquisition include field observations (such as borehole drilling, water level monitoring and water quality sampling), hydrocensus, maps, and more modern techniques such as remote sensing, Global Navigation Satellite System (GNSS) and computer-based models. The capturing, storage, transfer, and utilisation of data should be integrated and standardised as best as possible. This is outlined in the Guidance Document on Groundwater Data Collection (WRC, 2022).

2.2 AQUIFER UTILISATION AND WELLFIELD DESIGN

The Aquifer Utilisation aspect, i.e. groundwater scheme development and operation, comprises various principles, requirements, and unknowns that together need to inform decisions toward optimal use of the resource and sustainable function of the scheme. Groundwater scheme design becomes pertinent to how the scheme will be operated and managed in the long term. The considerations listed below have high importance in groundwater scheme design, development, and management.

Supply-demand and consumer relationship – understanding the consumer relationships is important to inform demand from a scheme in terms of volume and quality of water supply. An aspect of scheme management (regardless of scheme size) includes an understanding of the volumes that can be supplied from a scheme, at what times, and with what level of quality and quantity assurance. Demand and supply should be considered temporal and spatial factors which are limited by the environment. For example, some boreholes in a wellfield might provide water with a different quality and quantity than other boreholes in the same wellfield. In such an instance, it may be necessary to pump different yields of different quality from various clusters or “managed units” in the wellfield while still meeting demand and providing control on regional water levels, water quality and economics of groundwater use.

Demand informs storage patterns allowing for planned operation of a scheme, such that the wellfield (or a single borehole) does not respond directly to demand but rather the water in surface storage does. Understanding the implications thereof allows for routine operation, longer pumping times (as a best practice) and extended lifespans of equipment performance. The demand from a scheme may be dynamic with various changes in seasonal or daily trends. For example, demand is higher in summer than in winter, requiring an adjustment of the way the scheme is operated.

Aquifer characteristics and responses – understanding aquifer characteristics is integral to scheme management. An aquifer’s response to abstraction and recharge will manifest in local and regional groundwater levels. Aquifer type, recharge mechanisms, aquifer heterogeneity, presence of preferential flow paths and location of the scheme within the aquifer influence temporal and spatial responses in groundwater that may influence whether supply of required volumes can be sustained. Aquifer heterogeneity may split the aquifer into different units with varying properties, yields, water quality or water level responses. This reiterates the need for monitoring, modelling, and evaluating. Water quality is an inherent, dynamic property of an aquifer (or smaller aquifer units) and poses management challenges in terms of O&M (fouling, scaling, corrosion, and deterioration) and consumer relations (in terms of aesthetics and health), with potential implications for aquifer economics (treatment costs) and resource valuation.

Scheme design and layout – scheme design and layout should allow for energy efficiency, e.g. larger distances require larger reticulation networks to transmit water with higher energy demands. Electricity tariffs and supply concerns have implications on resource valuations, leading to more expensive groundwater schemes. Location of treatment systems and waste or by-products generated from treatment processes may pose environmental risks and financial limitations and require due consideration. The overall spatial extent of the scheme must be mindful of present and future land uses during initial scheme construction and long-term operation.

Design and layout must allow for optimised scheme operation. Boreholes should not be so close to each other that it results in borehole interference, leading to increased drawdown, loss of supply and potentially unforeseen environmental impacts. Water level and water quality monitoring sites must be strategically placed so that the required information can be obtained for decision-making and management. In light of electricity supply concerns and O&M-related downtime, the scheme may require backup or stand-by components for assurance of supply. Scheme design and layout must be mindful of O&M and monitoring objectives through robust planning and development of adaptable systems and procedures.

Design of scheme components – design of individual scheme components has direct bearing on the scheme’s performance as a whole and management requires a clear understanding of the design criteria for individual and collective components of the scheme. Borehole construction and pump installation details inform how a borehole can be optimally pumped to assure yield and minimise wear and tear. Operational water levels (OWLs) ideally should not be below the top of screen elevations or below large water strikes. One way to manage this is to pump more boreholes at lower individual yields, creating less drawdown while maintaining overall yield, optimum pump performance and energy consumption – this again informs pumping clusters and management units and allows for regional groundwater level control. Individual scheme components should be easily accessible for monitoring and maintenance through up-to-date maintenance management plans (MMPs). These can be simple for smaller rural supply schemes or more complex for large scale schemes.

Surrounding environment and other users – the surrounding environment, whether natural or anthropogenic, may pose threats of contamination or pollution. The scheme design and operation should account for hazards that may pose such threats and require mitigation to manage risks. Ongoing water quality monitoring and transport modelling is useful to evaluate contaminant behaviour. Ecological requirements need to be outlined and all possible impacts from abstraction, recharge, and changing water quality should be incorporated into the monitoring objectives throughout all phases of scheme development and operation.

Decisions and designs adopted in the development phase of the scheme should incorporate the long-term scheme utilisation. Once the principles above have been given due consideration and a groundwater scheme is ready to be developed, there are certain factors in its design and construction that require detailed consideration. See Guidance Document for Development of a Groundwater Scheme (WRC, 2022) for more information. Broad topics of scheme development that interlink with scheme management are explored below.

2.2.1 Location

- Wellfield and individual borehole locations require meticulous design and planning. The wellfield or borehole must target suitable aquifer(s) in terms of the quantity and quality of water that is required.
- Individual boreholes should target suitable structures or high yielding zones to maximise potential yield for a scheme to meet the demand.
- The wellfield or individual borehole should not be located so that treatment systems, storage, and consumers are at great distances. This will create an expensive and energy-intensive groundwater scheme as stronger/larger pumps and larger reticulation networks are required.
- Location is also important for efficient O&M activities to take place. Boreholes should not be too far apart that vast distances need to be travelled by field staff, however, these should be far enough from each other so that borehole interference is managed or avoided.
- The natural and/or built-up environment are also to be considered when deciding on a borehole or wellfield location. Access and landownership, proximity to water courses (wetlands, springs, seeps, rivers, etc.), potential contamination sources, service utilities and other groundwater users should be considered. These all influence the way the scheme is operated and managed, and often have associated legislative and regulatory conditions and controls.
- Groundwater scheme development should integrate with local and regional spatial development frameworks. Land use planning is an essential step in protecting a groundwater resource from potential contamination. Current surrounding land uses should be known and understood, while future land uses should be predicted and planned for so that potential sources of contamination can be identified and monitored for early warning systems under an effective O&M and monitoring protocol.

2.2.2 Drilling

- Appropriate and correct drilling techniques are important to avoid unproductive boreholes with high head losses, decreased yields, and shortened lifespans. There are numerous techniques available for different geological settings, and a professional hydrogeologist should be consulted to advise on which techniques are most suitable in different geological terrains.
- Most commonly, boreholes drilled in hard-rock aquifers are drilled using some variation of rotary percussion techniques while boreholes in unconsolidated aquifers are drilled using mud rotary techniques. Correctly selected drilling techniques and equipment not only have economic implications but can be the difference between successfully targeting an aquifer or having a failed borehole/wellfield.
- Drilling equipment, such as drill bits, pumps, compressors, etc. should be well maintained to avoid drilling issues such as skew and/or narrowing boreholes, which will make casing and pump installation, as well as future borehole maintenance, difficult.

2.2.3 Borehole Design and Construction

- Boreholes require adequate underground construction to prevent collapse, minimise head losses, ensure borehole efficiency and prolonged lifespan. The design and construction should be overseen by a professional hydrogeologist (see **Figure 2-2**).
- Correct borehole and casing diameters should be chosen to accommodate pump size, main risers, borehole monitoring equipment (such as dip tubes or downhole automatic loggers/probes) so that production is not hindered, and O&M and monitoring can be carried out efficiently.
- Screen aperture sizes, along with gravel pack installation, should be carefully chosen based on the geology encountered. Screen aperture and gravel pack size should be large enough to allow for efficient horizontal flow and entrance velocity of groundwater into the borehole, while preventing aquifer material from clogging the gravel pack or screens or entering the borehole and silting it up and damaging the pump.
- Various screen types and designs exist, such as slotted or mesh wire, or stainless steel and uPVC, all of which have a set of advantages and disadvantages that have implications for O&M procedures. Certain screen types can be subject to more rigorous or aggressive cleaning methods, while others may provide larger area of inflow. Casing joints should maintain a high degree of integrity.
- Aquifer hydrochemistry also plays a role in borehole design and construction. In certain areas biofouling and clogging is a common issue, while in others lime scaling or corrosion is a greater concern. Materials used should not be fatally susceptible to the water quality issues at hand.

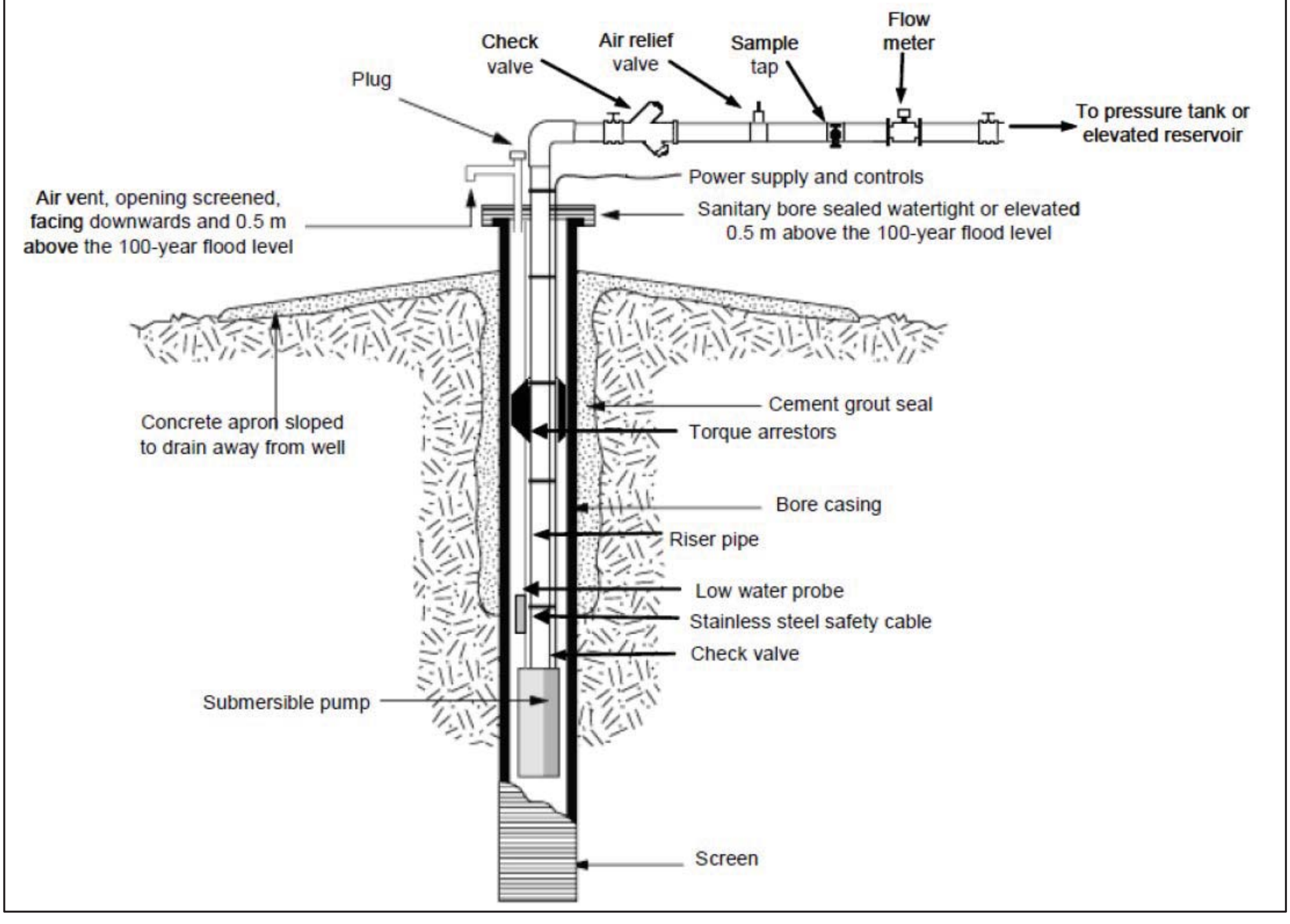

Figure 2-2 **Basic components of an adequately designed and constructed borehole (Ministry of Health, 2010).**

- The depth of screened intervals should correlate with depth of water strikes or water bearing units/layers, while solid casing and grouting (when applicable) seal off certain undesirable sections to prevent hydraulic connection between aquifers or cross contamination. Well-positioned screens will improve borehole efficiency and isolation of undesirable units will preserve water quality. Often in hard rock aquifers, the borehole is left open without screens or gravel pack and flow into the borehole occurs through open fractures.
- As best practice, pump depths should not be below screens or main water strikes to avoid drawing the water level below the screens or dewatering water strikes. Dewatering of fractures or pore spaces may result in compaction and loss of aquifer storage capacity, as well as weathering and silting of fractures which decreases transmissivity and yield.
- Additionally, exposing the aquifer to air (by drawing down the water level) exacerbates weathering, clogging, biofouling and scaling/precipitation of the borehole walls. This all leads to more frequent O&M requirements and loss of yields, and thus should be monitored, and avoided as best as possible. The same occurs on pump and reticulation infrastructure.
- Adequate borehole headworks and wellhead design are important. A borehole poses a direct and open pathway for contaminants to reach the groundwater with little to no protection. A sanitary seal, properly constructed wellhead and collar prevent the rapid ingress of contaminants in the immediate vicinity of the borehole.
- If artesian conditions are encountered, borehole construction should prevent any intermixing of waters with different quality and pressure through selective grouting of casing. The wellhead shall prevent any uncontrolled free-flowing water at surface.

2.2.4 Borehole Pumping

- Due to combined properties of the aquifer and effects of drilling and construction, the borehole will have some yield and efficiency. Test-pumping (see SANS 10299-4:2003) allows for the assessment of the yield and efficiency through the quantification of parameters such as transmissivity, radius of influence, storage, specific capacity (S_C), etc. These parameters are important for long term O&M and management of a groundwater scheme and should be quantified through regular test-pumping analysis by a hydrogeologist.
- Specific Capacity is a useful and important parameter in terms of O&M. It is defined by the aquifer and well (borehole) head losses which are related to the impacts of drilling and borehole construction. Each borehole in a wellfield should be allocated a baseline S_C to which routine S_C assessments can be compared. It is expected that the S_C of a borehole decreases over time due to clogging and biofouling, etc. and borehole cleaning and rehabilitation should be carried out regularly.
- Another important parameter is the radius of influence that a pumped borehole may achieve. The law of superposition implies that a greater drawdown is achieved in a borehole when multiple boreholes in the vicinity are pumping, which may lead to unexpected loss of yield due to borehole interference. Therefore, the radius of influence of a borehole must be known so unexpected drawdown can be avoided. This is particularly important for private users who may impact each other as this becomes difficult to manage and monitor, hence, communication between neighbouring users/schemes is vital.
- Due to heterogeneities in the aquifer, the best way to verify the impacts of borehole interference is through wellfield-scale pumping tests. This will inform on the best operating practices to ensure wellfield and resource sustainability and longevity. Borehole interference may also occur in separate privately owned boreholes which is often overlooked by individual users.
- Drawdown occurring at some distance from a borehole may be affecting the natural environment, such as springs, wetlands and groundwater dependent ecosystems. These effects are also important to monitor and manage for environmental protection.
- Once a recommended yield has been established by a hydrogeologist, a suitable pump to be installed at a specific depth is selected (based on pump efficiency and depth of water strikes). The pump set should be energy efficient while meeting the stipulated recommended yield and considering continuity of power supply. This ensures low operating costs and less frequent maintenance.

- Provisions should be taken for ease of testing and diagnostics of the pump and control system as part of the O&M objectives. Some pump types, such as surface mounted pumps, offer easier maintenance compared to others, such as submersible pumps which need to be removed from the borehole. Pressure and electrical loads at different flow rates should be checked as a baseline and routinely thereafter for comparison and monitoring of pump performance.
- Pump and electrical failures occur often, and provisions should be taken to provide back-up pumps and power sources to ensure that demand can be met. Spare pumps may be kept, although removal and installation may take some time and hinder supply. Fully equipped, back-up boreholes are a better alternative where possible. Back-up or stand-by and production boreholes should alternate regularly to maintain functionality. Generators or renewable energy capacitors can offer back-up electrical supply.

2.2.5 Water Quality

- The baseline water quality of the aquifer should be established before production occurs. This can be done through hydrochemical analysis of water sampled from the boreholes or wellfield. The water quality depends on the natural chemistry of the water and the host rock, as well as external sources such as anthropogenic contamination. The hydrochemical analysis should be carried out at a South African National Accreditation System (SANAS) accredited laboratory and interpreted by a hydrogeologist.
- Water quality needs to be evaluated in terms of the end user's needs. Water treatment may be required to meet the needs of the water use. Water treatment can become costly and temporal changes in water quality are frequently over looked in groundwater schemes.
- To maintain a standard of water quality, routine monitoring of raw and treated water is required. For drinking water standards, see SANS 241. Through comparison with the baseline water quality, the change in water quality over time can be assessed. Assessment of the raw water will inform dynamic aquifer conditions, potential contamination, and ultimately whether changes to treatment processes and capacity are required.
- Analysis of treated water will inform whether groundwater is suitable for its intended use, and whether there is degradation and inefficiency in the treatment processes which may need maintenance or optimisation.
- A water quality risk assessment should be carried out for identification, investigation, verification, and analysis of hazards in the local aquifer, catchment and water supply system. Identification of these hazards, such as nearby landfills or industrial zones, are important to consider in the operation and management of the groundwater scheme and require specific monitoring networks for early warning detection and proactive, rather than reactive, decision-making action and management. This feeds into the O&M and monitoring protocols as well as aspects of aquifer protection (see Guidance Document for Protection Zones [Delineation and Protection] [WRC, 2022]).
- Water treatment processes generally result in some losses. If losses are present, these need to be quantified and incorporated into the volume abstracted so that demand is still met. Additionally, by-products may also be generated which may alter the quality of the water. These by-products may be harmful in elevated concentrations and chemical reactions involved should be understood and monitored.
- If production occurs from multiple boreholes, the blended (combined) water quality should be monitored. Dilution, concentration, and other reactions may occur in the blended water which may alter the treatment requirements. Therefore, monitoring of flow and water quality prior to and post treatment should occur.
- Water treatment processes also generate waste which may pose a contamination risk. Waste streams should be carefully managed and kept separate from clean water streams to avoid contamination. Routine cleaning and maintenance of treatment equipment will ensure that treatment efficacy remains high. Waste products shall be properly disposed of so that the environmental impacts are minimised.
- If groundwater is used for industrial purposes, the use may alter the hydrochemistry of processed waters. The reactions and changes imposed on the water quality by the industrial processes must be

understood, and the final water quality of the processed waters should be monitored, treated, and appropriately disposed.

2.2.6 Storage and Reticulation

- Tanks and pipes are needed to move water from the source to consumer, so design and management thereof is integral. Most groundwater schemes require surface storage to function optimally, especially when water treatment systems are in place. This provides a buffer between borehole supply, treatment plants and reservoirs to avoid boreholes supplying the full yield for treatment during peak demand times.
- The storage will deplete during peak demand times and be restored during low demand. Understanding and managing this balance is important, and the water level in storage should be monitored.
- The size of the storage will depend on the demand and the treatment capacity (if treatment systems are in place). Storage that is too small may result in pumps turning on and off too regularly, an undesirable practice for borehole efficiency and pump maintenance. Volume of storage should also accommodate for downtime during maintenance of other scheme components.
- Water entering storage should mix well with water already in the storage tank to ensure that water quality remains uniform, especially after treatment.
- Storage tanks should also have some form of control so that they do not overflow when they are full, as well as a means to be drained for cleaning and maintenance. Permanent ladders or access points should be installed and maintained to allow for the latter, and their design should prevent ponding and inflow of unwanted water to avoid contamination.
- The same goes for reticulation systems. The design and size of the reticulation network needs to be able to meet the demand while minimising friction losses. The design should allow for maintenance and repairs while minimising disruption to supply, such as using valves and by-passes to isolate certain sections.
- Monitoring pressure changes in the system may identify leaks and friction losses. Additionally, increased pressures lead to increased leakage rates.

2.2.7 Environment and Legislation

- Groundwater schemes should also factor in environmental control and mitigation measures. Incident response and reporting procedures should be in place for potential spills or other environmental damages which may occur.
- Site and risk assessments, and baseline ecological/environmental data collection should be undertaken, especially in environmentally sensitive areas, to assess whether groundwater scheme development and operation is resulting in any adverse environmental impacts. For example, groundwater abstraction may result in wetland degradation and subsequent loss of habitat. Ecological offsets are often required when a project has unavoidable residual environmental impacts and activities that trigger the National Environment Management Act (NEMA) No. 107 of 1998.
- Monitoring and operation should consider the regulatory requirements of the water use, according to the National Water Act (NWA), Act No. 36 of 1998.
    - Water uses under Section 21 of the NWA require licenses which have specific conditions in terms of volume and water quality and the environment. These need to be monitored and complied with.
    - Schedule 1 use is generally a low volume, low-impact activity that is consistent with domestic/private use (household use, gardening, or small-scale non-commercial food garden irrigation), livestock watering, recreational use, and the use of water for emergencies (including fires or droughts).

- General Authorisations are issued to permit the use of groundwater without a licence. This qualifies if the intended use falls below the limits necessary for a water use license and comply with conditions set out in the gazetted General Authorisation.
- Existing Lawful Use (ELU) – this allows people or organisations, who were using groundwater water for commercial purposes before the NWA came into effect in 1998, to continue using the groundwater (provided it is registered, verified and validated) until such time that licensing becomes compulsory.

CHAPTER 3: TYPES OF GROUNDWATER SCHEMES

3.1 INTRODUCTION

A groundwater scheme may be as simple as a single borehole with a hand pump supplying a rural village or a large aquifer with over 100 boreholes, such as the Atlantis Water Resource Management Scheme. Development of a groundwater scheme can be straightforward, in the case of a single borehole, or highly complex, in the case of a bulk water supply scheme. Steps to the design and development of a groundwater scheme are covered in the Guidance Document to Groundwater Scheme Development (WRC, 2022), while concepts of scheme development relating to scheme management are discussed in **Chapter 2.**

Although the basic O&M principles are universally applicable across all groundwater schemes, the more detailed O&M tasks are location-specific as a scheme's scale can differ in complexity, and overall systems and technologies used (Dillon, 2019; SADC-GMI, 2019). The successful implementation of long-term routine monitoring and O&M procedures necessary to keep a groundwater source or wellfield running is highly dependent on the application of management principles by responsible institutions, whether these are private individuals, local O&M custodians, owners or Water Service Providers (WSPs).

The key is the implementation of realistic O&M procedures tailored toward specific schemes in individual localised circumstances (Cobbing et al., 2015). This chapter describes the various groundwater schemes that are commonly encountered in South Africa and the basic components that form important parts of O&M and monitoring, which are summarised in **Table 3-1**.

3.2 RURAL GROUNDWATER SCHEME

There are many areas in South Africa where it is not practical or economical to have surface water supply schemes because there either is little to no surface water available, or development costs are too high relative to the low supply required (Meyer, 2002). This is often the case for many rural areas and groundwater is the only alternative.

Rural groundwater schemes generally consist of one or a few boreholes which provide water supply to a few individuals or a community. These boreholes may have been drilled by the local municipality to fulfil service delivery duties, by mining or other industry companies that fulfil community outreach and social responsibilities, or by the local individuals themselves who have invested their private funds. These boreholes are often centrally placed with low-cost infrastructure installed, ranging from hand pumps (**Figure 3-1**) with water being carted using containers, to low-yielding pumps (electrical, diesel, solar or wind pumps) servicing a few storage tanks with a small reticulation network of some strategically placed communal taps. Often, if a borehole is owned by a community member or group of members then water is sold to other members of the community or neighbouring villages. Rural areas are often riddled with multiple boreholes that are in proximity but are drilled and operated in isolation, even though the collective effect will be that of a larger groundwater scheme. Sometimes spring discharge is also captured and used for supply.

Treatment is often non-existent to very basic, such as boiling before use, chlorination tablets, or aeration. Groundwater is normally abstracted for potable (sanitation and hygiene) and domestic use, hence, there is a reliance on the aquifer to offer a treatment step, trusting that groundwater abstracted is of a good standard. SANS 241 Drinking Water Quality Standards and South African Water Quality Guidelines (SAWQG) for Domestic Use are applicable.

These types of groundwater schemes are usually operated and managed by members of the community who are designated specific tasks to carry out. For example, a person will be designated as a pump operator and their duty is to turn the pump on and off when required. The rural groundwater scheme is comprehensively covered in the NORAD Toolkit and should be viewed in conjunction with this document. The key target for rural O&M procedures/tasks is simplicity, less specialised equipment that do not require specialist O&M technicians or spares, and a larger involvement of local community custodianship and maintenance/monitoring roles. Ultimately, citizen science should be encouraged.

Figure 3-1 **An example of a rural groundwater supply scheme with a hand pump (left) and JoJo tank used for storage (right).**

3.3 PRIVATE GROUNDWATER SCHEME

A private groundwater scheme, constituting decentralised supply (Seyler, 2019) occurs on a similar scale as rural supply schemes, however, they are owned by and supply a private entity, such as a household (Schedule 1 use according to NWA), body corporate, or small holdings, usually for small scale irrigation, recreational and/or potable use. These can occur in agricultural holdings, areas where municipal service infrastructure is lacking, or middle to high income areas, such as private households or residential estates which use groundwater as backup or alternative supply for irrigation of garden space and common areas, recreational, domestic or potable use. Although larger in terms of groundwater use volumes, golf courses or shopping malls (and other larger private establishments) may be included as private groundwater users.

Private groundwater schemes normally consist of one or a few boreholes with relatively low yielding submersible pumps or wellpoints, with abstraction volumes often within or slightly exceeding General Authorization (GA) limits, and small to medium storage capacities at surface (see **Figure 3-2** and **Figure 3-3**). Monitoring data is often lacking but maintenance and operations are relatively well funded, while high level groundwater management can be lacking, especially in cases where usage is not registered or licensed.

Treatment steps may be non-existent where groundwater use is not highly quality-sensitive (such as garden irrigation). In cases where treatment is applicable, SANS 241 Drinking Water Quality Standards and South African Water Quality Guidelines (SAWQG) for Domestic, Irrigation or Recreational Use may apply depending on the use. Treatment systems are usually small and innovative.

The decentralised, private groundwater scheme has the advantage that numerous small-scale abstractions occur over an aquifer which is more effective in harnessing groundwater as opposed to a few points where bulk abstraction occurs with high amounts of drawdown and volume abstracted. However, this must be carefully monitored and managed to avoid the effects of competition for groundwater. It also relieves stress on municipal surface water supply and reticulation networks, especially in times of drought, although this reduced demand means that municipal water revenue is decreased and alternative charges for sewerage, etc. are required for cost recovery (see **Section 2.1**) (Seyler, 2019).

Figure 3-2 A private groundwater scheme at a household where a borehole is used for non-potable, domestic supply. The borehole headworks can be seen with a large JoJo tank for storage, as well as a small filter and treatment system installed on the wall.

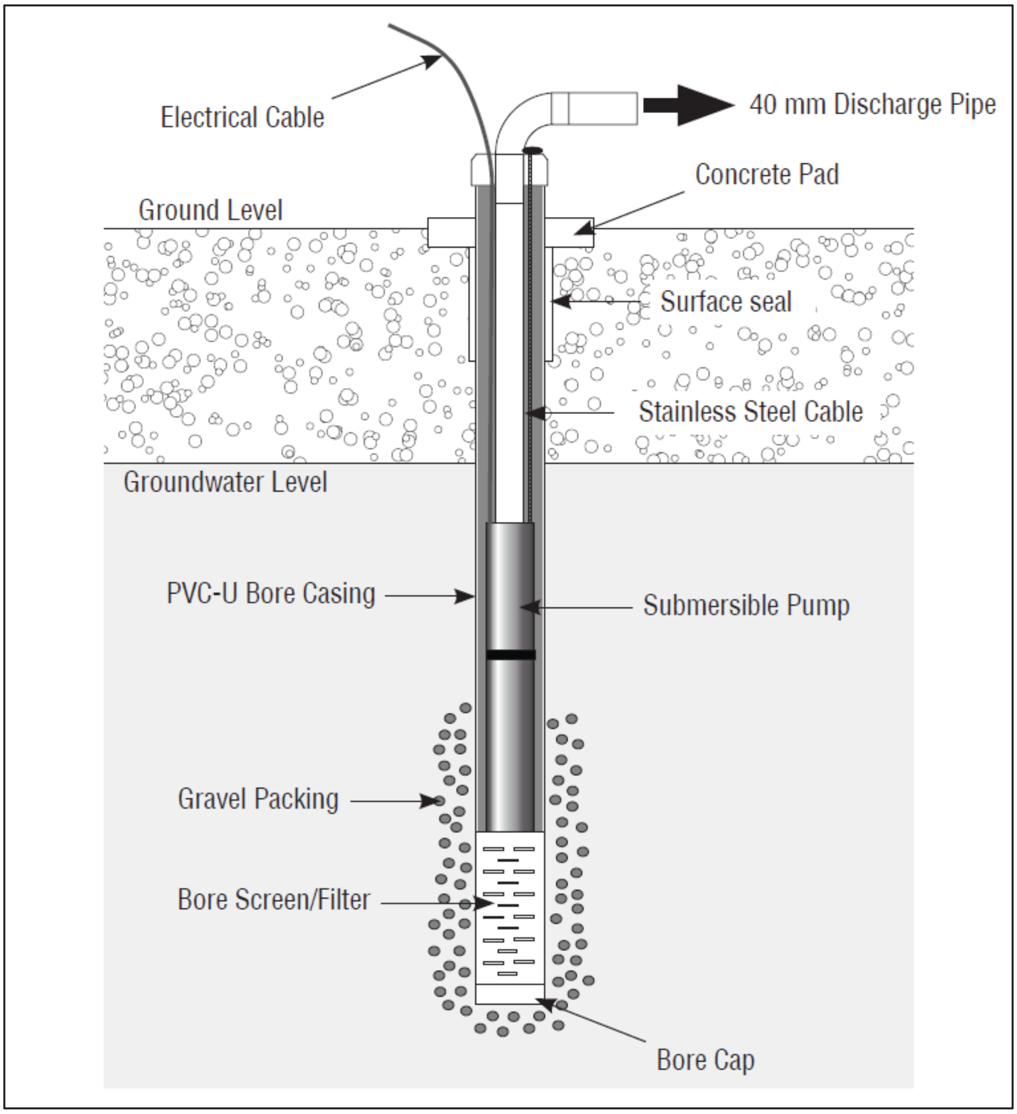

Figure 3-3 **General borehole construction for low yielding private and rural groundwater schemes with an electric submersible pump (National Uniform Drillers Licensing Committee, 2012). Little to no provisions are made for extensive monitoring.**

3.4 COMMERCIAL AGRICULTURE GROUNDWATER SCHEMES

Large scale agricultural and livestock farming practices require large volumes of water to maintain crop and livestock demands. These large parcels of land usually have numerous boreholes that are pumped simultaneously into concrete or earth fill storage dams which often have a large surface water component. Groundwater is commonly used to augment the surface water supply (**Figure 3-4**). Depending on size and scale of the farming activity and the property, abstraction volumes can vary from within GA limits to volumes amounting to millions of cubic meters per year that require Water Use Licences (WUL).

The agricultural sector frequently drills boreholes and develops groundwater schemes unregulated and without consultation from groundwater specialists, resulting in misinterpretation of drilling results, little to no record of drilling data and poorly executed borehole yield tests ("farmer tests") which do not meet national standards (SANS 10299-4:2003). This may lead to uncontrolled and unregulated large-scale usage of groundwater resources, and through mismanagement, boreholes "running dry" over time or the larger resource being stressed and depleted, and other important components such as the Reserve (ecological and basic human needs) are adversely impacted.

Depending on available financial budgets, these schemes can have low-cost infrastructure or modern, automated electronic systems. The irrigation and livestock watering are often not quality sensitive and treatment systems are reduced to settlement in storage. SAWQG for Irrigation and Livestock Watering Use may apply. Smaller scale treatment may exist if a component of the abstraction is used for potable/domestic use where SANS 241 Drinking Water Quality Standards and SAWQG for Domestic Use may apply. Low level management usually consists of one or a few farm workers who are designated operators, but data collection (in terms of water levels, abstraction volumes and water quality) is often lacking, even though high number of boreholes offer good monitoring and management opportunities. There can be forms of high-level management with collaboration between farmers, agricultural associations, irrigation boards and/or water user associations, but cases of unregistered/unlicensed use are relatively high.

Figure 3-4 **An example of a commercial farming groundwater supply scheme. (Top and bottom left) Boreholes are often used to augment storage in surface water bodies used for irrigation. (Right) Typical borehole infrastructure and headworks for irrigation supply.**

3.5 INDUSTRIAL GROUNDWATER SCHEME

Many businesses and factories use groundwater supply for processes which occur on site. Although these schemes are also privately owned, the intended use is different and so the management approach may differ. It includes industries such as refineries, chemical plants, fisheries, textiles, transport, health services, waste treatment and recycling, engineering, and utilities, e.g. power generation (see **Figure 3-5**). The Industrial Policy Action Plan (IPAP) 2018/19-2020/21 (DTIC, 2018) also sets out intentions of expanding the manufacturing sector which may increase industrial groundwater use across the country.

Groundwater is abstracted for use in industrial processes with some type of wastewater generated, and there is usually potential for contamination. These schemes may vary in size from one to numerous boreholes, depending on size of the operation and the water demand, with low to high-cost infrastructure and monitoring equipment installed. Storage units may range from JoJo tanks, to concrete or steel reservoirs, to lined earthfill dams. Groundwater use is often quality sensitive, depending on the process, so treatment systems may be large and complex and SAWQG for Industrial Use may apply as a minimum. Usually, there are WUL conditions for the processed water quality and treatment may be required prior to disposal or discharge.

Generally, monitoring boreholes (**Figure 3-6**) are a license requirement, and schemes consisting of monitoring boreholes only (no abstraction) should not be discounted as they will yield important data pertaining to water levels and water quality that inform management and decision-making. Due to nature of operations the groundwater monitoring, data collation, scheme operations and maintenance, and high-level groundwater management is usually of a relatively better standard and frequently undergoes audits for compliance.

Figure 3-5 **An industrial groundwater scheme where water is used in industrial processes, such as the generation of electricity using renewable solar energy. (Top left) Processed water is treated prior to discharge. (Top right) A monitoring borehole is shown in the foreground used for groundwater quality compliance monitoring. (Bottom) Array of solar panels used for generation of electricity.**

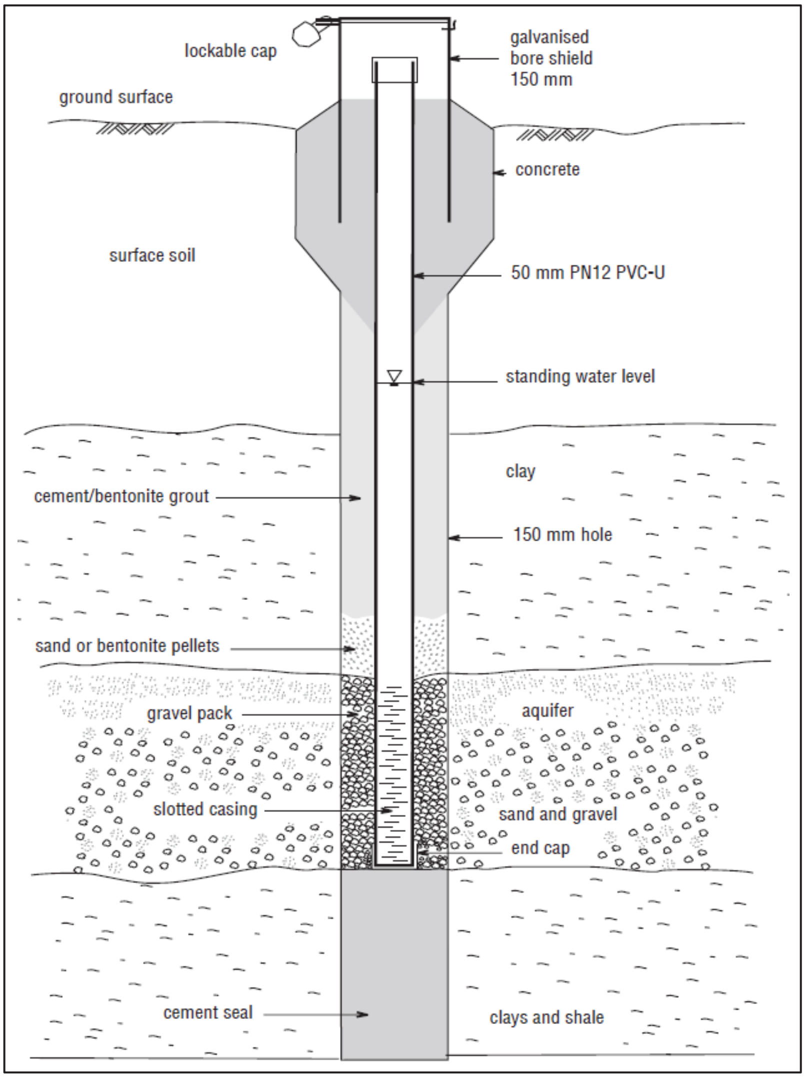

Figure 3-6 **Typical monitoring borehole construction used in monitoring for potential contamination (National Uniform Drillers Licensing Committee, 2012).**

3.6 MUNICIPAL/BULK WATER SUPPLY SCHEMES

Many towns in South Africa, particularly away from the metropole areas, depend on groundwater supply for municipal water services, and, in recent times, the metropole areas have looked towards using groundwater for large scale augmentation of surface water supplies as well. These groundwater schemes serve the public for industrial, agricultural, domestic, and potable water use through municipal infrastructure and are funded by government revenue.

Municipal groundwater schemes can vary in scale from one or a few boreholes supplying small, isolated towns, to large networks of high yielding production and monitoring boreholes in metropole areas where demand and budget is far higher (see **Figure 3-7** and **Figure 3-8**). These schemes are generally regional, or local government owned and operated, with appointment of consultants to carry out various tasks (such as drilling, monitoring or maintenance) being common practice. Operations and maintenance are highly dependent on budget allocations, but both low and high-level management are usually in place. In highly urbanised areas, scheme configurations can become a complex network of boreholes and wellfields, water treatment and reticulation configurations, monitoring systems, and multiple storage infrastructures, often augmenting bulk surface water supply in a conjunctive use approach. In some cases, extensive monitoring networks may include specialist monitoring components such as ecological and wetland monitoring, remote sensing, climate and recharge monitoring, and even global satellite navigation systems (GNSS) to monitor land subsidence.

Figure 3-7 **Example of a municipal bulk water scheme: The City of Cape Town Table Mountain Group Aquifers Steenbras Wellfield. A) Pump house structure. B) Installation of pump equipment during the construction phase by a contractor. C) Positive displacement pump installed at the production boreholes. D) Groundwater infrastructure pipeline (green) at a river crossing. E) Wellfield pipeline infrastructure development phase.**

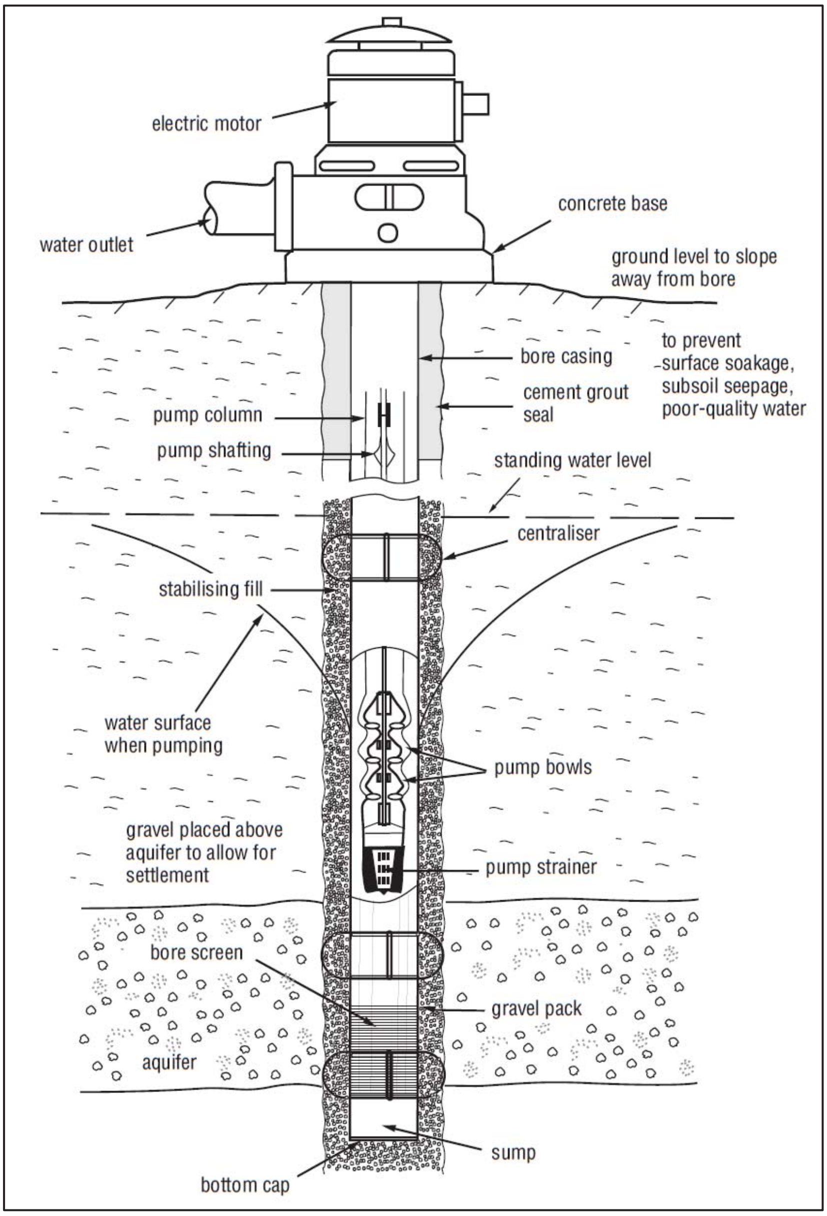

Figure 3-8 **Example of typical borehole construction for a high yielding, municipal/bulk water supply borehole (National Uniform Drillers Licensing Committee, 2012).**

3.7 MANAGED AQUIFER RECHARGE SCHEME

The National Artificial Recharge Strategy defines artificial recharge as storing water in the subsurface for later use, usually by allowing water to infiltrate into the subsurface through infiltration basins (**Figure 3-9**) or by injecting water into the aquifer using boreholes (DWAF, 2007b). Water is purposefully stored in aquifers and abstracted from abstraction boreholes downgradient of the recharge location. This forms part of the concept of Water Banking, which is defined as "…the process of storing surplus water to help maintain sufficient water for our needs, to be drawn on when demand requires" (DWA, 2010).

This is not common practice in South Africa with only few Artificial Recharge schemes existing: Atlantis Water Resource Management Scheme [AWRMS] and Elandsfontein Aquifer System (Western Cape); Kharkams, Vanwyksvlei and Williston (Northern Cape); Polokwane (Limpopo); another being developed (Cape Flats Aquifer Management Scheme); and a few existing pilot schemes such as Calvinia (Northern Cape); Sedgefield, Plettenberg Bay and Hermanus (Western Cape). Additionally, there are three existing mine related MAR Schemes namely Sishen, Kolomela, Eland Platinum Mine, and Elandsfontyn phosphate mine (Ebrahim et. al., 2020). The technology is underutilised, but with proper groundwater management it can contribute greatly to maximising the use and sustainability of water resources and should be considered and implemented when possible.

These schemes often require large amounts of capital and meticulous science. They are generally government owned, funded and operated with extensive groundwater, engineering and other related specialists' inputs. There are generally more components than other groundwater schemes, and recharge waters are often stormwater or treated effluent, requiring transdisciplinary and interdepartmental collaboration between low and high-level management. Small scale or private MAR should not be overlooked, however, and it can be easily implemented on smaller scales as well, for example, sand dams utilised in conjunction with rainwater harvesting (see **Figure 3-10**).

Figure 3-9 An infiltration basin where treated effluent is allowed to infiltrate into the aquifer through MAR, forming part of the AWRMS.

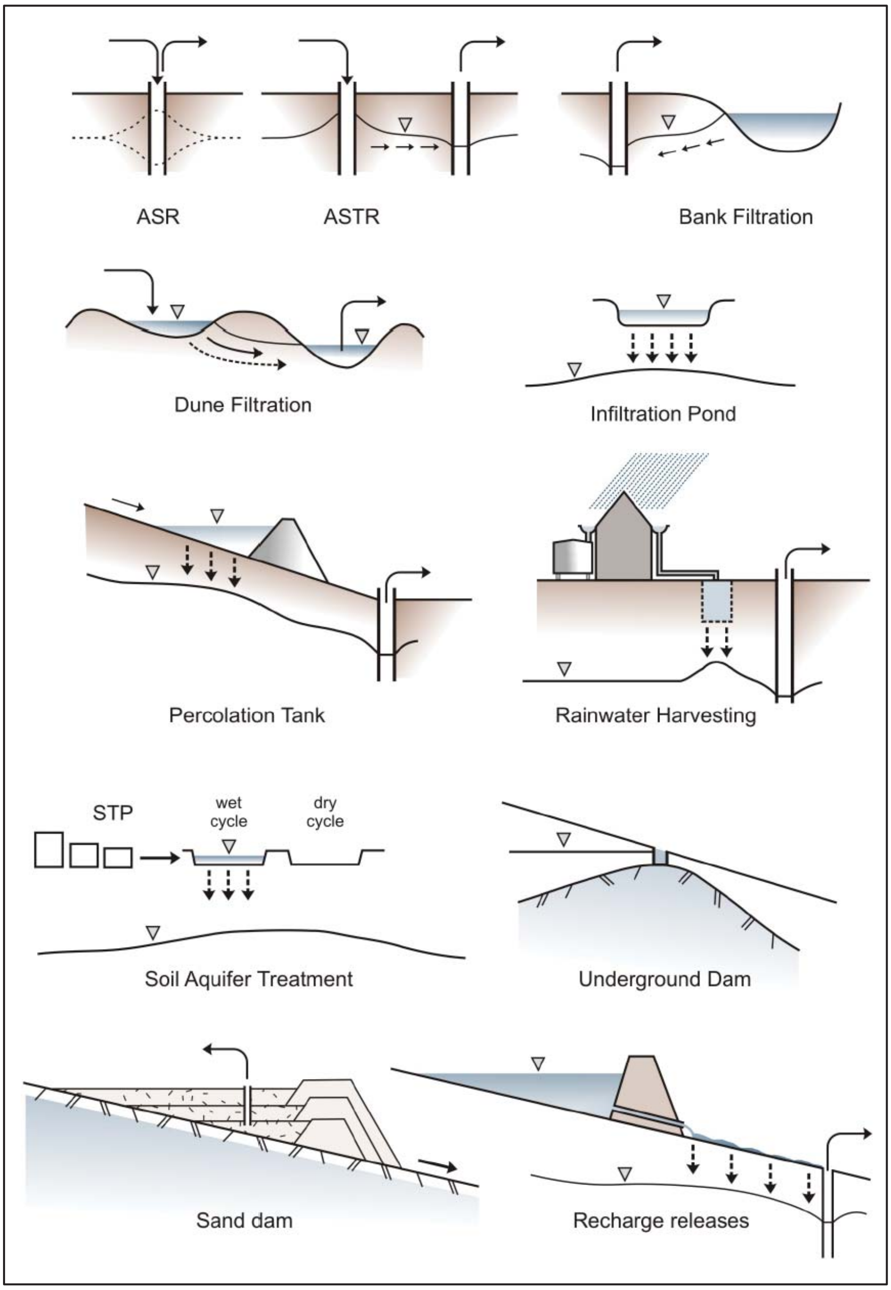

Figure 3-10 **Common methods of carrying out artificial recharge in a MAR scheme. Two major examples in South Africa include the AWRMS utilising the infiltration pond method, and the CFAMS utilising the aquifer storage transfer and recovery (ASTR) method.**

3.8 MINING AND CONSTRUCTION DEWATERING SCHEMES

When mines and construction sites require excavations or tunnelling into the subsurface, there is usually groundwater which seeps or flows into the excavation. Mines and constructions sites cannot operate if there is flooding, and so dewatering techniques are implemented (**Figure 3-11**). There are many different dewatering methods and techniques that can be employed, but they usually consist of strategically placed abstraction boreholes or a network of underground trenches, drains and pumps which capture and remove groundwater.

Dewatering volumes can be large, particularly with deep underground mines or large tunnels and it may be a long-term operation. The impacts of dewatering may be observed at large distances away from the activity, and if not properly monitored and managed may have detrimental effects on the environment. These schemes are generally well funded and engineered with high amount of specialist input. Large budgets and the critical nature of the dewatering activity means science, monitoring, maintenance, and operations (low level management) are generally excellent. High level management is usually highly involved, although there can be discontinuity due to sensitivity of the data. The abstracted water is usually discharged into the environment, used in the mining or construction processes, or provided as supply to nearby communities in which case it may become a rural or municipal groundwater scheme. Transparency regarding groundwater data, such as abstraction/dewatering volumes, water levels and water quality should always be encouraged.

Mining and construction dewatering schemes can vary greatly due to different problems that are encountered, and so the monitoring and management of these schemes are not covered in this document, only it is made apparent that these schemes do exist. WUL that are awarded govern the monitoring and operating of these schemes.

Figure 3-11 Example of an underground mine dewatering scheme where water is channelled to a central location and removed from the mine with large pumping systems.

Table 3-1 The basic components that are integral to the successful operation for the various types of groundwater schemes.

Groundwater Scheme Type	Borehole and Pump	Storage	Treatment	Reticulation	Aquifer Recharge
Rural	One or a few boreholes Mechanical pump (hand or wind) or submersible pump. Basic design and construction with little to no planning for monitoring. Groundwater source may be a spring rather than borehole	Plastic JoJo tank Steel or concrete reservoir Sometimes no storage	Non-existent or very basic (boiling before use, chlorination, or aeration) Reliance on the aquifer to offer a treatment step Usually potable use so SANS 241 Drinking Water Quality Standards and South African Water Quality Guidelines (SAWQG) for Domestic Use are applicable	Low budget and made of steel or HDPE/PVC/uPVC piping Water often collected straight from source (e.g. hand pump), or from strategically placed communal taps	-
Private	One or a few boreholes Electric pumps (usually submersible) Basic design and construction with little planning for extensive monitoring	JoJo tank Small concrete or earth fill dam, or water feature (e.g. private residential or golf estates)	Non-existent as use may not be quality sensitive (such as garden irrigation, etc.) SANS 241 Drinking Water Quality Standards may apply South African Water Quality Guidelines (SAWQG) for Domestic, Irrigation or Recreational Use may apply Treatment systems may be small and innovative	Small network of pipes to carry water from the borehole to treatment system, storage, or location use Low budget comprising of HDPE/PVC/uPVC piping	-
Commercial Agriculture	Numerous boreholes for backup and rotation of supply Electric, wind, or solar pumps Basic design and construction with minimal planning for monitoring unless budgets are high Large network of boreholes (operational and non-operational) which can serve as monitoring boreholes	In-channel, surface water fed earth fill dams augmented with groundwater Concrete reservoirs Large JoJo tanks	Depending on the crop or livestock, farming is often not very quality sensitive SAWQG for Irrigation and Livestock Watering may apply Small scale treatment if small component of groundwater is for potable use (SANS 241 Drinking Water Quality Standards)	Extensive network of pipes carry water from boreholes to treatment system, storage, or location of water use (irrigation/watering) Usually comprising of steel or HDPE/PVC/uPVC piping Booster pumps may be needed in some cases	-

Groundwater Scheme Type	Borehole and Pump	Storage	Treatment	Reticulation	Aquifer Recharge
Industrial	A few boreholes for back up supply Usually electric submersible pumps Design and construction often well planned with provision for monitoring Usually one or a few monitoring boreholes (upstream and downstream of regional groundwater flow) to monitor potential groundwater contamination	Often steel reservoirs or plastic JoJo tanks In some larger operations a lined, earth fill dam	May range from none to very complex, depending on specific process water quality requirements SAWQG for Industrial Use applies Portion of the abstracted groundwater may be used for potable consumption (SANS 241 Drinking Water Quality Standards) Processed waters may also require treatment before disposal, discharge, or reuse (treatment limits stipulated in license conditions)	Small or extensive network of pipes carry water from boreholes to treatment system, storage, or use Usually HDPE/PVC/uPVC piping or steel in larger operations	-
Municipal/ Bulk Water Supply	Numerous boreholes to ensure backup and rotation of supply Usually electric submersible pumps May be powered by solar or wind energy, particularly in smaller towns where services are lacking or where boreholes are drilled a distance away Design and construction often well planned with provision for monitoring Usually dedicated monitoring boreholes to assess aquifer response	Large steel or concrete reservoirs, or surface water dams augmented by groundwater supply Often multiple stages of storage are present along the supply line	Supply water for domestic and potable use (SANS 241 Drinking Water Quality Standards apply) Often multiple treatment stages with large treatment capacity to meet demand	Large network of pipes carry water from the wellfields to treatment system, storage, and consumer. usually comprised of steel, or HDPE/PVC/uPVC in smaller schemes Booster pumps are common to ensure water reaches the consumers	-
Managed Aquifer Recharge	Numerous boreholes to ensure backup and rotation of supply Usually electric submersible pumps May be powered by solar or wind energy, particularly in smaller towns where services are lacking or where boreholes are drilled a distance away Design and construction often well planned with provision for monitoring	Aquifer is utilised as storage May be on surface storage requirements for MAR source waters prior to MAR Storage after abstraction	Vadose zone and the phreatic zone offer natural treatment steps (such as natural attenuation and biotreatment) MAR source waters may require treatment before recharge occurs Generally supply water for domestic and potable use (SANS 241 Drinking Water Quality Standards apply)	Large network of pipes carry water from boreholes to treatment and storage stages, as well as MAR waters from source to recharge location Comprised of steel or HDPE/PVC/uPVC in smaller schemes	A means to artificially recharge the aquifer is required (e.g. injection or infiltration) Infrastructure can be extensive depending on technique used. In some cases, the natural terrain can be utilised, and extensive infrastructure is not required

Groundwater Scheme Type	Borehole and Pump	Storage	Treatment	Reticulation	Aquifer Recharge
	Usually dedicated monitoring boreholes to assess aquifer response	usually consists of steel or concrete reservoirs, or surface water dams augmented by groundwater supply	May be multiple stages of treatment, depending on the source water quality Treatment systems may be large to accommodate large volumes of water	Booster pumps usually required	Artificial recharge is usually undertaken with treated effluent or captured stormwater, so infrastructure related to effluent or stormwater capturing is also required

CHAPTER 4: MONITORING, OPERATIONS AND MAINTENANCE

4.1 INTRODUCTION

A critical element to groundwater management, both day-to-day and long-term, is the O&M procedures that encompass maintenance of infrastructure, planning and management of ongoing operations, and the monitoring that is necessary to inform decisions. As highlighted in **Section 2.2**, the initial phases of scheme design must consider the ease of scheme monitoring, maintenance, and operational requirements as these are the foundations of a sustainable groundwater scheme. Experience has shown that failure to implement or adhere to a comprehensive O&M plan often results in the inevitable failure of an entire groundwater scheme, as poor operations and management leads to constant equipment failures and borehole deterioration, with costly repairs and replacements being needed (WRC, 2011; Cobbing et al., 2015; WIN-SA, 2015; SADC-GMI, 2019).

Operations is defined as the timely and daily operation of the components of a water supply system such as pumping, treatment, transmission, and distribution of water. **Maintenance** is defined as the act of keeping the necessary (and auxiliary) systems, infrastructure, plants, machinery, equipment and other facilities in optimum working order. It can be:

- Routine maintenance – timeously restoration of something, e.g. regular descaling of pipes
- Preventative maintenance – to fix something before it breaks
- Reparative maintenance – to fix something that has broken
- Corrective maintenance – to fix something that functions but was done incorrectly.

Figure 4-1 outlines that, following initial scheme design considerations, operations and maintenance go hand in hand to form O&M protocols, which are informed by monitoring protocols and objectives. An integral part of the O&M is implementing and maintaining standards, best practice principles, scheme operational rules and monitoring objectives through management tools, such as Quality Management Systems (QMS), Standard Operating Procedures (SOPs), training workshops, and incident/emergency response plans. It is important to report on and keep record of monitoring data collected, and daily operations and maintenance procedures which have been carried out, to inform decision making and ensure that an adaptive management approach, rather than a reactive management approach, is followed.

Figure 4-1 **Overview of the key aspects of a sustainable O&M applicable across various groundwater schemes.**

4.2 MANAGEMENT TOOLS

For the scheme types mentioned in **Chapter 3**, a set of universal concepts and tools can be applied to ensure effective management. First are the operating rules and best practice principles, such as operating water levels and thresholds of potential concern amongst others, which are followed to operate a groundwater scheme with efficiency, longevity, and sustainability. These are pursued through monitoring objectives and maintenance plans which are then upheld through management instruments such as QMS, SOPs and training workshops.

Each groundwater scheme that is established, no matter the size and scale, should consider these factors and incorporate them into the management principles and practices.

4.2.1 Operating Rules and Best Practice Principles

An important aspect of groundwater scheme management are the operating rules. Aquifer parameters, continuous hydrogeological and ecological monitoring, borehole design, equipment and infrastructure all contribute toward determining a set of controls which should be decided prior to the commencement of scheme operation and should be continuously updated as more data is acquired throughout the scheme operation and monitoring.

<u>Recommended Yield</u>

Boreholes must be utilised in a manner that is most environmentally, socially, and economically sustainable, thus giving rise to the notion of a recommended yield. The recommended yield, also known as safe yield or sustainable yield, is the rate at which water can be abstracted from a borehole without having detrimental effects on the aquifer and the surrounding environment over time.

The recommended yield is established by assessing the conditions of the environment and properties of the aquifer, and the relationship between them, to ensure that drawdown and radius of influence does not impact the surrounding environment or lead to over-abstraction of the aquifer. This can only be done through analysis of competent test pumping that meet SANS 10299-4:2003 standards.

The term “recommended” yield is preferred over “safe” or “sustainable” yield because only long-term use and monitoring thereof can determine if the yield is sustainable. Conditions may also change, such as drought conditions or additional users, and what was once thought of as a sustainable yield may no longer be. Recommended yields are, therefore, subject to change as scheme operation and understanding of the system responses is ongoing. Groundwater scheme yields should be considered on an aquifer or resource scale and not limited to individual borehole constraints.

<u>Critical Water Level (CWL)</u>

According to the European Parliament (Union, 2008), critical level is defined as “a level fixed on the basis of scientific knowledge, above which direct adverse effects may occur on some receptors…”. This can have many different applications depending on the context. In terms of groundwater scheme management, the CWL is the elevation of the water level in the borehole which may not be exceeded based on a certain adverse outcome. These are vital in ensuring that the aquifer is not overstressed/pumped, degraded, or contaminated and the borehole infrastructure remains in good working order with minimal upkeep, maintenance costs and infrastructure damage.

The CWL may be an elevation maximum, such as the case for a MAR scheme to avoid flooding or ingress of water into foundations, or, in most cases, it is an elevation minimum to maintain:

- A water level above pump inlet so that the pump does not burn out or cavitate
- A water level above screen or water strike depths to avoid exposure to oxygen which will lead to accelerated biofouling and clogging
- A water level above fractures and water strikes to ensure they are not dewatered or weathered, and storage is not lost
- A water level above sea level to avoid saline intrusion
- A water level which does not result in a wetland or surface water body losing water.

- A water level which maintains a certain radius of influence such that undesirable water or sources of contamination are not drawn towards the borehole

These are some common reasons for setting a critical water level. CWLs should be determined by a hydrogeologist, however, as a best practice, the critical water level should be set as ~5 meters above the pump inlet, while the pump inlet is set ~5 meters above the screens or main water strike, provided it is not limited by another factor.

The concept of CWLs can also be applied to storage or treatment stages within the groundwater scheme.

Specific Capacity (S_C)

S_C is defined as the yield achieved per meter of drawdown in the borehole, and it describes the productivity of the aquifer and the borehole combined (Driscoll, 1986). The productivity of a borehole decreases over time due to head losses that occur. Head losses are the drawdown components experienced (see **Figure 4-2**) due to inefficiencies in flow within the borehole and aquifer. The head losses and S_C of a borehole are quantified through competent step-drawdown test pumping and analysis according to SANS 10299-4:2003 standards. These head losses occur initially in the disturbed aquifer media immediate to the borehole walls due to the effects of drilling and development; the undisturbed aquifer some distance away from the borehole; and within the borehole itself due to turbulence and inefficiencies associated with pumping. This is why adequate drilling techniques, borehole design and construction and development are important for efficient and manageable groundwater schemes – see **Sections 2.2.2** and **2.2.3.** These head losses get worse over time due to factors such as biofouling, clogging and incrustation, etc. within the borehole. It is important to define the initial S_C of a borehole so that, through periodic monitoring, the change in S_C can be assessed through routine step-drawdown pumping tests as part of the O&M protocol. When the S_C has decreased by no more than 25%, borehole rehabilitation should be undertaken to restore borehole performance. If the S_C decreases beyond 25%, it often becomes difficult and uneconomical to restore the S_C to (near) its original state.

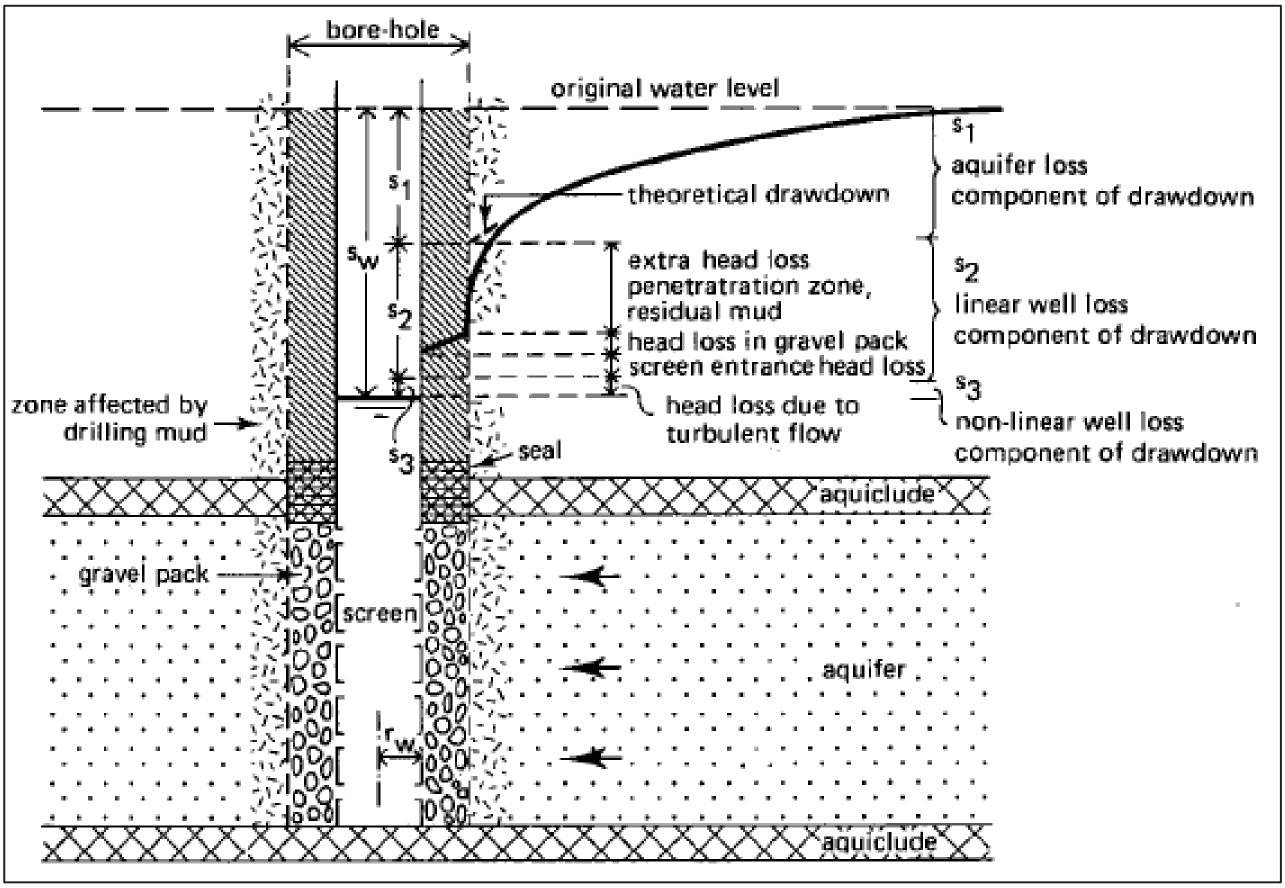

Figure 4-2 **Diagram showing the various head losses (i.e. drawdown components) that are experienced by a borehole (from Kruseman and de Ridder, 1990).**

Operating Water Levels (OWL)

The OWL is the desired water level in the borehole that is maintained under normal operating conditions. OWL is the water level which allows for the most efficient operations and management of a groundwater scheme, while the CWL is a limit that must be avoided (i.e. it is the ideal case vs extreme case). The OWL should consider factors such as:

- Optimum differential head for pump performance
- The collective effects of pumping multiple boreholes, i.e. pumping a wellfield in structured clusters
- Maintaining a regional, aquifer wide water level
- Avoiding adverse effects on the environment
- Avoiding ingress of unwanted or contaminated water
- Abstracting enough water to meet demand

Critical Control Point (CCP)

A CCP can be defined as a factor, practice, procedure, process or location that can be controlled in order to prevent, control, eliminate or reduce a hazard, or minimise the likelihood of its occurrence. In simpler terms, a CCP can be considered as a point, location, step, or process that if no control is applied, then the water is likely to be unsafe, unavailable, or inadequate for the desired use (adopted from Codex, 1999). The concept of CCPs was developed for use in the food industry to ensure that food products are and remain safe for consumption, and so it applies to groundwater supply systems as well. However, in the effort of aquifer protection and groundwater scheme management, the definition is extended to include not only safety for human consumption, but also suitability for intended use as well as environmental protection. Therefore, CCPs may also include controls on adverse impacts on the environment that critically need to be avoided, such as damage to nearby wetlands or the impacts of saline intrusion near the coast. **Figure 4-3** shows a decision tree which can be used to identify CCPs within a groundwater scheme. This usually feeds into part of a hazard analysis and critical control point (HACCP) plan.

Each groundwater scheme that is established should have its CCPs identified, defined, described, and monitored. A critical limit shall be assigned to each CCP based on the current knowledge and understanding, which can be adapted and revised with continued monitoring as knowledge and understanding of the system is improved. A critical limit can be a physical, chemical, biological or ecological parameter used to distinguish between (anthropogenically or environmentally) safe/desirable or unsafe/undesirable conditions which can be controlled to prevent, eliminate or reduce an adverse effect to an acceptable level. For example, a CWL is a physical critical limit applied to water level drawdown which is the CCP, which is controlled to prevent over abstraction of the aquifer. CCPs with chemical critical limits are most common.

In this way, the crucial monitoring points and parameters of a groundwater scheme are identified. The CCPs and their critical limits should form the monitoring protocol as a bare minimum. Routine monitoring is required to ensure compliance of the set critical limits and provides comparisons for reporting and data interpretations. It is encouraged that other points and parameters, which are not CCPs, are also monitored where possible for added value to inform good groundwater scheme management practices.

Threshold of Potential Concern (TPC)

Based on the identification of CCPs is the determination of thresholds of potential concern. These are limits or a range of limits, like critical limits, that are applied to monitoring points which, if reached, indicate the potential of forthcoming adverse effects. TPCs provide early warning systems for certain issues at hand which are meant to be flagged, rather than limits than ensure absolute anthropogenic or environmental safety. For example, the rise of EC measurements may flag the potential of saline intrusion. TPC is usually based on the limits required for the desired use, or the impacts of an undesirable effect such as contamination. TPCs can be assigned to various monitoring points across a scheme, such as borehole water level or water quality, treatment systems and even electrical systems, and they should be set for all groundwater supply schemes.

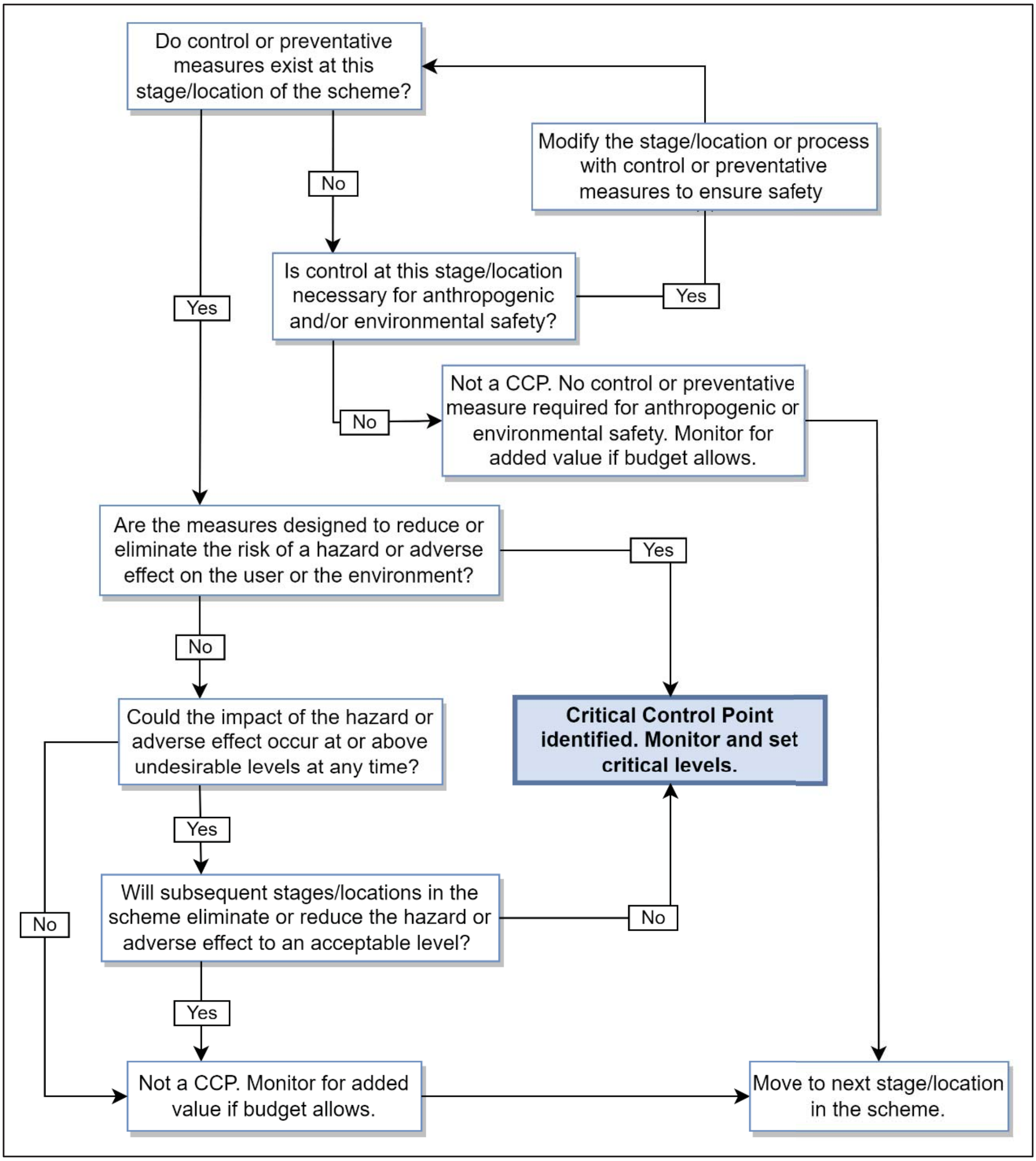

Figure 4-3 **The CCP decision tree designed to aid in identifying CCPs of groundwater scheme that must be monitored and controlled to avoid adverse effects on the scheme, user, and the natural and anthropogenic environment. It is adapted from Codex (1999) which was originally designed for use in the food industry.**

Potential Contaminating Activity (PCA)

PCAs can be considered as the potential origins of groundwater contamination which pose a risk to a groundwater resource and consequently a scheme. It is important to identify and keep an inventory of past and present PCAs so that monitoring can be undertaken accordingly. As a guide, the PCA inventory needs to include a list of activities that are associated with the following contaminants of concern:

- Microorganisms which pose a health risk, including faecal coliform bacteria, Escherichia coli, viruses, Giardia lamblia, and Cryptosporidium.
- Chemicals for which the maximum contaminant levels or groundwater quality standards for drinking, industrial and irrigation have been established, such as those listed in the SANS 241 or SAWQG documents.
- Contaminants of Emerging Concern (CEC) which do not all have established drinking water standards but are of growing concern in urban settings, particularly for schemes where water is used for potable supply and where MAR is undertaken with treated effluent.
- Turbidity and total organic carbon (TOC). Turbidity can affect treatment and monitoring for microbial contaminants, while TOC can influence the presence of disinfection by-products (such as chlorination), which have a carcinogenic concern.

These PCAs and their relevant contaminants can be used to inform TPCs so that early warning systems for the protection and management of a groundwater scheme are in place.

Groundwater Protection Zone (GPZ)

GPZ is defined as the surface and subsurface area surrounding a borehole or wellfield through which contaminants are reasonably likely to move toward and reach the borehole or wellfield, based on travel times within the aquifer and the time taken for a microbe/chemical contaminant to break-down, diffuse or retard (US EPA, 1987).

GPZ's are delineated areas which relate to decreasing levels of risk with the distance from point of abstraction. At the very least, a groundwater scheme should implement a wellhead protection zone in proximity to the borehole so that immediate contamination risk can be removed. Secondly, the recharge area should be located, mapped to some degree, protected, and monitored as best practice. It is important to protect recharge areas so that groundwater availability is not affected, and the resource is not polluted.

Methods on establishing groundwater protection zones is provided in the Guidance Document on Protection Zones (Delineation and Protection) (WRC, 2022).

4.2.2 Monitoring Objectives

Monitoring objectives of a groundwater scheme should aim to assess if the operating rules and best practice principles are being adhered to and provide a real time check of current operational impacts on (sometimes predetermined) aquifer health indicators such as water levels and water quality. Monitoring is the fundamental backbone of sustainable management. One cannot manage what is not monitored because monitoring generates data resulting in information which inform decisions. With routine monitoring and an adaptive management approach, the operating rules and principles can and should be continuously revised and updated through establishment of monitoring objectives.

Monitoring objectives can be based in water quality, water levels or abstracted volumes, or operations based, and a monitoring network must be established which covers all these aspects. A data management system must be included in these objectives as well, such as an electronic database and hardcopy filing system, including regular evaluation of the data and objectives. For each borehole and/or wellfield, the monitoring objectives (water quality, water level, volume, and operational) must be clearly defined and means of quality assurance and quality control must be in place to evaluate whether the monitoring has been successful in meeting the objectives. Further information and guidelines are provided in the Guidance Document for Groundwater Data Collection (WRC, 2022).

The groundwater scheme monitoring objectives shall indicate the following (WRC, 2011):

- What parameters should be observed
- Locations that they must be monitored at
- Methods or techniques of the monitoring and data collection
- Timing and scheduling of data collection
- Personnel requirements in terms of skills and training

- Equipment required to carry out the monitoring
- Methods for analysis of the data collected
- Storage and access of the data
- Data sharing and knowledge dissemination
- Feedback and revision policies

An example of a water level monitoring objective is to avoid water levels reaching the pump inlet during pumping. To meet this objective abstraction rates can be reduced. Another example, this time a water quality objective, is the prevention of salinisation of an aquifer which requires the monitoring of the electrical conductivity and may indicate that reducing the abstraction rate is required (SADC-GMI, 2019). In this way, it is clear to see how the monitoring objectives and operating rules, such as CWLs and TPCs, are linked.

Water quality monitoring objectives are generally informed by existing standards which relate to a particular use of groundwater. They may be site or scheme specific, for example, if there is risk of a particular contamination source, or it may be informed by the conditions stipulated in a water use license authorised by DWS. Water quality objectives must also consider operational effects of the water chemistry as it may have a detrimental impact on infrastructure, such as corrosion and scaling (linking to maintenance objectives).

Some water quality standards and guidelines that may be applicable in groundwater scheme monitoring and management include:

- SANS 241 Drinking Water Quality Standards – specifies the minimum acceptable quality of drinking water in terms of microbiological, physical, aesthetic, and chemical determinants, based on acceptable risk of two litres of consumption per day for 70 years by a person that weighs 60 kgs. If water is used for potable use, then it should comply with these standards as a monitoring objective. Part 2 of the document also provides related monitoring programmes and risk assessments processes.
- South African Water Quality Guidelines (SAWQG) – this set of documents provides comprehensive water quality guidelines for a variety of uses.
    - SAWQG Volume 1: Domestic Water Use Second Edition, 1996
    - SAWQG Volume 2: Recreational Water Use Second Edition, 1996
    - SAWQG Volume 3: Industrial Water Use Second Edition, 1996
    - SAWQG Volume 4: Agricultural Water Use: Irrigation Second Edition, 1996
    - SAWQG Volume 5: Agricultural Water Use: Livestock Watering Second Edition, 1996
    - SAWQG Volume 6: Agricultural Water Use: Aquaculture Second Edition, 1996
    - SAWQG Volume 7: Aquatic Ecosystems First Edition, 1996
    - SAWQG Volume 8: Field Guide First Edition, 1996

Water level monitoring objectives aim to inform on sustainable abstraction and avoid overexploitation of the aquifer. Local borehole water levels will provide insight into deteriorating borehole performance (i.e. S_C and CWLs), while regional aquifer water levels will indicate if there is unsustainable abstraction, or not enough abstraction which can lead to localised flooding or unwanted saturated conditions (i.e. OWLs). Water level fluctuations show aquifer response to recharge patterns (both natural and MAR) which are important for sustainable use. Water level monitoring at distance away from abstraction also indicates the radius of influence of pumping which needs to be managed to foresee groundwater competition and adverse effects on the environment. Water level monitoring as a broad category can also include monitoring of surface water flows and storage to assess if there is any surface water groundwater interaction, and any adverse impacts on wetlands, streams, or dams.

An additional, yet combined objective of water level and water quality monitoring should be to establish a baseline. **Baseline data** is important because it provides the criterion to which any change resulting from groundwater abstraction, or any other activity, can be compared through monitoring. Natural or initial (without the influence of the groundwater scheme operations) water level and water quality conditions should only be altered to a reasonable and recoverable extent. Another combined objective to consider is **event based monitoring** (or sampling) which is carried out to assess the impacts of a once-off event that may occur.

O&M monitoring objectives aim to keep the groundwater scheme in working order and maintain status quo. These objectives should prioritise aspects that are essential to maintaining a safe and adequate groundwater supply that are mainly related to scheme infrastructure. It must be noted that water quality and water level monitoring often feed into the O&M objectives. For example, if water quality is corrosive then components will need more frequent maintenance. Water level monitoring in the storage tanks inform if pumps should be switched on or not. Recall that these O&M objectives may be routine, preventative, reparative or corrective maintenance which may pertain to aspects such as:

- Pump operation and infrastructure
- Borehole condition and performance
- Power consumption and other electronic systems
- Leaks and breakages in reticulation and storage networks
- Build-up of silt, biofilm, and scaling in reticulation
- Monitoring and controlling water demand
- Maintaining clean and sterile storage infrastructure
- Essential equipment such as flowmeters, pressure gauges, valves, and monitoring equipment such as dip meters and pressure transducers, etc.
- Routine calibration of equipment for data quality assurance

Additional monitoring themes and tools include climate, ecological and GIS or remote sensing (RS). Climate is important to monitor as it feeds into overall water balance calculations and groundwater availability on local and more regional catchment scales. Rainwater and evapotranspiration offer insights into the amount of recharge. Climate monitoring also identify drought periods which imply that more water will need to be abstracted to augment surface water shortages.

Ecological monitoring is important in ecologically sensitive settings since groundwater abstraction can negatively impact the health of surface water ecosystems. Ecological monitoring includes wetland health or endangered species monitoring. Another specialised technique is monitoring the movement of the land surface – when groundwater is abstracted there is land subsidence and when there is recovery or recharge the land bounces back in an elastic way. If the elastic limit is exceeded, groundwater storage is permanently lost. Especially for bulk abstraction, this is an important aspect to monitor so that storage can be preserved and there are no detrimental effects of land subsidence on buildings and infrastructure. These additional aspects, although not CCPs, are beneficial to monitor as they have an impact on or are impacted by the groundwater scheme (directly or indirectly) and can support early warning systems.

Early warning systems for changes in both natural conditions and scheme operations are the result of effective implementation of the three main monitoring objectives, leading to a proactive and adaptive management approach (**Figure 4-4**), with intelligent monitoring and forecasting tools to predict outcomes and inform decisions before adverse effects are encountered. Routine monitoring and data collection feeds into conceptual, analytical and or numerical models which improves the understanding and knowledge of the scheme, system, and resource, which in turn facilitates knowledge-based decision making and improved management of a groundwater scheme. The use of telemetry systems for monitoring allows for real time remote control and supervision, with real time status and decision making.

4.2.3 Maintenance Plans

It is essential for a groundwater scheme to have a maintenance plan that fulfils the O&M monitoring objectives, and ultimately to prevent unplanned, reactive maintenance. It is important to have working knowledge of the equipment so that a scheme maintenance plan can be drawn up. The maintenance plan also allows for anticipatory cost planning and budgeting, while failure of implementing an effective maintenance plan will result in increased and unforeseen costs. Additional consequences may include the presence of water borne diseases and contamination. Basic first-line maintenance is an absolute necessity for sustainable operation of any groundwater scheme.

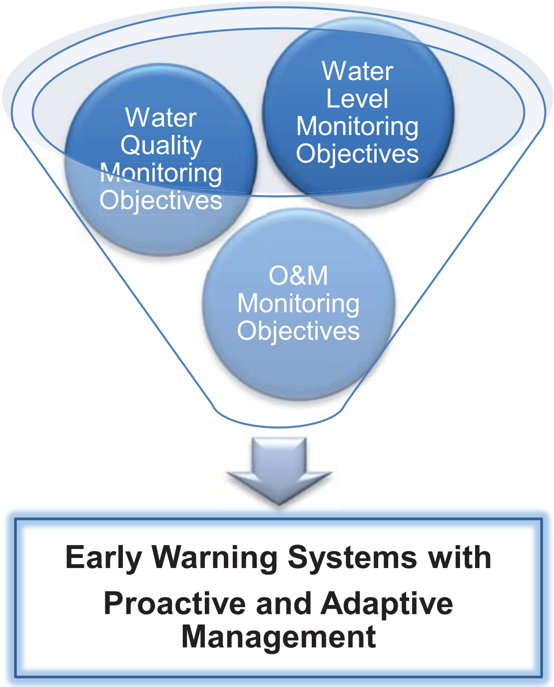

Figure 4-4 **Water level, water quality and O&M monitoring objectives collectively provide for early warning systems in a proactive and adaptive management approach.**

A groundwater scheme maintenance plan should:

- Outline schedules of inspection and routine maintenance tasks
- Assign personnel to carry out these tasks
- Set up an O&M database to store maintenance and equipment information
- Outline the work order and workflow of the scheme
- Keep an inventory of equipment and parts and their manufacturer documentation
- Keep record and reports of O&M activities carried out

The manufacturer documents should be consulted when creating equipment maintenance plans. Depending on the scale and frequency of use, scheduling and routine maintenance may differ. More frequent and large-scale use requires more frequent inspections and maintenance.

Some important scheme components and considerations which should be included in a maintenance plan are:

Boreholes

The borehole yard, caps, wellhead, sanitary seals, concrete pads and protective covers should be regularly inspected to protect the borehole from damage and direct contamination. The downhole status of the borehole must be tracked. Boreholes have a certain lifespan and should be decommissioned before failure. Casing integrity should be inspected for cracks and breakages which may lead to borehole collapse, and borehole depth should be checked routinely to assess extent of silting or potential collapse. Old, unused or decommissioned boreholes should be backfilled to avoid health (injury) or contamination risks and capped. They should be closed and sealed correctly to avoid casing corrosion leading to borehole collapse and subsequent hydraulic connection between aquifers.

Boreholes should be routinely cleaned to clear biofouling, clogging, silting or foreign matter. Routine step-tests should be done to analyse borehole performance and S_C with borehole rehabilitation being carried out when necessary.

Pumps

Pumps should be pulled, tested, and inspected routinely to assess performance, loss of power, pumping of silt or sand, the condition of the impeller, etc. They should be partially dismantled, cleaned of biofilm and encrustation, and disinfected before reinstallation. Pumps should be serviced routinely and run in reverse to clear out any debris build up. All mechanical parts should be checked and replaced if necessary. Abnormal vibrations may indicate loose mounting bolts, worn-out bearings or impellers, or misaligned shafts. The pump should be checked for signs of cavitation.

The more frequent the use and the greater the volume, the more frequent inspections and maintenance will be required on boreholes and pumps, however, in most cases annual checks should be adequate. There are various types of pumps each with their own specifications. Manufacturer documentation should be consulted when drawing up pump maintenance plans.

Storage

Storage tanks silt up and have a build-up of slime over time. This needs to be cleaned and disinfected regularly. It is also important to ensure that any access points are closed and sealed to avoid direct contamination of water in storage. Routine checks for leaks and cracks in the storage infrastructure should be undertaken and addressed immediately to avoid failure and flooding.

Pipes and Reticulation Network

Routine checks for leaks and cracks should be undertaken to avoid water losses or incidents such as burst pipes which can lead to erosion and flooding. Effects of corrosion should be identified and rectified as soon and often as possible. Reticulation networks should also be flushed routinely to wash out stagnant waters, with biofilm and scaling being purged concurrently. All fittings, valves, flow meters, taps and seals, etc. along the pipeline from borehole to consumer should be checked and replaced regularly. See Introduction to Operation and Maintenance of Water Distribution Systems (Van Zyl, 2014).

Treatment Systems

If treatment systems are in place, they require routine maintenance. Filters shall be replaced regularly, chemicals shall be stored and used safely and correctly, and regular diagnostics should be run on the treatment systems to check and maintain efficiency. Treatment system should be flushed and cleaned routinely, and by-products and waste should be disposed of correctly (such as licensed landfill sites).

Monitoring (and other) Equipment

Monitoring equipment should be kept in working order. Things like dip meters, handheld probes, pressure transducers and any other sensors or electronic monitoring systems shall be checked, tested, and calibrated routinely, and repaired or replaced when necessary. Manufacturer documentation should be consulted, and any software and firmware shall be kept up to date.

A stockpile of tools that are required to fulfil monitoring or other O&M duties must be maintained to capacity to ensure duties can be carried out when required. Inventory and stocktake should be done routinely and all equipment stored in a safe place which prevents theft and damage.

Any vehicles that are required by scheme staff and personnel should be sent for regular services and kept in working order so that duties, such as inspections, sampling and logistics can be carried out. Oil and hydrocarbon leaks from vehicles or any other equipment should be avoided and, if present, kept away from borehole or aquifer ingress by using drip trays, etc.

Power Supply

A groundwater scheme cannot function without power supply. It is important to maintain electric cabling and connections to ensure that water supply can continue uninterrupted, especially if it bears serious social or economic implications. Cabling and power systems should be protected from theft, vandalism, and for general health and safety reasons.

Backup power supply can also be put into place, especially during times of planned power cuts. Diesel (or other fuel) tanks and containers shall be filled routinely and stored in a safe place to minimise the effect of spills as well as theft or flammable hazard.

4.2.4 Incident and Emergency Response Plans

Effective management and O&M of a groundwater scheme includes the incorporation of incident and emergency response plans. Each groundwater scheme that is established should draw up such plans so that sudden, undesirable, and unforeseen happenings can be dealt with efficiently.

Some common issues that may require incident and emergency plans to be acted upon include:

- Contamination
    - Contingency plans for aquifer contamination are required. This should highlight procedures such as terminating abstraction and initiating backup supply, identifying, and understanding the source of contamination, and carrying out mitigation and remedial tasks.
    - Contamination can occur from outside sources such as nearby PCAs, or within the scheme such as boreholes or storage tanks (for example, when small animals fall in), or within leaky pipelines. All possible outcomes should be considered in the plan and event-based sampling provisions should be in place to assess the impacts on the environment.
- Power Failures
    - Back-up power and back up water supply should be planned for during times of unplanned power failure, and steps should be in place to identify and rectify the power failure.
- Spills
    - There may be spills that occur on site, such as hydrocarbon spills or chemical spills. Spill clean-up kits and other procedures should be made readily available to clean the hazard and protect health, and event-based sampling should be undertaken to assess the impacts on the aquifer and environment. Various chemicals will have different hazards and they should be identified and planned for with consulting of material safety data sheets.
- Infrastructure Failure
    - Burst pipes and storage failures can also occur. Depending on water volumes, this can have catastrophic results such as large-scale erosion and infrastructural damage, like roads washing away or damage of buildings and foundations. Emergency shut off valves should be in place, as well as plans for mitigation of environmental damage.
- Borehole Issues
    - Incidents such as borehole collapse or pumps and other items being dropped downhole can occur. There should be plans to deal with these issues and restore supply as soon as possible.
    - Vandalism is a common and unforeseen incident, and systems and equipment to repair and restore borehole integrity should be available and in place.
- Treatment Failure
    - Failure or reduction in treatment efficacy may also occur. Systems to deal with this should be put in place, undesirable water should be pumped to waste safely, and the source of failure must be identified and restored.
- Personnel Injuries
    - Even with general Health and Safety plans in place, injuries amongst groundwater scheme operators and staff still do occur. Physical injuries as well as harm by chemicals should be planned for with emergency health and first aid kits being available. Motor vehicle accidents may also occur.
    - Another consideration is harm occurring due to fauna or flora that may be present on site, such as snake or spider bites, bees, or wasp stings, etc. These creatures often inhabit borehole headworks.

4.2.5 Maintaining the Standard

Once operating rules, monitoring objectives and maintenance plans have been established and put in place, it is important that these are implemented to a desired standard to ensure optimum performance and longevity of the groundwater scheme. There are numerous management tools that should be used to uphold a standard and ensure tasks are carried out correctly. These include QMS documents, SOPs and manuals, training workshops and courses.

Additionally, it is important to create reporting, evaluation and revising systems to ensure that there is constant feedback and improvements to the operating rules, monitoring objectives, and O&M of the groundwater scheme. Groups and committees should also be established to assist in groundwater scheme management and provide critique and collaboration on decisions. These should be implemented for all types of groundwater schemes.

<u>Quality Management Systems</u>

QMS documents define what quality means to a management system and provide a guide to management, organisation, optimisation, and efficiency while creating transparency and standardisation. According to the international standard ISO 9001:2015, the basics of QMS should cover the following aspects:

- Quality Manual – defines the need, motivation, and business values for quality, e.g. to ensure high quality potable groundwater supply.
- Quality Objectives – defines the objectives of the management system and a means of measuring success and progress of the groundwater scheme management.
- Structure and Responsibility – provide the management structures, staff organograms and responsibilities of the staff or departments involved.
- Data Management – policies and procedures for managing data (collection, storage, and usage) that is collected through the monitoring objectives.
- Internal Processes – defining the internal processes that occur to transform input into products, such as abstraction, treatment, and storage of groundwater, as well as fiduciary duties.
- Customer Satisfaction – means of assessing and evaluating the satisfaction of the groundwater user.
- Improvement Opportunities – outline objectives to continuously improve the management of groundwater scheme.
- Quality Instruments – tools that are used to measure progress and success.

<u>Standard Operating Procedures and Manuals</u>

SOPs and manuals are informed by QMS and monitoring objectives. They detail how individual tasks within the broader management, monitoring and O&M of a groundwater scheme are carried out. Some common SOPs and manuals that apply to groundwater schemes include:

- Step-drawdown tests to assess borehole performance
- Borehole rehabilitation to restore borehole performance
- Removal and installation of borehole pumps
- Operating borehole pumps
- Carrying out downhole camera surveys to inspect borehole integrity and status quo
- Cleaning, descaling and disinfecting pumps
- Correct groundwater sampling techniques and procedures
- Connecting and repairing electrical and electronic systems (such as telemetry)
- Correct implementation of monitoring techniques, e.g. how to use dip meters, install pressure transducers and download data, etc.
- Cleaning and disinfecting storage units of slime, sludge and silt
- Correct procedures for replacing fittings, valves, flowmeters, seals, etc.

South African National Standards (SANS)

National standards are also constantly drawn up, revised and improved by the South African Bureau of Standards which aim to develop, promote and maintain standards for commodities, products and services across the nation. These SANS documents can be used as additional resources to ensure a high standard of O&M and monitoring tasks. Some of these documents that should be consulted in the management of a groundwater scheme are listed below:

- SANS 241
    - Specifies the minimum acceptable quality of drinking water in terms of microbiological, physical, aesthetic and chemical determinands, based on acceptable risk of two litres of consumption per day for 70 years by a person that weighs 60 kgs. Water service institutions and intermediaries should ensure that water provided by them complies with these standards through maintaining monitoring programmes and risk assessment processes described in Part 2.
- SANS 1160
    - Deals with the specific materials or products that come in contact with drinking water and the contaminants or impurities that are thereby directly imparted to the drinking water – i.e. it specifies the standards for the materials that the components and infrastructure of a groundwater scheme should be comprised of for safe supply.
- SANS 1529
    - Stipulates the characteristics and requirements of mechanical or electronic water meters for flow and volume measurement. This pertains to the accurate monitoring of a groundwater scheme.
- SANS 1731
    - Covers the material specifics and design requirements for polyethylene storage tanks used for water and chemicals. This includes the JoJo tanks which are often used as groundwater storage in rural, private or small-scale farming groundwater schemes.
- SANS 1808
    - This multi-part standard deals with the water supply and distribution components ranging from pipe couplings and connectors to various types of valves and taps, and even pipe repair saddles and clamps. This may form part of the operations and maintenance procedures related to a groundwater scheme.
- SANS 4427
    - Deals with quality and design of pipes and fittings of plastic (polyethylene) piping systems which are often used for reticulation in a groundwater scheme, especially for irrigation or small-scale supply.
- SANS 5667
    - This multi-part document offers standards on design of sampling techniques, preservation, and handling of various types of water samples, including rivers, lakes, groundwaters, effluent and contaminated waters. These standards are essential in order to avoid cross-contamination or inaccurate results, and to ensure safety of the staff carrying out the sampling. Water quality monitoring is an integral part of managing a groundwater scheme.
- SANS 10299
    - Deals with the design, development, maintenance, and management of groundwater resources. This includes standards on siting, designing, drilling and constructing a borehole; methods and techniques for test-pumping a borehole; selection, installation and commissioning of pumping equipment; the rehabilitation and management of a borehole; as well as standard procedures for decommissioning a borehole.

- SANS 10306
    - Outlines the management of water in potable distribution systems, mainly dealing with determination, calculation, impacts, mitigation, corrective measures and prevention of water losses from a supply system. The document also outlines approaches to management, policy, and monitoring systems to put in place. This standard will mostly be applicable to WSPs who operate and manage a groundwater scheme.

In addition to these, there are numerous individual standard documents which deal with:

- Laboratory preparation and analysis techniques of certain determinands that may be present in water. It is essential, when carrying out water quality monitoring, that samples are sent to a SANAS accredited laboratory to ensure that analysis adheres to these standards and quality is assured.
- The characteristics, requirements and test methods of various chemicals and products used for treatment of water intended for human consumption. This will be applicable to WSPs who utilise groundwater schemes for potable supply.

Training

Regular training workshops, toolbox talks, and courses can provide practical knowledge on how to operate equipment and keep staff up to date with skills and expertise. It is always good to have refreshers. All groundwater scheme personnel should undergo regular training workshops and keep up to date with relevant research and guidance documentations to ensure that best practices are up to date with industry standards. Training should occur on all levels of management from field technicians to high level management. Skills and capacity building should also include basics of data capturing, handling, analysis, and reporting, as well as basic hydrogeological and O&M concepts so that data can be interpreted in a meaningful way.

Reporting, Evaluating and Revising

Reporting on monitoring objectives should be done routinely. Water level and water quality reporting can be done on a bi-annual or annual basis and should cover short term and long-term trends in data. O&M reporting can be done on a weekly to monthly basis and should summarise the issues, alterations, repairs, and general operations which occur. Flow charts describing the flow of data, information and reporting should be drawn up for all monitoring objectives. Further information and guidelines on data capturing and flow are provided in the Guidance Document for Groundwater Data Collection (WRC, 2022).

A conceptual data flow model may be as follows:

- Data is captured by the field technician
- Data is passed to and checked by the field technician supervisor
- Data is passed to data capture clerk who captures, transforms, and stores the data
- Data reports are given to technical management from the data capture clerk
- Data and reports are analysed by technical management
- Recommendations made or instructions by technical management are provided to field technician and field technician supervisor
- Instructions or recommendations are carried out and data is captured again following the changes made. This completes the feedback loop.

Reporting helps in evaluating the results of monitoring and provides a record of decisions made with respective reasonings. It is important that this evaluation provides a feedback loop to the monitoring objectives, operating rules, and best practice principles such that they can be revised and improved to best protect and manage the aquifer and the groundwater scheme. Detailed analyses may only be necessary where there is a potential for failure, over-abstraction, or water quality concerns. Technical management should pass on all reports to the respective Catchment Management Agency or Water User Association (see **Chapter 5**).

Groups and Committees

Stakeholder engagement is a vital component of effective groundwater scheme management. It is important that monitoring committees and community groups are established to ensure coherent, consistent, transparent and accountable management can take place. This is particularly important when there are multiple users and schemes of one groundwater resource. Committees made up of interested and affected parties (IAPs) can make decisions and take actions democratically to the benefit of all parties involved.

4.3 O&M AND MONITORING PROTOCOL

A protocol (a schedule or procedure to be followed) must be established to carry out the monitoring and operational objectives and maintenance plans that have been discussed above. Each type of groundwater scheme discussed in **Chapter 3** will be operated differently and have different monitoring and maintenance requirements. An effective O&M and monitoring protocol is comprised of four major components:

- Parameters to monitor – this is essentially **what to monitor**, in terms of water levels, water quality, volumes abstracted, and operations and maintenance. It is informed by the type of groundwater use and its water requirements, as well as the monitoring objectives that have been discussed.
- A monitoring network – the monitoring network defines **where to monitor** the selected parameters so that the monitoring objectives may be met. This should be informed by the HACCP process, as well as groundwater, environmental and other specialist studies that identify any potential adverse effects, such as over abstraction or wetland impacts.
- A schedule or timeframe – this defines **how often** a certain parameter or site should be monitored or maintained. The frequency depends largely on the amount and frequency of use, as well as the design and materials of the components themselves. The larger the use and frequency, the greater the strain on the components, both natural (aquifer) and man-made (infrastructure).
- Assigned responsibility – a monitoring protocol must also define **by who** the monitoring is undertaken. The monitoring and O&M tasks must be assigned to personnel so that it can be carried out with accountability. There may be various levels of skills required in the O&M and monitoring protocol and it is important that the person being assigned a task is well trained and capable to carry out the task at hand.

Appendix A to **Appendix F** show a rudimentary, conceptual O&M monitoring protocol for the various types of groundwater schemes that have been discussed in **Chapter 3**. These are conceptual since it will differ from scheme to scheme and it should be used as a guideline, in conjunction with the management tools discussed thus far, to inform on drawing up unique O&M and monitoring protocol for individual groundwater schemes.

The tables outline what parameters to monitor in terms of water levels, water quality, volumes, and O&M, and where to monitor them (i.e. what component of the groundwater scheme). It provides basic equipment, methods or techniques that can be used to monitor the parameter, as well as how often it should be monitored as a guideline. These are based on the relative scale of the scheme type, the skills, equipment, and budget that would likely be available. Frequencies are subject to change based on the use of any individual scheme. Furthermore, it provides an idea of who should be assigned the responsibility of carrying out the monitoring task and the training that may be required, e.g. electrician or pump operator. Some of the staff positions and their basic job descriptions that are generally required in the O&M and monitoring of a groundwater scheme are listed in **Table 4-1**. Each groundwater scheme should have personnel assigned to carry out these tasks.

The O&M and monitoring protocols go on to explain some of the resulting implications, outcomes, or consequences of the monitoring – i.e. the reasoning behind monitoring something – which relate once again to the monitoring objectives. These monitoring results may trigger subsequent actions or decisions that may be required in terms of managing the resource and the scheme which are also briefly discussed. It also lists (where possible) the responsible party for carrying out these actions or decisions. Similarly, a rudimentary outline of a routine maintenance plan is shown in **Table 4-2**.

These are the conceptual criterion that must be incorporated into an O&M and monitoring protocol, together with the management tools listed above that constitute good and effective management of a groundwater scheme. Note that these are guidelines, and no scheme will be the same. Thus, careful and meticulous thought must be put into drawing up individual groundwater scheme O&M and monitoring protocols that are guided by strict operating rules, monitoring objectives, maintenance plans, incident and emergency response plans, and standards.

Table 4-1 Fundamental job descriptions of common staff positions involved in the O&M and monitoring of a groundwater scheme (after DWAF, 2004).

Staff	Job description
Pump Operator	• Operate groundwater infrastructure according to operational guidelines and national standards • Measure water levels and abstraction volumes • Maintain a borehole and data logbook, and other significant information • Ensure that the borehole monitoring equipment is kept clean, in working condition, stored in a secure place. • Implement recommendations provided by technical management and pump operator supervisor.
Pump Operator Supervisor	• Provide support to the pump operator in monitoring activities • Assess the pump operator's performance regularly • Provide training for the pump operator as and when required • Collection of data from the pump operator, and transferring this data to the data processor
Data Capture Clerk	• Enter monitoring and water quality data from log sheets into a computer database • Maintain a filing system for completed log sheets • Print reports and ensure that the reports are supplied to the technical manager
Mechanic	• Carry out preventative & breakdown maintenance on mechanical components • Trouble shooting of issues and faults
Electrician	• Carry out preventative & breakdown maintenance on electrical components • Trouble shooting of issues and faults
Technical Manager	• Overall responsibility for maintaining the groundwater scheme, and ensuring that all role-players fulfil their responsibilities • Review the operational reports • Consult with groundwater specialists where required • Report to local water service authority or regulator (see **Chapter 5**) • Make changes to the operation of the borehole, instructing the pump operator supervisor to implement changes, and ensure that the changes have taken place • Liaise with the health manager on water quality sampling and testing • Use of monitoring information in the planning of new infrastructure development
Water Quality Manager	• Ensure the regular sampling and testing for suitability for desired use • Provide water quality data to the data capture clerk • Report to local water service authority or regulator • Liaise with technical manager on projects with water quality problems • Plan and co-ordinate remedial action and infrastructure planning

Table 4-2 An example of a basic Maintenance Protocol

Routine Maintenance							
What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors it	Why monitor it	What to do	Who does it
Pumps	Moving parts (mechanics)	Visual, physical	Bi-annually	Pump operator	Wear & tear	Repair/replace when necessary to maintain scheme functioning	Maintenance crew/ engineer
Pump Power Supply	Electricity box/control panel, etc.	Voltage	Quarterly	Electrician			
	Fuel storage (if fuel pump)	Visual	Daily	Pump operator	Check diesel storage level to maintain operation	Fill up diesel to ensure supply	Pump operator
					Check for leaks/cracks in diesel tanks and pipelines.	Repair diesel leaks to prevent aquifer contamination	Maintenance crew/ engineer
Reticulation Network	Taps, valves, pipes and pipe connections, etc.	Visual	Bi-annually	Field technician	Leaks and worn connections will lead to water losses and decreased supply Potential environmental effects such as erosion and gullying. Scaling and biofouling must also be noted	Replace all worn components to prevent leaks and burst connections. Clean out scaling, biofilm, and corrosion.	Maintenance crew/ engineer
		Pressure tests	Bi-annually				
Storage	Float level	Visual, physical	Quarterly	Field technician	Wear & tear	Repair/replace when necessary to maintain scheme functioning	Maintenance crew/ engineer
	Staff gauge						
	Overflow outlet						
	Infrastructure		Bi-annually				
	Access doors						
Treatment systems (if applicable)	Filters, chlorination chambers, etc.	Visual, physical, chemical					

CHAPTER 5: GOVERNANCE STRUCTURES

5.1 INTRODUCTION

The monitoring and O&M tasks that are carried out, if carried out correctly, can generate an abundance of data over time which must be captured, stored, and interpreted correctly. It goes toward making informed, real-time decisions in a proactive manner. It is important that this data is not only utilised for the immediate management of the groundwater scheme, but also in the management of the groundwater resource. Groundwater resource management happens at high levels of the South African legislative framework. Overall, South Africa's groundwater legislation and governance structures are relatively comprehensive and align well with international principles. Generally, the concerns in South African groundwater management lie not in the legislation, but in the implementation and compliance thereof.

It is absolutely vital that groundwater users and scheme operators realise that management of their scheme does not end at the O&M and monitoring tasks, but it includes the passage of the information to the upper tiers of groundwater resource management so that they can make informed decisions to protect, allocate, develop, use, conserve and maintain the groundwater resource in a most sustainable and equitable way. No one owns groundwater and it must be shared with sustainability – this concept was brought into action by the National Water Act (NWA) No. 36 of 1998 which declared that water all water resources should be considered an indivisible national resource for which national government is the custodian.

Figure 5-1 highlights the ideal governance framework of a groundwater scheme which lies beyond the field staff and technical management that carry out the O&M and monitoring tasks of a groundwater scheme. Therefore, the term "groundwater scheme management" includes the groundwater governance structures and the high-level decision makers. Governance forms the integral backbone of resource management and the flow of information from all groundwater scheme types, no matter the scale, should reach the high levels of management. Effective groundwater governance starts with a high degree of participative and shared responsibility across all levels of government and all stakeholders involved.

5.2 GOVERNANCE AND STAKEHOLDERS

The major determining factor on the success of a truly sustainable groundwater supply lies in the adequate collaboration between all institutional bodies, specialists (engineering, environmental and hydrogeological), all stakeholders, and all groundwater users.

Once data and information has been collected in the field following the O&M and monitoring tasks, the flow thereof should follow the institutional hierarchy. The institutional bodies and stakeholders, and their responsibilities, are defined below – from water user intermediaries just beyond technical management, to the national government. It must be noted that there are areas in the country where not all these parties exist effectively, and often the flow of information is straight to Catchment Management Agency (CMA) or (DWS).

Although this document deals only with groundwater schemes, the information gathered by, and responsibilities of, these institutional parties as discussed here is not limited to groundwater alone but may pertain to surface water schemes as well.

5.2.1 Water Service Intermediaries (WSIs)

A WSI is a person or association that has the responsibility, under contract with a Water Service Provider (WSP), to provide water services of a certain quality, quantity, and sustainability. These WSIs were introduced to the water sector through the Water Services Act (RSA, 1997b). Farm owners or farming corporations who are responsible for providing water to employees that live on the property are an example of a WSI. Groundwater schemes are often used to fulfil the duties of a WSI, and they report to the Water User Association (WUA) or WSP.

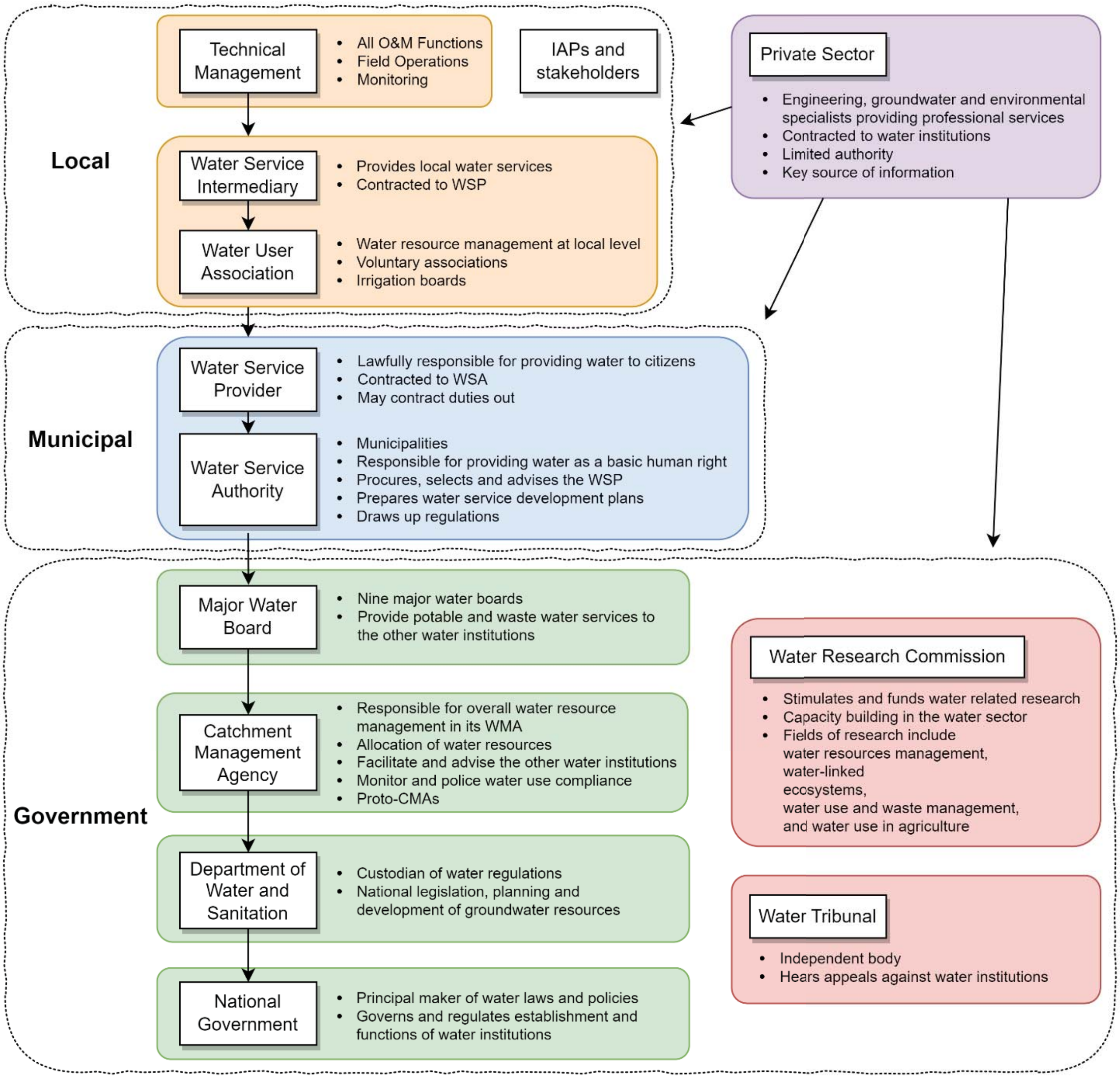

Figure 5-1 **Organisation of the major groundwater governance role players.**

5.2.2 Water User Associations (WUAs)

WUAs are defined by the NWA as “associations of individual water users who wish to undertake water-related activities for their mutual benefit with voluntary membership intended to support the management of local water resources in the common interest.” Common practice among farming areas is the establishment of Irrigation Boards which can be loosely classified as a type of WUA. There are roughly 220 Irrigation Boards and 90 WUAs operating across the country (OECD, 2021). The WUAs are responsible for groundwater resource management functions at a local level, representing individual water users and providing vehicles for public participation to the CMAs.

Some roles and functions of the water user associations, as stipulated in the National Groundwater Strategy document (DWA, 2010), include:

- Act as interface between consumers and management
- Ensure and regulate optimum usage of groundwater and distribution in a most sustainable way
- Prevent any unlawful act that can reduce the quality and quantity of the groundwater resource
- Prevent groundwater from being wasted
- Prevent unlawful use
- Protect area of operation and promote sustainable use
- Provide assistance in the data collection, capture and monitoring process
- Resolve disagreements between members
- Protect the environment and ecological systems

Data and information should be shared between community members and these WUAs and Irrigation Boards for the benefit of society and the resource. WUAs aid in collective management of individual groundwater schemes on a local level and, the technical management of groundwater schemes should contact the local WUA, share information and participate in collective management.

5.2.3 Water Service Providers (WSPs)

A WSP is an institution who, contracted to a Water Service Authority (which is usually the municipality), is responsible for providing water in accordance with the Constitution, the Water Services Act, and the by-laws of the Water Service Authority (i.e. municipality). Three cases can be considered (WRC, 2011):

- The Municipality has contracted out the WSP functions
- Municipality has separate departments for WSP and WSA functions
- Municipality has both WSP and WSA functions in one department, i.e. they are one and the same.

Hence, for the sake of completeness, a list of possible WSP institutions include municipalities, municipal entities, water boards, community-based or non-profit organisations, private operators (either locally or foreign owned), or others like WUAs, industries or mines.

The WSPs duties include collecting and capturing groundwater data, including monitoring data, which must then be passed on to the WSA for interpretation and analysis. The WSPs also ensure that set scheduled O&M and additional scheme performance activities are completed timeously. As mentioned, these duties are often contracted out to WUAs or WSIs. These role players must ensure that their data and information is passed on to the WSP, which is then passed on to the WSA.

5.2.4 Water Service Authorities (WSAs)

Access to basic water services is a constitutional right and it is the responsibility of the WSA to progressively make this a reality. The WSA procures and selects WSPs (including itself) to carry out water service provision responsibilities. It also carries out financial planning and tariffs, prepares the water service development plans, and draws up regulations and by-laws for its given jurisdiction/district. The WSA must also undertake performance monitoring and management of its WSPs (and by extension its other subsidiary institutions), promote water conservation and demand management, and facilitate user education and information sharing.

It is important that information from all types of groundwater schemes is provided to the WSA so that these responsibilities and decisions can be best informed with benefit to all of society and the environment in a most sustainable way. The WSA should analyse the monitoring data, advise the WSP on operational and managerial improvements (including pumping schedules, pumping rates and monitoring frequency) and provide the CMA and DWS with regular updates and reports on general compliance, abstraction volumes and groundwater monitoring (quantity and quality).

In addition to delegating some of the management responsibilities to the WSP, the WSA can also contract external organisations (including specialists and consultancies) to assist in specific actions, including (groundwater/ecological/hydrological) monitoring and reporting. See the Water Services Act (WSA), No.108 of

1997 and Municipal Structure Act No. 117 of 1998 for a further outline of WSP and WSA functions and responsibilities.

South Africa has 144 WSAs in total, often under the jurisdiction of local municipalities (OECD, 2021). It is the duty of the groundwater user, WSI, the WUA, and the WSP to know who their WSA is and ensure that data and information regarding O&M, monitoring and management of their groundwater scheme reaches the WSA and is held mutually accountable for carrying out its functions.

5.2.5 Major Water Boards

There are currently nine government owned Water Boards in South Africa (see **Figure 5-2**) which play a role in the water sector and resource management. The primary role of a water board is to provide both potable water and waste services, to other water service institutions, i.e. WSIs, WUAs, WSPs and WSAs, that fall within their area of jurisdiction/service. They may also be contracted by a WSA, or as a joint venture, act as a WSP to provide water to consumers, provide water directly for industrial use and accept industrial effluent, or supply untreated or non-potable water to non-household users. This may be done through the establishment of groundwater schemes and conjunctive surface water groundwater use.

In this way, the water boards may be the party that WSIs or WUAs report to directly, however, they normally receive data and information from the WSAs and report to CMAs or DWS. They are also responsible for performing water conservation functions, providing training, support, and management services to the other institutions, and promote co-operation.

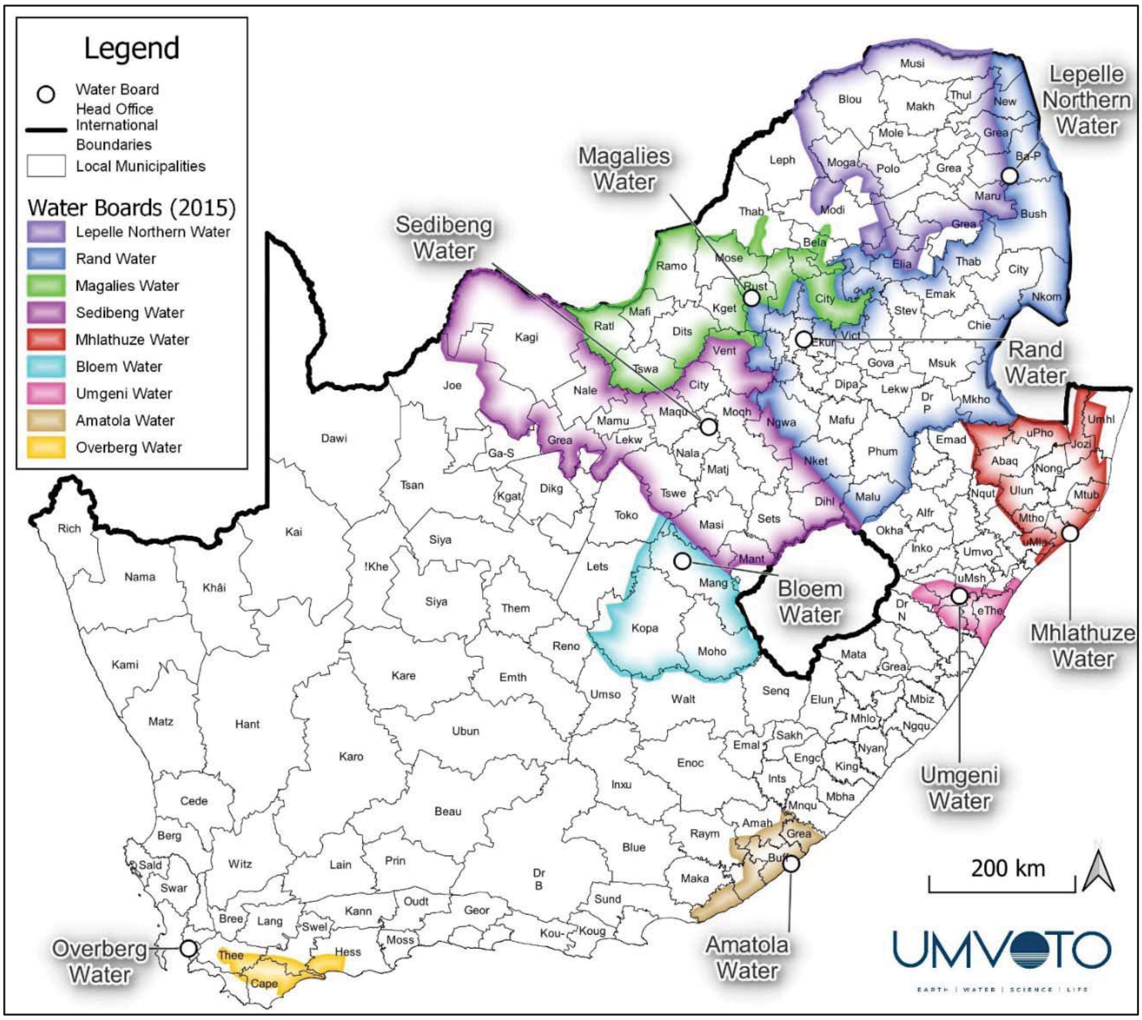

Figure 5-2 List and spatial distribution of the 9 water boards and their management areas (circa 2015) throughout the various local municipalities in South Africa.

5.2.6 Catchment Management Agencies (CMAs)

The National Water Policy (1997) and the NWA (1998) recognised that water resource should be based on hydrological boundaries (quaternary catchments) rather than political boundaries. This led to the establishment of 19 water management areas (WMAs) which have subsequently been reduced to be only nine (**Figure 5-3**). It is the intent that each of these WMAs have a corresponding CMA established to manage it.

There has been delay in establishing all nine CMAs, and only two CMAs have currently been established and are operational, namely the Inkomati-Usuthu CMA in Mpumalanga and the Breede-Gouritz CMA in the Western Cape. This delay has resulted in the establishment of "proto-CMA" bodies, which act as stand-in functional catchment management agencies run by regional DWS offices. Catchment Management Forums are another critical management body under the CMAs which aid in coordination between the CMA, WUAs, Irrigation Boards and the municipal WSA.

The CMA (or proto-CMA) has the primary responsibility of water resource management within its WMA and is arguably the most important institutional water body. CMA management functions include (WRC, 2020):

- Dealing with equitable and sustainable groundwater and surface water allocations so that catchment wide water balance is maintained, and the resource is utilised sustainably
- Responding to and aid in facing challenges such as climate change, combatting water shortages and helping resource poor farmers and other groundwater users
- Facilitate the establishment, transformation, management, and growth of the above-mentioned water institutional bodies (WSIs, WUAs, WSPs, WSAs and water boards).
- Keep up to date with Water Use Validation & Verification and water use licensing. CMAs monitor and police water use license compliance, and act on failure to comply which ensures that no one is using groundwater unlawfully and to the detriment of the environment or other users.
- CMAs also play a role in water use license processing with the DWS regional offices which helps to streamline the licensing process. It also helps the applicant to have a relationship with a licensing representative from the CMA who is local and knows the area.
- Through monitoring and information gathered, CMAs can focus on protection of water quality and water resources against pollution from dysfunctional wastewater works, mines, industry, agriculture, and other sources. The CMAs have better capabilities in terms of monitoring and policing of the various water uses.
- CMAs also raise awareness with locals and the public and support active stakeholder participation. Having local representatives from the CMA is a good way to involve the public and empower the public in being heard and understood. CMAs perform critical work on the democratisation of water resources and water management.

Hence, it is important that data and information of all groundwater schemes be provided accurately and efficiently to the CMAs through WSIs, WUAs, WSPs, WSAs and water boards, to inform the decisions and actions which have impacts at catchment scale. These are carried out through the establishment and implementation of Catchment Management Strategies, which should be viewed regularly by all groundwater users within the individual WMAs.

5.2.7 Private Sector

Consultants in the private sector include all the engineering, groundwater and environmental related specialists and professionals who carry out certain tasks related to groundwater scheme management under a contract to a WSI, WUA, WSP, WSA, water board, CMA or DWS. The tasks carried out are usually intensive and require a large amount of expertise and training with a large scientific knowledge base. They have limited to no authority within the groundwater management framework, unless contracted to carry out specific tasks, such as wellfield operations or monitoring, and generally inform and make recommendations to other water management bodies and stakeholders (i.e. clients) on their management needs.

Drilling and aquifer testing companies are the foundational first developers of a groundwater scheme (the boreholes) and offer a major key source of control and information. These contractors are also often capable of carrying out many groundwater scheme development, operations and maintenance tasks, such as drilling, borehole testing, borehole rehabilitation, borehole inspections, pump removal and installations, etc.

5.2.8 Water Research Commission (WRC)

The WRC is a government funded organisation that plays a key role in water research by establishing needs and priorities of the water industry and water related research, stimulating and funding the research, promoting the transfer of information and technology, and enhancing knowledge and capacity building in the water sector. Its fields of focus encompass water resources management, water-linked ecosystems, water use and waste management, and water use in agriculture.

All stakeholders involved in O&M, monitoring and management of a groundwater scheme should make themselves aware and familiar of research outputs of the WRC. There are many documents in the WRC database which can be of help to all stakeholders in carrying out their respective responsibilities.

5.2.9 Water Tribunal

The water tribunal is an independent body, consisting of members who have diverse technical skills and qualifications, which is established to hear appeals brought forward by anyone against any water management related directives, actions taken, or decisions made by any CMA, WSA or other water institutional body that are covered (or not covered) under the National Water Act. It allows people the chance to be heard and make a case for any issues relating to the use of a groundwater scheme.

5.2.10 Department of Water and Sanitation (DWS)

The DWS is the primary government institution that plays the role of the major “groundwater champion” in development, management, and regulatory functions. The DWS, as a functional department of the national government, and also remains the custodian of water regulation in terms of its use and transformation policies, as stipulated in the NWA. Ultimately, the DWS is responsible for national legislation and planning, development of national groundwater resource policy, regulation, monitoring, and provision of support to other water resource institutions. DWS regional offices also act as the de facto proto-CMAs.

The responsibilities of the DWS include:

- Co-ordination with other national departments on policy
- National communication strategies and the development of national water strategies
- Regulatory functions for the water sector such as water use authorisation
- Compulsory national standards for water services
- Infrastructure regulation through its Water Trading Entity and National Water Resources Infrastructure Branch
- Oversight of public entities reporting to the minister
- Regulation of competition
- Aspects of economic regulation including setting raw water tariffs and overseeing the setting of bulk water tariffs by water boards and retail tariffs by water service authorities
- Monitoring groundwater sector performance, including conformity to national norms and standards.

5.2.11 National Government

The national government is the principal maker of water regulatory policies and laws, such as the National Water Act, Municipal Structures Act, and the Water Services Act, which governs and regulates the establishment and functions of the water institutional bodies which have been discussed.

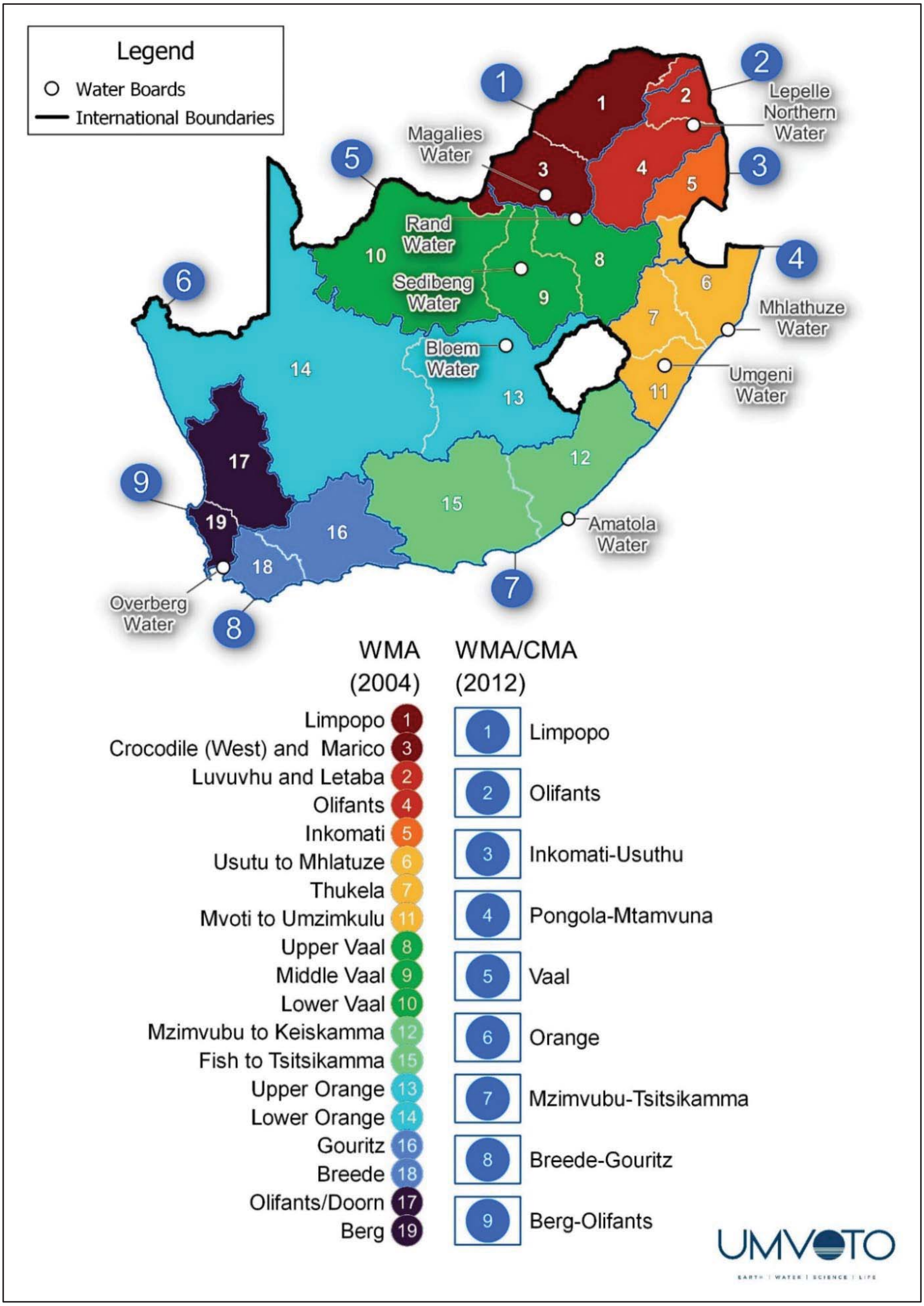

Figure 5-3 List and spatial distribution of the previous (19) and consolidated (9) WMAs and CMAs. Figure modified after NWRS2 (DWS, 2013a).

CHAPTER 6: GROUNDWATER CONFLICT

6.1 INTRODUCTION

Groundwater is a shared resource and so it should be protected for the benefit of all stakeholders. This was highlighted in the NWA which made the state the primary custodian of the shared resource, prior to which water was considered a “privately owned resource” in South Africa. The difficulty lies in the fact that groundwater divides do not align with socio-economic boundaries, such as private land, municipal jurisdictions or even international borders, but rather it is transboundary extending across multiple confines over large distances. If one party induces stress on the aquifer within their boundaries it will influence the aquifer within the surrounding boundaries as well. Resources boundaries and user domains are dynamic and transient which change all the time. Conflicts may arise in transboundary aquifers where water demands and approaches to water resource governance between relevant nations are misaligned or locally where groundwater resources are poorly understood and agreements for shared use and mutual benefit are lacking.

It is likely that conflicts will arise as competition for water resources continues to grow due to population growth and the effects of climate change. Conflict has been defined as “a social situation in which a minimum of two actors or parties strive to acquire at the same moment in time an available set of scarce resources” (Wallensteen, 2002). Water conflicts may arise due to factors such as (Darnault, 2008):

- Water scarcity (permanent or temporary)
- Differing goals and objectives
- Social, cultural and historical differences
- Misinformation
- Asymmetric power between parties
- Data gaps or questions of data validity and reliability
- Hydropolitical issues
- Non-cooperation
- Differences in values or ideologies
- Changes in law and legislation
- Uncertainty of responsibility and jurisdiction

At the core of groundwater conflict lies issues relating to overexploitation and pollution of the groundwater resource. It is important that groundwater schemes be managed with principles of hydrodiplomacy and water sharing for conflict prevention, management and resolution, and overall sustainable use of groundwater resources. This chapter aims to highlight some of these principles and approaches that can be utilised for groundwater conflict prevention or resolution. Although there is no blueprint for conflict management since no problem encountered is the same, the principles outlined here may aid in coming to a solution if applied efficiently.

6.2 TRANSBOUNDARY AQUIFER MODELS

Some common models and scenarios that may lead to groundwater conflicts are shown below (described by Eckstein and Eckstein, 2003). It must be noted that these were originally developed for international transboundary aquifers shared between states, such as the Karoo Sedimentary Aquifer, Ramotswa Aquifer, Stampriet Aquifer, and the Limpopo Basin. However, the scenarios can apply at local scales as well, for example, between two neighbouring properties. Therefore, the meaning of the word state extends to include any party that may have a groundwater scheme within a boundary (see **Figure 6-1**).

Model A

In this case, the river forms the boundary between the two territories. Under normal conditions, pollution found in one side of the aquifer is unlikely to affect the other side due to the presence of the river which is hydraulically connected to the aquifer. However, the pollution may affect the river itself. If it is a gaining stream then pollution from one side of the aquifer will flow into the river and this will impact other parties using the river. If the river is a losing stream, then any pollution within the river can affect both sides of the aquifer (i.e. both territories).

If one scheme over pumps the aquifer in their territory and the cone of depression extends to or beyond the river, it will deplete the available resources of the other party or scheme, as well as drawing any pollution from the other side due to the change in hydraulic gradient. These scenarios can lead to conflicts between two schemes located either side the river boundary. External factors such as drought may also create tensions.

Model B

In this case, the boundary between two territories bisects the river and aquifer rather than tracing along it. Flow in the river and aquifer generally follows the slope from the upgradient territory to the downgradient one, and any pollution along with it. Over pumping in the upgradient territory will also reduce the available groundwater in the downstream territory and draw any pollution in from the downgradient territory.

Model C

One of the two components (either the river or the aquifer, in this case the aquifer) is located across the border. The flow between territories is solely dependent on the hydraulic gradient of the aquifer. Here, groundwater recharged on the aquifer side flows into the other side towards the gaining river. Excessive pumping of the aquifer on one side may result in a change in flow direction which will draw pollutants with it from the river and from the other territory, as well as decreasing the available groundwater for the other territory.

Model D

Similar to model C, only one component of the system crosses the border, in this case the river which flows from the upgradient territory to the downgradient territory with the aquifer existing only in the downgradient side. Pollution in the upgradient river will affect the downgradient aquifer. Pollution (by both parties) and over pumping of the aquifer will only affect the downgradient party or scheme.

Model E

This scenario describes a confined aquifer that is not connected to any surface water bodies and is recharged through infiltration of precipitation. The recharge zone exists only in one territory while the aquifer exists across both territories. PCAs in the recharge zone will affect the aquifer underlying both territories, whilst diversion of or increase in runoff in the recharge zone in one territory will decrease the groundwater availability for both sides. Over pumping in either territory will affect the groundwater availability for both, and polluted groundwater may flow between both sides.

Model F

This case is unique as it is devoid of any connection with a surface water body or any recharge. It contains old and non-renewable groundwater, existing generally in arid zones of the country. This means that consequences are only a result of pumping the aquifer by one or both parties. The resource is completely limited and competition for water maybe high. These cases are also vulnerable to water quality concerns due to the lack of natural recharge and/or discharge preventing any natural remediation capacity.

6.3 MANAGAMENT APPROACHES

Although groundwater schemes are separate and are managed by separate entities, they utilise a shared resource. Management systems must, therefore, have a shared component as well, whether it be a shared philosophy, goal or shared data and information. **Separate management** of groundwater schemes will likely lead to unsustainable aquifer utilisation resulting in depletion and/or pollution. One concerned scheme or party may be unable to influence the issues imposed by another scheme or party. It problematic since separate management is usually the default approach for groundwater schemes because it allows independent power, has minimal and independent costs, and requires no special action to operate and manage. Other management approaches, such as coordinated management or joint management, may be beneficial to all parties involved, aid in avoiding conflict, as well as protect the resource and environment (Darnault, 2008).

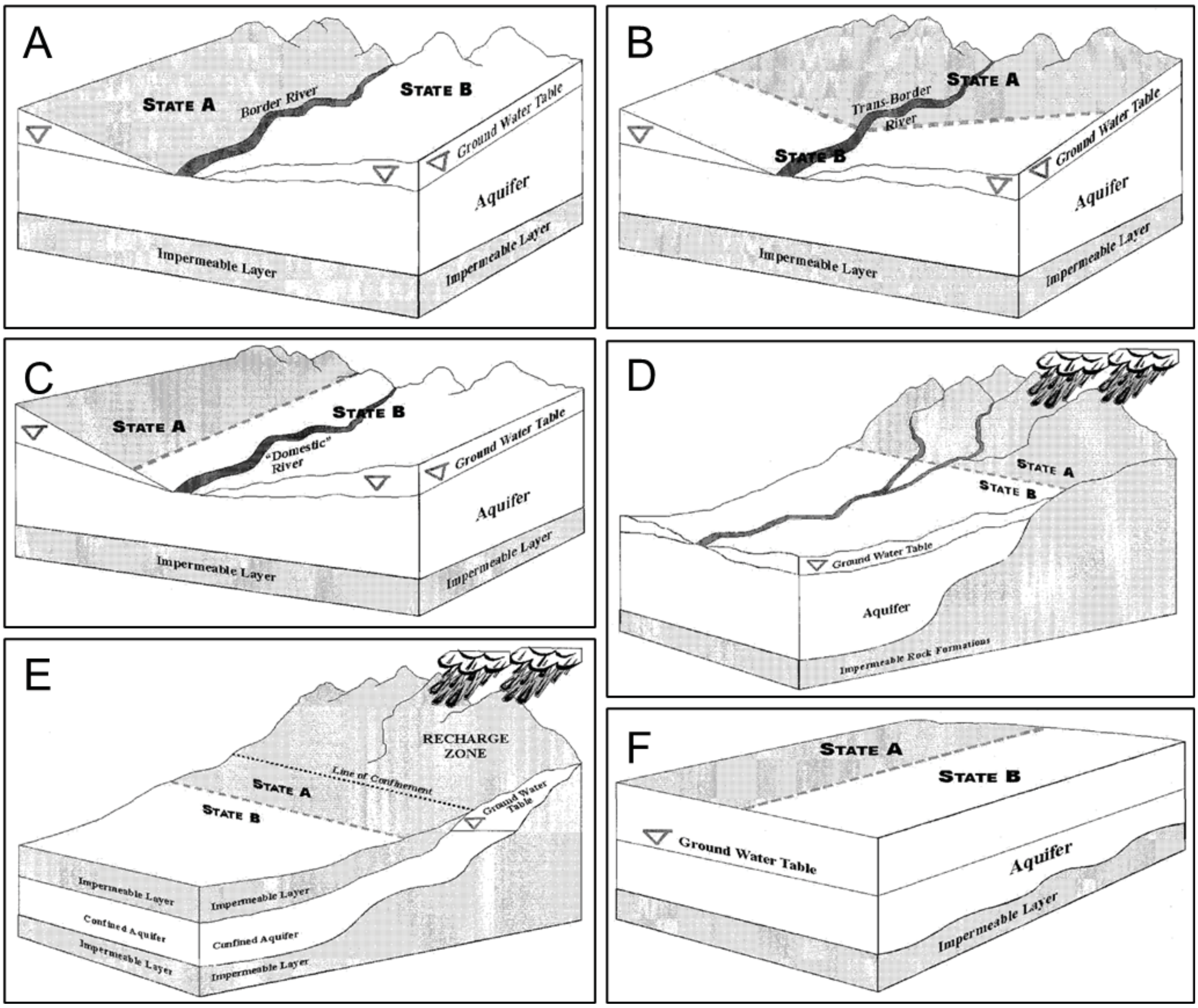

Figure 6-1 **Various transboundary aquifer models described by Eckstein and Eckstein (2003). A: an unconfined aquifer that is linked hydraulically with a river, both of which flow along a border (i.e. the river forms the border). B: an unconfined aquifer intersected by a border and linked hydraulically with a river that is also intersected by the same border. C: an unconfined aquifer that flows across a border and that is hydraulically linked to a river that flows completely within one of the territories. D: an unconfined aquifer that is completely within one territory but that is linked hydraulically to a river flowing across a border (the aquifer is located in the "downstream" territory). E: a confined aquifer, unconnected hydraulically with any surface water body, with a zone of recharge (possibly in an unconfined portion of the aquifer) that traverses a border or is located completely in another territory. F: A transboundary aquifer unrelated to any surface body of water and devoid of any recharge.**

Coordinated management allows each party or scheme to run independently and with full authority, however, some activities or elements are coordinated. For example, collection and sharing of data or modelling can be coordinated for mutual benefit. Coordinated management may even be effective for temporary implementation, such as during times of crisis or hardship. In **joint management** approaches, the parties or schemes develop a collective institutional structure for the sustainable and conservative utilisation of the aquifer and share both authority and responsibility. Another solution is the **delegation of management** and responsibility to an external party, such as hydrogeological consultants or regional water institutions. Some aspects of management are or may be privatised, such as monitoring or abstraction, with the original parties taking on a regulatory role (Darnault, 2008).

Ideally, **sequential and flexible management** should exist. This means that the management approach can change in response to specific problems from coordinated to joint management, for example, while evolving and improving over time. If parties remain separate, both will lose in the long term. There must be some extent of collaboration towards aquifer protection between schemes that share an aquifer, which requires a three-step cooperative effort. The first step is the qualitative and quantitative monitoring of the shared aquifer; the second is addressing the main threats to the schemes and shared resource, and the third being the development and imposition of standards (whether it be values, water quality or abstraction standards). Hence, all groundwater schemes should identify any neighbouring schemes and initiate a management relationship so that separate management is avoided, resulting in win-win situations, rather than win-lose or lose-lose situations (Darnault, 2008).

6.4 CONFLICT RESOLUTION

Groundwater conflicts may be difficult to resolve as surface water boundaries and socio-economic boundaries are not well suited for groundwater management, as highlighted in **Figure 6-1**. This, combined with the "invisible" nature of groundwater, results in a high degree of uncertainty. When sound understanding of a problem or system, and its respective solution remain contested for long periods of time, it is difficult to reach any resolutions. This is why monitoring of groundwater use, groundwater levels and groundwater quality for a scheme is so important as it may enable sound knowledge and understanding in times of conflict and accelerate resolutions (Darnault, 2008).

It is often more important to reach the consensus of "maybe" than "yes" because maybe initiates the **collaborative learning** process where all parties learn from each other through mutually focused thinking and productive discussions. This develops systems thinking, conflict management and good working relationships between parties and encourages acquisition of high-quality data and information to be brought forth (Darnault, 2008).

Any groundwater conflict should consist of three phases, namely creation, management, and resolution. Conflict creation is the initial process of identifying and diagnosing an existing issue with a joint search for data and information regarding the issue. Creation is then followed by conflict management, which constitutes building trust between parties involved through mediation and arbitration alongside input from neutral and expert data and information. Lastly, there is conflict resolution which includes reaching a consensus and establishing mutual goals through adjudication, alongside public search for information, data and input (Darnault, 2008).

Optimisation or compromise form a spectrum of groundwater conflict resolution. Optimal solutions between parties include maximising the desired results and outcomes for all parties while minimising any adverse effects in question. Although this is the optimal solution, it is not always possible to optimise all objectives. In this case, the word "optimise" is exchanged with "satisfy" as trade-offs between objectives are made that are not simultaneously optimal but still satisfy the parties in conflict. Other times, optimising or satisfying one objective cannot be achieved without direct deterioration of another objective. This is called a non-inferior solution and it may unfortunately be necessary to resolve certain conflicts (Darnault, 2008).

In the end, open and **public engagement** is paramount to conflict management, prevention, and increased consensus, and it can occur on three levels. Public awareness is a one-way stream of information conveyed to alert other parties on certain issues, while public involvement is a two-way exchange of communication, information, and data with other parties. Public participation is the most effective form of interaction and conflict prevention between authorities, experts, and citizens, although often the most time consuming. It facilitates leadership from all parties, with mutually beneficial planning and equal distribution of power and decision-making. Management of all private and public groundwater schemes should be transparent and accountable, and any stakeholders or interested and affected parties should be allowed to ask questions, provide input and offer feedback in collaboration towards aquifer protection (Darnault, 2008).

Lastly, it is the duty of groundwater professionals to learn skills of conflict prevention, management and resolution in order to minimise disputes between users and to protect the groundwater resource. There exists a plethora of social, economic and political elements beyond the mathematical, physical, chemical, and biological knowledge of groundwater resources. Groundwater professionals have both the opportunity and obligation to affect societal change (Darnault, 2008).

CHAPTER 7: CONCLUSION

Monitoring can be considered the entry point to management. Failure to implement or adhere to a comprehensive monitoring and O&M often results in the inevitable failure of a groundwater scheme, rather than the failure of the groundwater resource. Groundwater schemes of all scales should realise the importance of effective O&M and monitoring for groundwater scheme management, as well as the significance of data and knowledge transfer to higher levels of management, and the decisions and responsibilities that it all feeds into. There are six common types of groundwater schemes of increasing scale and complexity, namely rural, private, commercial agriculture, industrial, municipal bulk supply, and managed aquifer recharge schemes, for which conceptual O&M and monitoring protocols have been provided.

Certain, universally applicable, management tools and best practice principles should be adapted by all types of groundwater schemes. Considerations during the design and development of a groundwater scheme, namely location, borehole drilling, design and construction, borehole pumping and aquifer utilisation, water quality, storage and reticulation networks as well as environmental and legislative considerations, will inform and control how effectively a groundwater scheme can be monitored, operated and managed.

These groundwater scheme design and development factors impact the use of management tools and best practice principles for O&M, such as the operating rules and monitoring objectives. These operating rules and best practice principles that should be implemented for all groundwater schemes include setting recommended yields, associated CWLs to prevent adverse impacts and unsustainable use, S_C thresholds to maintain borehole performance, OWLs which keep the scheme in optimum condition, HACCP analysis to inform on monitoring networks and parameters, critical levels and TPCs, and identification of PCAs and GPZs for aquifer protection.

One cannot manage what is not monitored because monitoring generates data which inform decisions. Monitoring objectives of a groundwater scheme should aim to assess if the operating rules and best practice principles are being adhered to and provide a real time check of current operational impacts on (sometimes predetermined) aquifer health indicators. Monitoring objectives can be of water quality, water level or operational and maintenance in nature, however, these spheres are often overlapping. With routine monitoring and adaptive management approaches, early warning systems and forecasting tools are established, and the operating rules and principles can be continuously revised and updated. A data management system should be included in these objectives, as well as secondary objectives, such as the establishment of water level and water quality baselines, event-based monitoring or sampling, and other types of monitoring such as climate and ecological effects which provide added value to understanding of the system.

Maintenance plans for routine, preventative, reparative and corrective maintenance should be in place to maintain scheme components such as the boreholes, pumps, storage and reticulation, power supply and other monitoring equipment and tools. Similarly, each type of scheme should have incident and emergency response plans in place to deal with contamination and spills, power failures, infrastructure or treatment failure, borehole issues and occupational injuries. These allow for rapid and structured responses that are effective in minimising impacts and damage to the groundwater scheme

These tools for effective O&M, monitoring and management can be upheld to a standard through drafting of QMS documents and SOPs, reference to work manuals, manufacturer documentation, SANS documents and national guidelines, and regular training and capacity building. Furthermore, internal reporting, evaluating, and revision is highly important to ensure an adaptive management approach is maintained and decisions made, or actions taken, are followed with accountability.

It is important that data is not only utilised for the immediate management of the groundwater scheme, but also in the management of the groundwater resource. Groundwater resource management happens at high levels of the South African legislative framework, with institutional water bodies such as WSIs, WUAs, WSPs, WSAs, water boards, CMAs, DWS and national government all playing a role. Overall, South Africa's groundwater legislation and governance structures are relatively comprehensive and align well with international IWRM principles. Generally, the concerns in South African groundwater management lie not in the legislation, but in the implementation thereof. It is important that management of a groundwater scheme is seen as extending through to the high levels of groundwater resource management because the data and information gathered during O&M and monitoring serve to inform the decisions, strategies and policies made.

Lastly, some situations and reasons for potential groundwater conflicts are presented. At the core of groundwater conflicts lies issues relating to overexploitation and pollution of the groundwater resource. It is important that groundwater schemes be managed with principles of hydrodiplomacy and water sharing for conflict prevention, management and resolution, and overall sustainable use of groundwater resources. Coordinated, joint, or sequential flexible management with collaborative learning, objective optimisations and compromises, with thorough public engagement are good approaches that enable these principles.

All these factors come together as the fundamentals for effective management of a groundwater scheme. Application and implementation of these fundamentals will move toward an efficient, long-lasting and sustainable use of groundwater schemes and, by extension, groundwater resources, providing greater water resilience and sustainability for society and the environment.

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APPENDIX A: Rural Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it (objective)	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Field technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole. If static water level is increasing over time, there may be aquifer recharge	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Pump operator and Supervisor
						Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
Pumped (dynamic) Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Field technician	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased Aquifer is being over abstracted and groundwater use is unsustainable There is risk of the pump burning out if water level reaches pump inlet. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes Pump should be inspected for damage	Pump operator and Supervisor
						Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be revised.	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it (objective)	What to do	Who does it
Pumping Times	Clock	Note the time that pump is switched on or off, or total hours of operation per day	Daily	Pump operator	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning.		Pump Operator Supervisor and Technical Manager
Yield	Discharge point	Bucket and stopwatch,	Monthly	Pump operator/field technician	If yield is decreasing (while pumped water level is deepens or remains the same), then SC has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Pump operator and Supervisor
	Flowmeter	Stopwatch	Monthly	Pump operator		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist
Abstracted Volumes	Calculated	Multiply the pump run time by the yield	Monthly	Pump operator	Abstracted volumes need to be monitored to assess demand and supply. For compliance (GA or license limits). It also feeds into groundwater availability assessments, and overall resource sustainability	Adjust accordingly for balance between demand and supply. Decrease abstraction if GA regulations or license limits are exceeded.	Pump operator
	Flowmeter	Read off the meter	Monthly	Pump operator			
Raw Groundwater Quality	Before treatment or storage	Field/handheld parameters	Monthly	Sampled by field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis. Microbiological parameters should also be assessed monthly or quarterly.	Field technician and Supervisor
		Laboratory analysis (SANS 241)	Bi-annually		Rural groundwater schemes are mostly used for potable supply. SANS 241 Drinking Water parameters will	Short term: If limits are exceeded, sample again. If limits are exceeded again, use back up supply and investigate	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it (objective)	What to do	Who does it
					determine if water remains safe for drinking.	immediate contamination sources.	
						Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Alternative groundwater sources should be utilised, or treatment systems put in place.	Hydrogeologist/ Engineer
Storage Level	Inside the storage tank	Float ball valve	Daily	Pump operator	If storage level is low, pump needs to be switched on. If storage level is high, pump needs to be switched off.	Switch pump on or off to maintain storage and supply	Pump operator
		Staff gauge	Daily				
Treated Groundwater Quality	Post treatment stage (if applicable)	Field/handheld parameters	Monthly	Sampled by field technician	EC/pH changes serve as first indicators for changes in water quality/treatment capacity.	A change in EC/pH should trigger a laboratory analysis. Microbiological parameters should also be assessed monthly to quarterly.	Hydrogeologist
		Laboratory analysis (SANS 241)	Bi-annually		SANS 241 Drinking Water Parameters will indicate if treatment is sufficient.	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded more than once, treatment investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it (objective)	What to do	Who does it
						Reticulation and storage network may require flushing	

APPENDIX B: Private Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Private owner or Field technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Private owner
		Pressure transducer	Continuous	Downloaded by owner		Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
Pumped Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Private owner or Field technician	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased Aquifer is being over abstracted and groundwater use is unsustainable There is risk of the pump burning out if water level reaches pump inlet.	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes Pump should be inspected for damage	Private owner
		Pressure transducer	Continuous	Downloaded by technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be	Hydrogeologist/Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					There may be influence from a neighbouring borehole.	revised. Pump should be inspected for damage	
Pumping Times	Clock	Note the time that pump is switched on or off	Daily	Private owner or Field technician	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning		Pump Operator Supervisor and Technical Manager
Yield	Discharge point	Bucket and stopwatch	Monthly	Private owner or Field technician	If yield is decreasing (while pumped water level is deepens or remains the same), then S_C has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Private owner
	Mechanical Flowmeter	Stopwatch				Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist/Engineer
	Electronic Flowmeter	Read off display					
Abstracted Volumes	Calculated	Multiply the pump run time by the yield	Monthly	Private owner	Abstracted volumes need to be monitored to assess demand and supply. For compliance (GA or license limits). It also feeds into groundwater availability assessments, and overall resource sustainability	Adjust accordingly for balance between demand and supply. Decrease abstraction if GA regulations or license limits are exceeded.	Private owner
	Flowmeter	Read off meter					
Raw Groundwater Quality	Before treatment/ storage	Field/ handheld parameters	Monthly	Sampled by Private owner or Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Private owner
		Laboratory analysis (depending on use)	Bi-annually		It will indicate the type of treatment required. SANS 241 Drinking Water Parameters will indicate if	Short term: If limits are exceeded, sample again. If limits are exceeded again, use back up supply and	Private owner

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					water remains safe for drinking. SAWQG Domestic will indicate if water is adequate for household use. SAWQG Irrigation will indicate if water is adequate for irrigation. SAWQG Recreation will indicate if water is adequate for recreational use (residential estates)	investigate immediate contamination sources	
						Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Alternative groundwater sources should be utilised, or treatment systems put in place.	Hydrogeologist/ Engineer
Storage Level	Inside the storage tank	Float ball valve	Daily	Private owner	If storage level is low, pump needs to be switched on. If storage level is high, pump needs to be switched off.	Switch pump on or off to maintain storage	Private owner
		Staff gauge	Daily				
		Automated	Daily		Pump will switch on automatically when storage reaches a certain level.		
	Dam level (if applicable)	Visual, staff gauge	Daily		If storage level is low, pump needs to be switched on. If storage level is high, pump needs to be switched off.	Switch pump on or off to maintain storage	Private owner
Treated Groundwater Quality	Post treatment stage	Field/handheld parameters	Monthly	Private owner or Field technician	EC/pH changes serve as first indicators for changes in water quality/treatment capacity	A change in EC/pH should trigger a laboratory analysis.	Private owner or Field technician
		Laboratory analysis	Bi-annually	Private owner or Field technician	It will indicate the type of treatment efficacy is adequate.	Short term: If limits are exceeded, sample again.	Private owner

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		(depending on use)			SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking. SAWQG Domestic will indicate if water is adequate for household use. SAWQG Irrigation will indicate if water is adequate for irrigation. SAWQG Recreation will indicate if water is adequate for recreational use (residential estates)	Long term: If limits are exceeded more than once, investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required Reticulation and storage network may require flushing.	Hydrogeologist/ Engineer

APPENDIX C: Commercial Agriculture Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Filed technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by Field technician		Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
Pumped Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Pump operator	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased Aquifer is being over abstracted and groundwater use is unsustainable There is risk of the pump burning out if water level reaches pump inlet. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes Pump should be inspected for damage	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be revised. Pump should be inspected for damage	Hydrogeologist/Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Pumping Times	Clock	Note time that pump is switched on or off	Daily	Pump operator	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning		Pump Operator Supervisor and Technical Manager
	Automated	Keep record of automated schedule	Daily/weekly				
Yield	Discharge point	Bucket and stopwatch	Monthly	Pump operator	If yield is decreasing (while pumped water level is deepens or remains the same), then S_C has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Pump operator and Supervisor
	Mechanical Flowmeter	Stopwatch				Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist/ Engineer
	Electronic Flowmeter	Read off display					
Abstracted Volumes	Calculated	Multiply the pump run time by the yield	Monthly	Pump operator	Abstracted volumes need to be monitored to assess demand and supply. For compliance (GA or license limits). It also feeds into groundwater availability assessments, and overall resource sustainability	Adjust accordingly for balance between demand and supply. Decrease abstraction if GA regulations or license limits are exceeded.	Field technician and Supervisor
	Flowmeter	Read off meter					
Raw Groundwater Quality	Before treatment/ storage	Field/ handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source. Groundwater in agricultural areas often consistently increases in salinity due to agricultural practices	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
						Change in agricultural practices should be encouraged to minimise salinity.	Farm manager

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					(leaching of pesticides, herbicides, fertiliser, etc.)		
		Laboratory analysis (parameters depending on use)	Bi-annually	Field technician	It will indicate the type of treatment required before use. SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking. SAWQG Irrigation will indicate if water is adequate for irrigation. SAWQG Livestock Watering will indicate if water is safe for livestock.	Short term: If limits are exceeded, sample again. If limits are exceeded again, be cautious of and assess effect on crops/livestock	Field technician and Supervisor
						Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Farming practices may require adaptation.	Farm manager/ Hydrogeologist
Storage Level	Dam level	Freeboard marker	Daily	Pump operator	Supply for agriculture needs to be maintained. Often pumps will switch on/off automatically when storage reaches a certain level (CWL).	Switch pump on or off to maintain storage and supply	Pump operator
		Staff gauge					
		Visual					
	Inside storage unit	Float ball valve					
		Staff gauge					
		Automated					
Treated Groundwater Quality	Post treatment stage	Field/ handheld parameters	Monthly	Sampled by Field technician	EC/pH changes serve as first indicators for changes in water quality/treatment capacity	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters	Bi-annually	Sampled by Field technician	SANS 241 Drinking Water Parameters will indicate if	Short term: If limits are exceeded, sample again.	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		depending on use)			water remains safe for drinking. SAWQG Irrigation and Livestock watering are also applicable.	Long term: If limits are exceeded more than once, investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required Reticulation and storage network may require flushing.	Hydrogeologist/Engineer
Cone of depression	Water levels in adjacent, proximal boreholes	Dip meter	Monthly, before the end of a pump cycle	Field technician	Boreholes at some distance away from the pumped borehole should be monitored to assess the cone of depression of pumping. Simultaneously pumped boreholes may result in borehole interference leading to decreased yields. This is especially important where separate farmers are competing for groundwater.	This must be managed by pumping only certain boreholes together to minimise interference, or by lowering the yields to control drawdown. Carry out hydrocensus to assess influence of other users.	Farm Manager/ Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			
Regional Water Level	Water levels in distal boreholes	Dip meter	Monthly, before the start of a pump cycle	Field technician	Regional water levels at some distance away from the influence of pumping should be monitored to assess the trends in natural groundwater levels of the aquifer. Decreasing trends imply over abstraction and potential loss of storage. Increasing trends imply aquifer recharge and	Hydrogeological investigation is required, and abstraction volumes should be reassessed.	Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					increased groundwater availability		
Climate	Weather station sensors	Manual readings	Daily	Field technician	Climate must be monitored to assess parameters such as rainfall and evaporation which are related to the water balance. It will also indicate how much rain has fell on crops and groundwater abstraction can be adjusted accordingly.	During times of high rainfall on crops groundwater abstraction can be decrease, and vice versa.	Farm Manager
		Automated	Continuous	Field technician		The amount recharge can be assessed to establish a water balance and ensure that the aquifer is not being overexploited while maintaining crop yield.	Hydrogeologist/Climatologist

APPENDIX D: Industrial Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Field technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by Field technician		Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
Pumped Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Pump operator	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased Aquifer is being over abstracted and groundwater use is unsustainable There is risk of the pump burning out if water level reaches pump inlet. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes Pump should be inspected for damage	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be revised. Pump should be inspected for damage	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Pumping Times	Clock	Note time that pump is switched on or off	Daily	Pump operator	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning.		Pump Operator Supervisor and Technical Manager
	Automated	Keep record of automated schedule	Daily/weekly				
Yield	Mechanical Flowmeter	Stopwatch	Monthly	Field technician	If yield is decreasing (while pumped water level is deepens or remains the same), then S_C has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Pump operator and Supervisor
	Electronic Flowmeter	Read off display	Monthly	Field technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist/ Engineer
Abstracted Volumes	Calculated	Multiply the pump run time by the yield	Monthly	Pump operator	Abstracted volumes need to be monitored to assess demand and supply. For compliance with GA or license limits. It also feeds into groundwater availability assessments, and overall resource sustainability	Adjust accordingly for balance between demand and supply. Decrease abstraction if GA regulations or license limits are exceeded.	Field technician and Supervisor
	Flowmeter	Read off meter					
Raw Groundwater Quality	Sampled before treatment/ storage	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Bi-annually (or as stipulated in licence conditions)	Field technician	It will indicate the type of treatment required before use. Required quality will depend on the type of water use.	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					SAWQG Industrial will indicate if water quality is adequate for industrial use. SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Industrial practices may require adaptation, or treatment steps introduced, or alternative sources should be implemented.	Hydrogeologist/ Engineer
	Monitoring boreholes	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and supervisor
		Laboratory analysis (parameters depending on use)	Bi-annually (or as stipulated in licence conditions), or event-based sampling	Field technician	Industrial processes pose a groundwater contamination risk. It is usually a license condition to monitor groundwater on site for potential contamination. Monitoring boreholes should be strategically placed according to HACCP assessment. If groundwater quality in the monitoring boreholes change, then it may indicate groundwater contamination has occurred.	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Field technician and Supervisor
						Long term: If limits are exceeded successively, operations should halt and investigation into possible contamination should be undertaken. Contamination may be on site or from surrounding sites. Groundwater remediation plans should be initiated if necessary.	Hydrogeologist
Storage Level	Inside storage tanks	Float ball valve Staff gauge	Daily	Pump operator	Supply for industrial processes needs to be maintained.	Switch pump on or off to maintain storage and supply	Pump operator

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		Automated			Often pumps will switch on automatically when storage reaches a certain level (CWL).		
	Dam level	Freeboard marker					
		Staff gauge					
		Visual					
Treated Groundwater Quality	Post treatment stage	Field/ handheld parameters	Weekly/ Monthly	Sampled by Field technician	EC/pH changes serve as first indicators for changes in water quality/treatment capacity	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Bi-annually to quarterly (or as stipulated by license)	Sampled by Field technician	SAWQG Industrial use will indicate if water is adequate for industrial use. SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded successively, investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required Reticulation and storage network may require flushing.	Hydrogeologist/ Engineer
Processed Water Volumes	Calculated	Multiply the pump run time by the yield	Monthly	Pump operator	Volume of processed water that is discharged, disposed of, or reused must be monitored for compliance (GA or license). This also feeds into overall resource sustainability and contamination monitoring.	If discharge/disposal limits are exceeded, then processed volumes (from production) must decrease.	Industry manager
	Flowmeter	Read off meter	Monthly				
Processed Water Quality	Sampled before discharge/ disposal	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		Laboratory analysis (parameters depending on use)	Bi-annually (or as stipulated in licence conditions)	Field technician	Processed waters need to be discharged, disposed of, or reused. Only a certain water quality will be allowed for discharge or disposable (usually stipulated by license limits). This might require treatment steps. License limits or regulations will stipulate the required water quality of discharged/disposed water.	Short term: If limits are exceeded, sample again and divert water or stop discharge/disposal.	
						Long term: If limits are exceeded successively, investigation into sources of potential pollution (through industrial processes) is required. Treatment efficacy needs to be restored or improved.	Hydrogeologist/ Engineer
Cone of depression	Water levels in adjacent, proximal boreholes	Dip meter	Monthly, before the end of a pump cycle	Field technician	Boreholes at some distance away from the pumped borehole should be monitored to assess the cone of depression of pumping. Simultaneously pumped boreholes may result in borehole interference leading to decreased yields. This is especially important where separate industries are competing for groundwater.	This must be managed by pumping only certain boreholes together to minimise interference, or by lowering the yields to control drawdown. Carry out hydrocensus to assess influence of other users.	Industry Manager/ Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			
Regional Water Level	Water levels in distal boreholes	Dip meter	Monthly, before the start of a pump cycle	Field technician	Regional water levels at some distance away from the influence of pumping should be monitored to assess the trends in natural groundwater levels of the aquifer. Decreasing trends imply overabstraction and potential loss of storage.	Hydrogeological investigation is required, and abstraction volumes should be reassessed.	Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					Increasing trends imply aquifer recharge and increased groundwater availability		

APPENDIX E: Municipal/Bulk Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Field technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by Field technician		Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
Pumped Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Pump operator	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased Aquifer is being over abstracted and groundwater use is unsustainable	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes Pump should be inspected for damage	Field technician and Supervisor
		Pressure transducer	Continuous (10-minute intervals)	Downloaded by technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					There is risk of the pump burning out if water level reaches pump inlet. There may be influence from a neighbouring borehole.	revised. Pump should be inspected for damage	
Pumping Times	Automated	Keep record of automated schedule	Daily/weekly	Pump operator	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning.		Pump Operator Supervisor and Technical Manager
	Manual (clock)	Note time that pump is switched on or off	Daily				
Yield	Mechanical Flowmeter	Stopwatch	Monthly	Field technician	If yield is decreasing (while pumped water level is deepens or remains the same), then S_C has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Pump operator and Supervisor
	Electronic Flowmeter	Read off display	Monthly	Field technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist/ Engineer
Abstracted Volumes	Flowmeter	Read off meter	Monthly	Pump operator	Abstracted volumes need to be monitored to assess demand and supply. For compliance with license limits. It also feeds into groundwater availability assessments, and overall resource sustainability	Adjust accordingly for balance between demand and supply. Decrease abstraction if license limits are exceeded.	Field technician and Supervisor
	Calculated	Multiply the pump run time by the yield					

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Raw Groundwater Quality	Sampled before treatment/ storage	Field/ handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Quarterly (or as stipulated in licence conditions)	Field technician	It will indicate the type of treatment required before use. SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Field technician and Supervisor
						Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Treatment steps may need to be introduced or improved, or alternative sources should be implemented.	Hydrogeologist/ Engineer
	Monitoring boreholes	Field/ handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Quarterly (or as stipulated in licence conditions), or event-based sampling	Field technician	It is usually a license condition to monitor groundwater for potential contamination. Monitoring boreholes should be strategically placed according to HACCP assessment. If groundwater quality in the monitoring boreholes change, then it may	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Hydrogeologist
						Long term: If limits are exceeded successively, and investigation into possible	

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					indicate groundwater contamination has occurred.	contamination should be undertaken. Groundwater remediation plans should be initiated if necessary.	
Storage Level	Inside storage tanks	Float ball valve	Daily	Pump operator	Municipal water supply services need to be maintained. Often pumps will switch on automatically when storage reaches a certain level (CWL).	Switch pump on or off to maintain storage and water supply	Pump operator
		Staff gauge					
		Automated					
	Dam level	Freeboard marker					
		Staff gauge					
		Visual					
Treated Groundwater Quality	Post treatment stage	Field/ handheld parameters	Weekly to Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality (potential contamination) or treatment efficacy	A change in EC/pH should trigger a laboratory analysis.	Field technician
		In line (automated)	Continuous	Downloaded by Field technician			
		Laboratory analysis (parameters depending on use)	Quarterly	Field technician	SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded successively, investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required Reticulation and storage network may require flushing.	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Chlorine Content	Reticulation network	Field/ handheld parameters	Monthly	Field technician	At points in the reticulation network chlorine concentrations may decrease due to stagnation. This may lead to water unfit for consumption	Reticulation network should be flushed periodically	Field technician and Supervisor
		In line (automated)	Continuous				
Treated Water Volumes	Flowmeter	Read off meter	Monthly	Pump operator	Volume of treated water must be monitored to assess losses during treatment and to ensure that demand is met.	If supply exceed demand, then production can be decreased, and vice versa.	Field technician and Supervisor
		Automated	Continuous				
Cone of depression	Water levels in adjacent, proximal boreholes	Dip meter	Monthly, before the end of a pump cycle	Field technician	Boreholes at some distance away from the pumped borehole should be monitored to assess the cone of depression of pumping. Simultaneously pumped boreholes may result in borehole interference leading to decreased yields.	This must be managed by pumping only certain boreholes together to minimise interference, or by lowering the yields to control drawdown.	Technical Management/ Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			
Regional Water Level	Water levels in distal boreholes	Dip meter	Monthly, before the start of a pump cycle	Field technician	Regional water levels at some distance away from the influence of pumping should be monitored to assess the trends in natural groundwater levels of the aquifer. Decreasing trends imply over abstraction and potential loss of storage. Increasing trends imply aquifer recharge and	Hydrogeological investigation is required, and abstraction volumes should be reassessed.	Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					increased groundwater availability		
Climate	Weather station sensors	Manual readings	Daily	Field technician	Climate must be monitored to assess parameters such as rainfall and evaporation which relate to the water balance. For conjunctive surface water and groundwater schemes, it will also indicate how much rain has fell and how much surface water is available for supply.	The amount recharge can be assessed to establish a water balance and ensure that the aquifer is not being overexploited. Groundwater abstraction can be adjusted according to surface water captured (for conjunctive schemes).	Hydrogeologist/Climatologist
		Automated	Continuous	Downloaded by Field technician			

APPENDIX F: MAR Groundwater Scheme O&M and Monitoring Protocol

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
Static Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the start of a pump cycle	Field technician	If static water level is consistently getting deeper: Recovery may not be sufficient There may be over abstraction of the aquifer (i.e. recharge may be too low compared to abstraction). Storage capacity in the aquifer has been depleted. There may be influence from a neighbouring borehole.	Short term: Lower the pumping rate of the pump. Allow longer recovery time between pump cycles. Carry out a hydrocensus to check for neighbouring pumping boreholes. Adjust yield and/or pumping regime accordingly.	Field technician and Supervisor
		Pressure transducer	Continuous	Downloaded by Field technician		Long term: Pumping rates and regime should be revised in conjunction with groundwater availability assessment.	Hydrogeologist
	In the recharge area/ recharge boreholes	Dip meter	Monthly, before the start of a pump cycle	Field technician	MAR will cause groundwater mounding to occur. This must be monitored and controlled as it may lead to flooding or earth movements (e.g. landslides). These monitoring boreholes should be strategically placed proximal to the area of MAR	Control the amount of water being recharged in balance with the amount being abstracted.	Technical Management/ Hydrogeologist
		Pressure transducer	Continuous	Downloaded by field technician			
Pumped Water Level	In the pumped borehole (and in monitoring boreholes nearby if available)	Dip meter	Monthly, before the end of a pump cycle	Pump operator	If pumped water level is consistently getting deeper: Borehole efficiency is decreasing (clogging or biofouling) Pump yield has increased	Short term: Lower the pumping rate of the pump. Carry out a hydrocensus to check for neighbouring pumping boreholes	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					Aquifer is being over abstracted and groundwater use is unsustainable There is risk of the pump burning out if water level reaches pump inlet. There may be influence from a neighbouring borehole.	Pump should be inspected for damage	
		Pressure transducer	Continuous	Downloaded by technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated, pumping rates should be revised. Pump should be inspected for damage	Hydrogeologist/ Engineer
Pumping Times	Automated	Keep record of automated schedule	Daily/weekly	Pump operator	Comparing the pumping times and the yield can provide an indication of the total volume abstracted. This data is important for aquifer sustainability. It is also important for pump maintenance planning.		Pump Operator Supervisor and Technical Manager
	Manual (clock)	Note time that pump is switched on or off	Daily	Field technician			
Yield	Mechanical Flowmeter	Stopwatch	Monthly	Field technician	If yield is decreasing (while pumped water level is deepens or remains the same), then S_C has decreased. This may be due to pump and/or borehole efficiency.	Short term: Perform step tests to assess S_C.	Pump operator and Supervisor
	Electronic Flowmeter	Read off display	Monthly	Field technician		Long term: Borehole and pump infrastructure should be cleaned and rehabilitated when S_C decreases by 25%, pumping rates should be revised	Hydrogeologist/ Engineer
Abstracted Volumes	Flowmeter	Read off meter	Monthly	Pump operator	Abstracted volumes need to be monitored to assess demand and supply. For compliance with license limits.	Adjust accordingly for balance between demand, supply, and MAR volumes. Decrease abstraction if license limits or MAR volumes are exceeded.	Field technician and Supervisor
	Calculated	Multiply the pump run time by the yield					

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					It also feeds into groundwater availability assessments, and overall resource sustainability		
Recharge (MAR) Volumes	Weir	Manual measurement	Daily to monthly	Field technician	Volume of water recharged needs to be monitored and managed to maintain balance with abstraction. Avoid overfilling the aquifer which can lead to flooding.	Decrease recharge volume if abstraction decreases, Increase recharge volumes if abstraction increases. Decreases recharge volume if signs of flooding are seen.	Technical Management/ Hydrogeologist
		Automated	Continuous				
	Flowmeter	Read off meter	Daily to monthly				
		Automated	Continuous				
Raw Groundwater Quality	Sampled before treatment/ storage	Field/ handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Quarterly (or as stipulated in licence conditions)	Field technician	It will indicate the type of treatment required before use. SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Field technician and Supervisor
						Long term: If limits are exceeded more than once, investigation into sources of potential pollution is required. Treatment steps may need to be introduced or improved, or alternative water sources should be explored.	Hydrogeologist/ Engineer
	Monitoring boreholes	Field/ handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		Laboratory analysis (parameters depending on use)	Quarterly (or as stipulated in licence conditions), or event-based sampling	Field technician	It is usually a license condition to monitor groundwater for potential contamination. Monitoring boreholes should be strategically placed according to HACCP assessment. If groundwater quality in the monitoring boreholes change, then it may indicate groundwater contamination has occurred. Aquifer may not be sufficiently cleaning the MAR waters	Short term: If limits are exceeded, sample again. Investigation into immediate sources of contamination should be undertaken.	Hydrogeologist
						Long term: If limits are exceeded successively, and investigation into possible contamination should be undertaken. Groundwater remediation plans should be initiated if necessary	
MAR Source Water Quality	Sampled before recharge	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source.	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor
		Laboratory analysis (parameters depending on use)	Bi-annually (or as stipulated in licence conditions)	Field technician	Quality of recharge (MAR) water is important because the aquifer must have sufficient treatment capacity to improve the quality of water. Full suite laboratory analysis (parameters depend on MAR water source) will assess quality of MAR water. Treatment steps may need to be introduced/improved prior to recharge.	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded more than once, investigation into sources of poor water quality is required. MAR waters should be diverted (to waste) if quality is too poor for the aquifer	Hydrogeologist/ Engineer
	Monitoring boreholes	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality/source, which may allude to sources of contamination	A change in EC/pH should trigger a laboratory analysis.	Field technician and Supervisor

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
		Laboratory analysis (parameters depending on use)	Bi-annually (or as stipulated in licence conditions), or event-based sampling	Field technician	Monitoring boreholes should be strategically placed proximal and distal to MAR source. This will assess the change in groundwater quality and effectiveness of the aquifer to clean MAR waters	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded successively, operations should halt and investigation into possible contamination of MAR source water should be undertaken.	Hydrogeologist
Storage Level	Inside storage tanks/ reservoirs	Float ball valve	Daily	Pump operator	Water supply through storage needs to be maintained to meet demand. Often pumps will switch on automatically when storage reaches a certain level (CWL).	Switch pump on or off to maintain storage and water supply	Pump operator
		Staff gauge					
		Automated					
	Dam level	Freeboard marker					
		Visual					
Treated Groundwater Quality	Post treatment stage	Field/handheld parameters	Monthly	Field technician	EC/pH changes serve as first indicators for changes in water quality (potential contamination) or treatment efficacy	A change in EC/pH should trigger a laboratory analysis.	Field technician
		In line (automated)	Continuous				
		Laboratory analysis (parameters depending on use)	Bi-annually	Field technician	SANS 241 Drinking Water Parameters will indicate if water remains safe for drinking.	Short term: If limits are exceeded, sample again.	Field technician and Supervisor
						Long term: If limits are exceeded successively, investigation into treatment efficiency is required. Replace/repair treatment infrastructure if required	Hydrogeologist/ Engineer

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
						Reticulation and storage network may require flushing.	
Chlorine Content	Reticulation network	Field/handheld parameters	Monthly	Field technician	At points in the reticulation network chlorine concentrations may decrease due to stagnation. This may lead to water unfit for consumption	Reticulation network should be flushed periodically	Field technician and Supervisor/ Engineer
		In line (automated)	Continuous				
Treated Water Volumes	Flowmeter	Read off metered display	Monthly	Pump operator	Volume of treated water must be monitored to assess losses during treatment and to ensure whether demand is met.	If supply exceed demand, then production can be decreased, and vice versa.	Field technician and Supervisor
		Automated	Continuous				
Cone of depression	Water levels in adjacent, proximal boreholes	Dip meter	Monthly, before the end of a pump cycle	Field technician	Boreholes at some distance away from the pumped borehole should be monitored to assess the cone of depression of pumping. Simultaneously pumped boreholes may result in borehole interference leading to decreased yields.	This must be managed by pumping only certain boreholes together to minimise interference, or by lowering the yields to control drawdown.	Technical Management/ Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			
Regional Water Level	Water levels in distal boreholes	Dip meter	Monthly, before the start of a pump cycle	Field technician	Regional water levels at some distance away from the influence of pumping should be monitored to assess the trends in natural groundwater levels of the aquifer. Decreasing trends imply overabstraction and potential loss of storage.	Hydrogeological investigation is required, and abstraction/MAR volumes should be reassessed.	Hydrogeologist
		Pressure transducer	Continuous	Downloaded by Field technician			

What to monitor	Where to monitor	How to monitor it	How often to monitor it	Who monitors	Why monitor it	What to do	Who does it
					Increasing trends imply aquifer recharge and increased groundwater availability		
Climate	Weather station sensors	Manual readings	Daily	Field technician	Climate must be monitored to assess parameters such as rainfall and evaporation which relate to the water balance. For conjunctive surface water and groundwater schemes, it will also indicate how much rain has fell and how much surface water is available for supply.	The amount natural recharge can be assessed to establish a water balance and ensure that the aquifer is not being overexploited. This will also feed into stormwater quantifications for MAR.	Hydrogeologist/ Climatologist
		Automated	Continuous	Downloaded by Field technician			