GUIDANCE DOCUMENT ON PROTECTION ZONES (DELINEATION AND PROTECTION): DEVELOPMENT OF METHODOLOGICAL APPROACH AND IMPLEMENTATION PLAN

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Guidance document on Protection Zones (Delineation and Protection):

Development of methodological approach and implementation plan

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by

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EXECUTIVE SUMMARY

Groundwater is a vital source of freshwater (Walter, 2010) and its role in meeting water demands will only become more pivotal under future climate and population growth scenarios (Altchenko and Villholth, 2013). Already, in southern Africa, the South African Development Community (SADC) heavily relies on groundwater, with an estimated 70% of the SADC's population utilising this resource for basic water needs (McGill et al., 2019; GWC, 2001). However, the supply of groundwater to meet this demand is at risk; given its location and hydraulic nature, groundwater resources can be rapidly compromised by contamination. The continued and future use of groundwater resources requires effective management, with the protection of groundwater from contamination being of utmost importance.

Currently, there are no implemented legislative guidelines on establishing groundwater protection zones in South Africa. This guidance document aims to describe how knowledge-based and precautionary management approaches may be used to protect groundwater resources from existing pollution sources, and from future threats (quality and quantity) through delineation and establishment of a groundwater protection scheme.

This guideline deals only with aspects of pollution prevention rather than remediation or prevention of recharge reduction or over abstraction, which constitutes a fundamental, but separate component of aquifer protection. The groundwater protection scheme is applicable to groundwater resource supply schemes of all scales and uses where groundwater quality needs to be preserved. More specifically, this guideline outlines a methodological approach to implementing a groundwater protection scheme for pollution prevention, including delineation of groundwater protection zones, vulnerability mapping, and identifying potentially contaminating activities within protection zones.

A groundwater protection scheme is an effective and practical means of protecting groundwater quality. The need for groundwater protection schemes in South Africa is summarised as:

- Currently, there are no implemented legislative guidelines on developing a groundwater protection scheme in South Africa.
- The objectives of a groundwater protection scheme align with various South African legislation such as NWA, SPLUMA and NEMA by promoting groundwater quality protection and sustainable spatial development.
- Groundwater quality protection promotes water resilience to the effects of climate change, population growth and changes in land use.
- Proactive implementation of groundwater protection schemes has beneficial cost implications compared to retroactive clean up and remediation of contaminated groundwater.
- Surface water systems that receive groundwater contributions may be directly influenced by groundwater quality in terms of water supply viability and impacts to surface water ecosystems.
- Groundwater protection schemes analytically assist to define the monitoring frequency of a groundwater resource and inform on procedures for reporting compliance issues, should contamination occur.

Key principals of groundwater contaminant transport are outlined in this guideline document. Contaminants are subject to physical and chemical processes occurring in the aquifer. These processes, together with contaminant type and associated characteristics (such as phase preference), influence the shape and rate at which a contamination plume moves in an aquifer. The slower a contaminant travels through an aquifer (longer residence time), the more opportunity there is for inactivation or natural attenuation (dispersion, dilution, sorption and degradation) of the contaminant before reaching a borehole or wellfield. Therefore, understanding principals of contaminant transport are imperative to determining which activities are suitable within various groundwater protection zones.

Groundwater resources and their associated potential for development have a wide, but variable spatial distribution across the country due to the diverse and complex nature of South Africa's geology. South Africa comprises numerous and variable physiographic and climatic terrains resulting in diverse hydrogeological characteristics that determine the occurrence of aquifers and, therefore, the occurrence, movement, and distribution of groundwater. South Africa's hydrogeology is characterised by four major aquifer types, namely fractured, intergranular, intergranular and fractured (basement), and karstic. The delineation of protection zones is strongly based on groundwater flow paths and travel times from potentially contaminated areas towards water supply boreholes. Subsequently, groundwater flow paths and travel times are dependent on aquifer type and associated characteristics (i.e. fractured, karstic, unconsolidated and consolidated primary aquifers and groundwater head gradients).

Groundwater use may range in scale from a single borehole to a wellfield comprised of several hundred boreholes. The extent and type of land use and development, ranging from rural and urban environments to industrial, agricultural and mining activities, informs the contaminant load. The risk of groundwater pollution is determined by the vulnerability of the aquifer and the contaminant load the aquifer is subjected to. The vulnerability depends on the aquifer type and overlying geological deposits, as aquifer characteristics control groundwater flow paths and travel times, which in turn determine residence times and attenuation potential in the aquifer. Each groundwater use requires a unique approach to groundwater quality protection. The approach should consider what is most appropriate for the specific aquifer type, vulnerability, and groundwater use with the associated contaminant load exposed to the aquifer. The approach should also consider what is most appropriate for the size (number of boreholes, radius of influence, borehole interaction) and the resources available, i.e. budget, time, data and expertise.

This framework for groundwater protection schemes includes two key aspects, namely land-surface zoning and protection responses. Land-surface zoning incorporates natural aquifer characteristics and comprises groundwater protection zone delineation as well as vulnerability mapping and ranking. Protection response includes anthropogenic and management factors through the identification of existing Potentially Contaminating Activities (PCAs) and formulating a protection response plan. Collectively, these four components can be summarised as:

- **Groundwater protection zones:** Delineate groundwater protection zones (GPZs) based on the available hydrogeological information on groundwater flow, recharge, discharge, and travel time.
- **Vulnerability mapping and ranking:** Assess the risk of groundwater contamination and guide long-term planning and decision making. This pragmatic step informs future placement of potentially contaminating activities.
- **Potentially Contaminating Activities Identification and Ranking:** Identification of existing PCAs that may be considered a possible origin of microbial and/or chemical contamination within a groundwater source area and rank the associated risk of contamination.
- **Delineate different protection responses:** based on GPZ, aquifer vulnerability and PCA risk.

There are three major goals when delineating a groundwater protection zone:

1. The borehole/wellfield must be protected from direct contamination in the immediate vicinity of the borehole.
2. The borehole/wellfield must be protected from microbial contamination.
3. The borehole/wellfield must be protected from chemical contamination.

Using proven international legislation for GPZ delineation (including Denmark, Ireland, United Kingdom, USA Californian, and Australia) as well as South African best practice (due to the lack of legislation), four GPZs are outlined based on the risk to groundwater and the time taken for a microbe/chemical contaminant to become inactivated or naturally attenuate (dispersion, dilution, sorption and degradation). The definition of these four zones is supported by:

1. **Well-head protection zone/Inner zone (ZONE I)** with 10 m radius around the wellhead.
2. **Middle zone (ZONE II)** based on a two-year travel time.
3. **Outer zone (ZONE III)** based on a five-year travel time.
4. **Catchment Area (ZONE IV)** based on a ten-year travel time.

GPZ delineation may vary from simple to complex methodologies that include arbitrary fixed radius, calculated fixed radius, simplified variable shapes, analytical methods, hydrogeological mapping and numerical modelling.

Vulnerability mapping and ranking involves delineating areas susceptible to groundwater contamination based on aquifer characteristics which promote or inhibit movement of contaminants in the subsurface. Vulnerability mapping and ranking informs long-term planning and decision making (e.g. Spatial Development Frameworks). Numerous methods are available for assessing groundwater vulnerability, each with unique applications and data input requirements. Some common techniques include:

- GOD (G – the groundwater confinement, O – the overlying lithology D – depth to groundwater)
- AVI (The Aquifer Vulnerability Index)
- DRASTIC (Depth to groundwater, Recharge, Aquifer media, Soil type, Topography, Impact to vadose zone, Conductivity (hydraulic))
- Modified DRASTIC approaches
- Sensitivity analysis

An essential element of defining groundwater protection zones and prescribing associated activities is an inventory of existing PCAs. Approaches for undertaking a PCA inventory include either gathering information from local knowledge and hydrocensus, making use of open-source remote sensing and satellite imagery, information gathered from the local municipality or a combination of these. The PCA inventory needs to include a list of activities and locations associated to the following contaminants:

- Microorganisms, including faecal coliform bacteria, *Escherichia coli*, viruses, Giardia lamblia, and Cryptosporidium;
- Chemicals for which the maximum contaminant levels (MCLs) or groundwater quality standard for drinking, industrial and irrigation have been established;
- Contaminants of Emerging Concern (CEC) which do not always have established drinking water standards but are of growing concern in urban settings;
- 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, which have a carcinogenic concern.

Overlaying the GPZ with the vulnerability map and compiling a list of PCAs with the associated Level of Risk is the final stage of the groundwater protection scheme and risk assessment. A Protection Response number is calculated by summing the weighting of the protection zones, the weighting of vulnerability mapping and the PCA Level of Risk. The protection response number is categorized into different classes, which require varied degrees of monitoring (spatial and temporal distribution of monitoring), mitigation and responses.

Different approaches used to develop components of groundwater protection schemes have associated advantages and disadvantages. Some approaches use extensive hydrogeological analysis, providing a high level of confidence in contaminant probability (predicting the contaminant probability with a low margin of error), however this generally requires a broad range of robust hydrogeological data, and scientific expertise, which can become costly and time consuming to implement. By comparison, simplistic approaches have a lower degree of certainty (predicts the contaminant probability with a higher margin of error) but require less hydrogeological information, expertise, time and money. The approach applied should consider what is most appropriate for the groundwater use, type of aquifer, and aquifer vulnerability. Given the relationship between these variables, groundwater protection schemes may range from simple to intermediate or comprehensive. An example of the groundwater use, aquifer type and minimum data required for each scheme is also outlined. Additional considerations should be made based on the social and economic importance of the aquifer.

Roles and responsibilities for developing and enforcing groundwater protection schemes are outlined. Enforcement of land use limitations according to the groundwater protection zones should be a shared activity between the regulator, national and local government departments authorising land use activities as well as Water Users Associations, Water Service Providers and Water Services Authorities. Committee or task teams established between the regulator and relevant land use authorities can drive implementation of this shared authorisation process. Groundwater protection schemes require buy-in from stakeholders to ensure these are implemented at first and enforced going forward. This will vary based on the groundwater protection scheme selected. The processes for reporting pollution incidents are also detailed.

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ACRONYMS & ABBREVIATIONS

a	annum
CFA	Cape Flats Aquifer
CFAMS	Cape Flats Aquifer Management Scheme
CoCT	City of Cape Town
DNAPL	Dense nonaqueous phase liquids
DOC	dissolved organic matter
DRASTIC	Depth to groundwater, Recharge, Aquifer media, Soil type, Topography, Impact to vadose zone, Conductivity (hydraulic)
DSVI	DRASTIC Specified Vulnerability Index
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
e.g.	For example
EC	electrical conductivity
GIS	Geographic Information System
GPZ	Groundwater Protection Zone
GRP	Groundwater Resource Potential
ha	Hectare
IWRM	Integrated Water Resource Management
K	Hydraulic Conductivity
km	Kilometre
l/s	Litre per second
LNAPL	Light Nonaqueous Phase Liquide
m	metre

m^2/s	metres squared per second
m^3	metre cubed
m^3/a	metres cubed per annum
MAR	Managed Aquifer Recharge
Ml/d	Million litres per day
mm	Millimetre
mS/m	milli siemens per metre
NAPL	Non-Aqueous Phase Liquid
NGS	National Groundwater Strategy
NW	Northwest
NWA	National Water Act
NWRS	National Water Resource Strategy
PCA	Potentially Contaminating Activity
PHA	Philippi Horticulture Area
SADC	South African Development Community
SSC	Strategic Water Sector Cooperation
SWSA	Strategic Water Source Areas
TBA	Transboundary Boundary Aquifer
TMG	Table Mountain Group
TOC	Total Organic Carbon
UGP	Utilisable Groundwater Exploitation Potential
US EPA	United States Environmental Protection Agency
WCWSS	Western Cape Water Supply System
WMA	Water Management Area
WRC	Water Research Commission

WUL	Water Use Licence
ZAR	South African Rand

GLOSSARY

Adaptive management: The continuous integration of design, management, and monitoring to systematically test assumptions to adapt and learn.

Aquifer Protection: Activities undertaken to protect the aquifer from deterioration in water quality, the rehabilitation of an aquifer with respect to its water quality or reduction in aquifer recharge

Cone of depression: The depression of hydraulic head around a pumping borehole caused by the withdrawal of water.

Confined aquifer: A confined aquifer is bounded above and below by an impervious barrier. In a confined aquifer, the pressure of the water is usually higher than that of the atmosphere, so that when a borehole is drilled, the water in it stands above the top of the aquifer, or even above the ground surface.

Contamination: Contamination is simply the presence of a substance where it should not be or at concentrations above background.

Groundwater Protection Scheme: A component of Aquifer Protection that prevents pollution of groundwater resource supply systems for all scales and types of use where groundwater quality needs to be maintained.

Groundwater Protection Zone: The surface and subsurface area surrounding a borehole or wellfield, supplying a public water system, through which contaminants are reasonably likely to move forward and reach such a borehole or wellfield, based on the time taken for a microbe/chemical contaminant to break-down, diffuse or retard.

Hydraulic Head: The height above a datum plane such as sea level of the column of water that can be supported by the hydraulic pressure at a given point in a groundwater system.

Leaky aquifer: A leaky aquifer also known as a semi-confined aquifer, is an aquifer whose upper and lower boundaries are aquitards, or one boundary is an aquitard, and the other is an aquiclude. Water is free to move through the aquitards, either upward or downward.

Pollution: Pollution is contamination that results in or can result in adverse biological effects to resident communities. All pollutants are contaminants, but not all contaminants are pollutants

Potentially Contaminating Activity (PCA): Human activities that are actual or potential origins of contamination to a source. PCAs include sources of both microbiological and chemical contaminants that could have adverse effects upon human health.

Precautionary Principal Approach: An approach applied when an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause-and-effect relationships are not fully established scientifically.

Strategic Water Source Areas: Areas that form the primary source of water that sustains society and the associated economic activities.

Unconfined aquifer: An unconfined aquifer is bounded below by an impervious layer but is not restricted by any confining layer above it. Its upper boundary is the water table, which is free to rise and fall. Water in a borehole penetrating an unconfined aquifer is at atmospheric pressure and does not rise above the water table.

Vulnerability Assessment: Determination of the significant threats to a groundwater resource and the quality of the water supply, involving delineating areas of susceptibility to groundwater contamination based on aquifer characteristics which promote or inhibit movement of contaminants in the subsurface.

CHAPTER 1: INTRODUCTION

1.1 INTRODUCTION

Groundwater is a vital source of freshwater (Walter, 2010) and its role in meeting water demands will only become more pivotal under future climate and population growth scenarios (Altchenko and Villholth, 2013). Already, in southern Africa, the South African Development Community (SADC) heavily relies on groundwater, with an estimated 70% of the SADC's population utilising this resource for basic water needs (McGill et al., 2019; GWC, 2001). However, the supply of groundwater to meet this demand is at risk; given its location and hydraulic nature, groundwater resources can be rapidly compromised by contamination. The continued and future use of groundwater resources requires effective management, with the protection of groundwater from contamination being of utmost importance.

Groundwater contamination results in multiple, interlinked detrimental effects, including degradation of drinking water quality, loss of water supply, degradation of surface water systems and ecosystems, and potential health risks. Moreover, the cost of rehabilitation and/or sourcing alternative water supplies is high (US EPA, 2006). Therefore, it is crucial to ensure long-term protection of groundwater quality to mitigate the detrimental effects of groundwater contamination and ensure sustainable groundwater supply (Saatsaz et al., 2011). Groundwater contamination is primarily a result of anthropogenic impacts (US EPA, 2006; WRC, 2014), with a strong link to the unsuitable placement of human activities, such as waste disposal, urbanisation, industrial, mining, and agricultural activities (Nkhuwa, 2006; Nel et al., 2009). Development of groundwater protection schemes and emplacement of tighter controls on anthropogenic activities within the respective protection zones are therefore needed to minimise groundwater contamination potential. Groundwater protection schemes should consider the impacts of point and non-point source pollution occurring within and near groundwater resources, considering the potential pathways of contamination from current and future land use. Currently, in South Africa, there are no implemented legislative guidelines for the development of groundwater protection schemes (or its components: groundwater protection zone delineation or vulnerability mapping), therefore, a guideline is needed to define the development of groundwater protection schemes.

This Guidance document on Protection Zones (Delineation and Protection) aims to incorporate input from international legislation and methodologies but tailored to a South African context based on local hydrogeological understanding. This is to ensure that effective and implementable groundwater protection zones (both delineation and protection) are developed that ensure the sustainable use of groundwater in South Africa.

1.2 OVERVIEW OF GROUNDWATER PROTECTION

The Groundwater Management Framework (WRC, 2011) outlines that “Aquifer Protection” comprises three components namely, pollution prevention, remediation and rehabilitation, and prevention of recharge reduction (see **Figure 1-1**). This guideline focuses on the first component of aquifer protection shown in **Figure 1-1**, dealing with aspects of pollution prevention. The guidance document is targeted toward pollution prevention for groundwater supply schemes of all scales and types where groundwater quality needs to be maintained. A methodological approach to implementing a groundwater protection scheme for pollution prevention is outlined, incorporating delineation of groundwater protection zones (GPZs), vulnerability mapping and ranking, as well as identification and ranking of potentially contaminating activities (PCAs). Additionally, this guidance document informs the establishment of protection responses to determine monitoring frequencies and procedures for reporting compliance issues, such as pollution incidents. Note, it does not specify a direct course of action for remediation, but instead timeous reporting of compliance issues needed for remediation.

Since groundwater contamination risk is strongly linked to anthropogenic activities, considerations of current and future land use are critical aspects of a groundwater protection scheme. Therefore, this guideline incorporates the determination of land use restrictions within protection zones.

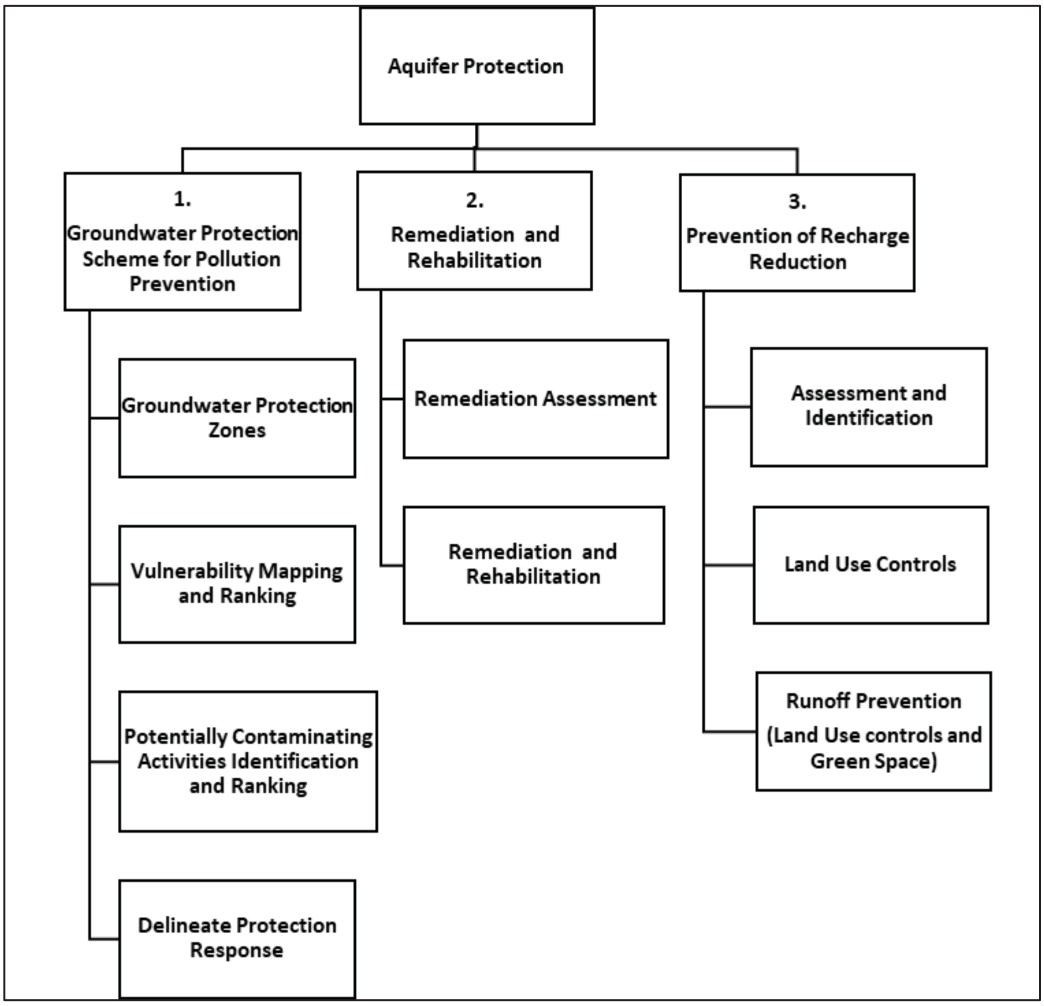

Figure 1-1 **The three components of Aquifer Protection and associated subcomponents namely, 1) groundwater protection scheme for pollution prevention, 2) remediation and rehabilitation and 3) prevention of recharge reduction (modified after WRC, 2011).**

1.3 PROJECT AIMS

This guidance document outlines knowledge-based management approaches for pollution prevention through the development of a groundwater protection scheme. The objectives set out to achieve the aim are:

1. Describe the importance of a groundwater protection scheme for pollution prevention;
2. Develop a methodological approach for executing the components of a groundwater protection scheme, namely groundwater protection zone delineation, vulnerability mapping, and identification of potentially contaminating activities within the respective protection zones – for all scales of groundwater use and aquifer types;
3. Stipulate roles and responsibilities of the various stakeholders to implement and enforce a groundwater protection scheme;
4. Highlight procedures on how to report compliance issues, such as pollution incidents;

1.4 PROJECT OUTCOMES

Currently, there are no implemented legislative guidelines on establishing a groundwater protection scheme for groundwater quality protection in South Africa. However, several policies and strategies developed (DWS, 2010; WRC, 2011; WRC, 2015 and RSA, 2015), outline the value and need for groundwater protection and sustainable spatial development but no methodological approaches have been approved or implemented at a legislative level. The earliest documented example of groundwater protection dates to 1964, where GPZs had been delineated in Barbados (Robins et al., 2007). Since then, many first world countries have progressed with implementing policies relating to groundwater protection. In contrast, South Africa has been less able to adopt and implement such policies and faces other pressing matters such as hunger, poverty, and disease outbreaks such as HIV Aids, all of which has taken the focus off groundwater protection and management (Robins et al., 2007).

Guidelines form the very base of the hierarchy of the South African legislative framework for water resource management (see **Figure 1-2**). This guidance document not only provides direction on how to implement groundwater protection schemes but also provides the foundation onto which a legislation for groundwater protection scheme development may be built. Any legislative outcomes from this guidance document should be set in context with the national water resource strategy, catchment management strategies and should align with the goals and objectives of other relating governmental departments, such as the Department of Agriculture, Land Reform and Rural Development (DALRRD).

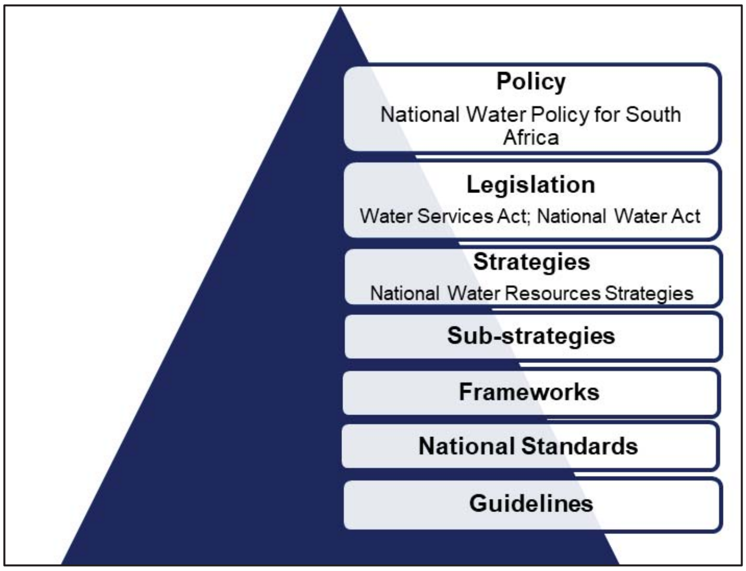

Figure 1-2 Hierarchy of South African legislative framework for water resource management.

CHAPTER 2: BACKGROUND

2.1 LEGISLATION THAT ALIGNS WITH GROUNDWATER PROTECTION SCHEMES

Although there is no implemented legislation for establishing groundwater protection schemes in South Africa, the objectives of groundwater protection schemes align with various South African legislative documents by promoting groundwater quality protection and sustainable spatial development. These legislations and the alignment with groundwater protection schemes are outlined below:

2.1.1 National Water Act

Prior to the political reform in 1994 and the new constitution released in 1996, South African groundwater was a highly neglected resource which was considered "private property", with little to no governing legislation in place. The post-1994 water policy reforms notably changed groundwater to a national “significant resource” which formed part of integrated water resource management (IWRM) in terms of the National Water Act (NWA), No. 36 of 1998 (RSA, 1998b), making the state the primary custodian of the newly indivisible resource. While groundwater plays an integral role in adaptive and alternative water resource for water supply diversification, it remains a finite natural resource that requires legislation, strategic frameworks and guidelines for protection and sustainable management, as stipulated in the NWA.

The NWA, Chapter 3 identifies the need to protect groundwater resources in relation to use, development, conservation, management, and control. Chapter 1, 2 and 3 recognize a series of measures that aim to ensure the comprehensive protection of water resources. These include classification of South Africa’s water resources, resource quality objectives and reserve determination. Chapter 3, Part 4 deals with pollution prevention and in particular the situation where pollution of a water resource occurs or might occur because of activities on land. It outlines that the person who owns, controls, occupies or uses the land in question is responsible for taking measures to prevent pollution of water resources on that land. If these measures are not taken, the catchment management agency (CMA) concerned may itself do what is necessary to prevent the pollution or to remedy its effects, and to recover all reasonable costs from the persons responsible for the pollution. Chapter 3, Part 5 deals with remediation of water resources following emergency incidents such as an accidental spill of a harmful substance that finds or may find its way into a water resource.

Use of a groundwater resource needs to be authorised under Section 39, as a General Authorisation (GA) or as a Water Use License (WUL), as provided for in terms of Section 21 of the NWA. A Water Use License Application (WULA) requires the submission of technical documents, reports and specialist studies. The exact requirements for a WULA are at the digression of the Department of Water and Sanitation (DWS) and municipalities based on the type and scale of water use. Often the WUL conditions require groundwater protection requirements which form components of a groundwater protection scheme. These may include delineating capture zones around boreholes for the residence time of, for example, 50 days, 100 days and 1-year based on a flow model and vulnerability mapping for each of the capture zones.

2.1.2 National Environmental Management Act

One of the intended outcomes of the National Environmental Act (NEMA) No. 107 of 1998 (RSA, 1998a) is the protection of the environment for current South African citizens and future generations. Section 24 of NEMA states that everyone has the right to an environment which is not harmful to their health or well-being. Section 24(2a) allows for certain activities to be prohibited and not granted environmental authorisation (EA) in a specified geographical area for a period if necessary for the protection of the environment, conservation of a resource or sustainable development. Sustainable development, according to NEMA, requires the integration of social, economic, and environmental factors in the planning, implementation, and evaluation of decisions to ensure that development serves present and future generations. This is what groundwater protection schemes aim to achieve through land use control to protect groundwater resources while still meeting social and economic goals.

2.1.3 Spatial Planning and Land Use Management Act

In South Africa, the Spatial Planning and Land Use Management Act (SPLUMA) (RSA, 2015) which is most applicable to the Department of Agriculture, Land Reform and Rural Development (DALRRD), is the legislation for all land use management and spatial planning. Spatial sustainability is one of the development principles detailed in SPLUMA Chapter 2. This is achieved through the conjunctive use of SPLUMA with other related planning legislation, such as the NEMA to ensure consistency, uniformity, and alignment with other legislation on land management. However, SPLUMA has not yet aligned with all spheres of legislation, such as the NWA. The NWA Chapter 3, Part 4 stipulates the responsibility of the land user to prevent pollution and does not outline more stringent legislation on restriction of certain activities in proximity of a drinking water resource, as would be stipulated in a groundwater protection scheme. These restrictions fall under the responsibility of the Department of Rural Development and Land Reform and SPLUMA and highlights the need for alignment between SPLUMA and NWA for effective groundwater protection.

2.1.4 National Groundwater Strategies

The Policy and Strategy for Groundwater Quality Management in South Africa (Department of Water and Forestry, 2000) identifies several functional approaches to provide adequate protection and efficient management of groundwater quality:

- A source-directed approach to prevent and minimise the impact of development on groundwater quality by imposing regulatory controls and by providing incentives. This can be enforced by implementing and developing licenses, standards, monitoring protocols, on-site management practices and certain requirements that pertain to the protection of groundwater quality.
- A resource-directed approach to groundwater quality management by implementing measures to protect the reserve and ensure suitability for beneficial use. In essence, this approach involves the development of a resource protection map using aquifer classification and a land-use planning map, both of which is necessary for the decision-making process.
- A site-specific and needs-specific approach to the remediation of degraded groundwater.

The National Groundwater Strategy (Department of Water Affairs, 2010) identifies the need for implementing ‘protection zones around groundwater abstraction points (and sometimes wellfields and even whole aquifers) within which activities that may pollute groundwater are controlled'. It also identifies the value and need for groundwater vulnerability mapping. It further outlines the necessity for a structured approach to the management of groundwater resources with two main components for groundwater management:

- A precautionary principal approach must be applied when making decisions on groundwater. This approach will be implemented for source-directed, resource-directed, and remedial management measures.
- A differentiated approach must be applied based on the aquifer vulnerability as well as the regional and local importance of the aquifers. This needs to be implemented because groundwater occurrence and use in South Africa can be widespread or highly localised, and it would be physically and economically difficult to protect all groundwater resources to the same degree.

2.1.5 Groundwater Management Framework

The Groundwater Management Framework (WRC, 2011) outlines aspects of aquifer protection which is defined as preservation of aquifer recharge and water-quality. Although the framework does not mention groundwater protection schemes as part of aquifer protection, the principals align with the overall goal of groundwater quality protection. The framework subcategorises aquifer protection into pollution prevention and remediation/rehabilitation protocols, which are established under the Water Services Act. The framework outlines aspects and details of each of these subcategories. Additionally, the framework outlines various levels of involvement required by diversely skilled staff of the relevant responsible institutions/stakeholders.

2.1.6 National Standards

The National Standards Act, No. 8 of 2008, was formed "to provide for the development, promotion and maintenance of standardisation and quality in connection with commodities and the rendering of related conformity assessment services" and allow for the establishment and continuation of the South African Bureau of Standards (SABS). A standard is something that must be done as a minimum and holds liability if not followed, while a guideline is a direction or recommendation to follow with addition or variation based on professional knowledge. The application of standards and supplementary guidelines form crucial tools for any national groundwater management framework.

The documents published by SABS are called South African National Standard (SANS) documents and exist across all commodity and services sectors. A review of the SABS catalogue reveals only a small handful of documents relating to water resources, and even less relating to groundwater protection. These include:

- **SANS 241:** Specifies the minimum acceptable quality of drinking water in terms of microbiological, physical, aesthetic and chemical determinands, based on acceptable risk. 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 19144**: Establishes the structures of a geographic information classification system. The South African National Land-Cover (SANLC) 2018 dataset has been generated from 20-meter multi-seasonal Sentinel 2 satellite imagery. The imagery used represents the full temporal range of available imagery acquired by Sentinel 2 during the period 01 January 2018 to 31 December 2018. The SANLC 2018 dataset is based primarily on the new gazetted land-cover classification standard (SANS 19144-2) with 73 classes of information and is comparable, with the previous 1990 and 2013-14 South African National Land-Cover (SANLC) datasets. This is valuable data input for vulnerability mapping that includes land use parameters used for defining vulnerability around a public drinking supply.

2.1.7 Reports and Guidelines

Additional to South Africa's legislation, some reports and guidelines have been written which align or contribute to groundwater protection schemes and its development in South Africa. Two of the keystone reports published through the Water Research Commission include *Towards a Guideline for the Delineation of Groundwater Protection Zones in Complex Aquifer Settings* (WRC, 2015) and *Groundwater Management Framework* (WRC, 2011)

2.2 BENEFITS OF A GROUNDWATER PROTECTION SCHEME

A groundwater protection scheme is a practical and proactive means to protect groundwater quality. It forms an additional methodology for groundwater management and resource protection. The importance for protecting water quality is recognised worldwide and extremely relevant in a South African context. Water quality protection benefits a multitude of stakeholders including water users, water service providers, water management institutions, health service providers and municipalities (Nel et al., 2009). The benefits associated with implementation of groundwater protection schemes for pollution prevention are summarised below and further elaborated in the subsequent sections:

- Terrestrial and aquatic ecosystem preservation
- Increased water resilience
- Cost benefit
- Monitoring frequency and reporting compliance issues

2.2.1 Increase Water Resilience

South Africa is a water-scarce country with many factors contributing to increased stress and vulnerability of the water resources, such as climate change, lower rainfall, increasing water demand and economic expansion, over-allocation, and storage depletion (such as siltation of dams) (Adams, 2019). Events such as the 2015-2018 "Day Zero" drought in the Western Cape and current drought in the Eastern Cape have also highlighted vulnerabilities in South Africa's water supply systems that are dominated by surface water supply. A solution to overcoming water stress and vulnerability in South Africa is to diversify our sources of water supply (Adams, 2019). Groundwater is an under-utilised water resource in South Africa, which water-related stakeholders can target. In conjunction with surface water supply, groundwater will increase water resilience for the future in South Africa. However, several studies show that the supply of water from aquifers in Africa are at risk of contamination due to improper placement of human activities such as agriculture, industries, and waste disposal sites (Nel et al., 2009). More specifically, the concern of contamination to water-supply aquifers is increasing in South Africa, due to rapid population growth and accompanying land-use change.

Through the proactive implementation of a groundwater protection scheme the potential threat of contamination to groundwater caused by human activities can be minimised. It promotes groundwater quality protection and increases sustainable supply of water which ultimately promotes water resilience in South Africa.

2.2.2 Terrestrial and Aquatic Ecosystem Preservation

Under typical conditions, groundwater moves from areas of recharge to areas of discharge, such as wetlands and surface water bodies. Surface water systems that receive groundwater contributions may be directly influenced by groundwater quality in terms of water supply viability and impacts to surface water ecosystems. Groundwater protection schemes provide protection to groundwater quality and thus indirectly protection of groundwater dependant surface water bodies such as wetlands, lakes, and rivers. This promotes sustained ecosystem health and preservation.

2.2.3 Cost benefit

Many studies (US-EPA [1995], Thomsen and Thorling [2003] and Nel et al. [2009]) have calculated that the economic costs associated to implementing proactive groundwater protection zone delineation is less than retroactive clean up and remediation of contaminated groundwater. A groundwater protection scheme will prevent harmful contaminants from entering the water supply boreholes and springs which will reduce the cost of treating the groundwater by water supply companies

This cost-benefit is especially true in South Africa where there are approximately 16 060 (3.6%) deaths per year linked to groundwater contamination (Statistics South Africa, 2005). Moreover, indirect advantages include a benefit to communities through decreasing the level of anxiety, fear, and morbidity of potential health problems. It also promotes a healthy work force, as it encourages productivity, motivation, absence management and staff retention which is economically beneficial. Protection schemes can also benefit water supply companies by preventing harmful contaminants from entering the capture zone of water supply boreholes and ultimately reducing purification costs (Nel et al., 2009). The reduction in purification costs will also reduce the cost of water to its users. Proactive groundwater quality protection additionally prevents contamination of groundwater fed wetlands and other groundwater dependant ecosystems. This in turn, protects wetland species and prevents remediation and clean-up costs due to contamination (Nel et al., 2009).

2.2.4 Allocation of Monitoring Frequency and Compliance Issues

A groundwater protection scheme analytically assists to define the monitoring frequency of a groundwater resource and inform on procedures for reporting compliance issues. This helps to guide groundwater users on the appropriate means to monitor and manage their groundwater supply as well as provide an early warning for contamination should it occur.

2.3 PRINCIPALS OF CONTAMINATION IN GROUNDWATER

2.3.1 Mechanisms of Groundwater Contamination

Although GPZs are delineated based on principles of groundwater flow, it is imperative to understand how groundwater becomes contaminated. A contaminant released into the aquifer from a potentially contaminating activity (PCA) requires a certain time before there is inactivation (natural attenuation) of the contaminant. The occurrence and placement of PCAs are critical for sufficient residence time and inactivation of a contaminant before reaching a wellfield/borehole. The four main ways in which groundwater can be contaminated are: recharge from surface waters, infiltration, direct migration, and inter aquifer exchange. This section will briefly review the mechanisms of contaminant hydrogeology (USEPA, 1994).

2.3.1.1 Recharge from Surface Water

Under typical conditions, groundwater moves from areas of recharge to areas of discharge, such as wetlands and surface water bodies. Thus, the flow of pollutants is from recharge areas towards discharge zones. Under atypical (changed hydraulic conditions), pollutants can move in the reverse direction, i.e. from a wetland into groundwater.

2.3.1.2 Infiltration

Infiltration refers to the process in which water at surface infiltrates into the soil through pore spaces in the soil matrix. As water moves downwards, under the influence of gravity, it dissolves materials that it encounters, forming leachate, composed of inorganic and organic constituents. When the leachate meets the saturated zone, it will spread in the horizontal direction following groundwater flow or depending on the density of the substance, move vertically. The main source of infiltration is via recharge of rainfall.

2.3.1.3 Direct Migration

Contaminants enter directly into the groundwater from below-ground sources, e.g. leaking pipelines, storage tanks, pit-latrines, septic tanks, landfills, cemeteries, and leakage of borehole seals. The sources of contamination lie either within the unsaturated zone or the saturated zone (depending on the water table), usually resulting in high concentrations of the contaminant with relative ease of spreading.

2.3.1.4 Inter-aquifer Exchange

Groundwater may become contaminated through inter-aquifer exchange where one water-bearing lithology (aquifer unit) becomes hydraulically connected to another. This can occur when a borehole penetrates more than one aquifer and causes a hydraulic connection between aquifers. Each aquifer has a specific hydraulic head and under natural conditions groundwater will move from the aquifer with a high hydraulic head to the aquifer with a lower hydraulic head. When the aquifer with the higher hydraulic head contains contaminants or poorer water quality, it may degrade the water quality in the other hydraulically connected aquifer.

2.3.2 Contaminant Characteristics

Groundwater contaminants exist in several different forms and are classed by their biological, physical, and chemical characteristics (Usher et al., 2004). It is imperative to classify the type and characteristic of a contaminant as this infers the physical and chemical processes occurring in the aquifer (such as phase preference) and ultimately, effects the shape and rate at which a contamination plume moves in an aquifer (longer residence time) (DOELG, 1994 and WRC, 2014).

2.3.2.1 Types of Compounds

2.3.2.1.1 Inorganic Chemicals

Inorganic chemicals are substances not usually found in living things, with the main difference between organic and inorganic chemicals being the basic skeletal structure of the molecules or compounds. Inorganic molecules such as nitrates, ammonia, and ions in solution (e.g. sodium and chloride) are common in groundwater and can be highly mobile and persistent due to their high solubility in water (US EPA,1987).

Inorganic compounds enter groundwater via several sources, mainly anthropogenic in origin: industrial spills, leachate from landfills, wastewater management facilities, and urban and agricultural run-off. The primary source of recharge is rainfall which is heavily influenced by atmospheric particulate matter, such as dust, salt, and air pollution. This means that activities outside the aquifer area can impact groundwater, i.e. acidic rain caused by air pollution. In addition to this, changes in the soil matrix, through invasive activities such as large-scale farming, or mining can also influence the groundwater below. The primary mode of transport for inorganic contaminants is through advection, with dispersion and dilution being the most effective mechanisms for reducing the concentration of contaminants in groundwater. The retardation process is dependent on the type of contaminant, i.e. nitrate undergoes denitrification, precipitation of minerals, etc. (US EPA, 1987) (transport processes are outlined in **Section 2.3.3**).

2.3.2.1.2 Organic Chemicals

Organic compounds can occur naturally or are synthetically made, e.g. pesticides, synthetic hydrocarbons and solvents. Some organic compounds do not (or only to a limited extent) mix with water; referred to as nonaqueous phase liquids (NAPLs). There are two types of NAPLs, which fundamentally behave differently to water due to a density contrast. The first, known as Light NAPLs (LNAPL), has a density less than that of water, such as diesel and motor oils and can be found near to the phreatic surface. The second type, known as Dense NAPL (DNAPL), has a density greater than water, such as chlorinated solvents, resulting in the contaminant sinking in the groundwater system (Usher et al., 2004).

Organic compounds can be persistent in groundwater, however, there are several chemical reactions, microbial activity and/or metabolism that may reduce or enhance the concentration of the contaminants in the groundwater. These processes can metabolise or destroy the contaminant by transformation or consumption, or they can produce by-products that are sometimes more toxic or more persistent than the original contaminant. These processes are affected by factors such as the volume of the contaminant, the pH, the redox state and temperature of the solution, the solubility properties, and the availability of certain organic and inorganic materials (EPA,1987).

2.3.2.1.3 Particulate Matter

Microorganisms, such as viruses, bacteria and protozoa, present a major threat to the quality of water. Microorganisms can occur naturally in the groundwater system or can be enhanced by human activities, such as leaking sewage pipes, wastewater treatment works or agricultural activities. Although surface waters are likely to contain higher concentrations of these microorganisms, groundwater systems that are under the influence of surface water systems may also be affected or if a groundwater resource is directly contaminated by a land-based activity such as pit latrines (Nel, 2014).

The transport of microorganisms (e.g. organic matter) in groundwater systems are more complex than the counter abiotic colloids (e.g. inorganic matter), simply because they are alive. Similar to the abiotic colloids, various physiochemical phenomena, such as pH, redox state and temperature, can affect the transport and longevity of the microorganisms in the groundwater. Although poorly understood, there are also biological processes that can affect microorganism transport behaviour, such as metabolic state, predation by other microorganisms and changes in surface properties (WRC, 2014).

2.3.2.2 Mechanisms of Aqueous Solubility

Aqueous solubility is the concentration of a chemical in the aqueous phase when the solution is in equilibrium (Schwarzenbach et al., 1998). The main factors which govern aqueous solubility are sorption, pH, temperature, and redox processes (Delleur, 1999). The aqueous solubility of a contaminant will influence the transport and toxicology of that compound in groundwater as well as the time it will take for a contaminant to attenuate (WRC, 2014).

2.3.2.2.1 Sorption

Sorption describes the physical and chemical process of one substance becoming attached to another (Nel, 2014). Sorption is the general term to describe two phenomena – absorption and adsorption. Absorption is the process in which a fluid is dissolved by a liquid or a solid, known as the absorbent. Adsorption describes the process in which atoms, ions or molecules of a substance adhere to the surface of the adsorbent and sorption involves the formation of bonds between the solid phase and the contaminant constituent (Nel, 2014). Differing bond strengths result in three types of sorption, namely chemisorption, physisorption and ion exchange (Delleur, 1999). Chemisorption is irreversible, whereby the bond formation between the solute and the solid surface is strong, resulting in covalent bonds, or near-covalent bond strength. Physisorption and ion exchange processes are reversible due to the weak bonds between the solute and the solid surface such as those associated with van der Waal's forces. Weak bond formations are susceptible to changing conditions, such as pH and temperature (Delleur, 1999). Sorption decreases contaminant migration as it reduces the amount of contaminant in the aqueous phase. Contaminants that have sorbed, will however be less available for chemical degradation reactions, which will reduce the effectiveness of many remedial technologies.

2.3.2.2.2 pH

pH is a highly influential factor governing the aqueous solubility of a contaminant in groundwater (Nel, 2014). The pH of a solution affects the ability of a contaminant to donate or accept protons, whilst additionally determining the speciation of all the acids and bases in the solution (DOELG, 1994). An equilibrium of the solution is changed when H+ ions are accepted or donated (Delleur, 1999). The redistribution of H+ ions add to the buffering effect which describes how the solution can resist changes to pH, by adjusting the direction of their chemical reactions (Nel, 2014). Buffers, therefore, consume acids and bases to maintain equilibrium in the system. The pH of groundwater plays an integral role in the 'liberation' of certain contaminants, i.e. the sorption processes (Nel, 2014). Various metals and pesticides, for example, have high sorption percentages with high pH values (>8) and limited sorption takes place at lower pH values (<6). The pH of groundwater is an indicator of the equilibrium conditions and the buffering capacity of the solution (Nel, 2014).

2.3.2.2.3 Temperature

Groundwater temperature is an important factor as it not only dictates the direction of chemical reactions but also the rate of reactions (Delleur, 1999). Furthermore, the pH of a solution is directly dependent on the temperature, where pH decreases with increasing temperature. This, however, does not mean that the water becomes more acidic at higher temperatures since a solution is considered acidic if there is an excess of hydrogen ions over hydroxide ions. The changes in pH, resulting from temperature changes, affect the sorption properties of constituents, and this may result in changes in acidity, as ions that are capable of donating protons may be liberated from solid surfaces (Schwarzenbach et al., 1998). Increasing the temperature translates into more thermal energy in the system; as molecules and ions vibrate, the resulting collision between different constituents of the system will increase the rate of reactions. Thermodynamics plays an important role in the equilibria and kinetics of precipitation and dissolution of minerals, as well as rates of biological transformation processes (Delleur, 1999).

2.3.2.2.4 Redox Processes

The reduction and oxidation processes exert an important control on the natural concentrations of O_2, Fe^{2+}, SO_4^{2-}, H_2S, CH_4 among others, in groundwater. In addition to this, they also determine the fate of some pollutants, such as nitrates leaching from agricultural practices, contaminants leaching from landfills, industrial spills, or heavy metals in acid mine drainage (Appelo and Postma, 2009). Redox reactions can be defined as a chemical reaction, in which electrons are transferred between two reactants participating in the reaction (Delleur, 1999). The order in which they proceed can be predicted from standard equilibrium thermodynamics. Redox processes in groundwater typically occur through the addition of an oxidant, such as O_2 or NO^{3-} to an aquifer containing a reductant. However, the addition of a reductant, such as dissolved organic matter (DOC) that leaches from soils or landfills can also be important (Appelo and Postma, 2009).

The oxidation state is an important factor in determining the behaviour of elements in the natural environment. For example, Fe^{2+} (ferrous iron), is more soluble in water than Fe^{3+} (ferric iron). If water containing high amounts of Fe^{2+} is exposed to oxygen (from a fluctuating water table, or injection water containing a high amount of dissolved oxygen), the ferrous iron will oxidise to ferric iron. This is problematic because iron hydroxide would precipitate out of solution, clogging pore spaces and changing the physical nature of aquifer material (Appelo and Postma, 2009). Many redox reactions occur in aquifers, **Figure 2-1** displays some of the more important processes.

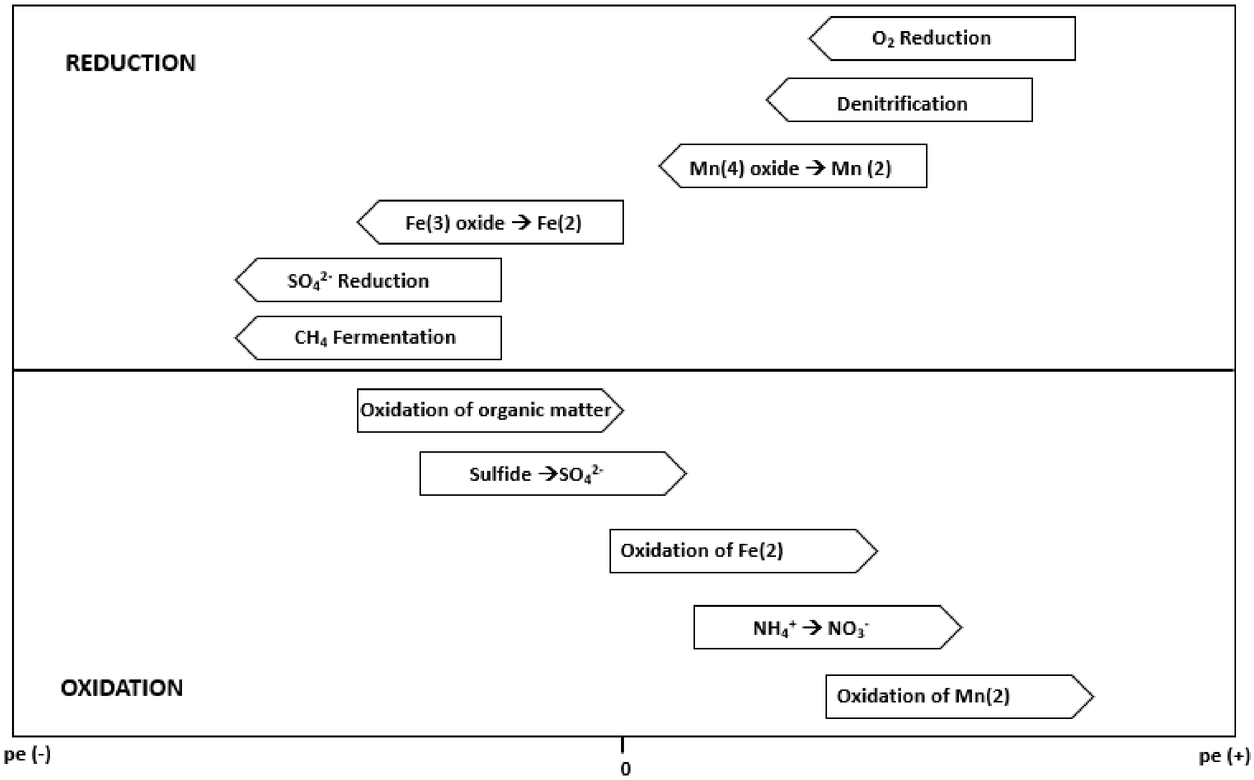

Figure 2-1 **Sequences of important redox processes at pH = 7 in natural systems (Appelo and Postma, 2009).**

2.3.3 Mechanisms of Contaminant Transport

Transport mechanisms of contaminants are discussed in the simplest one-dimensional form. The physical processes namely, advection, diffusion, dispersion, retardation and decay are discussed to give a conceptual understanding of contaminant transport within groundwater (Delleur, 1999 and Appelo and Postma). Once a chemical contaminant enters groundwater, several transport mechanisms are present, these affect the rate and direction of contaminant movement. Some mechanism can promote movement, but the movement can also be lessened by others. The slower a contaminant takes to travel a certain distance through the aquifer the longer it remains in the aquifer (longer residence time), and as a result, the more opportunity there is for inactivation (natural attenuation) of the contaminant before reaching the wellfield/borehole (Harter, 2002).

2.3.3.1 Advection

Advection is the mass transport of a contaminant by the movement of water (Delleur, 1999). Advection is based on the aquifer properties and the average hydraulic gradient causing flow. Darcy’s law is one of the simplest ways for quantifying the rate of fluid flow through an aquifer, however it does not consider dispersion, diffusion or adsorption which can increase or decrease the rate of contaminant transport (US EPA, 1987)

2.3.3.2 Diffusion

Diffusion is the flux of solutes from areas of higher concentration to areas of lower concertation due to random molecular motion (Delleur, 1999). Diffusion occurs if a concentration gradient exists, regardless of groundwater movement and will therefore spread away from the area it was introduced. The rate of diffusion is a function of the concentration gradient and the porosity of the aquifer media (US EPA, 1987).

2.3.3.3 Dispersion

Dispersion is defined as the spread of a solute due to heterogeneities of the pore sizes and shapes (mechanical dispersion) or heterogeneities in the aquifer (macro-dispersion). The contaminated groundwater does not all travel at the same velocity and as a result mixing occurs along the flow path. This is termed mechanical dispersion and results in dilution of the contaminant in the direction of groundwater flow. Mechanical dispersion comprises of longitudinal mixing in the direction of groundwater flow and transversal mixing which occurs normal to the flow path and results in lateral spreading of the contaminant. Dispersion occurs once the contaminant enters groundwater, the advecting groundwater carries the contaminant with it and in the process, the contaminant spreads, decreasing the maximum concentration with time, however the contaminant is spread over a wider area (US EPA, 1987).

2.3.3.4 Biodegradation

Biodegradation results from the transformation of organic compounds by microbes (mainly bacteria, fungi, algae, and yeasts). Biological treatment can help eliminate hazardous organic wastes in a groundwater system by transforming them into harmless, non-toxic forms by degrading them by mineralisation to carbon dioxide (US EPA, 1987).

2.3.3.5 Retardation

The two main mechanisms that retard contamination movement are sorption and biodegradation. Chemical retardation occurs when a contaminant reacts with the aquifer media and the rate of movement is retarded relative to the advective groundwater velocity.

2.4 GROUNDWATER IN SOUTH AFRICA

2.4.1 Aquifer Types

Groundwater resources and associated potential for development have a widely, but variable spatial distribution across the country due to the diverse and complex nature of South Africa's geology (Diamond et al., 2019). South Africa comprises numerous and variable physiographic and climatic terrains resulting in diverse hydrogeological characteristics that determine the occurrence of aquifers and, therefore, the occurrence, movement, and distribution of groundwater. The delineation of protection zones is strongly based on groundwater flow paths and travel times from potentially contaminated areas towards water supply boreholes (Rajkumar & Xu, 2011). Subsequently, groundwater flow paths and travel times are dependent on aquifer type (fractured, karstic, unconsolidated and consolidated primary aquifers)aquifer characteristics and extent of overlying geological deposits (whether shallow aquifer or protected by overlying sediments), and groundwater head gradients. Thus, a differentiated approach needs to be implemented that considers the local aquifer type, associated aquifer characteristics and distribution, and use to correctly implement groundwater protection in South Africa. South Africa’s hydrogeology is characterised by four different aquifer types namely fractured, intergranular, intergranular and fractured (basement), and karstic (DWAF, 2000) **Figure 2-2**shows the hydrogeology of South Africa with the approximate yields associated with each aquifer type.

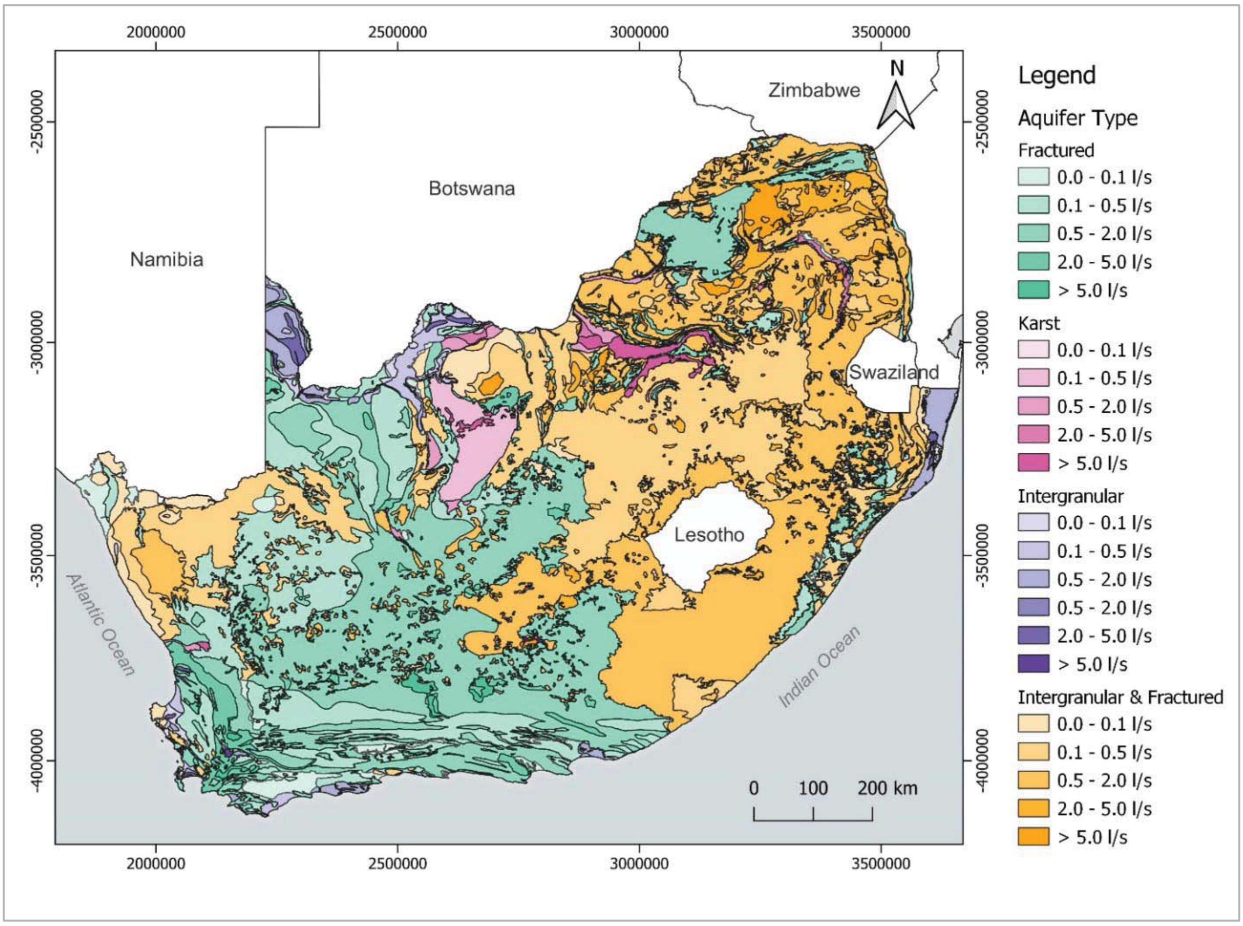

Figure 2-2 **Hydrogeological map of South Africa illustrating the different aquifer types and their approximate yields (1:2 000 000 scale WR, 2012).**

2.4.1.1 Intergranular

Intergranular aquifers have primary porosity and comprise of unconsolidated to semi consolidated material ranging from boulders to sand and clay-sized particles existing in varying proportions. Extensive intergranular aquifers are located in the dunes of the Kalahari region and along the coast of South Africa, such as the Langebaan, Atlantis, and Cape Flats Aquifers along the west coast. On average, these aquifers have a yield between 3 to 16 l/s (Pavelic et al., 2012). Typical hydraulic conductivity values are between 0.1 and 100 m/day and an average storage coefficient between 7 and 25% (Freeze and Cherry, 1979 and Driscol, 1989). Recharge rates in these aquifers are generally high, which marks these aquifers as vulnerable to pollution from surface contaminants, however high recharge rates help dilute pollution and disperse infiltrating pollution. Groundwater moves via porous flow with contamination retardation a function of the porous matrix, contamination chemistry and surface area (Nel et al., 2009).

2.4.1.2 Fractured Aquifers

Fractured Aquifers are found in hard rock environments such as the highly fractured brittle quartzites of the Table Mountain Group (TMG), the basement aquifers such as the Malmesbury Group shales in the Western Cape or fractures zones of the dyke swarms in the Karoo Supergroup. These aquifers are characterised by having very little primary porosity with groundwater flow controlled by fractures, faults, and joints. Conduit flow conditions are expected in individual fractures; however, fracture density needs to be high enough for hydraulic connectivity through the system (Nel et al., 2009). Aquifer properties depend on the development of fractures and weathering. This is, as in many cases, micro-fissures store most of the water which gets transmitted to the large fractures (Ó Dochartaigh et al., 2018). High yielding fractured aquifers are therefore associated with regional fault zones (WRC, 2014). Attenuation of contaminants in fractured aquifers are much less than that of intergranular aquifers mainly due to the surface area available to retard and disperse contaminants. It has been estimated that a one metre by one metre block of fractured media will have a surface area 1 000 to 100 000 times smaller than that of intergranular media, therefore contaminant retardation will be roughly proportional (Nel et al., 2009).

2.4.1.3 Intergranular and Fractured Aquifers

Intergranular and fractured aquifers include weathered granite, dolerite and sandstone formations that are found throughout the central to northern regions of South Africa. These are where fractures and inter-fracture blocks or rock matrix are hydraulically connected, which increases storage and productivity. These aquifer systems have both primary and secondary porosity with both diffuse and conduit flow (Nel et al., 2009). Hydraulic conductivity values for intergranular and fractured aquifers vary between 0.03 and 1 m/day with values up to 100 m/day in weathered contacts between formations (Freeze and Cherry, 1979 and Driscol, 1989). Water flowing in an intergranular and fractured aquifer will mix between the fracture and intergranular matrix. Thus, contaminants entering the groundwater will move via diffusion from the fractures to the intergranular matrix even if the matrix permeability is low. The direction and velocity of contaminant transport will be controlled by fracture flow as fractures have a higher hydraulic conductivity compared to the intergranular matrix. With an increase in fracture density the system becomes increasingly pervious and can display porous flow characteristics. Larger particles such as microbiological contaminants are not able to enter the small pores of the matrix and hence travel faster through the fracture flow (Nel et al., 2009).

2.4.1.4 Karst Aquifers

Karst aquifers such as the Malmani Subgroup dolomites are a very important water source to the north and central regions of South Africa (North West, Mpumalanga, Gauteng and Limpopo provinces) (**Figure 2-2**). They are formed by the dissolution of carbonate rocks by circulated weak carbonic acid. Due to this dissolution, dolomites contain large volumes of water in cavities, sink holes and even cave formations (Ó Dochartaigh et al., 2018). Dissolution channels can extend along fractures and extend to the surface causing direct recharge and groundwater flow. Karstic aquifers are vulnerable to pollution as they are not protected by overlying geological formations, due to thin soil cover and high transmissive characteristics (Ó Dochartaigh et al., 2018). In general groundwater quality in karstic aquifers are good if no pollution from surface occurs (Diamond, 2019).

2.4.2 Types of Groundwater Use

Groundwater use may range in scale from a single borehole to a wellfield comprised of several hundred boreholes. The extent of land use and development, ranging from rural and urban environments to industrial, agricultural, and mining activities generally inform the contaminant load. The risk of groundwater pollution is determined by the vulnerability of the aquifer and the contaminant load the aquifer is subjected to. The vulnerability depends on the aquifer type, as aquifer characteristics control groundwater flow paths and travel times which determines residence times and attenuation of contaminants in the aquifer. **Figure 2-3** illustrates the complex relationship of these factors.

Each groundwater use requires a unique approach to groundwater quality protection. The approach should consider what is most appropriate for the aquifer type, vulnerability, groundwater use and the associated contaminant load exposed to the aquifer (as shown in **Figure 2-3**). The approach should also consider what is most appropriate for the size (number of boreholes, radius of influence, borehole interaction) and the resources available, i.e. budget, time, data and expertise. The relationship between these variables, ultimately translates to groundwater protection schemes ranging from simple to more comprehensive approaches (further outlined in **Chapter 4**). Some common groundwater uses and risk to groundwater contamination are introduced below and summarised in **Table A-1, Appendix A.**

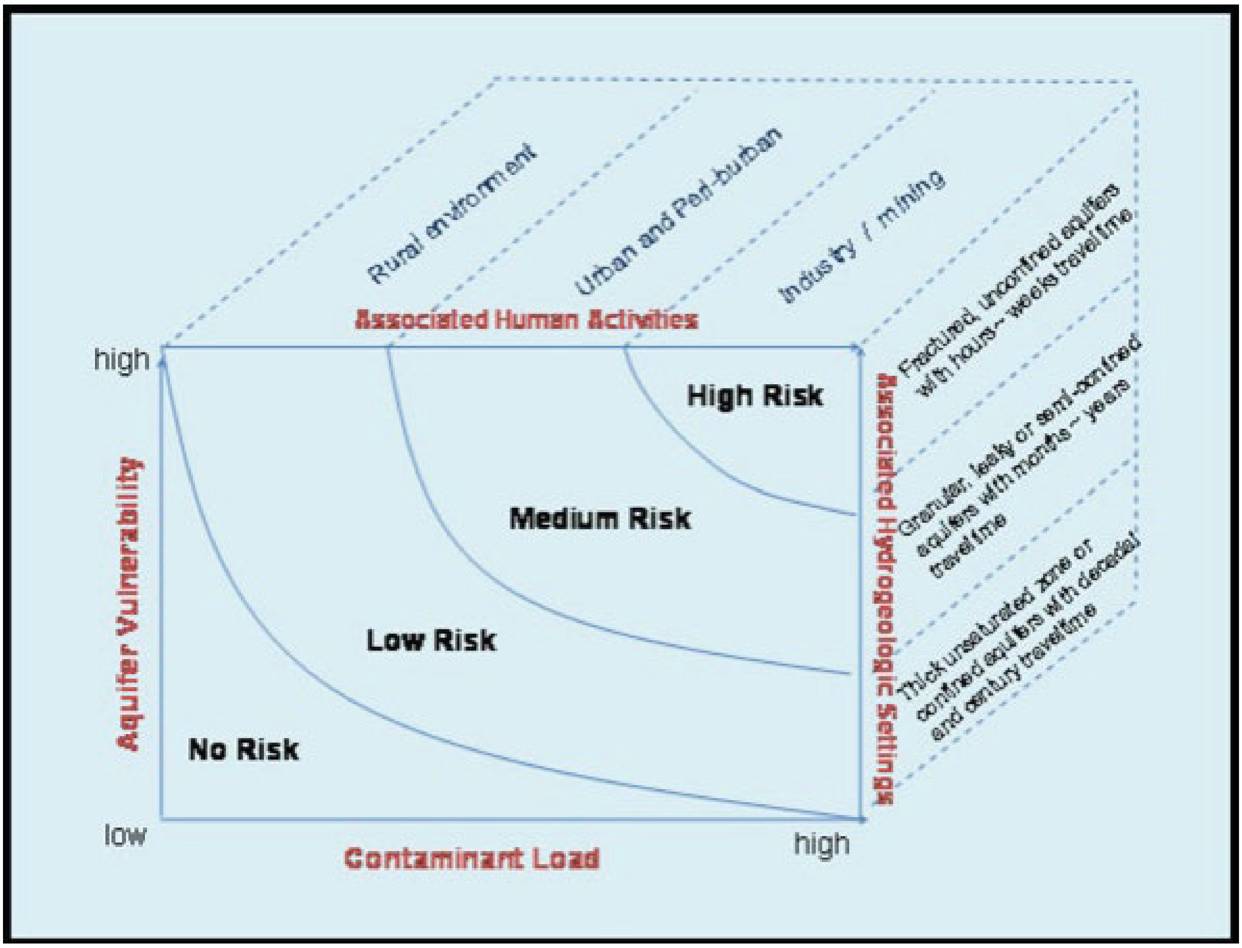

Figure 2-3 Groundwater risk assessment (Rajkumar, and Xu, 2011).

2.4.2.1 Rural

For many areas in South Africa surface water supply schemes are not practical or economical and therefore groundwater is the only alternative (Meyer 2002). Rural groundwater use generally consists of many small capacity wells or boreholes widely spread over the aquifer outcrop. These are developed with low budgets and consist of one or a few boreholes which provide water supply to a small number of individuals or a community. Boreholes may have been drilled by local and provincial municipalities to fulfil service delivery duties, by mining or other industry companies that meet community outreach and social responsibilities or by the local individuals who have invested their private funds. These boreholes are often placed central to homesteads and equipped with hand pumps or low-yielding pumps servicing a few storage tanks with a small reticulation network of strategically placed taps (**Figure 2-4 A**). The extent to which pumping lowers the water table – the radius of influence or the cone of depression – is generally small for a rural use in comparison to other larger scale groundwater uses. This is due to lower yields abstracted, boreholes spread far apart (i.e. less borehole interaction), fewer boreholes pumping simultaneously, or a combination of these. Due to the small radius of influence, the capture zone will span over fewer land-use types and fewer heterogeneities in the aquifer will be encountered. In more densely populated rural areas, more boreholes may be situated near one another, resulting in a larger area of influence, and this should be treated as a more extensive groundwater use if recognised.

Common potentially contaminating activities (PCAs) may include pit latrines, ablution blocks, small-scale farming of livestock and irrigated crops, landfills and dumps, runoff/stormwater, washing in rivers that are connected to the groundwater system (**Figure 2-4**). Rural groundwater schemes are usually operated and managed by members of the community who are designated with tasks to carry out. In many cases, maintenance is poor, monitoring data is lacking, and high-level management (regional, provincial, and national) is deficient. Although rural groundwater use is on a small scale and may target low-yielding aquifers, it could be the primary source of water that sustains society and the associated economic activities.

Figure 2-4 Examples of rural groundwater use and PCAs located in rural areas. A) Borehole equipped with hand pump and protective concrete wellhead to prevent direct migration of surface contaminants. B) Flooding in an informal settlement due to blocked stormwater drains. C) Several pit latrines. D) Rubbish gathered in the Lotus Canal in Cape Town that is in direct connection with the underlying aquifer.

2.4.2.2 Private

Private groundwater use (termed as decentralised supply by Seyler, 2019) occurs on a similar scale to rural use, however, they are owned by and supply a private entity, such as a household (Schedule 1 use according to NWA, Act no. 36 of 1998), body corporate, or small holdings. These can occur in agricultural holding 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 domestic supply, for irrigation of garden space and common areas, or recreational use (see **Figure 2-5**). Although larger in terms of groundwater use volumes, golf courses can be included as private groundwater users.

Private groundwater use normally consist of one or a few boreholes with relatively low yielding submersible pumps. Abstraction volumes are often within or slightly exceeding General Authorization (GA) limits. As with rural use, the radius of influence due to pumping is small compared to other groundwater uses and the capture zone will therefore only span over a few land-use types and heterogeneities within the aquifer. PCAs may include swimming pool maintenance, lawn and garden care, insect/rodent control, septic tanks, urban runoff/stormwater, household hazardous wastes and golf course irrigation. While the collection of monitoring data and high-level groundwater management can be lacking (especially in cases where usage is not registered or licensed) maintenance and operations is relatively well funded.

Figure 2-5 **A private groundwater use at a household where a borehole is used for non-potable, domestic supply. The borehole headworks, with a large JoJo tank for storage, as well as a small filter and treatment system are noted.**

2.4.2.3 Commercial Agricultural

Large scale agricultural and livestock farming practices require large volumes of water to maintain crop and livestock demands. These extensive parcels of land usually have numerous boreholes that are pumped into large concrete or earth fill storage dams (often these also have a surface water supply component) (**Figure 2-6**). Groundwater is commonly used to augment surface water supply. Depending on size and scale of the farming activity and property, abstraction volumes can vary from within GA limits to volumes amounting to millions of metres cubed (m^3) per annum that require Water Use Licences. The radius of influence due to pumping for commercial agricultural use is larger than rural and private groundwater use. This is due to multiple boreholes, often situated in proximity to one another, that are pumped simultaneously (i.e. more borehole interaction), or due to higher yields, or a combination of these. The capture zone of these boreholes will likely only span over extensive agricultural land-use type, however, due to the large spatial influence of pumping, more heterogeneities in the aquifer may be encountered.

The agricultural sector frequently drills boreholes without consultation with groundwater specialists or, in some instances, the required regulators. This leads to scarce records of data and misinterpretation of the available hydrogeological data. In some cases, this may lead to uncontrolled or unregulated large-scale use of groundwater resources. Often groundwater quality protection is not considered. Common PCAs include, septic tanks, automotive wastes from farm machinery repair, animal feeding operations, grazing animals, farm chemical distribution such as pesticides and fertilizers, above and below ground storage tanks of diesel fuel and other chemicals.

Depending on size of agriculture and groundwater use required, budgets may be low or well-funded. 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. 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 common.

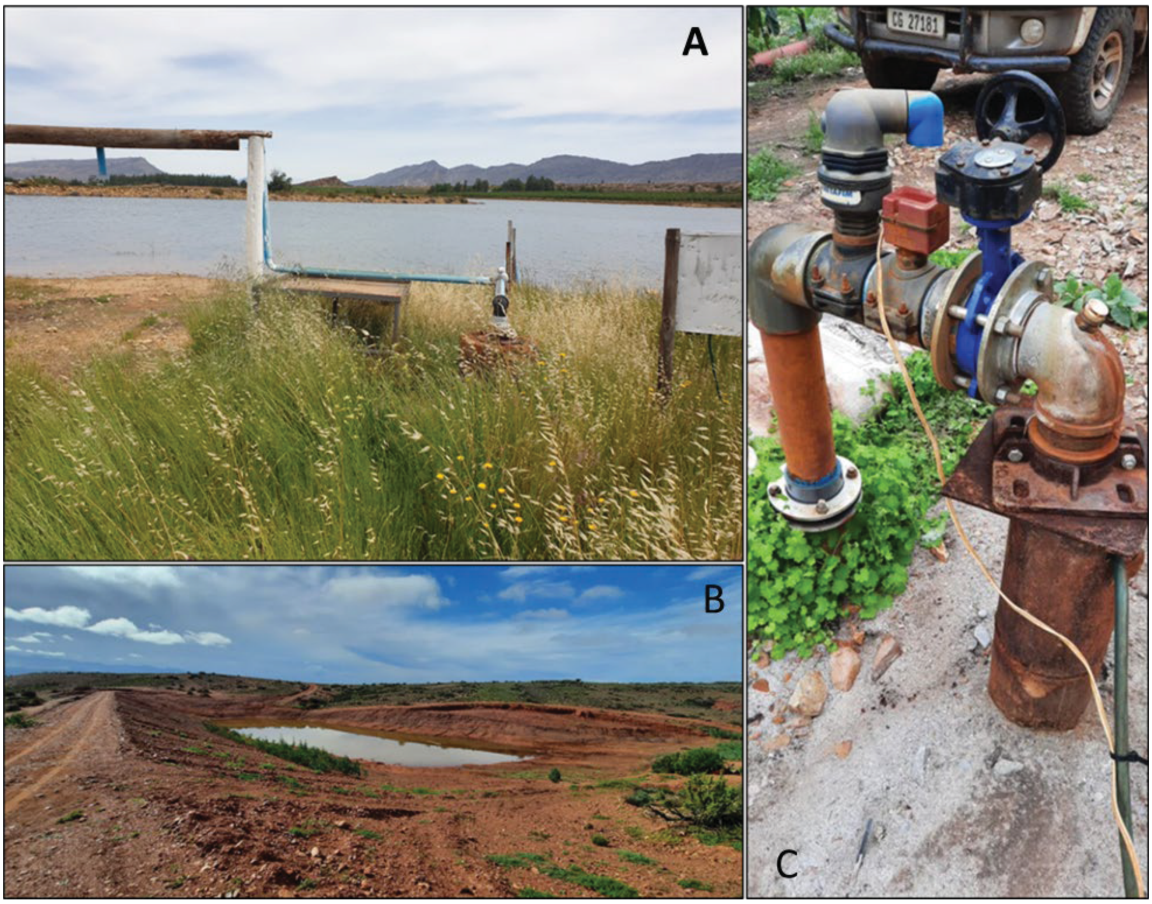

Figure 2-6 **An example of a commercial farming groundwater use. A & B) Boreholes are often used to augment storage in surface water bodies used for irrigation. C) Typical borehole infrastructure and wellhead for irrigation supply.**

2.4.2.4 Industrial

Many businesses and factories use groundwater supply for processes which happen on site. Industrial groundwater use is usually privately run and owned, and the intended use ranges, requiring variations in groundwater protection and management. Examples of industries with multiple uses are refineries, chemical plants, fisheries, textiles, transport, health services, waste treatment and recycling, engineering, and utilities, e.g. power generation (**Figure 2-7**). Groundwater is abstracted for use in industrial processes and some type of wastewater is generated – this being the main difference from other types of groundwater use.

Industrial land use poses a high risk for potential contamination to groundwater. PCAs occurring in industrial land use include, above and below ground storage tanks for wastewater, diesel fuel, heating oil, other chemical and petroleum products, water transfer/recycling stations, utility stations/ maintenance areas, septic tanks, stormwater runoff, landfills, dumps and other activities specific to the industry. Industrial groundwater use may vary in size from one to more than 10 boreholes, subject to the size of the operation and the water demand, with budgets also varying from low to well-funded based on the size and infrastructure required. Often the spatial development planning allows for industries to only be situated in one area of a town or city, as such boreholes may be located near one another, resulting in a greater area of influence. Therefore, industrial groundwater use can be treated as a large-scale use. The radius of influence from pumping can be small (like that in rural and private groundwater use) or may be large (as commercial agricultural use). Due to the nature of industrial areas, the capture zone associated with pumping will likely span over multiple land-use types, including industrial, residential, landfills/dumps, recreational parks or sportsgrounds.

Due to nature of operations, groundwater monitoring, data collation, scheme operations and maintenance, and high-level groundwater management is usually of a relatively high standard and frequently undergoes audits supporting compliance.

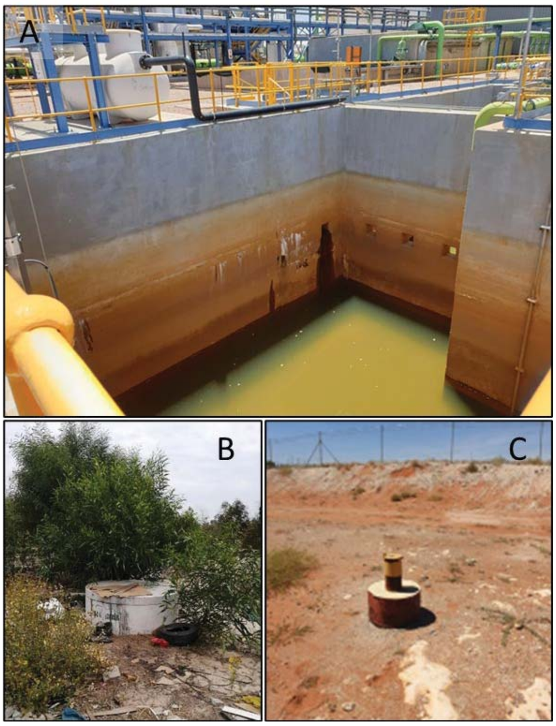

Figure 2-7 An example of industrial groundwater use, where water is used in industrial processes, such as the generation of electricity using renewable solar energy. A) Processed water is treated prior to discharge. B) Monitoring borehole located within a concrete manhole to prevent direct migration of surface contaminants (such as that from dumping) to the groundwater via the borehole. C) A monitoring borehole is shown in the foreground used for groundwater quality compliance monitoring.

2.4.2.5 Municipal/Bulk Water Supply

Many towns in South Africa depend on groundwater for municipal water supply, particularly in areas distant from the metropole areas. Metropole areas have also recently looked towards using groundwater for large-scale augmentation of surface water supply. Municipal groundwater use 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 (**Figure 2-8**). These schemes are generally regional, or local government owned and operated, with the appointment of consultants to carry out various tasks (such as drilling, monitoring, or groundwater protection).

Similar to the industrial groundwater use, the radius of influence of pumping can vary. However, municipal groundwater management will aim to maintain a critical water level (CWL). The European Parliament defined a critical level 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 quality protection and groundwater use management, the critical water level 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, and the radius of influence of pumping does not extend to areas outside the wellfield where potential contamination to groundwater may occur.

Ideally, spatial development planning (SDF) and municipal groundwater use design will position wellfields in areas of natural vegetation or areas where there are no or few PCAs to prevent the ingress of contaminants from land use. However, this is not always possible depending on the existing spatial development over the aquifer and wellfields may extend over multiple land use types such as urban and/or rural residential areas, agricultural, industrial, recreational parks, and sports grounds which could result in a variety of PCA's.

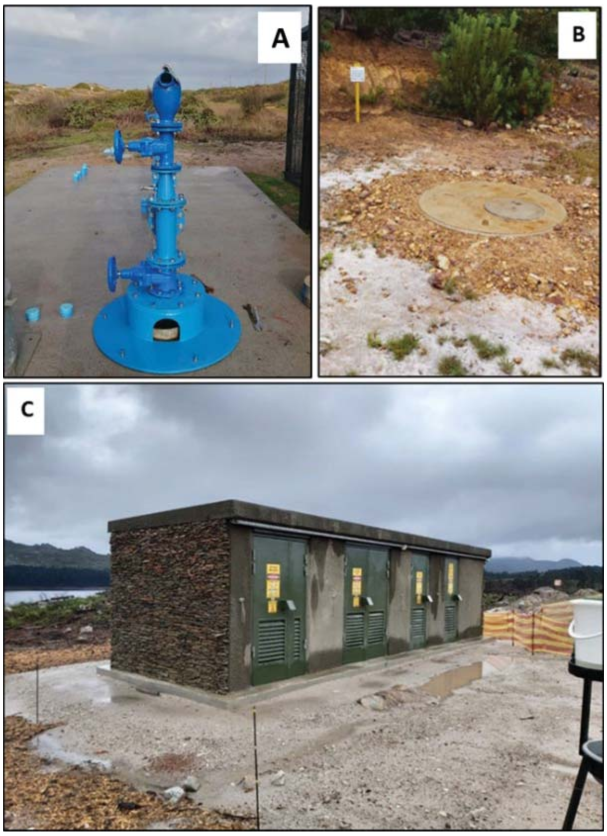

Figure 2-8 **Example of a municipal bulk water use. A) Installation of pump equipment in the Atlantis Aquifer for the City of Cape Town. B) Monitoring borehole equipped with a concrete manhole and a sanitary seal to prevent direct migration of surface contaminants to groundwater via the borehole. C) Pump house structure over an abstraction borehole for bulk water supply by the City of Cape Town from the Table Mountain Group Aquifers, Steenbras Wellfield**

2.4.2.6 Mining and Construction Dewatering

When mines and construction sites require excavations or tunnelling into the subsurface, there is usually groundwater which seeps or flows into the excavation. Mines pose a large threat of contamination to groundwater. Contamination sources may include mine spills or tailings that often contain metals; acids; highly corrosive mineralized water, metal sulphides, metal acids, other hazardous and non-hazardous chemicals (**Figure 2-9**). Mines and construction sites cannot operate if there is flooding, and so dewatering techniques are implemented. 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 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 effectively monitored and managed may have detrimental effects on the environment. In general mining is a large potential threat to groundwater contamination due to the number of potential sources of contaminants emanating from the mining process or required for the operation.

Mining and dewatering are generally well funded and engineered with high amount of specialist input which means that monitoring, and data collection of groundwater are usually well established, although there can be discontinuity due to confidentiality of the data. The abstracted water is usually discharged into the environment, used in mining or construction processes, or provided as supply to nearby communities in which case it is similar to rural or municipal groundwater use.

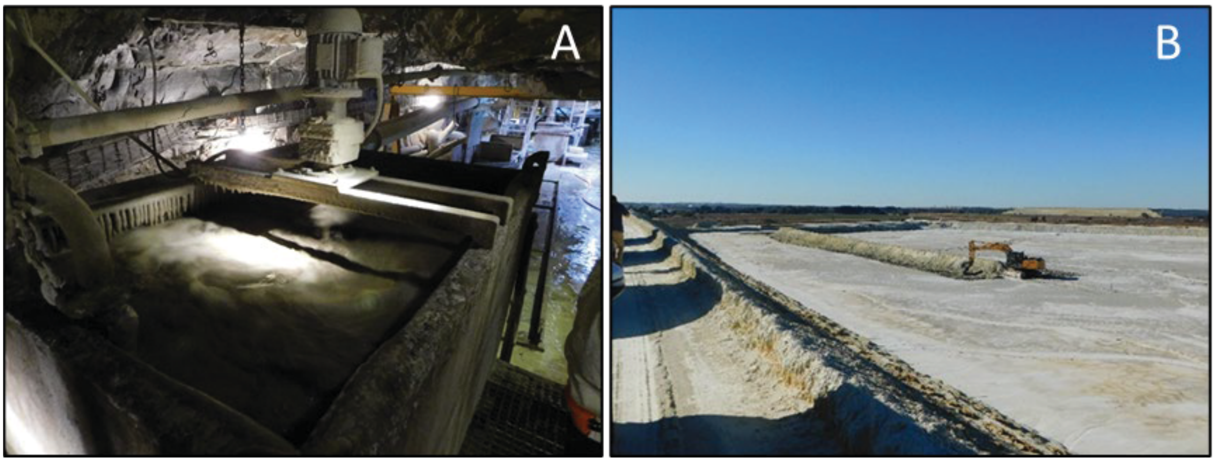

Figure 2-9 Example of a miming and dewatering use. A) Treatment of the acidic water with lime prior to dewatering. B) Tailings dam.

2.4.2.7 Use from Transboundary Aquifers

Transboundary Aquifers (TBAs) are defined as a body of groundwater that extends across a political border (Cobbing et al., 2008). There is significant potential for dispute over the shared groundwater resource as the aquifer may be well maintained in one country while over-exploited and ill managed in another country. Contaminants released into the aquifer from one country may travel into parts of the aquifer in other countries. Therefore, groundwater protection schemes developed for TBAs should be developed and co-managed as a shared resource (Davis et al., 2013). Any of the groundwater uses described above may be developed on transboundary aquifers.

South Africa has seven transboundary aquifers which are shown in **Figure 2-10**. In a review of the TBAs shared by South Africa, Cobbing et al. (2008) states that TBAs on South Africa's borders are not managed in a holistic, cooperative manner. Since countries have different legislations, governments should collaborate and come to agreements on the approach for developing and enforcing groundwater protection schemes.

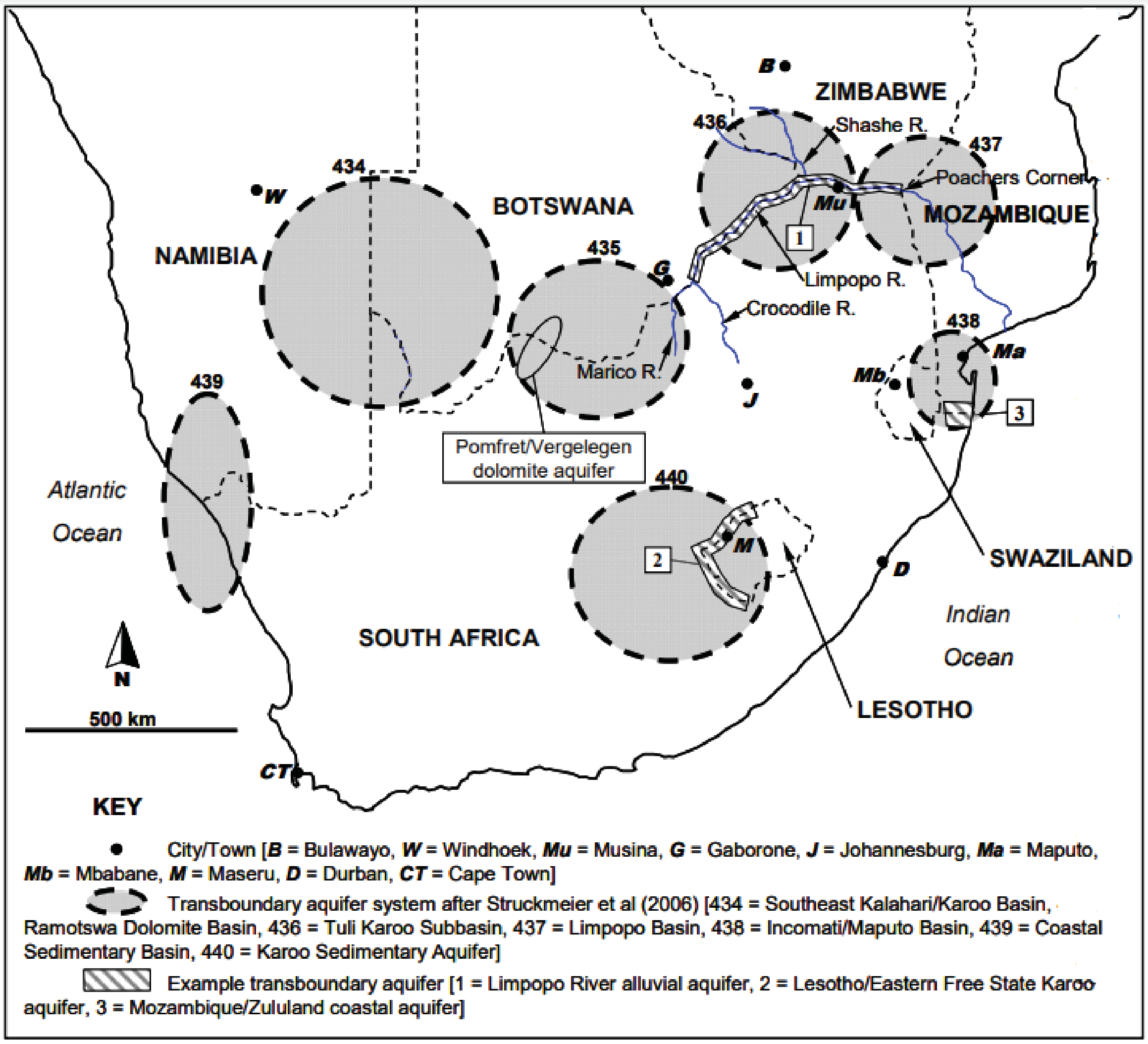

Figure 2-10 Map of southern Africa showing the approximate locations of seven transboundary aquifer systems (after Cobbing et al. 2008)

CHAPTER 3: GROUNDWATER PROTECTION SCHEME DEVELOPMENT

3.1.1 Framework

The goal of a groundwater protection scheme is to protect groundwater quality and ensure sustainable use of a groundwater resource under consideration (Nel et al., 2014). Before a groundwater protection scheme can be implemented, a groundwater assessment and development are commonly undertaken. A groundwater assessment involves obtaining a basic understanding of the aquifer system and includes gathering information on the type of aquifer targeted, intended groundwater use to be developed and location of abstraction borehole(s) and wellfield(s). Information from the groundwater assessment is used for the development of a groundwater resource which is further detailed in Guidance Document to Groundwater Scheme Development; WRC, (2022). The assessment and development provide an overview of the degree of certainty of analysis required, data, expertise, budget, and time available which ultimately influence the type of groundwater protection scheme that should be implemented.

There are two different spheres to groundwater protection schemes: *land-surface zoning*, which deals with the natural aquifer characteristics and *protection response* which encompasses anthropogenic and management factors. Land-surface zoning incorporates groundwater protection zone delineation and vulnerability mapping and ranking, while protection response involves identifying existing PCAs and delineating a protection response plan. Collectively, these four components can be defined as (**Figure 3-1**):

- **Groundwater protection zones:** Delineate groundwater protection zones (GPZs) based on the available hydrogeological information on groundwater flow, recharge, discharge, and travel time.
- **Vulnerability mapping and ranking:** Assess the risk of groundwater contamination and guide long-term planning and decision making. This pragmatic step informs future placement of potential contaminating activities.
- **Potentially Contaminating Activities Identification and Ranking:** Identification of PCAs that may be considered a possible origin of microbial and/or chemical contamination within a groundwater source area and rank the associated risk of contamination.
- **Delineate different protection responses:** based on GPZ, aquifer vulnerability and PCA risk.

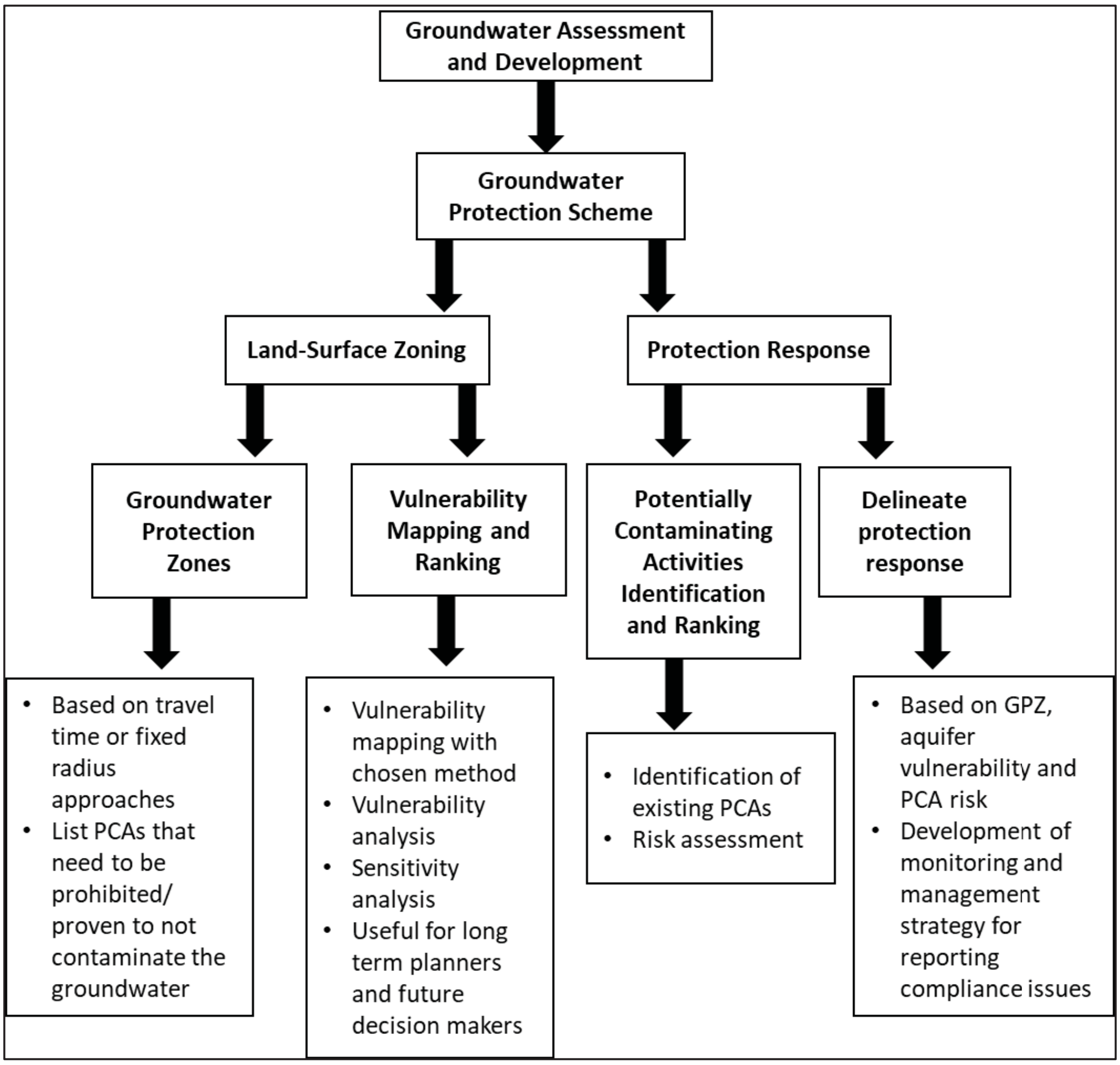

Figure 3-1 Groundwater Protection Scheme framework (Adapted from US EPA, 1994)

3.1.2 Groundwater Protection Zone Delineation

A groundwater protection zone (GPZ) for drinking water supply is defined by Harter (2002) as ‘the surface and subsurface area surrounding a borehole or wellfield, supplying a public water system, through which contaminants are reasonably likely to move forward and reach such a borehole or wellfield'. This guidance document defines groundwater protection zones not only for drinking water resources but to include other groundwater uses (e.g. drinking supply, irrigation, domestic use) and to include areas (such as the groundwater resources of the Strategic Water Source Areas [SWSA]) where groundwater is the primary source of water that sustains society and the associated economic activities. Protection zones are put in place to ensure the integrity of groundwater quality within the aquifer by restricting activities within respective protection zones as the risk of contamination to a groundwater resource increases with human activity and has a direct link to land use (WRC, 2014).

Three major goals of groundwater protection zones are outlined below (Harter, 2002):

1. The borehole/wellfield must be protected from direct contamination in the immediate vicinity of the borehole.
2. The borehole/wellfield must be protected from microbial contamination.
3. The borehole/wellfield must be protected from chemical contamination.

Using proven international legislation for GPZ delineation (including Denmark, Ireland, United Kingdom, USA California, and Australia) as well as South African best practice (due to the lack of legislation), four GPZs are outlined based on the risk to groundwater and the time taken for a microbe/chemical contaminant to naturally attenuate (**Figure 3-2**). Each zone requires a different assessment, protection level, and management measures (Rajkumar & Xu, 2011). Certain restrictions are applied to the type of activities that may take place within each protection zone. These activities are outlined in **Section 3.1.4**, **Table 3-7**.

1. **Well-head protection zone/Inner zone (ZONE I)** with 10 m radius around the wellhead. The purpose of this zone is to prevent the direct rapid ingress of microbial/chemical contaminants. No activities of any sorts are allowed in this area, and the land must be routinely cleared and kept clean, with any residues, products or liquid substances cleared out. Production boreholes should be constructed with a sanitary seal, and ideally, a protective concrete wellhead to prevent direct migration of surface contaminants to the groundwater via the borehole. This GPZ can be delineated using a fixed radius approach (see **Section 3.1.2.1**).
2. **Middle zone (ZONE II)** based on a two-year travel time. Literature notes that pathogens and bacteria cannot survive in groundwater for more than two years (Division of Drinking Water and Environmental Management, 1999). Two groups of restrictions are applied to this zone. The first group includes activities that are prohibited in the area due to the high susceptibility to contamination and modified flow in the catchment. The second group includes activities which may be allowed if they can prove to not contaminate the groundwater through prior approval and monitoring.
3. **Outer zone (ZONE III)** based on a five-year travel time. This zone provides an adequate amount of time to respond to possible chemical spills to prevent chemical contamination of the water supply, and to protect the drinking water source for the long-term. Like the middle zone, two groups of restrictions are applied to this zone. The first group includes activities that are prohibited in the area due to the high susceptibility to contamination and modified flow in the catchment. The second group includes activities which may be allowed if they can prove to not contaminate the groundwater through prior approval and monitoring.
4. **Catchment area (ZONE IV)** based on a ten-year travel time. This zone provides adequate amount of time to respond to possible chemical spills of more persistent chemicals in order to prevent chemical contamination of the water supply and protect the drinking water source for the long-term or provide an alternative water source. As with the outer zone, two groups of restrictions are applied to this zone. The first group includes activities that are prohibited in the area due to the high susceptibility to contamination and modified flow in the catchment. The second group includes activities which may be allowed if they can prove to not contaminate the groundwater through prior approval and monitoring.

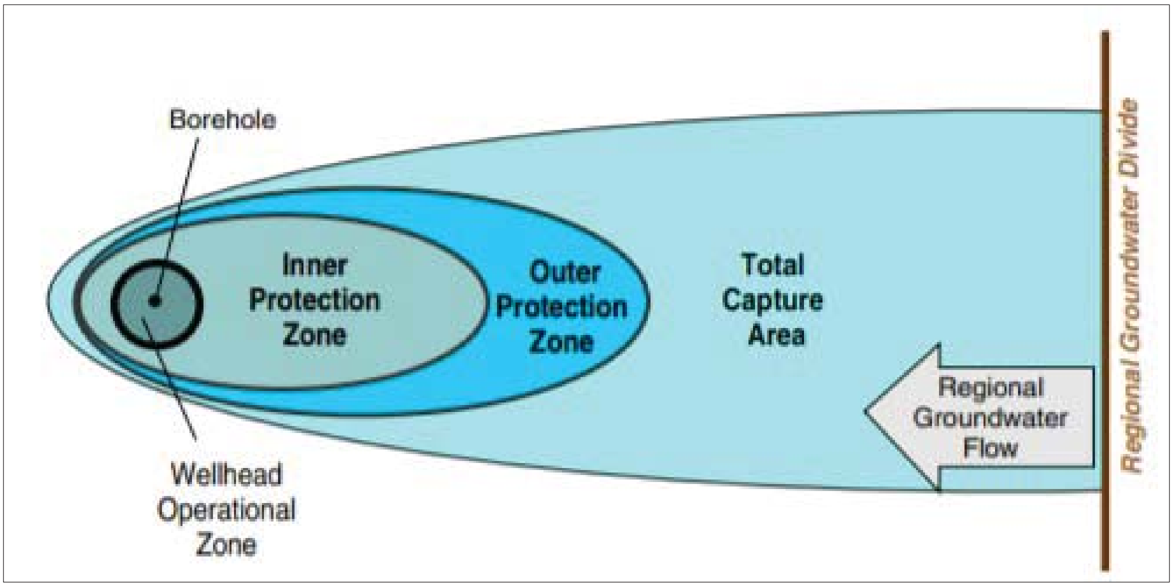

Figure 3-2 Groundwater Protection Zones around a production borehole (Rajkumar & Xu, 2011).

The delineation of groundwater protection zones is strongly based on hydrogeological and contaminant characteristics. The following principles may be used alone or in combination to delineate groundwater protection zones (US EPA, 1994; Chave et al., 2006):

- **Distance:** the distance from the abstraction at the water supply borehole to PCAs.
- **Drawdown**: the extent to which pumping lowers the water table, which is essentially the cone of depression or radius of influence.
- **Time of travel:** the time it takes for the contamination to reach the abstraction point.
- **Assimilation capacity:** the degree to which contaminants may attenuate in the subsurface to reduce concentration. This may occur by the processes explained in **Section 2.3**.
- **Flow boundaries:** demarcation of recharge areas or hydrogeological features, which control groundwater flow (such as wetlands or faults).

The approach chosen to delineate GPZs are selected based on what is the most appropriate for the aquifer type, vulnerability, scale, and use of the groundwater resource. The most common approaches vary from simple to complex which includes arbitrary fixed radius, calculated fixed radius, simplified variable shapes, analytical methods, hydrogeological mapping and numerical modelling. These approaches are explained below (US EPA, 1994; WRC, 2014). In cases where there are multiple abstraction boreholes, the radius around each borehole may be merged to define a protection zone for the entire wellfield.

Additionally, the construction of a borehole is imperative for groundwater protection. Monitoring boreholes are often a license requirement, and schemes consisting of monitoring boreholes only (for example, monitoring boreholes around a landfill site) yield important data pertaining to water levels and water quality that inform management and groundwater protection decision-making. Monitoring boreholes may, however, be a direct pathway for migration of surface contaminants to the aquifer. They should therefore be constructed with a sanitary seal and ideally covered with a concrete wellhead to prevent contamination to groundwater. The same should be done to abstraction boreholes.

3.1.2.1 Arbitrary Fixed Radius

The most straightforward approach for delineating GPZs is the fixed radius approach. This approach is carried out by drawing a circle of fixed radius around an abstraction point. The radius is arbitrarily based on generalised travel times and attenuation of contaminants in the aquifer. This approach is simple, fast, inexpensive, and requires limited information and scientific expertise. It does, however, have lower confidence in the probability of contamination and attenuation of contaminants in the aquifer within the GPZs as it does not consider local hydrogeological conditions or interaction between adjacent boreholes that may influence the local flow conditions. This may result in highly vulnerable or economically and socially important aquifers being under protected. This approach is suitable to delineate the well-head protection zone/Inner zone (ZONE I), as this is a 10 m radius around the borehole or groundwater uses.

3.1.2.2 Calculated Fixed Radius

The calculated fixed method makes use of a volumetric flow equation to calculate a fixed radius around an abstraction borehole through which water will flow at a specific travel time. The radius is calculated using **Equation 3-1** which ultimately defines an isochrone around a borehole which delimits a cylinder with a pore volume equal to the volume of water pumped during the specified period (travel time for each GPZ).

$$r = \sqrt{\frac{QT}{\pi b n_{eff}}}$$

Equation 3-1

Where:
r = radius (distance from abstraction borehole) in metres
Q = maximum approved pumping rate of the borehole (m^3/day)
T = saturated travel times for each borehole (2 years, 5 years, 10 years)
b = saturated thickness of borehole screen
n_{eff} = aquifer effective porosity

The volumetric flow **Equation 3-1** assumes all the water for abstraction comes from the aquifer and does not consider recharge. This results in overprotection of semi, leaky and unconfined aquifers as it does not consider flow into the aquifer. Additionally, the equation assumes a negligible regional gradient (< 0.001) as steeper gradients disturb flow across the cylinder. This approach is, therefore, most applicable in confined aquifers where there is not vertical leakage from the overlying confining aquifer and is not appropriate for unconfined aquifers due to recharge and as a cone of depression creates an aquifer geometry that is not cylindrical. The benefit of this approach is that it is relatively easy and inexpensive to implement and is based on simple hydrogeological principles that require limited expertise.

The vertical flow of water into the aquifer can be analysed using test pumping data or Darcy's Law (see **Section 3.1.2.4**). Leakage can be incorporated into the volumetric flow **Equation 3-1** using **Equation 3-2**. However, there are two unknowns as Q_l and Q_a depend on the radius. Therefore, a trial-and-error solution is needed to determine the radius at which $Q_a + Q_l$ equals the pumping rate.

$$Q = Q_a + Q_l$$

Equation 3-2

Where:
Q_a = volume of water pumped from the aquifer
Q_l = volume of water entering the aquifer through leakage.

3.1.2.3 Simplified Variable Shapes

This approach involves generating a set of shapes representing an array of hydrogeologic and pumping conditions. The shapes are calculated by computing a combination of drawdown and time of travel analytical solutions (shown in **Section 3.1.2.4**). If aquifer characteristics (porosity, hydraulic conductivity) are relatively uniform, standard shapes for different levels of drawdown are established. For aquifers where characteristics are variable, many different combinations of aquifer parameters and pumping rates are tested to determine various sets of shapes to establish the typical shapes for different characteristics and pumping rates. The appropriate shape, most representative of the hydrogeologic and pumping conditions at the abstraction borehole is selected. The shape is then orientated according to groundwater flow patterns. This approach is therefore less accurate in heterogenous, anisotropic aquifers.

The approach is easy to implement, however compared to the fixed radius approaches, slightly more data regarding the aquifer characteristics are required. Additionally, sufficient expertise and understanding of the aquifer is needed to determine which shape is best suited to represent the aquifer conditions as well as a general understanding of the natural groundwater flow to orientate the shape. These approaches are most applicable for groundwater use where site-specific data is limited but regional or generalised information is available.

3.1.2.4 Simple Analytical

Numerous analytical equations have been developed to solve groundwater flow problems. This is because different hydrogeological settings require modifications of basic groundwater flow equations such as Darcy's Law. When delineating GPZs using analytical approaches, it is imperative to choose the equation with assumptions most appropriate to the borehole and aquifer in question. There are two main types of simple analytical approaches: ***travel time approaches*** that calculate the time it will take for water to travel a certain distance to the abstracting borehole and ***drawdown approaches*** that calculate the boundary beyond which water will not flow towards the borehole under pumping conditions.

A high level of expertise with hydrogeological and mathematical knowledge is required for this approach. It also requires large datasets to implement, such as pumping rate/ discharge, duration of pumping, hydraulic conductivity, specific yield, porosity, aquifer thickness, and saturated thickness. If the relevant data is available, these approaches are relatively cheap and fast to implement compared to numerical modelling approaches. However, these approaches have several assumptions, and if the assumptions are inappropriate to the groundwater resource being protected, then the confidence in the approach will be decreased.

Table 3-1 summarises several of the most common analytical approaches. The US EPA, (1994): *"Handbook: Ground Water and Wellhead Protection"* can be referred to for further explanations and formulas on simple analytical approaches for GPZ delineation. In addition to the approaches summarised in **Table 3-1**, slightly more mathematically involved solutions to the basic nonequilibrium equations have been derived for special situations, these include:

- Isotropic, nonleaky confined aquifer with fully penetrating boreholes and constant-discharge conditions,
- Isotropic nonleaky confined aquifer with partially penetrating boreholes and constant-discharge conditions,
- Isotropic leaky confined aquifer with fully penetrating boreholes and constant-discharge conditions without water released from storage in the confining layer,
- Isotropic, unconfined aquifer with fully penetrating borehole and constant-discharge conditions.

Table 3-1 Summary of the common simple analytical approaches avalible to calcualte GPZs.

Simple Analytical Approach	Explanation of approach	Assumptions	Author
Travel time approaches			
Travel time using Darcy's Law and Flow Net	• Simplest equation for calculating travel time • Form of Darcy's law • Describes average linear Velocity	• Aquifer is homogenous, isotropic • Aquifer has infinite areal extent (no boundary conditions) • Confined aquifer with no leakage or recharge • Flat water table	Darcy (1856)
Cone of Depression travel time (Flat Regional Hydraulic Gradient)	• Accounts for gradient of cone of depression in the vicinity of the borehole • Calculating the travel time for various incremental distances from the borehole using the hydraulic gradient for each increment (values for n and K remain the same for each calculation) • The total travel time to a given point is the sum of the times of travel of each increment • Intermediate times of travel can be estimated graphically or the distance between increments can be adjusted until the sum of the incremental travel time equals the target travel time	• Aquifer is homogenous, isotropic • Aquifer has infinite areal extent (no boundary conditions) • Confined aquifer with no leakage or recharge • Accurate measurement or estimation of the cone of depression geometry is known • The gradient of the cone of depression is uniform	Darcy (1856) Kreitler and Senger (1991)
Travel time with Sloping Regional Potentiometric Surface	• Accounts for asymmetrical gradient of the cone of depression in the vicinity of the borehole (e.g. slope with drawdown extending farther upgradient than downgradient) • Requires trial and error calculations using different distances until the equation yields the desired travel time	• Aquifer has infinite areal extent (no boundary conditions) • Confined aquifer with no leakage or recharge	Walton (1962, 1967) Bear and Jacob (1965) Hutoon (1980) Keely and Tsang (1983) Javandel and Tsang (1986) Mclane (1990) Kreitler and Senger (1991) Pekas (1992)
Inter-aquifer Flow and travel time	• Considers inter-aquifer flow either upward or downward (therefore GPZ will be larger) • Requires trial and error calculations to determine area in which the volume of water from the aquifer and the volume of water from leakage equals the volume of water pumped from a well	• Aquifer is homogenous, isotropic	Kreitler and Senger (1991)

Simple Analytical Approach	Explanation of approach	Assumptions	Author
Drawdown approaches			
Uniform Flow Equation (Sloping Gradient)	• Calculates the boundary of the extent that produces inflow to the abstraction borehole • Considers a homogenous aquifer with sloping piezometric surface	• Asymmetrical cone of depression • Confined aquifer with no leakage or recharge • Drawdown is less than 10% of saturated thickness	German Forchheimer (1930) Todd (1980)
Thiem Equilibrium Equation	• Used to calculate the radius of influence that pumping has when the aquifer has reached equilibrium	• Aquifer is homogenous, isotropic • Aquifer has infinite areal extent (no boundary conditions) • Well penetrates the entire aquifer • Regional water table is nearly flat	Thiem (1906) Kreltler and Senger (1991)
Nonequilibrium Equations	• Used to calculate the radius of influence at a certain rate of pumping	• Aquifer is confined, homogenous and isotropic • Aquifer has infinite areal extent (no boundary conditions) • Well penetrates the entire aquifer • Borehole diameter is infinitesimal • Water moved from storage is discharged instantaneously with decline of head • Regional water table is nearly flat	(Theis, 1935)

3.1.2.5 Hydrogeological Mapping

Hydrogeological mapping essentially encompasses the development of a conceptual model to present a groundwater system using hydrogeological principles and the physical and hydrogeological characteristics of an aquifer. The conceptual model is then used to understand groundwater flow in the aquifer and to identify groundwater flow boundaries, which govern the delineation of GPZs for this approach. Groundwater flow boundaries may include, geological contacts, groundwater divides or structural features such as fault or fracture zones. Data required to develop the conceptual model and subsequent delineation of GPZs, includes aquifer contacts, depth to water table, recharge zone, presence of anisotropy in the aquifer and influence of a pumping borehole in the aquifer. This data additionally forms the baseline data needed for numerical modelling approaches and thus, hydrogeological mapping is commonly used in combination with numerical modelling approaches.

3.1.2.6 Numerical Modelling

Numerical modelling methods involve more complex analytical or numerical solutions and consider groundwater flow and contaminant transport processes. Numerical models allow hydrogeologic characteristics to suit the highly anisotropic and heterogeneous aquifer settings (Liu et al., 2019). Protection zone modelling has evolved over recent decades. One of the more well-known approaches is Exit Probability (EP) (Uffink 1989, Wilson and Liu 1995, Neupauer and Wilson 1999, Neupauer and Wilson 2001). This approach delineates the GPZs using groundwater flow paths which are determined in the model by placing “particles” at abstraction boreholes. The model will then map the probability of capture for particles within the area surrounding the borehole (or spring, stream, etc.) (Frind and Molson, 2018). This EP approach makes use of the analogy between the (non-reactive) solute transport problem and the capture zone delineation problem. Both involve predicting the path of a dissolved contaminant between a source and a receptor, the basic processes being advection, dispersion and diffusion. Both problems can be solved by means of the advection-dispersion equation, where the dispersion term represents a spreading effect due to the structure of the medium, which can act on the distribution of a solute as well as on the probability of capture.

According to Kunstmann and Kinzelbach (2000), the EP approach is equivalent to particle tracking with a random walk component, which is valid for representing uncertainty due to intra-unit heterogeneities by means of the dispersion term. Large-scale geological or external uncertainties such as recharge are represented by scenario analysis. The EP approach can be easily extended to produce time-dependent protection zones (isochrones) by using the life expectancy (LE) approach (Molson and Frind 2012), which solves the groundwater age equation for life remaining in a parcel of water before being captured by the well (Frind and Molson, 2018). Compared to standard particle tracking, EP can provide much more information on a capture zone: Heterogeneity effects can be considered via dispersion and flow times can be determined through temporal spreading of the probability plume. In combination with mean lifetime expectancy, expected travel times towards a well can be determined.

Numerical modelling approaches are the most accurate of all the methods for delineating groundwater protection zones and can be used in complex aquifer settings. Unlike the previous approaches mentioned, numerical modelling considers the principles of contamination in groundwater (advection, dispersion and diffusion). A high degree of hydrogeological and modelling expertise is required as well as extensive aquifer specific data, such as in developed, large scale municipal bulk water supply schemes. However, in small types of groundwater use where such resources are not readily available, this method may be timely and costly to implement in terms of manpower, data collection and analysis.

3.1.3 Vulnerability Mapping and Ranking

Vulnerability assessments have been introduced by several countries (for example United Kingdom, Australia and Ireland) as a part of their protection practices and policies. The California Department of Health Services (1999) defines vulnerability assessments as a determination of the significant threats to a groundwater resource and the quality of the water supply. Vulnerability mapping and ranking involves delineating areas of susceptibility to groundwater contamination based on aquifer characteristics which promote or inhibit movement of contaminants in the subsurface (US EPA, 1994). Vulnerability assessments do not have absolute meaning but allow for the assessment of relative vulnerability (US EPA, 1994) and therefore, are most powerful when assessed in conjunction with the other components of a groundwater protection scheme, such as groundwater protection zones to identify areas that are at high risk of contamination (see **Figure 3-3**). Many methods are available for assessing groundwater vulnerability, each with its unique application and data input requirements. Several common techniques for vulnerability mapping are described below.

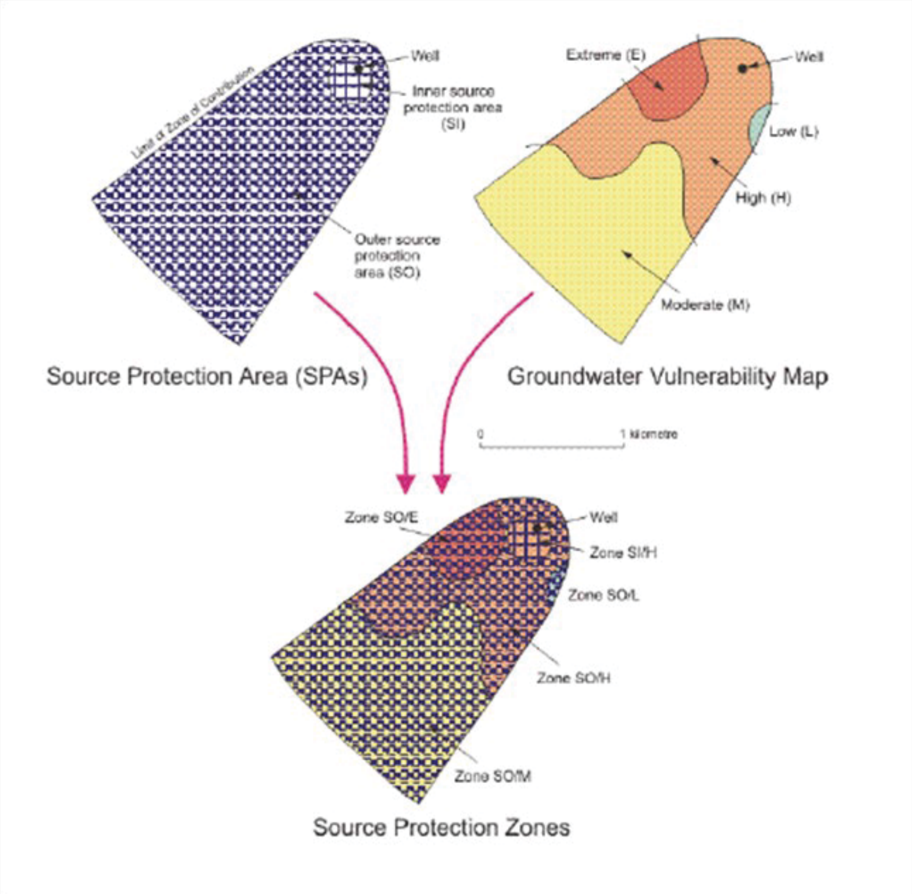

Figure 3-3 **Schematic illustrating how groundwater protection zones and vulnerability mapping can be overlain to better constrain groundwater protection zones for abstraction boreholes (adapted from DoELG, 1999).**

3.1.3.1 AVI (The Aquifer Vulnerability Index)

This approach, developed by Van Stemvoort et al. (1992), measures groundwater vulnerability based on two physical parameters:

1. the thickness of the sedimentary layers in the vadose zone above the uppermost, saturated aquifer surface (d)
2. estimated hydraulic conductivity of the sedimentary layer (K)

Based on these two parameters the hydraulic resistance can be calculated using **Equation 3-3**. The hydraulic resistance is a theoretical factor used to describe the resistance of an aquifer to vertical flow and as such a parameter to estimate aquifer vulnerability. Lateral migration of contaminates is not considered.

$$\boldsymbol{c = \frac{\sum d_i}{K_i}}$$ **Equation 3-3**

Where:
c = hydraulic resistance
d_i = thickness of sedimentary layer in the vadose zone
K_i = hydraulic conductivity for sedimentary layer

3.1.3.2 GOD

The GOD approach was first developed by Foster (1987) and similar to the aquifer vulnerability index (AVI) approach assesses the vulnerability of an aquifer in terms of vertical percolation. GOD is an acronym that stands for the three parameters used in the analysis:

1. G – the groundwater confinement
2. O – the overlying lithology
3. D – depth to groundwater

These three parameters are assigned a score between 0 and 1 based on the contribution to aquifer vulnerability (0-low and 1-high contribution to aquifer vulnerability) (see **Figure 3-4**). The GOD vulnerability index is calculated by multiplying these three parameters according to **Equation 3-4**. The vulnerability index describes the aquifer pollution vulnerability ranging from 0, negligible aquifer pollution vulnerability to 1, an extremely high aquifer pollution vulnerability.

$$GOD\ index = G \times O\ \times D$$

Equation 3-4

Where:
G = lithology of the unsaturated zone
O = is the type of aquifer
D = depth to aquifer

This approach is a classical approach that offers a simple and quick method for delineating aquifer vulnerability without the need for extensive expertise, data, time, and budget. The GOD approach has been modified since it was first developed to consider other parameters such as soil media (Foster, 2002).

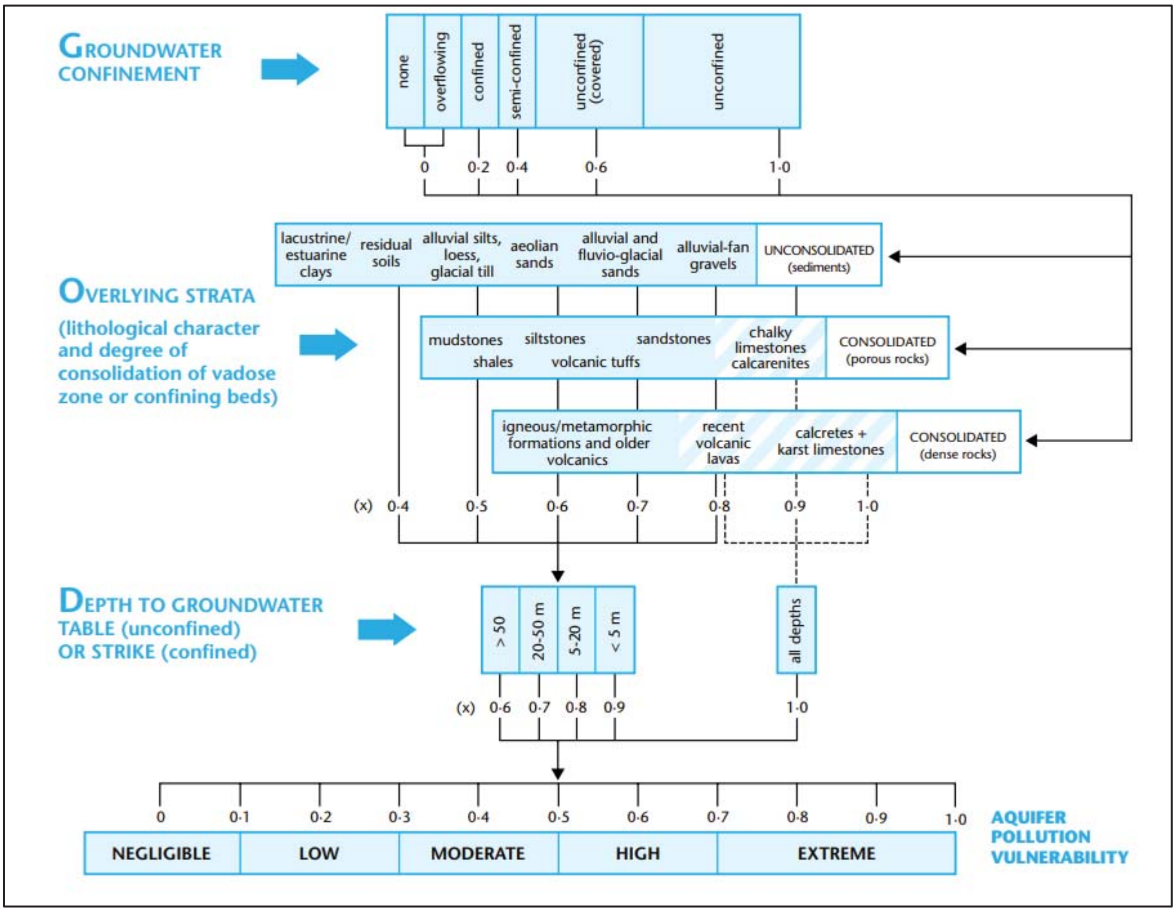

Figure 3-4 **GOD system for evaluation of aquifer pollution vulnerability (from Foster et al., 2007).**

3.1.3.3 DRASTIC

DRASTIC (also known as pollution potential), set out by the US Environmental Agency (Aller et al., 1987), is one of the most widely used vulnerability assessment methods. DRASTIC is an acronym for the parameters included, as basic requirements, in assessing the general pollution potential in a hydrogeological setting: D = Depth to water table, R = Net recharge, A = Aquifer media, S = Soil media, T = Topography, I = Impact of the vadose zone, C = Hydraulic conductivity.

Each of the DRASTIC parameters are ranked by three parts: weights, ranges, and rating (Aller et al., 1987). To determine the relative importance of each factor concerning the other, each DRASTIC parameter is assigned a relative weight rating from 1 to 5, where 5 is the most significant weighting and 1 the least significant weighting (see **Table 3-2**). Each DRASTIC parameter is then divided into ranges and each range assigned a specific rating (between 1 and 10) to determine the relative significance of each range with respect to pollution potential. Typical ranges and ratings are defined by Aller et al. (1987) but these should be adjusted based on more specific knowledge of a groundwater system. An example of the respective rating and weighting of the DRASTIC Specific Vulnerability Index (DSVI) parameters is listed in **Table B-1**, **Appendix B**.

The product of each rating factor, r, by the assigned weighting, w, produces a weighted DSVI value ΔrΔw (Leal & Castillo, 2003). The objective of DSVI is to display the spatial variation of vulnerability across an aquifer. The final DSVI score for each point is obtained through **Equation 3-5** below:

$$DRASTIC\ INDEX\ (DSVI) = D_rD_w + R_rR_w + A_rA_w + S_rS_w + T_rT_w + I_rI_w + C_rC_w$$

Equation 3-5

Where:
w = weight of the parameter (as described in **Table 3-2**)
r = rating for the parameter evaluated (as described in **Table B-1**)
D = depth to groundwater
R = net recharge,
A = aquifer media,
S = soil media,
T = topography,
I = impact of the vadose zone,
C = hydraulic conductivity,

Each parameter results in an individual map, and the final DSVI map is an overlay of each of the respective maps. Once the final DSVI score for each point has been calculated by the sum of all ratings multiplied by the assigned weight, then a map can be generated using Kriging. The higher the DSVI value, the more vulnerable that point of the aquifer is to pollution, and vice versa for lower values (**Table 3-3**).

Table 3-2 Description of the significance of each weighting (Aller et al., 1987).

Weight (w)	Significance	*Description*
1	Least	Negligible contribution to factors that have an impact on an aquifer.
2	Less	Little effect in the enhancement or reduction of vulnerability due to the feature properties.
3	Moderate	Medium effect.
4	More	Consideration in the assessment process is crucial due to its properties in relation to aquifer vulnerability.
5	Most	Has important properties that could affect aquifer vulnerability.

Table 3-3 DSVI classes of vulnerability

DSVI value	*Class*
< 86	Extremely Low (EL)
86-107	Very Low (VL)
107-128	Low (L)
128-149	Moderate (M)
149-170	High (H)
170-190	Very High (VH)
190-270	Extremely High (EH)

This method is most widely used as it is proven to be effective, as it is relatively straightforward, the data required is commonly available and it produces a product that can be easily interpreted as spatial groundwater information that can be conveniently displayed and understood by all those involved in groundwater protection (Xu and Reynders, 1995). However, the list of parameters included in DRASTIC are not all-inclusive and therefore various modifications to DRASTIC have been developed over the years. Some of these modifications are described in **Table 3-4.**

Table 3-4 Modified DRASTIC methodologies

Modification	Explanation	Author
Pesticide DRASTIC	Adopts the same parameters as DRASTIC but with different weights	Aller et al. (1987)
DRASTIC-LU	Incorporates land use to encompass anthropogenic impacts to a groundwater source	Leal and Castillo (2003)
DRASTIC - Fm	Incorporates a fracture matrix (Fm) parameter for fractured aquifers which includes: • fracture density • fracture length • fracture orientation	Denny et al. (2007)
SINTACS	S = static water level depth, I = net recharge, N = non-saturated zone, T= soil type, A = aquifer type, C =hydraulic conductivity and S = topographic slope	Civita (1990a, 1990b)

3.1.3.4 Sensitivity analysis

To account for the uncertainty associated with the parameters, and to show the relationship between theoretical and effective weight of the DSVI parameters, a sensitivity analysis is carried out. The analysis will help to address the subjectivity as well as evaluate the relative importance of the parameters for aquifer vulnerability. The approach taken is described below:

Removal of a single map indicates the influence of each map layer on the final vulnerability measurement. To achieve this, the aquifer is sub-divided into different areas, and the effective weight of each sub-area is estimated by **Equation 3-6** and **Equation 3-7**. This will lead to an understanding of whether the assigned weighting is ideal, or if it needs modification (Shirazi et al., 2012).

$$\boldsymbol{Sensitivity, S_V} = \left(\frac{\boldsymbol{n-V}}{\boldsymbol{V}}\right) \times \mathbf{100}$$ **Equation 3-6**

Where V, is the DSVI score of all map layers/parameters, and n is the DSVI of one map layer or parameter removed.

$$\boldsymbol{W_e} = \left(\frac{\boldsymbol{P_r\ P_w}}{\boldsymbol{V_p}}\right) \times \mathbf{100}$$ **Equation 3-7**

Whereby W is the difference of the theoretical weight and the effective weight, and P is the DSVI value with the removal of a single parameter, and V is the DSVI score without the removal of any parameters.

3.1.3.5 Comparison between studies

Serval studies comparing the different approaches for vulnerability mapping and analysis have been conducted and are summarised in **Table 3-5**. These studies can be referred to for further insight when selecting the appropriate approach for vulnerability mapping and analyses for a groundwater protection scheme. It should also be noted that if resources allow, two or more analyses may be conducted, and results overlapped so that any pitfalls of one approach may be met with another approach.

Table 3-5 Summary of studies where vulnerability mapping approaches have been compared.

Approaches Compared	Author	Result
• DRASTIC • SINTACS • GOD • AVI	Corniello et al. (1997)	The study found that the SINTACS method generates very high vulnerability zones in the areas concerned with surface waters and aquifer interactions.
• GOD • AVI • DRASTIC	Vıas et al. (2005)	Study found that the GOD method could be adequate for a vulnerability in karstic carbonate aquifers at small-moderate scales.
• DRASTIC Pesticide • DRASTIC	Anane et al. (2013)	Study revealed that DRASTIC identified low vulnerability and underestimated the pollution risk, while the DRASTIC pollution parameter better defined the aquifer vulnerability.
• GOD • DRASTIC	Afonso et al. (2008)	Study found that GOD method is best suitable for large design while DRASTIC has good accuracy.

3.1.4 Potentially Contaminating Activities Identification and Risk Assessment

An essential element of defining groundwater protection zones and associated activities is an inventory of existing potentially contaminating activities (PCAs). PCAs can be considered as the potential origins of contamination for groundwater within the protection zones.

According to the Division of Drinking Water and Environmental Management (1999) (California based guidelines), an inventory of PCAs serves three important functions:

1. Provide information on the existence of PCAs and the proximity to the well-head (abstraction borehole), especially those that present the greatest risk to the water supply;
2. Identify past and present activities that pose a threat to the drinking water supply, based on the potential for contaminating groundwater or surface water;
3. Provide an effective means of educating the public about potential problems.

There are a few approaches for conducting a PCA inventory such as gathering information from local knowledge and a hydrocensus, making use of open-source remote sensing and satellite imagery (Google Earth, GIS), information gathered from the local municipality or combination of all these approaches. The PCA inventory needs to include a list of activities, with their location, that are associated with the following contaminants of concern:

- Microorganisms, including faecal coliform bacteria, *Escherichia coli*, viruses, Giardia lamblia, and Cryptosporidium;
- Chemicals for which the maximum contaminant levels (MCLs) or groundwater quality standard for drinking, industrial and irrigation have been established;
- Contaminants of Emerging Concern (CEC) which do not have established drinking water standards but are of growing concern in urban settings;
- Turbidity and total organic carbon (TOC). Turbidity can affect treatment effectiveness and monitoring for microbial contaminants, while TOC can influence the presence of disinfection by-products, which have a carcinogenic concern.

PCA's are then assigned a Level of Risk. Risk can be defined as the likelihood or expected frequency of a specified adverse consequence. When applied to groundwater, this definition can be expressed as the likelihood of contamination arising from potentially contaminating sources or activities. A PCA presents a risk when it is likely to affect groundwater quality (DoELG, 1999). This forms the basis of a risk assessment, whereby the risk ranking is based on the general nature of the activities and the associated contaminants, not on facility-specific management and practices. The following Level of Risk, with a definition are provided below in **Table 3-6**, and a list of activities with the respective Level of Risk are described in **Table B-3**, **Appendix B**. Based on the principles of contamination (outlined in **Section 2.3**), such as the time it takes a contaminant to break down, the activities that should be restricted within each GPZs are listen in **Table 3-7.**

Table 3-6 Level of risk ranking, the risk imparted and the respective definitions per level.

Level of Risk	Risk Imparted	Definition
1	Low	The least potential for drinking water contamination.
2	Moderate	Lower potential for drinking water contamination than level 4, but greater than level 1.
3	High	Lower potential for drinking water contamination than level 4, but greater than level 2
4	Very High	The highest potential for drinking water contamination

Table 3-7 **List of PCAs which are limited or prohibited per GPZ (Division of Drinking Water and Environmental Management, 1999 (California-based guidelines)).**

PCA	ZONE I (10 m)		ZONE II (2-year)		ZONE III (5-year)		ZONE IV (10-year)	
	Prohibited	Prior Approval	Prohibited	Prior Approval	Prohibited	Prior Approval	Prohibited	Prior Approval
Dry cleaners	X		X			X		X
Metal plating/finishing/fabricating	X		X		X			X
Category A Mines	X		X		X			X
Category B and C Mines	X			X		X		X
Confined animal feeding operations	X		X			X		
Sanitary facilities and septic tanks	X		X		X			X
WWTW	X		X			X		X
Cemeteries	X		X			X		X
Aeronautic infrastructure and installations	X		X		X		X	
Petrol stations, fuel service areas, historic petrol stations and fuel tanks	X		X		X			X
Storage, transport or dumping of radioactive materials, hydrocarbons, and/or dangerous substances	X		X		X		X	
Pipelines of toxic substances, excluding sewage	X		X		X		X	
Landfills and rubbish dumps/historic waste sites	X		X		X		X	
Chemical industries, refineries	X		X		X			X
Managed forests	X		X			X		X
Military installations	X		X		X			X
Plastic/synthetic producers	X		X		X			X
Airports	X		X		X		X	
Underground storage tanks	X		X		X			X
Automobile body shops/repair shops, car washes	X			X		X		X
Cement/concrete plants	X			X		X		X
Food processing	X			X		X		X
Funeral services	X			X		X		X
Electrical/electronic manufacturing, home manufacturing, hardware/lumber/parts	X			X		X		X
Medical/vet offices	X			X		X		X
Office buildings/complexes, parking lots, malls, apartments, campgrounds, housing, schools, construction sites	X			X		X		X
Fire stations	X			X		X		X
Golf courses, parks, reserves	X			X		X		X
Waste transfer/recycling, utility stations	X			X		X		X
Photo processing/printing	X			X		X		X
Research laboratories	X			X		X		X
Sewer lines	X			X		X		X
Wood processing/treating, wood/pulp/paper processing and mills	X			X		X		X
Grazing animals, diaries, farm machinery repairs, farm chemical distributors/application services, irrigated crops, non-irrigated crops, sludge application to land, agricultural drainage, pesticide/fertilizer/petroleum storage	X			X		X		X
Lagoons, recreational use of surface water bodies, surface water stream/lakes/river/dams	X			X		X		X
Fleet trucking/trucking/bus terminals, motor pools, transport corridors	X			X		X		X
Junk/scrap yards	X			X		X		X
Machine shops	X			X		X		X
Above ground storage	X			X		X		X

3.1.5 Delineating Protection Response

Overlaying the GPZ with the vulnerability map and compiling a list of PCAs with the associated Level of Risk is the final stage of groundwater protection scheme and risk assessment. The GPZ and the DSVI score of each PCA identified must be noted. Each GPZ and each DSVI category has a different weighting, which needs to be used to calculate a protection response number (**Table 3-8**). The protection response number is calculated by summing the weighting of the protection zones, the weighting of the DSVI category and the PCA Level of Risk (**Equation 3-8**).

$$\textbf{Protection Response Number} = \mathbf{GPZ_w + DSVI_w} + \textbf{PCA level of risk}$$

Equation 3-8

The protection response number is categorized into different classes, which require varied degrees of monitoring – including different levels of monitoring frequency, mitigation measures, and responses (**Table 3-9**).

Table 3-8 Weighting for GPZ and DSVI Rating.

GPZ		DSVI Rating	
Zone	**Weight**	**Category**	**Weight**
		EH	5
Zone 1	4	VH	4
Zone 2	3	H	3
Zone 3	2	M	2
Zone 4	1	L	1

Table 3-9 Protection response numbers, classes and the respective monitoring scheme.

Protection Response Class	Protection Response Number	Monitoring Scheme	Mitigation and Remediation
A	2-4	Annual monitoring	
B	5-7	Bi-annual monitoring	
C	8-10	Quarterly monitoring	Emergency response plan
D	11-13	Immediate investigation	Emergency response plan

The approach is illustrated in **Table B-4**, **Appendix B**. The matrix encompasses both the hydrogeological and contaminant loading aspect of the risk assessment. The red squares represent highest likelihood of contamination and increasing consequence, whilst the green squares represent the decreasing likelihood of contamination and decreasing consequence.

CHAPTER 4: IMPLEMENTING GROUNDWATER PROTECTION SCHEMES

4.1 TYPES OF GROUNDWATER PROTECTION SCHEMES

As described in **Chapter 3**, several different approaches, each with advantages and disadvantages, can be used to develop each component of a groundwater protection scheme. Some approaches implement extensive hydrogeological analysis, providing a high level of confidence in contamination probability (predicting the contamination probability with a low margin of error), however this generally requires a broad range of robust hydrogeological data, and scientific expertise, which can become costly and time consuming to implement. By comparison, simplistic approaches have a lower degree of certainty (predicting the contamination probability with a higher margin of error) but require less hydrogeological information, expertise, time, and money. The approach applied should consider what is most appropriate for the specific groundwater use, type of aquifer, and aquifer vulnerability. Given the relationship between these variables, groundwater protection schemes may range from simple to comprehensive depending on the type of approach applied (see **Figure 4-1**).

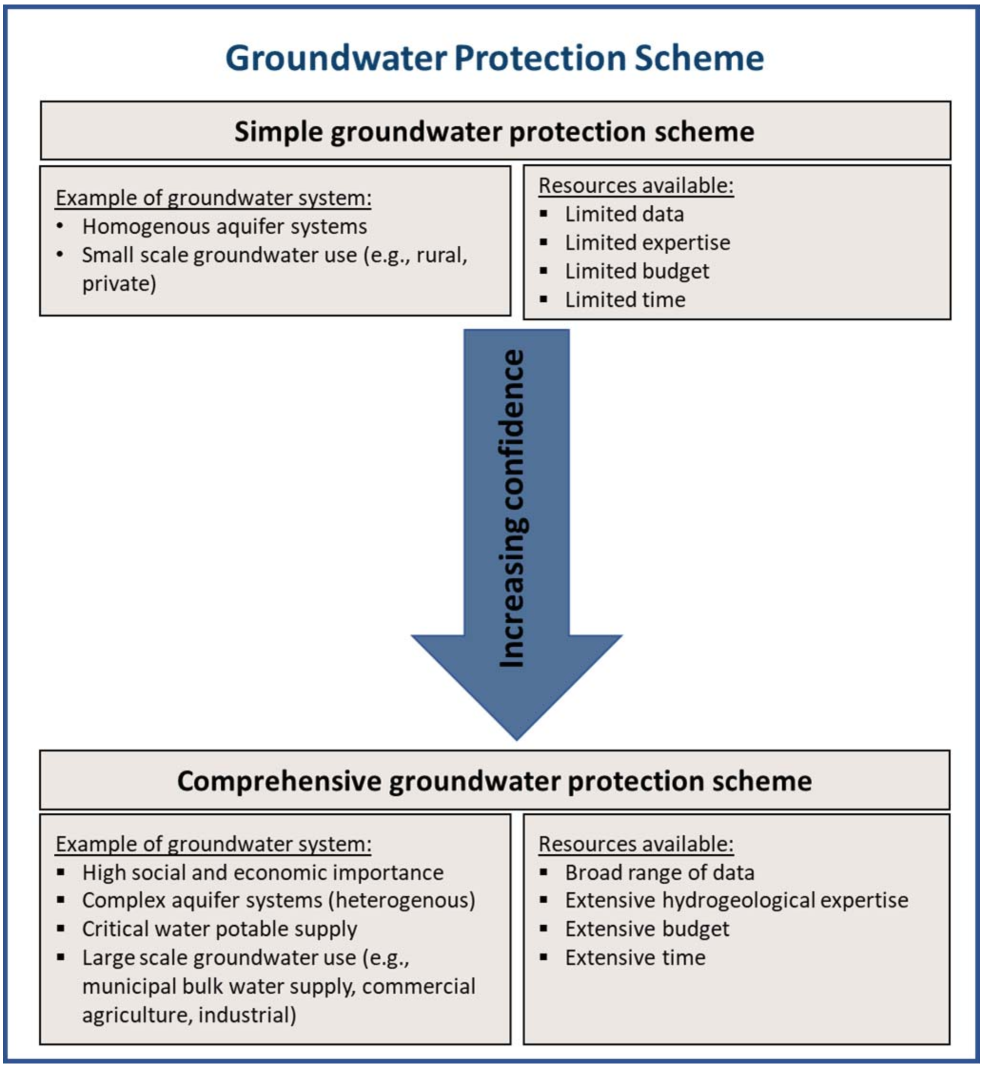

Figure 4-1 **Summary of the factors influencing the type and scale of groundwater protection schemes.**

Three board groundwater protection schemes are outlined in **Table 4-1**, namely, simple, intermediate, and comprehensive schemes. An example of groundwater use, aquifer type and minimum data required for each scheme is also outlined.

Simple groundwater protection schemes implement basic hydrogeological approaches and methodologies suitable to protect groundwater supply from homogeneous aquifer systems that are used for rural and private supply. These usually only have limited resources available, namely, hydrogeological data, expertise, time, and budget. Rural, and private groundwater use often comprises many individually owned or operated wellpoints and boreholes of smaller capacity that are widely dispersed over an aquifer. As such, intermediate to more comprehensive approaches for groundwater protection schemes cannot be easily applied, but simple groundwater protection schemes around individual boreholes can be implemented. Development and implementation of a simple groundwater protection scheme often goes hand in hand with education and discussions between a trained hydrogeologist and the borehole owner or village leader. This is especially important for placement of land-based activities, for example, the concept of placing pit latrine down-gradient from a wellpoint or borehole to avoid contamination is obvious to a trained hydrogeologist and can be made obvious to a borehole owner or village leader once the logic of groundwater flow is explained (Robins et al. 2007). The simple groundwater protection scheme should be considered the minimum requirement to protect a borehole from contamination and should be coupled with good borehole construction practice and adequate sanitary seals.

Intermediate groundwater schemes encompass the implementation of more involved methodologies and approaches; however, they do not require extensive resources to implement. Intermediate groundwater schemes are therefore suitable for protecting groundwater supply to medium sized groundwater users, such as agriculture and industry where increased confidence in the contamination probability is required but there are limited resources available to implement very complex hydrogeological approaches and methodologies.

Comprehensive groundwater protection schemes make use of extensive hydrogeological methodologies and approaches more suitable to protect groundwater supply from complex, heterogenous aquifer systems. These extensive hydrogeological approaches provide a high level of confidence in contamination probability which is often required by larger groundwater users such as large-scale agriculture, industrial or municipal bulk water supply. The resources needed to implement extensive hydrogeological methodologies and approaches, such as hydrogeological data, expertise, time, and budget, are often available from these groundwater users.

These three groundwater protection schemes should not be treated as fixed or rigid plans but rather serve as a guide for the type of approaches suitable to a certain scenario (groundwater use, aquifer type and resources available). In reality, the groundwater protection scheme required may not fit into one of these three schemes. The three groundwater protection schemes can be used as a sliding scale based on what is required to protect the quality of the groundwater resource at hand. Following adaptive management principles, developed groundwater protection schemes may be modified over time if factors, such as additional data, budget, or time available change.

There are several additional factors that are important to consider when selecting the most appropriate groundwater protection scheme. These are listed below and discussed in subsequent sections:

- Aquifer type
- Socially and economically important aquifers
- Recharge protection
- Considerations for developed areas

Table 4-1 **Types of groundwater protection schemes, showing an example of groundwater use, aquifer type and minimum data required for each approach.**

Types of Groundwater Protection Scheme	Example of groundwater use	Example of aquifer type	Groundwater Protection Zones	Vulnerability Mapping and Ranking	PCA Identification and Ranking	Delineating Protection Response	Minimum Data Required
Simple Approach (minimum requirement)	• Rural • Private	• Intergranular • Homogenous	• Fixed radius • Calculated fixed radius	• none required • GOD/AVI if resources available	• Identification of PCAs using local knowledge and hydrocensus • No PCA risk assessment	• Protection response not needed • PCA identification • Use **Table 3.7** for PCAs which are limited or prohibited per GPZ • minimum annual monitoring or maximum monitoring that resources allow for	• Location of abstraction boreholes • Location of PCAs
Intermediate Approach	• Agricultural • Industrial	• Intergranular • Homogenous	• Simplified Variable Shapes • Simple Analytical • Numerical Modelling if data available	• GOD/AVI • DRASTIC if resources available	• Identification of PCA using local knowledge and hydrocensus or open-source remote sensing and satellite imagery • PCA risk assessment	Conduct full protection response: • Use **Table 3.7** for PCAs which are limited or prohibited per GPZ • Overlapping the GPZ with the vulnerability map and compiling a list of PCAs with associated Level of Risk within the bounds of the GPZ • Calculating Protection Response Number and using that to determine monitoring scheme.	• Location of abstraction boreholes • Location of PCAs • Aquifer type • Aquifer parameters • Abstraction rates • Information of borehole construction • Hydraulic gradient • Direction of groundwater flow

Types of Groundwater Protection Scheme	Example of groundwater use	Example of aquifer type	Groundwater Protection Zones	Vulnerability Mapping and Ranking	PCA Identification and Ranking	Delineating Protection Response	Minimum Data Required
Comprehensive Approach	• Municipal bulk water supply	• Fractured • Karst • Heterogenous	• Numerical modelling	• DRASTIC • Modifies DRASTIC for specific scenario	• Identification PCA using combination of: - local knowledge - hydrocensus or - open-source remote sensing and satellite imagery - information gathered from the local municipality • PCA risk assessment	Conduct full protection response: • Use **Table 3.7** for PCAs which are limited or prohibited per GPZ • Overlapping the GPZ with the vulnerability map and compiling a list of PCAs with associated Level of Risk within the bounds of the GPZ • Calculating Protection Response Number and using that to determine the monitoring scheme.	• Location of abstraction boreholes • Location of PCAs • Aquifer type • Aquifer parameters • Abstraction rates • Information of borehole construction • Hydraulic gradient • Soil media • Topography • Vadose Zone • Direction of groundwater flow • Aquifer geometry • Hydraulic boundaries • Recharge rates

4.1.1 Aquifer Type

As briefly discussed, a groundwater protection scheme needs to consider the aquifer type and complexity. This is because groundwater flow paths and travel times depend on aquifer characteristics. Comprehensive groundwater protection schemes incorporating more involved approaches, such as GIS and modelling, are better suited to protect groundwater resources from complex heterogenous aquifer systems. They allow for sufficient simulation of the aquifer's behaviour to understand contamination probability and contaminant attenuation. Simple groundwater protection schemes can be implemented to safeguard homogenous aquifer systems, as the simple approaches used are sufficient to understand the aquifer system, it's behaviour and vulnerability. Specific approaches have also been developed for certain aquifer types and should be applied where appropriate (e.g. modified DRASTIC-fm for fractured aquifers).

4.1.2 Recharge Protection

Recharge is when water is added to an aquifer from rainfall, surface water bodies, neighbouring aquifers or from artificial recharge systems (manged aquifer recharge – MAR) (Murray et al., 2008). Recharge sources from surface water bodies, occurring inside the GPZs are treated as a PCA with a high risk (level 3) as they are potential pathways for contaminants to reach the aquifer (**Table B-3**), leading to degradation of the water quality for supply. In some cases, recharge areas may exist outside of delineated GPZs (depending on the distance of the borehole to the recharge zone and aquifer characteristics). Although contaminants entering recharge areas outside of the GPZs will have sufficient time to attenuate before reaching the water supply source, these areas need to be protected as land use can affect the potential volume recharged. For example, increased impermeable surfaces result in increased runoff and reduction in recharge volumes, reducing groundwater availability. This is related to part 3 of aquifer protection shown in **Section 1.2** but not addressed in this report.

4.1.3 Socially and Economically Important Aquifers

Aquifers considered of high social and economic importance, require a high level of confidence in contamination probability to safeguard the integrity of the water quality. This may include groundwater resources that form the primary source of water that sustains society and the associated economic sector, such as those outlined in the Strategic Water Source Areas (SWSA) (WRC, 2018). The precautionary principal approach should be implemented meaning that a comprehensive groundwater protection scheme should be used to protect these resources as these aquifers should always get the highest protection due to their importance. Once more is known about the aquifer system and its vulnerability and pollution potential is established, a simpler approach may be implemented.

4.1.4 Considerations for Developed Areas

In developed areas, PCAs which are limited or prohibited per GPZ may already exist prior to the development of a groundwater protection scheme. In these cases, these prohibited PCA's must be controlled retrospectively to ensure groundwater quality is sufficiently protected without restricting economic development. This may occur in four ways:

- Increase water quality monitoring around existing but prohibited PCA's. Monitoring will determine the effect the existing PCA has on the groundwater system.
- Ensure that PCAs are not expanded or increased. This will ensure no increased risk of contamination to the groundwater.

- Phase out the operation of the PCAs to ensure alignment with the developed groundwater protection scheme.
- In the case where the groundwater source has not yet been developed, boreholes may be sited in relation to existing PCAs to ensure there is sufficient travel time for contaminant degradation or time to respond to any contamination. This is often only applicable for small scale groundwater users where small volumes of water are required. An example can be siting a borehole up-gradient of a pit latrine.

CHAPTER 5: ROLES AND RESPONSIBILITY

5.1 GOVERNANCE AND STAKEHOLDERS

The ultimate responsibility for groundwater protection in South Africa resides with the Department of Water and Sanitation (DWS), however successful sustainable groundwater management lies in the effective collaboration between institutional bodies, specialists, the stakeholders, and groundwater users. **Figure 5-1** highlights the framework of major role players in groundwater governance. Roles and responsibilities of government institutions and stakeholders for groundwater management are outlined in detail in WRC, 2022 – *Guidance Document for Management of a Groundwater Scheme.* In terms of successful groundwater protection, roles and responsibilities of government institutions and stakeholders are detailed below.

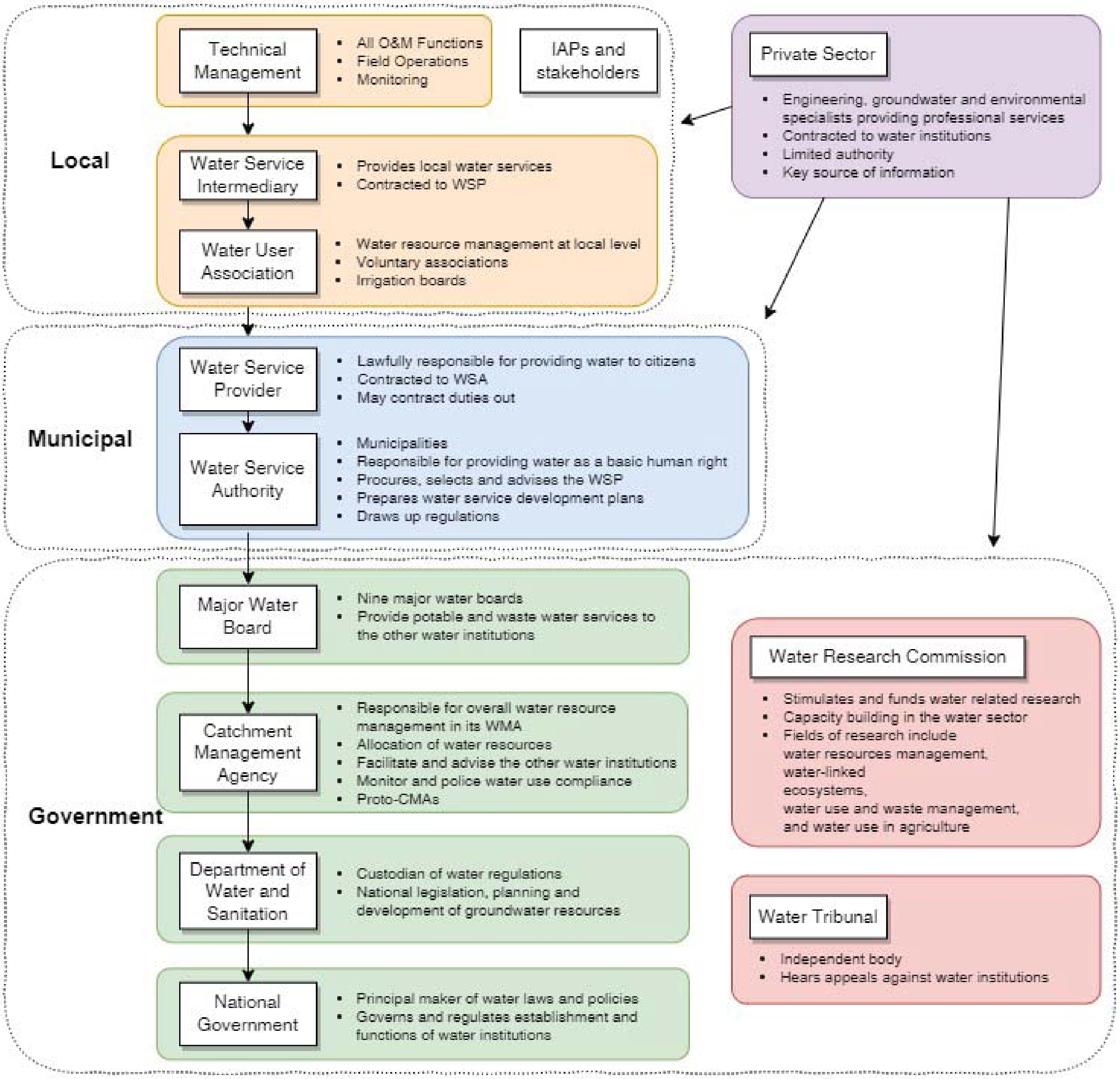

Figure 5-1 **Organisation of the major role players in groundwater governance.**

Governance forms the integral backbone of resource management and protection. Various government institutions and stakeholders carry different roles and responsibilities for implementing groundwater protection schemes (simple, intermediate, and comprehensive – as outlined **Chapter 4**). However, it is important to note that the flow of information from all groundwater protection scheme types, no matter the scale, should reach the highest 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.

5.1.1 Water Service Intermediaries (WSIs) and Water User Associations (WUAs)

These institutions manage small groundwater users such as farm owners, farming corporations or mining companies who are responsible for providing water to employees that live on the property. The responsibility to implement and manage simple groundwater protection schemes lie with the WSIs and WUAs. They should ensure the minimum requirement to protect a borehole from contamination is implemented, coupled with good borehole construction and adequate sanitary seals. WSIs and WUAs should also be responsible to ensure that data and information are shared between the community members, specifically proposed new PCA's. In some cases, WUAs are responsible for management of large-scale groundwater users such as commercial agriculture. In these cases, the implementation and management of intermediate to comprehensive groundwater schemes are then implemented by WUAs.

5.1.2 Water Service Providers (WSPs)

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 bylaws of the Water Service Authority (i.e. municipality). 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. They hold the responsibility to identify where groundwater protection schemes should be implemented and to implement the appropriate scheme to protect the water supplied. WSPs also have the responsibility of collecting and capturing monitoring data, which, through adaptive management, must be used to update the groundwater protection scheme. WSPs should ensure that land use restrictions according to the GPZs are adhered to.

5.1.3 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 groundwater protection responsibilities. WSA's manage groundwater protection schemes that are implemented by WSPs, WSAs and WUA to ensure that land use restrictions are adhered to and that the schemes are updated as new information or new boreholes become available. Groundwater protection schemes need to be included in bylaws and Spatial Development Frameworks (SDF) to ensure enforcement. This will facilitate the required qualified people to be notified about proposed changes in land-use and make the correct educated decision on the proposed changes. Groundwater protection schemes should be regularly reviewed by stakeholders through adaptive management to determine if they are meeting the required protection or require updating (to a comprehensive approach or simplifying).

WSAs carry out financial planning, implement tariffs, draw up regulations and bylaws for its given jurisdiction/district, therefore it is their responsibility to ensure that water boards and CMAs support them in implementing groundwater protection schemes. Groundwater protection schemes cannot operate without stakeholder and user by in. WSAs are responsible to facilitate education and information sharing among stakeholders and users.

5.1.4 Major Water Boards

There are currently nine government owned Water Boards in South Africa 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. 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 the DWS. Therefore, it would be the responsibility of the water boards to ensure that other water service institutions have sufficiently implemented the selected groundwater protection scheme with appropriate land use restrictions. Additionally, they would be responsible for promoting the groundwater protection scheme, providing training, support, and management services to the other institutions, and promote co-operation and data sharing.

5.1.5 Catchment Management Agencies (CMAs)

The National Water Policy (1997) and the NWA (1998) recognised that water resources should be based on hydrological boundaries (quaternary catchments) rather than political boundaries. This led to the establishment of 9 water management areas (WMAs). It is the intent that each of these WMAs have a corresponding CMA established to manage it. The CMA has the primary responsibility of water resource management within its WMA and is arguably the most important institutional water body. Their responsibility would be to ensure that the WSIs, WUAs, WSPs, WSAs have sufficient resources to identify the need and implement groundwater protection schemes around their water supply. They also need to ensure 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 decisions and actions that could have catchment scale impacts. This is carried out through the establishment and implementation of Catchment Management Strategies, which should be viewed regularly by all groundwater users within the individual WMAs. CMAs are also responsible to ensuring institutional bodies below them have the appropriate channels and are available for stakeholders and government institutions to report compliance issues.

5.1.6 Private Sector

Consultants in the private sector include engineering, groundwater and environmental related specialists and professionals who carry out certain tasks related to groundwater protection scheme development and management under contracts to a WSI, WUA, WSP, WSA, water board, CMA or DWS. Required tasks include the implementation of comprehensive groundwater protection schemes which requires sound scientific knowledge, training and expertise. 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.

5.1.7 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. They fund water related research, promote the transfer of information and technology, and enhance 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 management of a groundwater resource should make themselves aware and familiar of research outputs from the WRC. There are many documents in the WRC database which can be of assistance to stakeholders in carrying out their respective responsibilities.

5.1.8 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. The water tribunal should therefore allow people the chance to be heard and make a case for any issues relating to the implementation of a groundwater protection scheme, specifically relating to landuse restrictions.

5.1.9 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, is 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 should hold the ultimate responsibility to plan and develop, implement and enforce groundwater protection schemes. 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.

Groundwater protection schemes require buy-in from stakeholders to ensure that they are implemented at first and then enforced going forward. This will vary based on the groundwater protection scheme selected that can vary from a rural community to all citizens of a municipal area. The small-scale users (such as rural or private) that implement simple groundwater protection schemes can get buy in more easily compared to the larger scale groundwater users (such as industrial or municipal bulk water supply) that implement comprehensive groundwater protection schemes. This is because larger scale groundwater users require involvement from multiple stakeholders and governmental departments, e.g. the Cape Flats Aquifer Management Scheme (CFAMS) involves various departments across the city, including spatial development planers, Water and Sanitation, Environmental Management, Solid Waste Management, and Recreation and Parks. Education of stakeholders is critical to get by in for the implementation and enforcement of a groundwater protection scheme. Stakeholders should be aware of the risk of PCAs and the benefits of a groundwater protection scheme for protecting groundwater resources for economic and social importance as well as drinking water supply.

5.1.10 National Government

The national government is responsible to gazette a legislative guideline for groundwater protection schemes in South Africa. Should this be done then the national government would be held responsible to regulate the water institutional bodies that would implement and enforce groundwater protection schemes.

5.1.11 Department of Agriculture, Land Reform and Rural Development

Enforcement of land use limitations according to groundwater protection zones must be a shared activity between DWS, National and Local departments authorising land use as well as Water Users Associations. Land use authorisation must consider the possible impacts on users and must therefore consult with DWS and local users before authorisation. A committee should be established between DWS and the relevant land use authorities to ensure the implementation of this shared authorisation process.

5.2 WELLFIELD DESIGN AND MANAGEMENT TO LIMIT CONTAMINATION

The extent to which drawdown associated with pumping lowers the local and regional water table – the radius of influence or the cone of depression – is one of the main factors effecting the delineation of GPZs (see **Section 3.1.2**). A set of operating rules and best practice principals should be developed prior to wellfield operation and implementation of a groundwater protection scheme to ensure that drawdown associated with does not impact the surrounding environment or lead to over-abstraction of the aquifer (see WRC, 2022 – *Guidance Document for Management of a Groundwater Scheme* for further explanations). Operating rules and best practices include:

- a recommended yield that each borehole may be pumped at,
- critical water level (CWL) which is the elevation of the water level in the borehole which may not be exceeded
- operating water levels (OWL) which is the desired water level in the borehole that is maintained under normal operating conditions.

These operational rules can be used as inputs for a groundwater protection scheme and the delineation of GPZs. Once the wellfield is in operation these rules should be monitored and strictly adhered to ensure that the groundwater protection scheme remains suitable for the wellfield’s operation. Through adaptive management principals, the operating rules and best practices can be updated as more data is acquired through scheme operation and monitoring. The groundwater protection scheme and specifically GPZ delineation can then be updated as required to ensure that it is applicable to the wellfield’s operation.

5.3 REPORTING COMPLIANCE ISSUES

All incidents should be reported to the main responsibility (e.g. CMAs, DWS) and the regulator immediately. They can then decide on the appropriate remediation plan, considering which zones (travel time) the incident occurred in. Remediation plans are specific to the incident that occurred and therefore can only be developed once required. Groundwater protection schemes should include the relevant contact details, e.g. for rural use the leader and for large scale use the pollution control office, to ensure that stakeholders know who to contact in the event that contamination takes place and can do it timeously. Timeous notification is critical because everything is related to travel times and remediation and action plans need to be put in place according to the protection response or risk.

CHAPTER 6: CONCLUSION

Currently, there are no implemented legislative guidelines on establishing groundwater protection schemes in South Africa. Therefore, this guidance document aims to define and guide the creation of groundwater protection schemes in South Africa. This guideline deals only with aspects of pollution prevention rather than remediation or prevention of recharge reduction or over abstraction, which constitutes a fundamental, but separate component of aquifer protection. The groundwater protection scheme is applicable to groundwater resource supply schemes of all scales and uses, where groundwater quality needs to be preserved. More specifically, this guideline outlines a methodological approach to implementing a groundwater protection scheme for pollution prevention, including delineation of groundwater protection zones, vulnerability mapping and ranking, identifying potentially contaminating activities within protection zones and determining a protection response number based on its risk.

The guideline outlines the various approaches used to develop components of groundwater protection schemes and lists their associated advantages and disadvantages. The selected approach should consider what is most appropriate for the specific aquifer type, vulnerability, groundwater use and the associated contaminant load exposed to the aquifer. It should also consider what is most appropriate for the size (number of boreholes, radius of influence, borehole interaction) and the resources available, i.e. budget, time, data, and expertise. Based on these approaches, three broad groundwater protection schemes are outlined, namely, simple, intermediate, and comprehensive schemes. These three groundwater protection schemes should not be treated as fixed or rigid plans but rather serve as a guide for the type of approaches suitable to a certain scenario (groundwater use, aquifer type and resources available). The three groundwater protection schemes can be used as a sliding scale based on what is required to protect the quality of the groundwater resource at hand. Following adaptive management principles, developed groundwater protection schemes may be modified over time if factors, such as additional data, budget, or time available change.

Roles and responsibilities for developing and enforcing groundwater protection schemes are also outlined. Enforcement of land use limitations according to the groundwater protection zones should be a shared activity between the regulator, national and local government departments authorising land use activities, as well as Water Users Associations, Water Service Providers and Water Services Authorities. Committee or task teams should be established between the regulator and relevant land use authorities to drive implementation of this shared authorisation process. Groundwater protection schemes require buy-in from stakeholders to ensure these are implemented at first and enforced going forward. This will likely vary based on the groundwater protection scheme selected. This report also outlines how a groundwater protection scheme analytically assists to define the monitoring frequency of a groundwater resource and inform on procedures for reporting compliance issues. This helps to guide groundwater users on the appropriate means to monitor and manage their groundwater supply as well as provide an early warning for contamination should it occur.

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APPENDIX A: Groundwater Use

Table A-1 Summary of groundwater use and impact on groundwater pollution.

Use	Budget	Supply Purpose	Supply Yield	Relative Radius of influence	Common Landuse	Common Potentially Contaminating Activities	Management monitoring and data collection
Rural	Low	• Potable use • Domestic	• Low yield • 1 or a few boreholes	Small	Generally, few types encountered: • Informal residential • Smallholdings • Landfills	• Pit latrines • Ablution block • Small-scale farming • Landfills and dumps • Runoff/stormwater • Washing in rivers	• Management and monitoring carried out by members of the community • Hydrogeological and monitoring data is often limited
Private	Low	• Potable use • Domestic • Recreational	• Low yield • 1 or a few boreholes	Small	Generally, few types encountered: • Residential • Smallholdings • Landfills	Related to housing including: • Swimming pool maintenance • Lawn and garden care • Insect/rodent control • Septic tanks • Urban runoff/stormwater • Household hazardous wastes • Golf course irrigation and lawn care	• Management and monitoring carried out by the owner of the borehole and DWS • Hydrogeological and monitoring data is often limited
Commercial Agriculture	Low to well-funded	• crop irrigation and livestock watering	• High yield • numerous boreholes (i.e. 5-20)	Vary from small to large	Generally, one or few types encountered: • Commercial agriculture • Smallholdings	• Automotive wastes from farm machinery repair • Animal feeding operations • Grazing animals • Farm chemical distribution such as pesticides and fertilizers • Above and below ground storage tanks of diesel fuel and other chemicals	• Management collaboration between farmers, agricultural associations, irrigation boards and/or water user associations, but cases of unregistered/ unlicensed use are common • Monitoring and data collection often lacking
Large Scale Industrial	Low to well-funded	• Operations for manufacturing and processes occurring at industry	• High yield • numerous boreholes (i.e. 1-20)	Vary from small to large	Generally multiple types encountered: • Urban and/or residential • Landfills and dumps • Recreational parks • Sportsgrounds	• Above and below ground storage tanks • Water transfer/recycling stations • Utility stations/ maintenance areas • Septic tanks, stormwater runoff • Landfills and dumps • Other activities specific to the industry	• High- and low-level management by industries, consultancies, local government and DWS • Frequent monitoring and data collection

Use	Budget	Supply Purpose	Supply Yield	Relative Radius of influence	Common Landuse	Common Potentially Contaminating Activities	Management monitoring and data collection
Municipal/ Bulk Water Supply	Low to well-funded	Municipal water supply	• High yield • numerous boreholes (i.e. 1-20)	Vary from small to large	Generally, few types encountered: • Urban and/or residential • Landfills and dumps • Recreational parks • Sportsgrounds	PCAs relating to urban and residential areas most common: • Housing • Parks • Wastewater facilities	• Management by local government, DWS and operated with appointment of specialist consultants • Frequent and extensive monitoring and data collection
Mining and Construction Dewatering Schemes	Well-funded	Mining water supply and dewatering for construction and mining	• High yield • numerous boreholes (i.e. 1-20)	Large	• mining	• mine spills • tailings dam • heavy metal contamination	• Management by mine and associated specialists, government, and DWS • Frequent and extensive monitoring and data collection. May have issues with data sensitivity.

APPENDIX B: Groundwater Protection Scheme

Table B-1 Example of DRASTIC DSVI parameters, with associated range, ratings, and the weighting of each parameter. Adapted from (Aller et al., 1987.)

Parameter (Xr)	*Range*	*Rating*	*Weighting*
Dr - Depth to ground water (mbgl)	*>30*	*1*	*5*
	20-30	*2*	
	15-20	*3*	
	10-15	*5*	
	5-10	*7*	
	1,5-5	*9*	
	0-1,5	*10*	
Rr - Net recharge per annum (mm)	*0-125*	*1*	*4*
	125-250	*3*	
	250-1270	*6*	
	1270-2540	*8*	
	>2540	*9*	
Ar - Aquifer Media	*Massive shale*	*1*	*3*
	Metamorphic/igneous rocks	*3*	
	Weathered metamorphic/igneous rocks	*4*	
	Glacial till	*5*	
	Basalt	*6*	
	Bedded sandstone, limestone and shale sequence	*7*	
	Massive sandstone	*8*	
	Massive limestone	*9*	
	Sand and gravel	*9*	
	Karst limestone	*10*	
Sr - Soil Media	*Non-shrinking and non-aggregated clay*	*1*	*2*
	Muck	*2*	
	Clay Loam	*3*	
	Silty Loam	*4*	
	Loam	*5*	
	Sandy Loam	*6*	
	Shrinking and/or aggregated clay	*7*	
	Peat	*8*	
	Sand	*9*	
	Gravel	*10*	
	Thin or Absent	*10*	
Tr - Topography (% slope)	*>18*	*1*	*1*
	12-18	*3*	
	6-12	*5*	
	2-6	*9*	
	0-2	*10*	
Ir - Impact of the vadose zone (geology specific to Western Cape)	*Silt/Clay*	*1*	*5*
	Shale	*1*	
	Confining layer	*1*	
	Basalt	*2*	
	Limestone	*3*	
	Metamorphic and Igneous rocks	*4*	
	Sandstone	*6*	
	Bedded limestone, sandstone and shale	*6*	
	Sand, silt with clay	*6*	

Parameter (Xr)	Range	Rating	Weighting
	Sand and gravel	8	
	Karst limestone	10	
Cr - Hydraulic conductivity at water table (m/sec)	Unweathered marine clay (8×10^{-13} to 2×10^{-9})	1	3
	Clay (1×10^{-11} to 4.7×10^{-9})	1	
	Till (1×10^{-12} to 2×10^{-6})	2	
	Silt, loess (1×10^{-9} to 2×10^{-6})	2	
	Fine sand (2×10^{-7} to 2×10^{-4})	6	
	Medium sand (9×10^{-7} to 5×10^{-4})	8	
	Coarse sand (9×10^{-7} to 6×10^{-3})	9	
	Gravel (3×10^{-4} to 3×10^{-2})	10	
Lr - Land-use	Bare soil	0	1
	Low/low vegetation	0	
	Moderate vegetation	0	
	High/Dense vegetation	0	
	Irrigation dams	5	
	Wetland occasional	1	
	Wetland seasonal	1	
	Wetland permanent	1	
	Open water	1	
	Urban smallholdings	2	
	Wetland inundated	2	
	Cultivation	5	
	Wetland transformed to cultivation	5	
	Landfill site	5	
	Mine	6	
	Urban formal low density	6	
	Urban formal high density	7	
	Urban commercial	7	
	Urban informal high density	8	
	Urban transformed from wetland	8	
	Urban infrastructure	8	
	Urban industrial	8	
Fm - Fractured Media			
Length (max. length per 500 m^2)	0-2	2	3
	2-4	4	
	4-6	6	
	6-8	8	
	>8	10	
Fracture Density (fracture/500 m^2)	0-2	2	
	2-4	4	
	4-6	6	
	6-8	8	
	>8	10	
Orientation/azimuth	**E-W** trending oblique fractures	6	
	NW-SE cross-joints		
	NE-SW longitudinal fractures that trend subparallel to the fold hinges or SBMZ	6 8	

Table B-2 Example of DSVI classes of vulnerability

DSVI value	*Class*
< 86	*Extremely Low (EL)*
86-107	*Very Low (VL)*
107-128	*Low (L)*
128-149	*Moderate (M)*
149-170	*High (H)*
170-190	*Very High (VH)*
190-270	*Extremely High (EH)*

Table B-3 **List of PCA's. The highest level of risk is represented by the number 4, and the lowest level of risk is represented by the number 1 (Division of Drinking Water and Environmental Management, 1999 (California-based guidelines))**

Source	***Contaminants***	***Level of Risk***
Commercial/ Industrial		
Automobile body shops/repair shops	*Waste oils; solvents; acids; paints; automotive wastes[4], cutting oils*	*3*
Car washes	*Soaps; detergents, waxes; miscellaneous chemicals; hydrocarbons*	*2*
Gas stations/sumps	*Oils; solvents; miscellaneous wastes*	*4*
Cement/concrete plants	*Diesel fuels; solvents; oils; miscellaneous wastes; salts; high pH*	*2*
Chemical/petroleum processing/storage	*Hazardous chemicals; solvents; hydrocarbons; heavy metals; asphalt*	*4*
Dry cleaners	*Solvents (perchloroethylene, petroleum solvents, Freon); spotting chemicals (trichloroethane, methylchloroform, ammonia peroxides, hydrochloric acid, rust removers, amyl acetate)*	*4*
Electrical/electronic manufacturing	*Cyanides; metal sludges; caustic (chromic acid); solvents; oils; alkalis; acids; paints and paint sludges; calcium fluoride sludges; methylene chloride; perchloroethylene; trichloroethane; acetone; methanol; toluene; PCB's*	*3*
Fleet trucking/trucking/bus terminals	*Waste oil; solvents; gasoline and diesel fuel from the vehicles and storage tanks; fuel oil; other automotive waste[4]*	*3*
Food Processing	*Nitrates; salts; phosphorous; miscellaneous food wastes; chlorine; ammonia; ethylene glycol*	*2*
Funeral services/graveyards	*Formaldehyde; wetting agents; fumigants; solvents; leachate; lawn and garden maintenance chemicals[5]*	*2*
Hardware/lumber/parts store	*Hazardous chemicals products; heating oil and forklift oil from storage tanks; wood-staining and treating products, i.e. creosote; paints; thinners; lacquers; varnishes*	*2*
Home manufacturing	*Solvents; paints; glues and other adhesives; waste insulation; lacquers; tars; sealants; epoxy wastes; miscellaneous chemical wastes*	*3*
Junk/scrap/salvage yard	*Automotive wastes[4]; PCB contaminated wastes; any wastes from businesses[6]; and households[7]; oils; lead*	*3*
Machine shops	*Solvents; metals; miscellaneous organics; sludges; oily metal shavings; lubricant and cutting oils; degreasers (tetrachloroethylene); metal marking fluid; mold-release agents*	*3*
Medical/vet offices	*X-ray developers and fitters[8]; infectious wastes; radiological wastes; biological wastes; disinfectants; asbestos; beryllium; dental acids; miscellaneous chemicals*	*1*

Source	***Contaminants***	***Level of Risk***
Metal plating/finishing/fabricating	*Sodium and hydrogen cyanide; metallic salts; hydrochloric acid; sulfuric acid; chromic acid; boric acid; paint wastes; heavy metals; plating wastes; oil; solvents*	*4*
Category A Mine	*Any mine with any kind of extractive metallurgical process, including heap leaching. (This will include most other precious and base metal mines), and any mine where pyrites occur in the mineral deposit*	*4*
Category B and C Mine	*No contaminants of significant impact on the water environment, only leakages from vehicles and machinery may occur (Hydrocarbons; heavy metals; building wastes)*	*2*
Office buildings/complexes	*Building wastes[6]; lawn and garden maintenance chemicals[5]; gasoline; motor oil*	*1*
Parking lots/malls	*Hydrocarbons; heavy metals; building wastes[6]*	*2*
Photo processing/printing	*Bio sludges; silver sludges; cyanides; miscellaneous sludges; solvents; inks; dyes; photographic chemicals*	*3*
Plastic/synthetic producers	*Solvents; oils; miscellaneous organic and inorganics (phenol, resins); paint wastes; cyanides; acids; alkalis; wastewater treatment sludges; cellulose esters; surfactant glycols; phenols; formaldehyde; peroxides*	*4*
Research laboratories	*X-ray developer and fixers[8]; infectious wastes; radiological wastes; biological wastes; disinfectants asbestos; beryllium; solvents; infectious materials; drugs; disinfectants; quaternary ammonia hexachlorophene, peroxides, chlornexade, bleach; miscellaneous chemicals*	*3*
Sewer lines	*Sewage*	*3*
Wood preserving/treating	*Wood preservatives; creosote, pentachlorophenol, arsenic*	*3*
Wood/pulp/paper processing and mills	*Metal acids; minerals; sulfides; other hazardous and non-hazardous chemicals[9]; organic sludges; sodium hydroxide; chlorine; hypochlorite; chlorine dioxide; hydrogen peroxide; treated wood residue (copper quinolate, mercury, sodium bazide); tanner gas; paint sludges; solvents; creosote; coating and gluing wastes*	*3*
Agricultural/Rural		
Confined animal feeding operations	*Livestock sewage waters; nitrates; phosphates chloride; chemical sprays and dips for ticks and insects; bacterial, fungal, and viral pests on livestock; coliform[10] and non-coliform bacteria; viruses protozoa; TDS*	*4*
Grazing animals, other animals operations	*Livestock sewage waters; nitrates; phosphates; coliform and non-coliform bacteria; protozoa; viruses; TDS*	*3 (>5 animals/acre)* *2 (<5 animals/acre)*

Source	**Contaminants**	**Level of Risk**
Dairies	*Livestock sewage wastes; nitrates; TDS; salts; phosphates; potassium*	*2*
Farm chemical distributor/application services	*Pesticides[11]; fertilizers[12]; hydrocarbons from moto vehicles and storage tanks*	*3*
Farm machinery repair	*Automotive wastes[4]; welding wastes*	*3*
Irrigated crops	*Pesticides[11]; fertilizers[12]; nitrates; phosphates; potassium (can be worsened due to over-watering)*	*2*
Lagoons	*Nitrates; livestock sewage waters; salts; pesticides[11]; fertilizers[12]; bacteria*	*3*
Non-irrigated crops	*Pesticides[11]; fertilizers[12]; nitrates; phosphates; potassium*	*1*
Pesticide/fertilizer/petroleum storage and transfer areas	*Pesticides[11] fertilizers[12]; petroleum residues*	*3*
Rural homesteads	*Machine shops:* *Automotive wastes[4]; welding wastes; solvents; metals; lubricant sludges* *Septic systems:* *Septage; coliform[10] and non-coliform bacteria; viruses; nitrates; heavy metals; synthetic detergents; cooking and motor oils; bleach; pesticides[5,13]; paints paint thinners; photographic chemicals; swimming pool chemicals[14]; septic tank/cesspool cleaner chemicals[15]; elevated levels of chloride, sulfate, calcium, magnesium, potassium and phosphate*	*2*
Sludge application to land	*Organic and inorganic chemicals, coliform and non-coliform bacteria; viruses; protozoa[16]*	*2*
Agricultural drainage	*Pesticides[11]; fertilizers[12]; TDS; TOC; nitrates*	*2*
Residential/ Municipal		
Airports (maintenance/fueling areas)	*Jet fuels, de-icers; diesel fuel; chlorinated solvents; automotive wastes[4]; heating oil; building wastes[6]*	*4*
Apartments and condominiums	*Swimming pool chemicals[14]; pesticides for lawn and garden maintenance and insect/rodent control[5,13]; wastes from on-site sewage treatment plants; household hazardous wastes[7]*	*1*
Campgrounds/RV parks	*Septage; gasoline; diesel fuel from boats; pesticides for controlling mosquitoes, ants, ticks, moths and other pests[11,13]; household hazardous wastes[7]*	*1*
Drinking water treatment plants	*Treatment chemicals; pesticides[11]*	*2*
Fire stations	*General building wastes[6]; hydrocarbons from test burn areas*	*1*
Golf courses	*Fertilizers[12]; herbicides[11]; pesticides for controlling pests[5]*	*2*
Housing	*Household hazardous wastes[7]:* *Household cleaners; oven cleaners; drain cleaners toilet cleaners disinfectant; metal polishes; jewellery cleaners; shoe polishes; synthetic detergents;*	*2*

Source	***Contaminants***	***Level of Risk***
	bleach; laundry soil and stain removers; spot removers dry cleaning fluids; solvents; lye or caustic soda; household pesticides[13]; photo chemicals; printing ink; paints; varnishes; stains; dyes; wood preservatives (creosote); paint and lacquer thinners; paint and varnish removers and de-glossers; paint brush cleaners; floor and furniture strippers *Mechanical Repair and other maintenance products:* *Automotive wastes[4]; waste oils; diesel fuel; kerosene; heating oil; grease; degreasers for driveways; asphalt and roofing tar; tar removers; lubricants; rust proofing; car wash detergents; car waxes and polishes; rock salt; refrigerants* *Lawn/garden care:* *Fertilizers[11]; herbicides and other pesticides used for lawn and garden maintenance[5] (can be worsened by overwater)* *Swimming pools:* *Swimming pool maintenance chemicals[14]* *Urban runoff/stormwater[3]* *Gasoline; oil; other petroleum products; microbiological contaminants*	
Landfills/dumps	*Leachate; organic and inorganic chemical contaminants; waste from households[7] and businesses[6]; nitrates; oil; metals; solvents sludge*	*4*
Motor pools	*Automotive wastes[4]; solvents; waste oils; hydrocarbons from storage tanks*	*2*
Parks	*Fertilizers[12]; herbicides[5]; insecticides[11,13] (can be worsened by over watering)*	*2*
Railroad yards/maintenance/fueling areas	*Diesel fuel; herbicides for right of way[11]; creosote for preserving wood ties; solvents; paints; waste oils*	*3*
Recreational use of surface water sources (body contact)	*Microbial contamination from swimmers*	*1*
Recreational use of surface water sources (motorized watercraft)	*Gasoline fuel from watercraft, marinas*	*2*
Schools	*Machinery/vehicle serving wastes; gasoline and heating oil from storage tanks; general building waste; pesticides*	*1*
Septic tanks	*Septage; coliform[10] and non-coliform bacteria; viruses; nitrates; heavy metals; synthetic detergents; cooking and motor oils; bleach; pesticides[5,13]; paints and paint thinners; photographic chemicals; swimming pool chemicals[14]; septic tanks/cesspool cleaner chemicals[15]; elevated levels of chloride sulfate;*	*4*

Source	***Contaminants***	***Level of Risk***
	calcium; magnesium; potassium and phosphate; other household hazardous wastes[7]	
Sewer lines	*Sewage*	*3*
Utility stations/maintenance areas	*PCBs from transformers and capacitors; oils; solvents; sludges; acid solution; metal plating solutions (chromium, nickel, cadmium); herbicides from utility rights of way*	*3*
Waste transfer/recycling stations	*Residential and commercial solid waste residues*	*2*
Wastewater	*Municipal wastewater; sludge*[16]*; treatment chemicals*[17]*; nitrates; heavy metals; coliform*[10] *and non-coliform bacteria; non-hazardous wastes*	*4*
Other		
Informal settlements	*Unknown sanitation facilities – pit latrines, ablution blocks, mobile toilets, open defecation, etc.*	*2*
Above ground storage tanks	*Heating oil, diesel fuel; gasoline; other chemicals*	*2*
Construction/demolition areas (plumbing, heating, air-conditioning, painting, paper hanging, decorating, drywall and plastering, acoustic insulation, carpentry, flowing, roofing and sheet metal, etc.)	*Solvents, asbestos, paints; glues and other adhesives; waste insulation; lacquers; tars; sealants; epoxy waste; miscellaneous chemical wastes*	*2*
Historic petrol stations	*Diesel fuel; gasoline; kerosene*	*4*
Historic waste dumps/landfills	*Leachate; organic and inorganic chemicals; wastes from households*[7] *and businesses*[6]*; nitrates; oils; heavy metals; solvents*	*4*
Hospitals	*Various chemical and radiological substances and microorganisms*	*2*
Injection wells/drywell/sumps	*Stormwater runoff*[3]*; spilled liquids; used oils; antifreeze; gasoline; solvents; other petroleum products; pesticides*[11]	*4*
Managed forests	*Pesticides; fertilizers; TDS*	*4*
Medical/dental offices and clinics	*Various substances*	*1*
Military installations	*Wide variety of hazardous and non-hazardous wastes depending on the nature of the facility and operation*[3,9]*; diesel fuels; jet fuels; solvents; paints; waste oils; heavy metals; radioactive wastes*	*4*
Seawater Intrusion	*Salinity, disinfection by-products*	*3*
Silviculture	*Pesticides, fertilizers, TDS*	*2*
Surface water – stream/lakes/rivers/dams	*Directly related to the water quality of the surface body way water which recharges the groundwater/*	*3*
Transportation corridors	*Herbicides in high-way right of way*[5,11]*; road salt, anti-cracking additives (ferric ferrocyanides, sodium ferrocyanide); anticorrosive (phosphate and chromate); automotive wastes*[4]	*2*
Underground storage tanks	*Diesel fuel; gasoline; heating oil; other chemical and petroleum products*	*4*
Wells, agricultural (such as irrigation wells, or abandoned wells)	*Strom water runoff*[3]*, irrigation water runoff; nitrates, pesticides, and other substances*	*2*

Source	**Contaminants**	**Level of Risk**
Wells gas, oil geothermal	*Various petroleum-related substances, inorganics*	*3*

[3] Stormwater Run-off: it is not possible to list all the contaminants in stormwater run-off or from military installations

[4] Automotive wastes include gasoline, antifreeze, automatic transmission fluid, battery acid, engine and radiator fluids, engine and metal degreasers, hydraulic brake fluid and motor oils

[5] Pesticides: common pesticides that are used for lawn and garden maintenance, such as weed killers, mite, grub, aphid controls. The pesticides typically include chemical compounds such as, 2,4-D, chlorpyrifos, diazinon, benomyl, captan, dicofol and methoxychlor.

[6] Building wastes: include automotive wastes, residues from cleaning products that may contain chemicals such as xylenols, glycol esters, isopropanol, 1,1,1-trichloroethane, sulfonates, chlorinated phenols and cresols

[7] Household hazardous wastes: common household products that contain a variety of toxic or hazardous components.

[8] X-ray developers and fixers may contain reclaimable silver, glutaldehyde, hydroquinone, potassium bromide, sodium sulfite, sodium carbonate, thiosulfates and potassium alum.

[9] Hazardeous waste: solid waste that may cause an increase in mortality or serious illness or pose a substantial threat to human health and the environment when improperly treated, stored, transported, disposed of, or otherwise managed. A waste is hazardous if it exhibits characteristics of ignitability, corrosivity, reactivity and/or toxicity.

[10] Coliform bacteria: can indicate the presence of pathogenic (disease-causing) microorganisms that may be transmitted in human faeces. Diseases such as typhoid fever, hepatitis, diarrhoea, and dysentery can result from sewage contamination of water supplies.

[11] Pesticides include herbicides, insecticides, rodenticides, fungicides and avicides. There are about 50,000 registered pesticides, many of which are highly toxic and mobile in the subsurface.

[12] The EPA National Pesticides Survey found that the use of fertilizers correlates to nitrate contamination of groundwater supplies.

[13] Common household pesticides for controlling pests, such as ants, termites, bees, wasps, flies, cockroaches, silverfish, mites, ticks, fleas, worms, rats, mice all contain an active ingredient including, naphthalene, phosphorus, xylene, chloroform, heavy metals, chlorinated hydrocarbons, arsenic, strychnine, kerosene, nitrosamines, and dioxin.

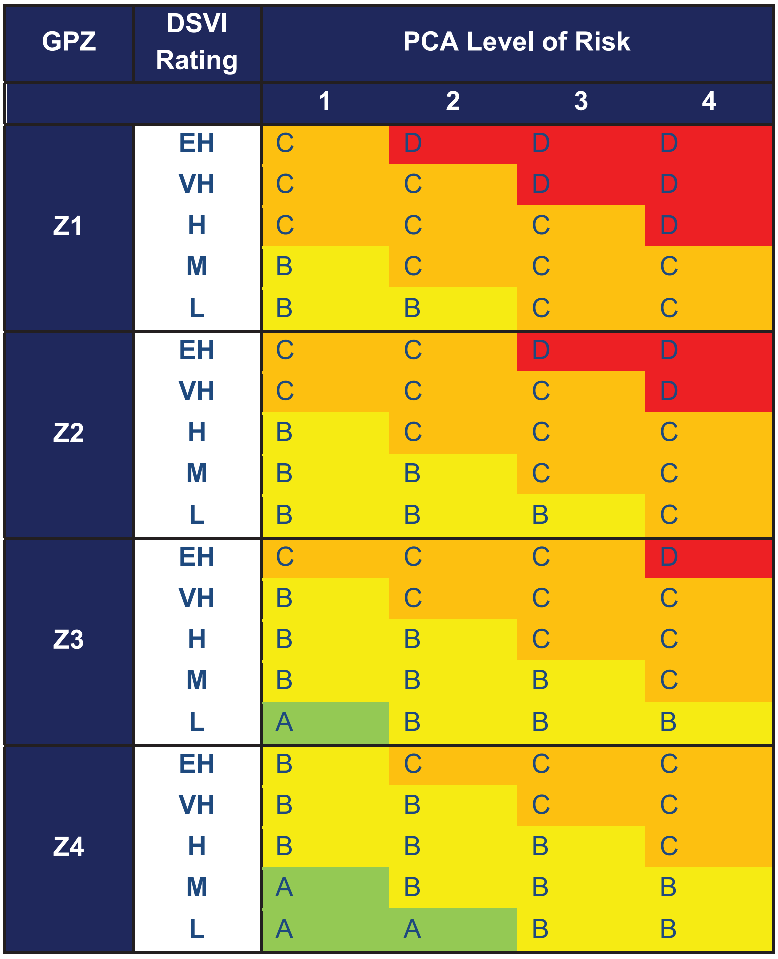
[14] Swimming pool chemicals: contain free and combined chloride; bromine; iodine; mercury based, copper based, quaternary algaecides; cyanuric acid calcium or sodium hypochlorite; muriatic acid; sodium carbonate

[15] Septic tank/cesspool cleaners: include synthetic organic chemicals such as 1,1,1 tricholorethane, tetrachloroethylene, carbon tetrachloride and methylene chloride

[16] Municipal wastewater treatment sludge: can contain organic matter, nitrates, inorganic salts, heavy metals, coliform and noncoliform bacteria, protozoa (giardia and cryptosporidium) and viruses

[17] Municipal wastewater treatment chemicals: include calcium oxide, alum, activated alum, carbon, silica, polymers, ion exchange resins, sodium hydroxide, chlorine, ozone, and corrosion inhibitors.

Table B-4 **Example of Protection Response Matrix. Red squares represent the highest risk, whilst green squares represent the lowest risk.**



GPZ	DSVI Rating	PCA Level of Risk			
		1	2	3	4
Z1	EH	C	D	D	D
	VH	C	C	D	D
	H	C	C	C	D
	M	B	C	C	C
	L	B	B	C	C
Z2	EH	C	C	D	D
	VH	C	C	C	D
	H	B	C	C	C
	M	B	B	C	C
	L	B	B	B	C
Z3	EH	C	C	C	D
	VH	B	C	C	C
	H	B	B	C	C
	M	B	B	B	C
	L	A	B	B	B
Z4	EH	B	C	C	C
	VH	B	B	C	C
	H	B	B	B	C
	M	A	B	B	B
	L	A	A	B	B

GUIDANCE DOCUMENT ON PROTECTION ZONES (DELINEATION AND PROTECTION): DEVELOPMENT OF METHODOLOGICAL APPROACH AND IMPLEMENTATION PLAN

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WATER RESEARCH COMMISSION

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